SCOPE 24

Noise Pollution

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SCOPE 24

Noise Pollution

Effects and Control

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Contents

PART I FUNDAMENTALS OF NOISE AND HEARING

PART II EFFECTS OF NOISE ON MAN

PART III SOURCES OF NOISE AND CONTROL

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Preface

J. B. Large

Perhaps the title does not reflect the true content of this book, which comprehensively covers the major topics in what has become generally the subject of acoustics. The book contains chapters on the basic physics of vibration and sound and their effect upon man. There are 18 chapters, which are divided into three sections: fundamentals of noise and hearing, effects of noise on man, and sources of noise and its control.

Fifty years ago noise pollution did not exist as a subject to be studied and acoustics was basically a branch of physics with the embryonic topics of architectural acoustics and electroacoustics acknowledged by only a few cognoscenti. Concern for noise as a social problem was nominal except for a couple of pioneering programmes in San Francisco and New York in the late 1920s and early 1930s. During the decade before the Second World War there was a growing resentment to the noise caused by the expansion of road and air transportation systems. It was during this period that municipal airports were sited and their expansive development was begun. The British govermment study in 1938 concluded that the problem of aircraft noise nuisance was one which inhibited a major expansion of the industry.

The Second World War was not an opportune period to raise concern for noise pollution but as in many other fields, it did foster the development of much basic science, and technology was developed that served as a foundation for many of the post-war developments. Besides the increasing sophistication of electroacoustics, which provided the device for noise measurement and analysis, two other developments greatly aided the post-war work. The first was in the technique of psychophysics, which led relationships between physical stimuli and psychological response. Without these methods it would have been impossible to carry out the many laboratory and noise survey programmes. The second development was the collection of data on the propagation of noise from various sources and over a variety of terrains and ground covers. Some of these data are still of value but it gave an insight into the complexities of an analytical approach.

After the war it became apparent that the most spectacular new noise source was the jet-powered aircraft. Initially this noise problem was confined to air force bases, and the concern for the effects of this noise pollution on the inhabitants produced a significant study by the US Air Force, and a result of this study was the community noise rating index. This most valuable programme only received public recognition by the US government many years after the work began. In the late 1950s civil air transportation had reached a level of activity which was giving cause for alarm in those communities close to major airports. Just prior to the introduction of jet aircraft the Port of New York Authority developed far-reaching criteria for aircraft take-off noise. This resulted in the setting-up of a specific noise level for jet aircraft and also the introduction of a new unit based upon the concept of noisiness, which have profoundly affected subsequent developments in civil aviation.

Contemporary with this initiative was the beginning of a comprehensive review of noise effects by the Wilson Committee in the UK, resulting in 1963 in their financial report on the problems of noise. This British study stimulated a variety of field surveys and laboratory tests into the effects of road traffic and aircraft noise. The most famous and significant was the first London Airport noise survey, conducted in 1961, which has served as a prototype of most noise surveys since that date. The next fifteen years witnessed an upsurge of interest in control of the environment and the problem of noise pollution became a universal problem. Once again the pattern of development was led by the noise problems created by aircraft. Aircraft noise did not occur on such a grand scale as traffic or industrial noise but it produced a series of disturbances for about 5 per cent of the population. Serious progress in solving the noise problem was possible because of the financial and technological support given to the air transportation industry. A combined legislative approach through noise certification of new aircraft and by environmental regulations is producing a sustained decrease in noise exposure. Since the introduction of noise certification similar processes have been developed for other forms of transportation. There are many national and international organizations currently involved in noise legislation over a wide range. It is difficult to remain aware of all of these activities although the contents of this monograph provides a comprehensive guide. Noise control has become complicated, particularly in some Western European countries who as part of the European Community are subject to local regulations, European Community criteria, and international standards.

During the active period of environmental concern the basic science and technology developed rapidly. Study of the work of some great nineteenth century scientists such as Helmholtz, Rayleigh and Lamb became fashionable and provided a basic insight into the physics of noise. Their work was extended and enhanced so that it could be applied in a contemporary context. James Lighthill perhaps provides the best example of someone whose research linked scientific work with modern technology requirements. The skills of the medical practitioner, social scientist and psychologist have been directed at many facets of the noise pollution problem, and is well illustrated by the diversity of the authors. Perhaps it is necessary to offer a word of warning to the reader, who will learn of the effects of noise on people, of the available technology to make quieter road vehicles or aircraft, or of the noise regulations and criteria developed to effect control, but that the technology will only be effective if regulations are enforced. The cost of noise control can be enormous and more work is urgently required to identify the true cost. The need for noise control must be placed alongside other social and political priorities. Also the reader must carefully screen the many scientific facts and conclusions contained throughout this book, for the variability of the data particularly applied to conclusions affecting the general population is enormous. The work contained in this book clearly identifies that high levels of noise exposure can affect us in many different ways. Data are usually presented for a single source such as aircraft, road traffic or industrial machines, but we do not live in a single-source environment. Our noise exposure is varied, and research must be directed to examine the effect of complex noise environments experienced in everyday life. Although this is a difficult and detailed process, until we can produce such evidence our work can rightly be viewed as oversimplification of the problem and perhaps penalising one source of noise is inadequate in an environment composed of many sources. The book is a true reflection of our current knowledge and indicates how much intellectual effort is now at work to overcome the problems of noise pollution.

Noise Pollution
Edited by A. Lara Sáenz and R. W. B. Stephens
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Noise Pollution — Introductory Survey

R. W. B. STEPHENS

> 'There is no sound but shall find some lovers, as the bitter'st confections are grateful to some palats.'
>
> ... Ben Jonson

POLLUTING

'Polluter pollutes and Sufferer suffers the consequences. The (marginal) costs of pollution abatement are such that it is cheap to clean-up a little; but it becomes harder and harder to get cleaner and cleaner, until the last bit of pollutant is very expensive, if not impossible to eradicate. The (marginal) damage to the Sufferer is just the opposite. That last bit of pollutant at the clean end of the range causes little damage and might even go unnoticed. Successive additions of pollutant become more serious as one moves, perhaps, from aesthetic considerations, to inconvenience, to damaged health'.*

Noise is concerned with sounds which annoy us and may have a long-term physiological effect on an individual. In order to describe any sound we must measure its magnitude and frequency spectrum, and the variation of these parameters with time. These objective measurements are comparatively easy to carry out with modern instrumentation. The real problem is the subjective aspect, i.e. to predict the cumulative impact of sound on people, and this entails the development of a methodology which modifies the physical measurements so that they give a reasonably accurate indication of the physiological impact.

It is said that at the beginning of this century four out of every five humans lived in the countryside, but by the year 2000 it is estimated that at least one-half of the world's population will live (or work) in urban areas. An enormous increase in the world population will also take place and this, with the increase in magnitude and speed of modern transportation and the advances in technology, will accentuate the problems of maintaining and improving the standards of the human environment. The deterioration of the

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*From *Games as Models of Social Phenomena* by Henry Hamburger, published by W. H. Freeman & Co.

'habitat' conditions which has occurred during recent decades is described by the general term 'pollution', of which 'noise pollution' is a specific field.

Sound, and hence noise, results from periodic disturbances of the air and at room temperature is propagated in air at a speed of approximately 340 m/s. In water and steel for example the speed is much greater, being respectively about 1500 m/s and 5000 m/s. As the disturbance spreads geometrically its effect will decrease with its distance from the sound source but the diminution in sound intensity will also be affected by the damping of the sound waves by the transmitting medium. This effect may arise in the atmosphere and is influenced by the degree of humidity and the frequency of the sound. It is of particular importance in a closed space, such as a concert hall, where the geometrical spreading is almost eliminated. Here it becomes desirable from the musical and speech intelligibility points of view to introduce sound absorbing material or resonator devices at the walls or ceiling to reduce the prolongation of a given sound, i.e. to control the reverberation of the sound. These absorbing materials are usually of a porous nature and their particular absorbing powers will depend on the frequency of the incident sound; typically they can absorb between 50 to 90 per cent of the sound energy incident upon their surfaces.

The sounds we are concerned with in industry generally emanate from the vibrating surfaces of machines, etc. These vibrations are transmitted through the body of a machine and the vibrational energy is partly transformed into sound vibrations in the air, i.e. structure-borne noise in the environment. Apart from this possible noise nuisance, the monitoring of the acoustic emission of a machine during its continual operation can give indications of any developing faults in its performance efficiency.

It is often quoted that 'one man's music may be another man's poison' and noise is generally accepted as sound of any kind which is undesired by the recipient at a given time and place. There is an old riddle which asks the question of what comes and goes with a moving carriage but which is of no use to the carriage. The answer is noise, but that emanating from an old-time carriage would have provided, most probably, only a warning signal to the pedestrian on the highway. However, on the cobbled streets of a village it could have disturbed the peace and quiet of an invalid living on the borders of the highway, so that noise control would sometimes be applied in the form of layers of straw placed on the road surface. Noise appropriately shares a common Latin root with the word nausea' and its disturbing influence on people has existed even in the distant past. It has often been quoted that Julius Ceasar prohibited the driving of chariots along the stone-cobbled streets of Rome at night.

Again, in the middle of the nineteenth century the German philosopher, Arthur Schopenhauer, writes in his *Studies in Pessimism* that 'noise is a torture to intellectual people' and he regarded in particular the cracking of whips as intolerable. This sound source is not very evident today but the noise nuisance has been accentuated with the growth of population and of engineering technology in its various forms. Even specifically generated warning signals could be necessarily of high intensity in order to achieve their pupose and, during the last century, the disagreeability of noise was recognized in the British Navy by the payment of 'noise-money' to the ship's crew during the operation of fog signals.

Although some individuals might think that total silence would seem heavenly, this thought would rapidly disappear if one was committed to spend any length of time in an anechoic room (i.e. a room in which almost complete sound absorption takes place), when the movement of body fluids and of heart beats would be quite apparent in the 'deadly silence' of such an enclosure. It is interesting to note that a silent vacuum cleaner was developed but almost the only customers were the hospitals, and a similar reaction came from secretary and typist on the appearance of a very silent typewriter.

The extent of the annoyance and discomfort experienced by an individual subjected to noise will depend not only on the frequency spectrum and intensity of the sound but also upon the aural sensitivity of the listener and upon the activities being undertaken at the time of noise exposure. Furthermore psychological, physiological and pathological aspects are involved.

Although there are some sounds that are universally regarded as noise at any time and place, there are other sounds which are valuable to man in one situation, for example as warning signals, but which at another location may prove to be quite unacceptable. It follows from the foregoing that the assessment of whether a particular sound is to be considered as noise may not be a straightforward operation and requires considerable discussion and analysis by a body which is fully representative of the involved community. Furthermore the pattern of noise is not necessarily static and can alter locally with changing transportation and industrial activity, so that regular monitoring is most desirable such as is carried out in the immediate neighbourhood of airports.

The main attention has been given to urban areas but noise can also affect the rural community, who are generally assumed to be more sensitive to noise than those living in towns and suburbs, which is usually attributed to lower background levels, around 25–30 dB(A). Typical noise nuisances in rural areas arise from agricultural and forestry operations, early-morning noisy cockerels, demolition and construction work, etc. In such rural areas in the UK the local authority is required to make periodic surveillances to ascertain the existence of any new noise nuisance.

Audio noise is often popularly described as grumbling, metallic or hissing, according to whether the source emphasizes respectively the low, high or very high audio frequencies. These distinctions lead to the idea of 'coloured noise', and the optical analogy is carried further in speaking of 'white noise' when the sound energy is evenly distributed over the whole of the audible frequency range, just as white light is a combination of all the colours of the optical spectrum. Furthermore, the infrared and ultraviolet regions of the optical spectrum have their counterparts in the infrasound and ultrasound respectively of the acoustical spectrum. Again, just as a very rapid sequence of light intensity changes in a cinema film can exhaust the optical nervous system of the observer, so does a similar effect arise with corresponding changes in a sound source. The characteristics of a sound source are influenced by the onset-time: the shorter the time the larger the number of observable overtones of the fundamental frequency. The time-variation of acoustic radiation may be conveniently divided into continuous harmonic cycling, random excitation, pulse operation and impulse.

ACOUSTICS AND ITS INTERDISCIPLINARY NATURE

To many people sound, or acoustics to give its more comprehensive title, is associated solely with speech and music (Figure I.1), and this was largely true a century ago. The improvement in modern instrumentation however has enabled mechanical vibrations to be easily detected below and above the normal range of human hearing. The former are low-frequency sounds below about 15 Hz. (i.e. cycles/second) and are termed infrasound, while above the human audio upper limit of approximately 20 kHz is ultrasound, which is now definable experimentally almost up to the limit imposed by the interatomic distance in solids (Figure I.2).

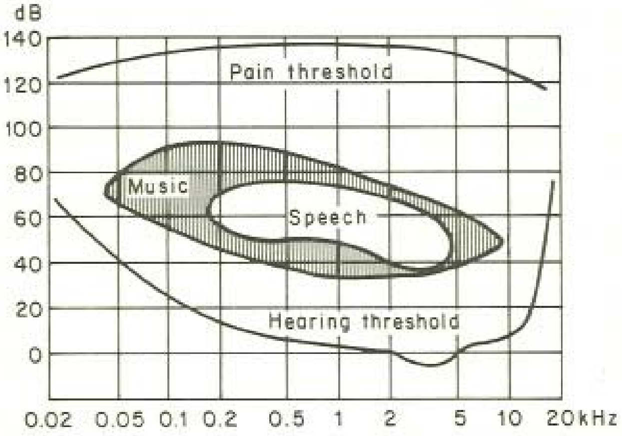
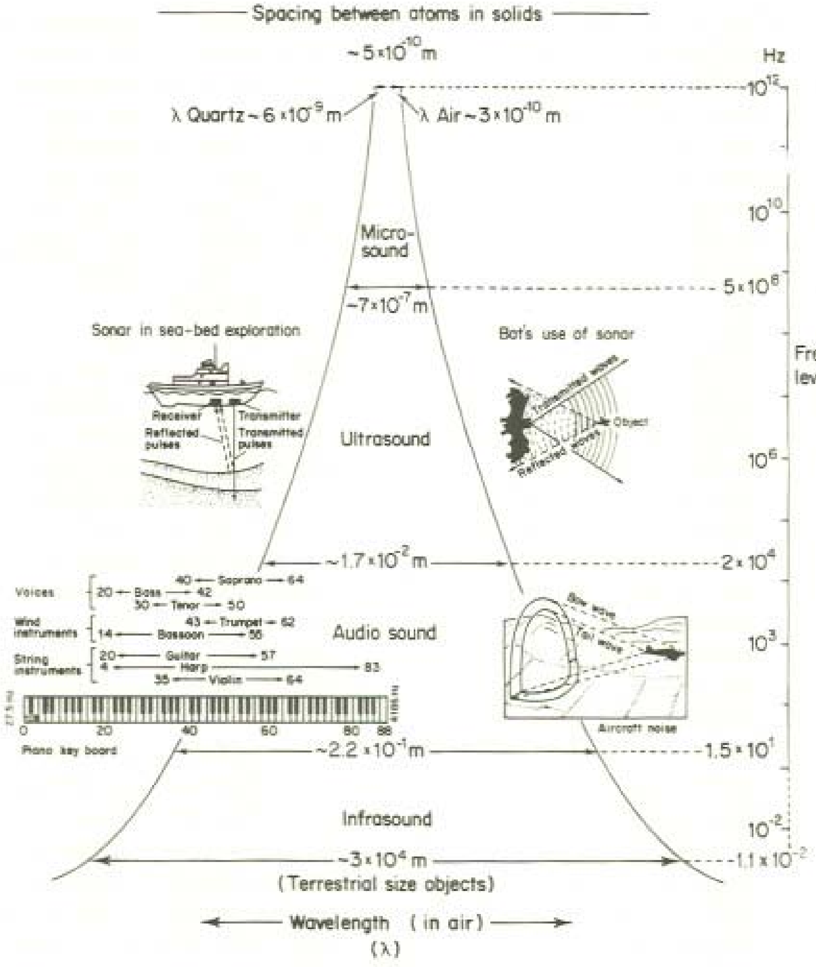


Figure I.1 Sensing areas of audible sound

Even if our atmospheric environment is seemingly silent there are present sounds of infrasonic frequencies which may, however, be quite feeble, with pressure fluctuations as low as 10^{-7} of an atmosphere but could be about



Velocity of sound at approx. 15°C
Air 340 m/s Water, pure 1440 m/s Sea water 1500 m/s Steel 5050 m/s Aluminium 5200 m/s

Figure 1.2 The Acoustic Spectrum

500 times as great. This higher value would still be only about one-tenth of the random pressure fluctuations created by a 30 kph wind, but they are still detectable by microphones of long-time constants and which are separated by several kilometres. At such distances, which are large compared even with infrasonic wavelengths, the wind fluctuations would be uncorrelated. Infrasound can be generated by jet-streams in the atmosphere, inside the cabin of a fast-moving car with an open window, by the movement of heavy lorries, by industrial compressors, etc. This

infrasound of frequencies of the order of 15 Hz or less, can be quite significant in its effect on humans, provoking a similar effect to seasickness by its action on the semicircular canals of the ear, and it can also give rise to extreme nervous tension. On the 'credit' side it should be mentioned that the central verges of many motorways have become rich in fauna. This has been attributed to the low frequency vibrations of heavy lorries which entice worms to the surface as is done by the ground tapping of certain birds. The low damping of infrasonic waves in the atmosphere was made evident in the Krakatoa volcanic eruption of 1883, when the waves traversed around the earth several times and the sound pressures were still detectable on barographs all over the world.

In its modern interpretation acoustics is generally considered to cover periodic mechanical motion of all forms and as such is effectively concerned with many aspects of modern life. This interdisciplinary nature is indicated by the roulette diagram of Figure I.3 and is succinctly expressed by Henry Crow (1930) in *The Nature of Sound*. He writes 'To the mathematician the problems of wave-motion offer a field for his highest powers of analysis; to the physicist they suggest experiments demanding all the skills at his disposal; to the engineer and to those who go down to the sea in ships these problems are matters of life and death, while to the poet and artist they are "The sea dancing to its own music".' During the half-century since these words were written many environmental changes have taken place, such as advances in high-speed air travel and in pop music with its electronic amplification, thus leading to objectionably high levels of sound intensity.

This interdisciplinary aspect of acoustics provides a broad base for showing the interdependence of the biological and physical sciences and revealing the connection between the arts, science and engineering. The control of noise also has its legal aspects and codes of practice and so becomes associated with town-planning and general societal problems. These various aspects are dealt with in detail by various international specialists in their particular fields in the chapters of the book which follow, and in this introduction it is hoped to convey a general perspective of the acoustic pollution problem.

An important milestone in the attention given to the acoustic environment of man, and on a worldwide basis, was the Second International Congress on Acoustics held in Cambridge, Massachusetts, USA, in June 1956. The theme of the meeting, attended by representatives from eighteen foreign countries, was Sound and Man. As emphasized in an opening address and which is just as significant today, is that science and technology should provide the means to 'make gentle the life of mankind', an objective attributed to the Ancient Greeks.

In the UK considerable impetus was given to the study of noise problems by the publication in 1963 of the Wilson Report on Noise, to which many scientific and technical bodies made distinctive contributions. The report contained various recommendations on the limits of noise level for particular sources and conditions and on the practical and economic aspects of enforcing them. The

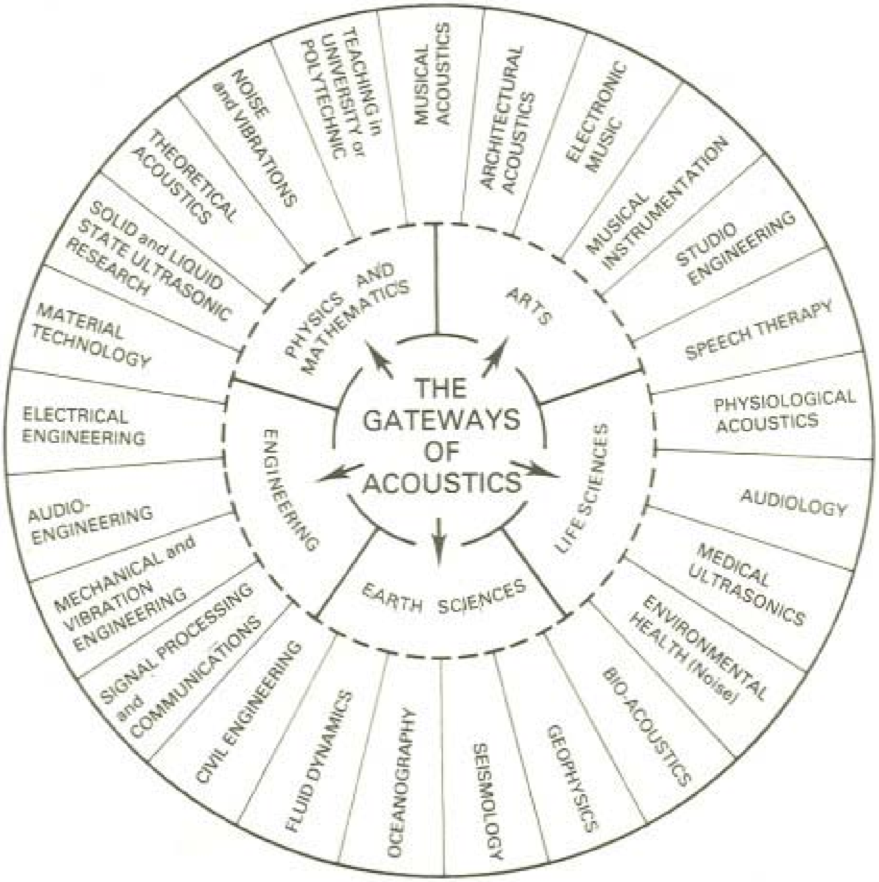


Figure I.3 The Acoustical Roulette

need for research in certain areas was also indicated and a number of courses on applied acoustics were established and stimulated provision of student bursaries by the government. Since 1963 there have been various stipulated and recommended regulations and controls, but not all are legally enforceable. The UK Control of Pollution Act 1974 embodies all of the Wilson Committee recommendations but does not lay down definite standards e.g. for neighbourhood noise. This may have been influenced by the tendency to devise different units for different sources to accommodate their particular characteristics. A different suggestion was proposed in a report of the Noise Advisory Council (UK, 1975), namely that L_{eq} might be universally used for all sources. Also, a relative measure has been suggested for rating airports in the form of the ratio of inhabitants who are seriously disturbed by the aircraft noise to the number of passengers using the airport.

NOISE MEASUREMENT

In the measurement of noise a careful choice must be made of the equipment to be used in regard to a particular type of sound and to obtain the required accuracy of measurement, also whether the instrumentation satisfied the specifications laid down by national standards organizations and by international bodies such as the International Organization for Standardization (ISO) and the International Electrotechnical Commission (IEC). The type of sound can be differentiated according to its intensity or sound pressure level, i.e. whether it remains fairly constant (so-called steady-state), if it fluctuates considerably, i.e. is intermittent, or if it exhibits very steep changes of level in a very short-time interval and which is characteristic of impulse sound. The latter could arise from gun-fire, ranging from ~ 170 dB in the immediate area of a military or naval gun to ~ 140 dB for a firework cracker, the decay time however is very short. On the other hand in the ringing (or reverberant) time of impulse noise, as created by a forge hammer, the sound may decay comparatively slowly as in a bell-tone. Although the same reading may be obtained on the fast response of a sound level meter for an impulsive as for a transient sound, the former has the greater annoyance value. This arises from the human ear having a faster response than the sound level meter with its associated circuitry and has led to the introduction of impulse sound level meters, which have a rise-time about four times faster than do the normal fast-response meters.

The sound level (L)* in decibels (dB) is defined by $L = 10 \log_{10} (P^2/P_0^2) = 20 \log (P/P_0)$, where P_0 is the reference pressure of $20\ \mu\ \mathrm{Nm}^{-2}$ and P is the sound pressure under investigation. This definition however takes no account of the different response of the human ear to noise of various frequencies and intensities and to compensate for these effects on electrical weighting network (one of four different characteristics) is incorporated in the measuring system. However, since the level at any location will generally vary with time, a method is required which will time-average the observed levels, and an international standard for environmental noise has emerged. It is the equivalent continuous A-weighted sound pressure level (L_A eq), which is the equivalent steady noise level, that in a stated period of time, would provide the same noise energy as the time-varying noise during the same period. Figure 1.4 shows the 'noise thermometer' which relates SPL and the sound pressure for various habitat activities.

THE HUMAN PATHWAY OF RECEPTION AND INTERPRETATION OF SOUND

As the main aspect of this monograph is the concern for the health and hearing

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* Also referred to as Sound Pressure Level (SPL).

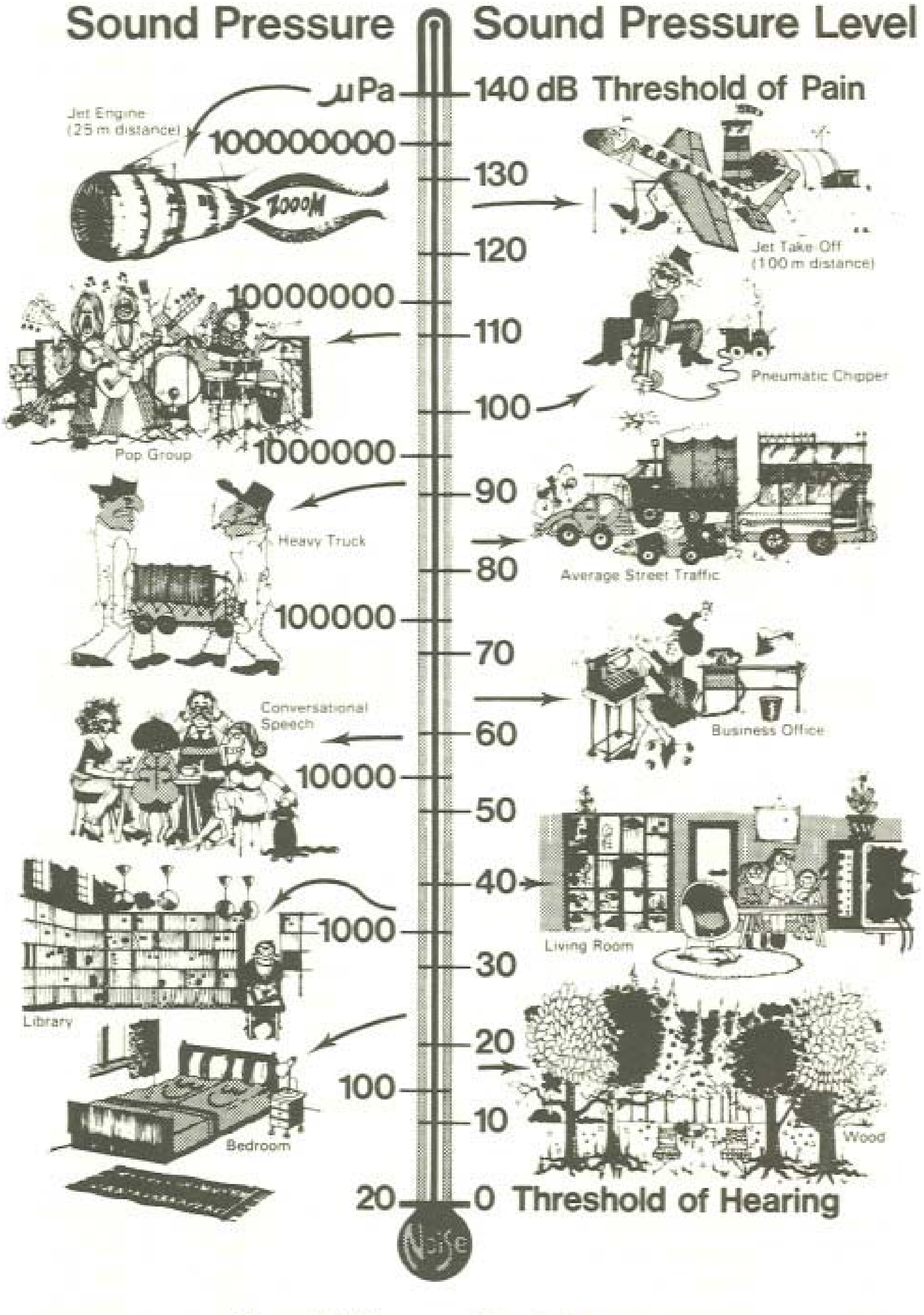


Figure I.4 (Courtesy of Bruel & Kjaer)

condition of the individual, it is appropriate at this stage, to give a short resumé of the human hearing mechanism and its general reaction, to intense sound sources. As in the case of the high optical sensitivity of the eye, the ear is very sensitive to noise and can detect the weak rustling of the leaves on trees, i.e. an acoustic intensity of the order of 10^{-10} W/m^2. At the same time the ear can accept intensities as high as 10 W/m^2, such as are generated in the vicinity of jet aircraft (there is a strong possibility, however, of physiological harm if subjected to high level signals over a long period of time. See Chapters 7 and 11). Furthermore, because of the diffraction effect, there is the possibility of sound waves bending round obstacles in their path. Hence particularly for low-frequency sound waves, whose wavelengths are comparable with the linear dimensions of earthly objects, it becomes possible for man to detect sounds not in his direct line of vision. Sound may also reach the observer from the 'hidden source' by reflection or scattering from suitably situated local surfaces. It is evident therefore that the 'blocking' of noise in the external pathway from the source to the listener may be difficult to accomplish. The use of sound barriers is dealt with in Chapters 3 and 12.

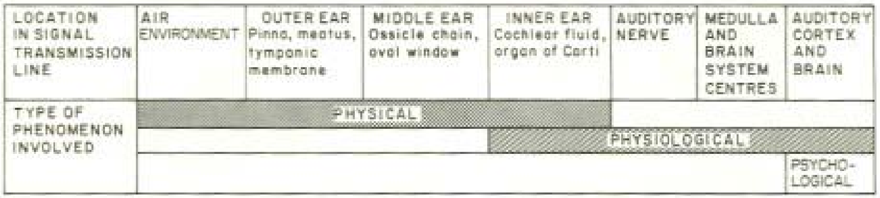


Figure I.5 The complete auditory pathway from reception to interpretation

Figure I.5 shows the complete auditory pathway, from the reception of the sound waves to the final interpretation in the brain. Before dealing with the various sections in more detail attention is directed to a broader aspect of the hearing process. It is seen that there are three different disciplines involved and that the physiological overlaps with both the physical and the psychological regions. Physiology is thus associated with the whole of the neural interactions up to the production of the sensation and interpretation of sound.

THE AUDITORY PATHWAY

Reception and Mechano-Electrical Transduction

It is the human ear which is essentially man's ultimate judge of the nature and intensity of a sound, and so the final assessment by the individual is related to the personal characteristics of his ears. The general structure of the three main compartments is shown in Figure I.6(a), but not to scale. The sound vibrations

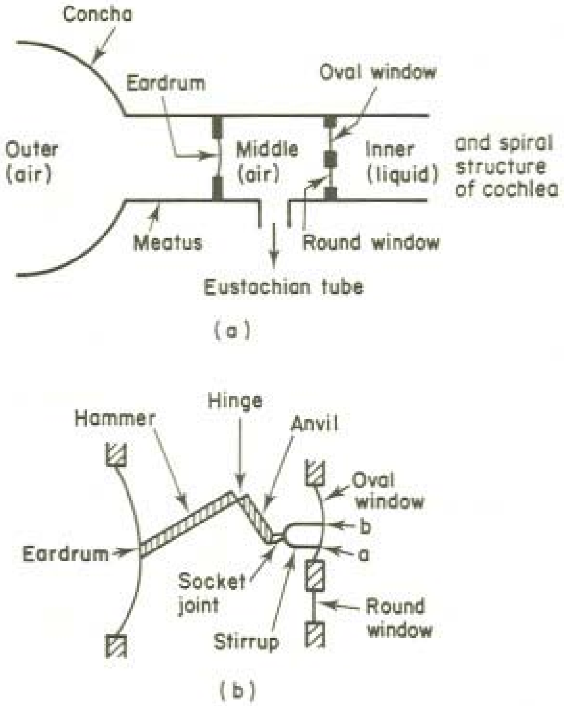
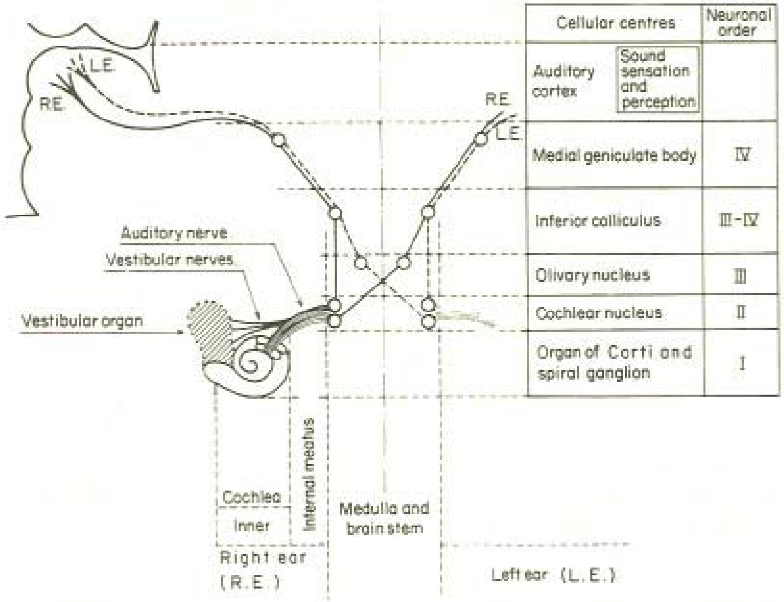


Figure I.6 The acousto-mechanical pathway of the ear: (a) from outer receptor to cochlea; (b) details of middle ear

are propagated in turn, through the air of the outer ear, the solid bones of the middle ear and finally the liquid of the inner ear. These sections have their respective functions of collecting the incident sound waves, of converting them first into solid vibrations, then into hydrostatic pressure waves and finally into electrical impulses. As is common to all types of energy transfer, from one medium to another of different density, the greatest efficiency of transfer involves 'the matching of impedances' (see Chapter 1). It is at high frequencies the external meatus, acting like a horn, provides efficient coupling between the sound-field and the ear-drum. The middle-ear bones (hammer, anvil and stirrup in Figure I.6b), the ear-drum with its relatively large surface area and the small oval window, act together as an efficient transmitter to the inner ear only below 1 or 2 kHz. It is interesting to note that the displacement of the eardrum in ordinary conversation would only be of the order of 10^{-8}cm. The excitation of the oval window leads to travelling sound waves in the cochlear fluid and by transduction to electrical pulses in the organ of Corti, where the pulses are codified. The Eustachian tube communicates with the nasal cavity and enables the air pressure within the middle-ear to be quickly adjusted to sudden pressure changes in the outer ear, as is experienced for example during rapid motion in a deep lift-shaft.

Signal Interpretation

The codified electrical impulse signals from the organ of Corti are transmitted to the brain through some thirty thousand individual fibres, which form the auditory nerve (Figure I.7). The main trunk of the nerve branches out into numerous individual nerve cells, called neurons. The number of cells which are activated depends on the strength of the electrical impulse and so could be an indication of the loudness of the acoustic signal. The sensation of sound is derived by the decodification of the nerve impulse in the auditory area of the cortex while interpretation occurs by interaction, in an associated cortex area, with the brain mental functions.



Cellular centres		Neuronal order
Auditory cortex	Sound sensation and perception	
Medial geniculate body		IV
Inferior colliculus		III-IV
Olivary nucleus		III
Cochlear nucleus		II
Organ of Corti and spiral ganglion		I

Figure I.7 The interpretation pathway: from the cochlea to the brain (after Lara-Saenz)

Loss of Hearing

Loss of hearing is the pronounced physiological effect induced by excessive noise levels. It was becoming of concern in the late nineteenth century, in particular amongst boilermakers. Recent work (see Chapter 5) suggests there is a threshold for noise-induced hearing loss around 75 dB (A-weighted).

Other factors than noise can lead to hearing loss, such as infection and illness. Losses in sensitivity may be conductive, cortical or nerve. The latter arises from sensitivity impairment in the hair-cells of the inner ear, is usually frequency-dependent and there exists no medical remedy. Cortical losses arise from damage or degeneration of neurons in the brain, which is an irreversible process. As regards conductive losses, which result from defects in the external canal, the eardrum and the ossicular chain, there is some possibility of alleviation by surgical treatment.

The loss of hearing with age, termed presbycusis, is almost universal and is primarily associated with the inner ear and possibly partly to the degeneration of brain neurons. It is quite considerable, even in people who have avoided serious illness and exposure to high noise levels, and at the higher frequencies is somewhat greater for men than for women.

The Vestibular System

This system, shown schematically in Figure 1.7, is not concerned with the hearing process but provides the balance mechanism of man. It comprises two cavities, the utricle and the saccule, together with three semi-circular canals, which are filled with fluid and contain gelatinous strips with attached hair-cells. These latter act as static receptors and convey information to the brain regarding the position of the head in space. The three semi-circular canals are set perpendicular to each other in three planes to form a small organ, the criston. It is the dynamic organ of position and will give informtion about movement in all directions.

AUDIOMETRY IN INDUSTRY

The question of excessive noise conditions in industrial working is one that concerns many industries, ranging from shipbuilding with its structural steel workers with their pneumatic hammers to those engaged in tin-can or wooden furniture manufacture. In the UK it has been estimated that at least a million people work in a noisy atmosphere which could create a risk of hearing damage. The problem which faces industry is the cost of reducing the maximum noise level from 90 dBA to the recommended Brussels EC (European Community) level of 85 dBA, a level which is below that usually accepted in heavy traffic.

The value of audiometry in industry as a means of protecting people against hearing damage has been for long a topic of discussion. This interest has received support from the increasing activity in the legal field of common law actions for occupational deafness compensation. A working group in the UK has recently published its observations on the subject and it concluded that at very high noise levels there is strong support for the use of audiometry as an aid in the early detection of people suffering hearing damage, arising for example from defective ear protection. On the other hand the introduction of audiometry at lower noise levels would involve the examination of very large numbers of workers and lead to a serious consideration of the balance between expenditure of resources on control of noise and on the medical supervision of workers. A more positive aspect of the report is concerned with advice on procedures and equipment for measuring of hearing down to a hearing level of −10 dB and describes the categorization of audiograms and their use in deciding the initial action to be taken following audiometry. It should be emphasized that the individual conducting the testing should have undergone an appropriate course of instruction in the theory and practice of audiometric testing in an industrial context and is able to satisfy the designated medical practitioner as to his (or her) competence. In general self-recording audiometry is preferred.

The presence of high noise peaks of short durations can occur in the industrial environment, such as in the iron and steel industry. The occurrence of these peaks in the region 4–6 kHz will be amplified in the outer and middle ear and it is significant that hearing loss starts in this region. Hence in making noise measurements it is particularly important to take into account the impulsive noise as well as the total noise dosage.

HEARING HAZARD DUE TO NOISE EXPOSURE

The first effect experienced by the listener exposed to an intense noise source is an elevation of the threshold of audibility directly following the exposure, but if the source intensity and its operating period have not been too great then only a temporary threshold shift (TTS) will have occurred. If intensity and time of exposure are increased, however, then damage to the cell tissues of the inner ear could mean a permanent threshold shift (PTS). Very little is known regarding the effect of chemical and other environmental factors on the cellular structure in relation to noise-induced hearing loss. It is not possible so far to identify people susceptible to this loss and it is only by frequent monitoring of persons working in a noisy environment that signs of hearing deterioration can be detected and appropriate action taken. It follows that national standards of acceptable noise level are always statistical and can only relate to a certain predicted percentage of a population that will acquire a hearing loss below an agreed 'acceptable' level, on exposure to a noise source level below a specified value.

In many jurisdictions, occupational exposure to no more than 90 dB(A) for 8 hours/day is considered acceptable. According to a new ISO standard, near daily exposure at this level without personal hearing protection for 30 years would lead to 9 dB or more hearing loss at 2000 Hz and 19 dB or more at 4000 Hz in the most sensitive 10% of the exposed population. Noise-induced hearing loss is, of course, additional to losses due to ageing, etc.

NOISE CONTROL AND HEARING CONSERVATION IN INDUSTRY

Industrial noise control together with a hearing conservation programme is designed to protect factory employees from permanent hearing loss in the frequency range of speech. Exposure to a high level noise, for even a short duration can create a temporary hearing loss for the listener. This can eventually become a permanent loss if the individual is exposed to high noise levels regularly for many years. The hearing conservation programme was established to identify any employees who have a high susceptibility to noise-induced hearing loss so that they may be given extra protection or located in quiet areas of the factory.

In investigating occupationally induced deafness it is essential to relate the degree of deafness to a specific noise environment of a worker, for often he may have worked in a variety of industrial situations or he may have been a soldier subjected to heavy gun-fire. It was fortunate that the jute mills in Dundee, Scotland, provided a ready-made test facility of workers who had spent their working lives with the weaving-looms. The noise level was so high that about sixty per cent of a group of women weavers were found to practise lip-reading. It was about twelve years ago that a worker in the UK was successful with a common law claim for occupationally-induced deafness and in this case the noise-level of the workshop, involving the use of pneumatic hammers for shaping metal propellers, was particularly high, being between 115 and 120 dB.

Besides the hearing threshold shifts some industrial workers in noisy surroundings following daily exposure can suffer such discomforts as tinnitus (ringing sounds in the head), vertigo (giddiness), headache or feeling of fatigue. These deleterious effects can last for a short or longish time and are not taken into account in the fixing of criteria. Tinnitus can be a very distressing complaint and the 'head noise' can be located in one or both ears or elsewhere in the head. Although its presence cannot be tested objectively, its possible origin through noise should be an added reason for the protection of employees from excessive noise in industry.

As regards the effect of air-borne ultrasound on man there is no definite evidence of permanent biological changes, including that of hearing loss, although the higher levels met in some industrial processes, such as those involving cavitation, may be the cause of subjective discomfort like headaches or a feeling of fatigue.

Hearing Protection or Remedial Help

As a first line of defence against noise hazards or where it is not practicable to control the noise at source then personal hearing protection should be invoked (Chapter 11). Such devices include ear-muffs and plugs and acoustic enclosures. The efficiency or suitability of a particular ear defender will depend upon the sound frequency content of the environment.

A problem associated with conventional hearing protectors is that the better the protection, i.e. the greater the attenuation of the incident sound, the stronger is the feeling of community isolation for the wearer. Modern electronic techniques can overcome this negative effect by suitable circuitry excluding dangerous noises above 85 dB(A).

It has been reported that low-frequency aerial sound affects the same human body receptors, the so-called Pacinian corpuscules, as does vibration, so that low-frequency noise of intensity > 120 dB would require protection for the whole body.

A remedial approach may be possible when the hair cells of the inner ear become defective, following drug reaction or trauma, and conventional hearing aids are of no help. There exists the theoretical possibility of bypassing the defective cochlea and injecting electrical signals directly into the auditory nerve. This idea is based on the earlier work of Galvani and Volta, about two hundred years ago, when they found that electrical stimulation of the auditory nerve gives rise to sound sensation. However, to obtain the essential characteristics of speech requires the injected signal to have a sufficient degree of complexity. Realization of this objective has only become possible with the advanced instrumentation of today, and experiments in the USA concerning the development of suitable neurostimulation electrodes of the required micro-size and dimensional accuracy and which will endure immersion in a hostile saline environment appear promising. In another approach being made by workers in Australia a small receiver-stimulator is implanted in the mastoid bone behind the ear, while a speech processor is carried in the pocket. It is also of interest to note here that the skin sensitivity of man to vibration has prompted the possibility of an alternative pathway from the world of sound to the brain, allowing a deaf person with lip-reading skill to use a simple sensory auxiliary aid operating through tactile means. This is an area of research for the future.

HUMAN NERVOUS REACTION TO NOISE

Man's nervous system reacts to noise in a similar manner to the other stress-producing agencies of heat, cold, intense light or pain. The knowledge of such reactions to sound is very limited so there is uncertainty as to its significance as a health hazard. Among the autonomous reactions of a short-term nature are the changes in the blood circulation and the heart-beat rate, and blood pressure can be increased by a sudden intense sound, while continuous sounds of high intensity can bring about a redistribution of blood. The relation between the reactions of different stresses acting simultaneously is not known. Sound in excess of 80 dB affects the secretion of many hormones and a complicated system in the brain allows the possibilities of many interactions between various stimuli so that even if sound has only a direct influence on a few stimuli it can cause changes in a great number of systems through the interactions.

In industrial situations the pollution atmosphere may sometimes be quite complex in nature, as for example in the working enclosure of an electric-arc furnace for steel-making. Here both audio- and infra-sound exist in the atmosphere as well as ground vibrations, strong light illumination from the arc and the prevailing hot and dusty atmosphere which can all influence the total nervous reaction of the workers. There is a law of specific nerve energies which states that no matter how a nerve is stimulated it will produce the same sensation. However, it is only acceptable in general terms for the cornea of the eye has only one kind of receptor and yet heat, pain or touch can be sensed if the appropriate stimuli are applied to the cornea. It is assumed that the effects of infrasound on man is through pathogenic mechanisms, so great importance must be attached to neuro-humoral regulations of the functions. In experimental studies changes have been reported in the functional state of the central nervous and cardiovascular systems and in the auditory analysis also degradation has been found in the tissues of the brain and a number of internal organs. Many workers have noted that low-frequency acoustic vibrations induce a feeling of euphoria akin to intoxication, also a ringing in the ears. The presence of low-frequency sound in the interior of a car driven with an open window is detectable by a modulation of the speech of the occupants.

CONTROL OF NOISE

This brief review will be restricted to a few broad aspects. The three general methods of minimizing the noise problem are: to control the sound source; to modify the acoustic path from the source to the listener; to protect the ears of the listener. When practicable the first-named alternative is most desirable and the reduction of the radiated acoustic power may be achieved by the introduction of mufflers, by mounting the vibrating system on isolating mounts, by introducing vibration damping operation, etc. Other procedures which might be possible are: increasing the length of the sound path; re-orienting the sound source with respect to the receiving area; introduction of sound barriers between source and received (Chapters 3 and 12); completely enclose the source, etc. Finally the listener may be aurally protected by the use of ear-muffs or ear plugs (Chapter 11). The control of sound within an enclosure may be achieved by the use of sound absorption materials such as porous tiles for ceilings and hard surfaces where stronger reflection is desired. This form of sound attenuation is known as 'passive absorption' and is not efficient in its application to low frequencies. At these frequencies the alternative technique of 'active attenuation' in its modern development has the advantage.

The problem of reducing noise intensity at source gets more difficult as the level is reduced and it must be remembered that only a small fraction of the source energy is actually dissipated as acoustic radiation. As indicative of the comparatively small amount of energy involved it is pertinent to quote the statement made by Kaye some years ago that the energy expended by 100,000 spectators shouting during the course of a 1–2 hour football game would just about be sufficient to make a cup of tea.

Source Location

An important aspect of noise abatement is the localization of the noise sources so that noise reduction technique may be applied to minimize the acoustical power output. Using scanning microphones to scan the acoustic field is not particularly successful in locating sources since the presence of other surrounding sound fields gives rise to interference and focusing effects. Recent developments, however, use a microphone scanner and appropriate photographic apparatus to employ acoustical holography as a laboratory tool to analyse the far-field sound radiation from complex sound sources. Such a procedure, when combined with near-field measurements employing the scanning microscopy technique, enable a complete analysis to be made of the sound radiated from vibrating structures.

Active Attenuation

In contrast to the passive type of sound attenuation devices the last decade has seen the re-emergence of an old idea based on the principle of superposition of two or more waves passing through a given location. Depending on the relative phases of the waves overlapping in any region it is possible to obtain destructive or constructive interference, so that the intensity of the resulting sound field is respectively greatly weakened or strengthened. This idea has been made more realizable with the coming of the electronic age and advances in instrumentation. Its possibilities were in fact realized by Lueg in the USA about 50 years ago and he used a combination of a microphone and loudspeaker placed in a duct but suitably displaced with respect to one another. The electrical signal transmitted from the microphone on the transmission of sound within the duct was suitably processed before reaching the loudspeaker so as to be an odd multiple of π out of phase with the arrival of the duct sound wave at that instant of time. This simple system of Lueg was essentially restricted to a single frequency.

The recent interest and studies in active noise control were initiated 10 years ago by the work of Swinbanks on controlling sound propagation in long ducts. This theoretical study has formed the basis for most of the subsequent duct-based work and has stimulated many different lines of approach. One of the major problems in broadband duct control is eliminating the 'feed-back' interference from the cancelling source to the monitoring microphone. Swinbanks originally suggested the use of either directional microphones or directional cancelling source or even both together. In later work he eliminated the feedback by duplicating it electronically and subtracting it from the microphone signals. One interesting alternative solution to this problem favoured by Leventhall at Chelsea College, London, was the use of the 'Chelsea' dipole. Here two cancelling sources were arranged in a duct and the sensing microphone was positioned between the two at a position where the two cancelling sources produced no sound.

An extension of the frequency bandwidth over which these duct systems can provide useful attenuation has been achieved by both Chaplin and Ross by choosing digital electronic control in preference to an analogue system.

Active Control of Periodic Noise

In the control of repetitive (periodic) noise there is the consequent simplification of the control strategies and the elimination of stability problems. Sound produced by a rotative machine may vary very little from one cycle to the next. Knowledge of this permits the use of a computer-based controller which records the noise of previous cycles and these are applied to construct the cancelling signal for the noise in the next cycle. Many types of computer algorithm can be designed to suit the particular characteristics of the system under control. The robustness of repetitive sound controllers has been shown by the considerable success which has been achieved in various applications such as in annulling of the noise from diesel engines in various environments and of the periodic noise from newspaper presses. It is hoped also to eliminate the low-frequency drumming sound in the cabins of propeller aircraft by using as many as eight interconnected control channels to control the cabin modes.

An alternative approach, which has been applied by Chaplin to the control of repetitive noise in reverberant fields, is to use lightweight open-headphones. These can cancel the local repetitive noise field while allowing the wearer to hear speech and warning signals unimpeded.

Active Control in Confined Spaces

Recent work on the problem of noise inside the cabins of commercial vans has shown great promise and a noise reduction of 13 dB has already been achieved.

The ultimate in confined space active control research is being carried out at the ISVR in Southampton. Wheeler has developed a headset to be worn by jet fighter aircrew that uses the communication loudspeaker to cancel the intense random noise generated by the turbulent boundary layer on the canopy. A microphone in the earpiece of the headset monitors the noise and the system is designed to cancel the noise at this microphone position. Recently adaptive gain controls have been fitted so that these devices need no adjustment and they are small enough so that they can easily be carried in the breast pocket.

The better physical understanding of such systems and advancement in electronic technology holds a promising future in the application of the system for noise control if it is accepted that it is primarily a low frequency 'device'. It is interesting to note that workers at Cambridge, UK have now extended active control to open spaces in reducing the low frequency sound radiated into the open by the exhaust of a static Rolls Royce Avon gas turbine.

SOME SPECIFIC NOISE PROBLEMS

A number of specific noise problems are briefly described below but it is to be noted that our noise environment in everyday life is usually more complex and time-dependent so that the final assessment of the situation is more difficult to obtain.

Aircraft and Traffic Noise

In most industrialized countries motor vehicles are the dominant source of environmental noise but aircraft noise is by no means negligible. Community objection to aircraft noise became strong in the UK during the early 1960s when a number of groups or societies were formed whose objective was to provide a 'mouthpiece' for safeguarding the interest of the populace, particularly those near airports or below the flight paths. The groups were represented at public enquiries regarding the routing of flight paths, monitoring of aircraft noise and the establishment of new airports or extensions of those already in existence, etc. They would have appeared to achieve some success in their efforts for by the late 1970s the activity of the groups had greatly diminished.

Aircraft Noise

As exemplifying the problem of minimizing the impact of aircraft noise on man's habitat the precautions taken at Heathrow Airport, London will be briefly discussed, as it is one of the world's worst airports as regards the number of people affected by aircraft noise. The Greater London Council and the London Boroughs most affected by aircraft noise operate an independent monitoring system in order to provide information for planning decisions and policy formulation. It involves two fixed sites for monitoring landing noise and four transportable systems to cover various locations in course of time. Outdoor microphones are linked to data loggers via threshold detectors.

Under westerly operating conditions all approaching aircraft cross London, while under easterly conditions parts of western London are affected by departing aircraft. These follow minimum noise routes designed to avoid built-up areas as much as possible and to follow noise-abatement procedures to ensure that the specified noise limits are not exceeded. In order to enforce these limits the British Airport Authority operates a noise monitoring system which comprises thirteen automatic recording stations located close to the airport at the edges of the nearest built-up areas and covering all departure routes. All departing aircraft are monitored and infringements are recorded and referred to the appropriate airlines. The data obtained will form a basis for assessing the degree of insulation required for buildings in the affected areas.

This noise arises mainly in take-off and landing of aircraft, in taxiing and servicing, and due to its intermittent nature is not assessed in the same way as traffic noise. In the UK the unit most favoured is the Noise and Number Index (NNI) which depends on the average number (N) of aircraft, landing or taking-off, in the period 0600 hours to 1800 hours and a logarithmic average of the maximum perceived level PNLmax observed during the passage of successive aircraft, i.e. $\text{NNI} = \text{PNLmax} + 15 \log N - 80$. Hence when NNI is zero it signifies there is no annoyance.

A different aircraft noise problem, as compared with a fixed-wing aircraft, is presented by a helicopter, both in its noise characteristics and operational modes. Additionally the heliport is usually located in a built-up area thus adding to the complexity of the problem.

Aerodynamic Noise

Aerodynamic noise is generated by compressible fluid flow and besides its obvious relevance to aircraft noise it is a growing industrial nuisance owing to the increasing use of pneumatic tools and compressed-air devices in various applications. An obvious method of reducing the noise is by lessening the turbulence through diminishing the air velocity. This can be attained by exhausting the air through sintered metal (i.e. porous) but has the disadvantage of machine operation being below its maximum performance. The optimum solution as always is the application of acoustic control principles at the design stage of a device or machine.

Discotheque Noise

This is a problem mainly concerned with night occurrence and has arisen largely through the advancing technology of the audio equipment industry. This development has meant that large dance-hall bands of live music and the accompanying size of hall are no longer necessary. Hence the type, size and location of the ‘hall’ has changed for the whole musical equipment is easily transportable and only three to six players or just a disc-jockey is required. It is evident with sound peak levels which can reach 120 dB(A) and halls with inadequate acoustic insulation that a local noise problem is created. In particular the heavy low-frequency beat will penetrate deeply into the environment. It is significant to note that in the UK the licensing of premises for music and dancing is primarily concerned with avoidance of injury through overcrowding or fire hazard.

In the case of open-air concerts held in stadia near residential areas the possible noise problems should at least be anticipated by careful planning and background noise monitoring before the event. Also close cooperation with local council officials and the police should be maintained before and during the event.

Community Noise

In community noise we are concerned about the intrusion of noise into our daily lives that would reduce the quality of our home environment. Noise limits set by legislation would influence the construction and location of new buildings and highways and the regulation of aircraft flight paths. The S.L. A-weighted meter provides a basic measurement of community noise but for defining time-varying noise and for predicting its human reaction other measurement parameters are employed. For example the so-called ambient noise which includes all the sounds which occur in an environment is expressed by L_{Aeq}, which is the equivalent continuous A-weighted level over the whole time period.

Community response to noise exposure has been chiefly derived from the study of high-intensity transportation noise and it is of interest to note the results of an urban noise survey made in the USA a few years ago, which was very broad in perspective and wide in location. It was concluded that speech interference was a good predictor of response but that for high-level transportation noise was not necessarily directly applicable to the case of general urban noise.

Traffic Noise

This nuisance appears to be the dominant world-wide problem and is the focus of greatest concern. The most significant control is to reduce the noise emission from the vehicles but complementary procedures are the use of noise barriers (Chapters 3 and 12), planned routing of traffic, etc. It is always expensive and generally not possible to obtain complete satisfaction in reducing existing noise. Hence regional and town planners have a key role to play in the task of minimizing noise in future developments and today they are helped by the fact that noise levels from sources such as road and air traffic can often be predicted. Four different procedures are available: scale model techniques, computer simulation, theoretical methods and empirical analysis. The use of all four procedures has led to the underlying principles on which UK traffic noise prediction is currently based.

A traffic control procedure of universal adoption is to augment the traffic on a few major roads since a doubling of the traffic volume increases the noise level by less than 3 dB(A) and at the same time traffic movement is discouraged in quiet residential areas, particularly at night. This control is implemented by means of traffic signs. An Act which has proved of great value in the UK is the Land Compensation Act 1973, where the creation of new and improved roads has unavoidably worsened the noise problem in some areas, and the Act can provide some financial compensation or provide better sound insulation for the habitat affected.

The regulation noise limits at present for passenger cars vary from 80dBA in European communities to 81 dBA in Japan and are unregulated in USA, while the corresponding figures in dBA for heavy lorries are 88, 86 and 89. Alexandre (1980) has indicated that the proportion of people exposed to more than 65 dBA will increase by 30 per cent in the year 2000 unless there are imminent improvements with noise abatement procedures. Any improvement in car technology would require to be related with any increase in cost for this would influence the rate of replacement of existing vehicles.

Railway Noise

The noise from railways is quite complex and comprises that emanating from the motive power, i.e. diesel or electric motor, that from wheel–track interactions, which effectively constitute a sequence of point–sources, and the overall combination of the various noise contributions yielding an effective line-source. However, although the overall train-noise is high, the surveys appear to show that it is generally acceptable, which is perhaps not so surprising as might be thought initially. People living near a railway may do so by choice with the confidence that in general the density of traffic is unlikely to be heavily increased. Also the time interval between trains will still appreciably segregate their individual noises and the intrusion of their sound at the listener will be gradual and hence less objectionable. Also to the urban commuter his closeness to a railway, and hence a station, is a boon for his workday travel, and these factors tend to make a moderate noise level socially acceptable.

Noise Isolation in Apartment Buildings

The question of poor noise isolation in apartment buildings arises often, not from the lack of appropriate techniques or even due to poor acoustical design, but from the lack of a fuller appreciation of the acoustical requirements by the contractor and his workforce. Hence the problem is often more of a social one as less attention is given in general to the execution of acoustical directives than to those of constructional strength and of heating and plumbing. This fact again emphasizes the need for more acoustical knowledge to be imparted in school technical education, which should not be difficult as there is a close similarity between thermal isolation and sound absorbing materials. This latter fact can also be helpful to householders in countries such as USA and UK by reason of the financial support given under energy conservation measures to provide thermal insulation, as at little extra cost acoustic isolation could also be obtained at the same time.

CONDITION MONITORING OF MACHINES

This is an area of growing industrial interest and it concerns the noise emitted from machines when in operation and how it relates to their life-cycles or present-day well-being, or health. The sudden breakdown of a machine could be a danger besides causing an economic loss in production. In order to detect any deterioration of performance with usage, the condition of the machine at its installation requires to be known and also the fatigue behaviour of the machine material with continued cycling. Condition monitoring of rotating machinery has become a complex effort demanding a high reliability from the measuring system to give the extent of any deterioration and the need or otherwise for immediate corrective action. Acoustic emission, i.e. the generation of stress waves within a body due to some local instability, is used as a means of detecting a degradation of a machine. Their detection is by a suitable piezoelectric transducer in close contact with the test surface.

SOUNDS WITHIN MAN

An interesting contribution in the present volume (Chapter 6) by E. Evans relates to sound emission within the aural system; this draws attention to the general topic of human body sounds, which is now being revived after a long lapse of time. It was over 300 years ago that Robert Hooke of elasticity fame wrote about listening to sounds in bodies, both human and inanimate. The idea was taken up by doctors about 150 years later in the form of the stethoscope, but it was not until the middle of this century that the effect received earnest investigation largely as a result of improved instrumentation. The observed phenomenon is usually referred to as acoustic emission and now finds application for example in a field pertinent to this book, namely that of monitoring health. It is also of interest to record another relevant observation in the middle of the seventeenth century by the Italian scientist Grimaldi (famed for his work on optical diffraction) who, by inserting his thumbs in his ears, was able to detect low-frequency sounds from activated muscles. In this example also the topic was not revived until about 150 years later when the British scientist and physician Wollaston (also noted for his optical work in which he invented the prism which bears his name) carried out a most interesting experiment. Reverting to our earlier reference of sound produced by carriages moving over cobblestone, Wollaston utilized the effect to estimate the frequency of the 'muscle-rumble' by varying the carriage speed until the sounds were 'matched'. Knowing the constant width of the cobblestones he could calculate, from the speed, the number of 'cobbles hit per second', i.e. the pitch of the sound, which he estimated as about 25 Hz. The low frequencies of these muscle sounds are normally inaudible to humans and to detailed investigation but recent advances in instrumentation and the application of computer sciences have altered the scene. The advent of the Fast Fourier Transform has meant an enormous saving in computer time so that the calculation of the vibrational spectrum from muscle contractions becomes a feasibility and could provide a useful tool for investigation of the effects of vibrations upon man.

POLLUTION IN MEDICINE

In using ultrasonic radiation for probing the human body it is especially important to be aware of the possible forms of pollution that can arise. The interaction of ultrasound, if sufficiently intense, with human tissue can give rise directly to appreciable thermal and non-thermal effects. The former arises from the fraction of the incident radiation energy which is absorbed by the medium and contributes to the damping or attenuation of the transmitted waves. This mechanical energy loss is converted to thermal energy and produces a rise in temperature of the medium. Biologically the thermal effects can lead to generalized tissue damage, changes in blood flow and an increase in the rate of metabolism. The 'non-thermal' effect is associated with the fraction of the incident energy which is scattered from the receiving surface and plays a significant role in the 'imaging' of the scattering body. This scattered energy also represents an abstraction of energy from the on-going incident ultrasonic beam.

If the intensity of the ultrasonic radiation is such that the ambient pressure in the receiving liquid medium is exceeded then cavitation can occur, which involves the formation and subsequent growth and oscillation of small gas-filled bubbles. In stable cavitation the oscillating bubbles set up shear stresses in the medium, while for transient cavitation the violent collapse of the bubbles can create high temperatures and pressures in the immediate environment, which can lead to disruption of local tissue and damage to blood cells.

The cavitation threshold, i.e. the ultrasonic intensity required to initiate cavitation, will depend on the frequency, temperature and pulse-length of the probing ultrasound. Furthermore the increased radiation pressure of the ultrasonic beam will lead to a significant flow of the liquid medium. This so-called acoustic streaming can produce particle movement and possible membrane damage.

It is evident that in audible communication as in ultrasonic diagnosis it is essential, for a given situation, to know both the magnitude and distribution of the sound pressure levels. This increased urge for better quantification is emphasized by the use of the term 'non-destructive evaluation' in preference to 'non-destructive testing' ('or inspection').

VIBRATION POLLUTION

In noise pollution the concern has been associated mainly with the discomfort and possible hearing damage to the individual when immersed in an atmospheric environment, where the levels of audible sound are in excess of those regarded as acceptable in normal conditions. The concept of noise pollution however also extends to the exposure of the human body as a whole to appreciable vibratory motion as experienced for example in a transport vehicle, particularly in its passage over very uneven surfaces, on a ship in a rough sea or in the severe low-frequency oscillations of an aircraft flying in turbulent air.

As most mechanical industrial processing also involves mechanical vibration as well as noise to various degrees, it is an important area of consideration in acoustic pollution. The problem tends to be accentuated with increased mechanization and speeds of production. As already mentioned faults in the running of machinery besides often creating noise nuisance problems can also give rise to a dangerous mechanical condition resulting from metal fatigue, undue stress and possible breaking of structural members, etc.

In general the stress waveform and the motion of the vibrations of a machine or surface are complex, but may be most simply regarded as resolvable into their sinusoidal Fourier components, commonly in the frequency range of a few to several hundred Hertz. Additionally any point on the vibrating surface may have components in the three co-ordinate axes, although only one may be of prime importance, e.g. the vibration of a metal panel normal to its surface. The majority of vibration detectors give a response to motion mainly in one direction and so may be applied if necessary to determine the three components in turn. It would be out of place to go into details of the measurement system except to say that by the inclusion of an integrating or differentiating electrical circuit it is possible to derive displacement, velocity and acceleration waveforms of the vibrating surface, (*see* Chapter 14). The techniques used for the control of air-borne noise may equally well be applied to periodically produced structure-borne vibrations but the problem is more involved since transverse shear and surface waves etc. are involved, besides the longitudinal compressional waves of sound propagation.

VIBRATIONS AND MAN

The effects of vibration upon man and animals may be conveniently divided into four main groups: biodynamics, pathology, physiology and psychology. Human reaction to vibration varies widely and is not only influenced by various physical factors but also by psychological reactions such as fear and resentment. Although the human body is a complex dynamical system whose component parts vary considerably as regards stiffness, strength and density, we can gain some general enlightenment as regards frequency response from a model built up of a number of simple systems such as given in Figures I.8(a), and 8(b). M, S and D refer to the mass, spring (elasticity) and damping of the elementary unit subjected to the vibratory force V. Each unit will have a characteristic frequency and the particular mode excited will depend upon the direction in which the forcing agency is applied with respect to the anatomical axes of the subject. At very low frequencies, < 3 Hz, the body moves effectively as a single unit and the effects are those associated with motion sickness. For higher frequencies various internal organs are displaced to varying degrees by the fluctuating forces imposed on them. In the case of the heavy and lightly supported organs their movement may 'lag' behind that of the forcing motion giving rise to internal distortions. The tolerance of the human body to acceleration depends more on this body distortion than on the reactive force due to the acceleration. Figure I.8(c) shows the calculated peak acceleration for various frequencies to achieve a given compression of the human tissue so, assuming that this is a measure of the body response, then the curve should give the acceleration level required for a given degree of human response. The subjective observations made by Goldman 1957 for 5–20 minute exposures show a general qualitative agreement with a low-frequency plateau, a minimum at middle frequencies, arising from spring–mass resonance, and a rise at the higher frequencies. The general inference gives support to the human body being regarded as an acceleration-sensitive device. It is noteworthy that Goldman suggests that lorry drivers and air pilots who suffer exposure over long periods may experience more troublesome effects than have been indicated. Figure I.8(d) gives the general reaction of man to different magnitudes of acceleration at different frequencies. As mentioned previously at low frequencies $0.1 \sim 1$ Hz intense vibrations can provoke sickness and the balance organs are affected, while in the range 3–15 Hz at acceleration levels $> 0.5\,g$, breathing and speech are disturbed and the nervous system affected in general. At higher acceleration values of $\sim 2\,g$, in the frequency range 2–10 Hz, whole body vibrations for more than a few seconds can be injurious. At still higher acceleration amplitudes $5 \sim 10\,g$ infrasonic

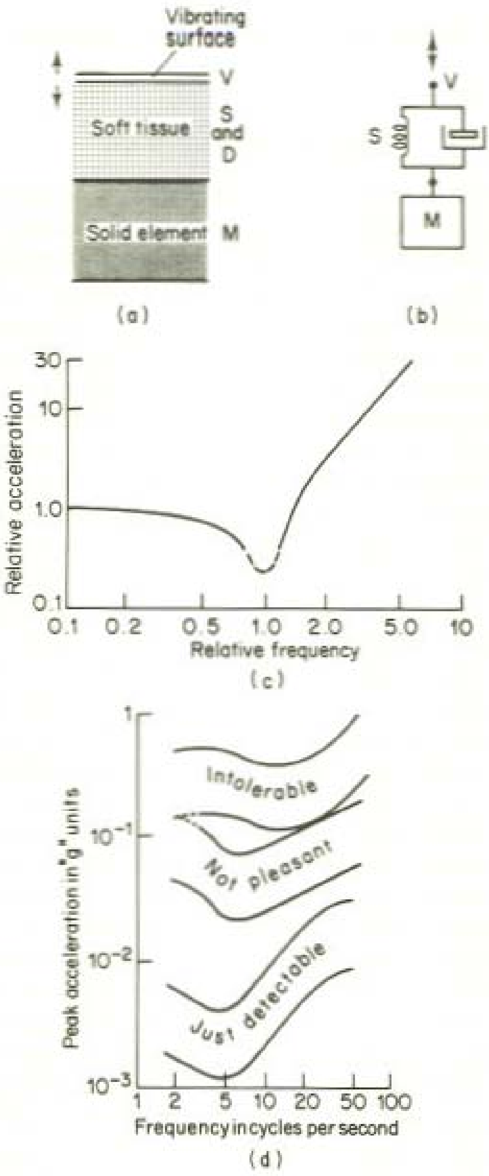


Figure I.8 Simple model to illustrate the vibration sensitivity of the human body. (a) Simple equivalent human structure; (b) equivalent mechanical system; (c) calculated frequency curve of applied acceleration (in arbitrary units) to produce a given magnitude of compression in the soft tissue layer; (d) curves showing regions of human reaction frequencies can cause haemorrhage in the lungs. The parameters of transmissibility and mechanical impedance (Chapter 1) are most favoured in analysing resonance phenomena in man and animals, supplemented often by high-speed cinematography.

For control of the effects of vibration on passengers or drivers of heavy lorries or aircraft pilots the question of seating is of prime importance. The main technique by which man can be protected against the effects of vibrations entering his body is by a suitable choice of his posture and orientation with respect to the direction of the external vibration. Furthermore it is desirable if possible to spread the distribution of the applied force over his body surface. At a low frequency of vibration near to body resonance the human response may be reduced by adopting a slouching posture or by leaning backwards on a reclining seat which spreads the applied force. Although at higher frequencies the vibrations will be effectively dampened by the body, if applied through the seat, the isolation of the head may be short-circuited through the stiff frame, arm and head rests. Suspension isolation is an alternative, as exemplified by the naval hammock, and as an approximate guide the resonant frequency of the loaded system should not be greater than one half of the lowest frequency from which is it required to isolate the load. Non-linear springs are desirable in order to reduce the displacement at high exciting forces and the seat-cushioning should avoid the possibility of resonant conditions and consequent undesirable amplification. Figure 1.9 shows the advantage of a suspension seat as regards attenuation at frequencies in the region of the body resonance, i.e. ~ 3 Hz, but some amplification is indicated at 1 Hz. When seated on a conventional seat cushion man shows a strong resonance at 3 Hz.

It is of interest to note that the legs of a standing person provide little attenuation of vertical vibrations when they are kept stiff but with bent knees the lower limbs function as efficient vibration isolators. This effect was utilized by charioteers in the past and could perhaps be followed by commuters of today — instead of strap hanging!

Man is more sensitive to mechanical vibration than is generally realized and moreover has a larger cover of frequency, from around 1 Hz to 100 kHz, than the range of human audibility. He tends to overestimate the amplitude of vibration whereas the fingertips are able to detect amplitudes of the order of 10^{-8} m, while whole-body vibration amplitude around 10^{-4} m can be felt, depending on the frequency. By measuring seat-to-head transmissibility of vibration it has been found that no major resonances are present above 15 Hz. When the body is excited, either by sinusiodal vibration or by impact, along the spinal axis then a prominent vibration between 4 and 6 Hz is detected.

SOME SPECIFIC VIBRATION PROBLEMS

Traffic-induced Vibrations

In the early part of this century it was expected that structural damage to

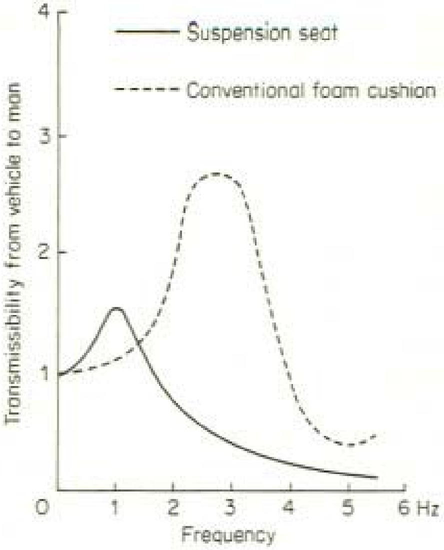


Figure I.9 Transmissibility of vertical vibration from vehicle to passenger as a function of frequency showing the advantage of a suspension seat (after Radke)

buildings in large cities would result from the rapid increase of vehicular traffic, in number and size. Fortunately by improved road construction and the better 'springing' of vehicles this has not seriously materlialized. The parameter of 'particle velocity' is now regarded as a more useful criterion than vibrational amplitude as a warning threshold of impending structural damage.

This cause of disturbance to man and buildings arises first from variations in the contact surfaces between the wheels of a vehicle and the road surface, leading to stress waves being transmitted into the surface, both bulk (shear and longitudinal) and Rayleigh surface waves, the latter decaying much less rapidly than the bulk waves, (Chapter 14). In a layered road the transmission becomes more complex and gives rise to other modes of propagation. The second problem is due to pressure fluctuations in the atmosphere and consequent noise arising from engine, exhaust, etc., and from the movement of the vehicle in the air. The vibrations are usually in the infrasonic range and can affect, i.e. rattle, the larger size flexible building components such as windows and doors, but are not normally liable to cause structural damage; a 100 dB sound signal is only equivalent to an air pressure of $2\,N/m^2$. The vibrations of windows, etc., can induce air vibrations, i.e. sound, within the building.

The traffic-induced vibrations of buildings are in the frequency range 1 to 45 Hz, while for highway bridges they are in the lower range of 1 to 20 Hz. In the latter case the duration of the energy exchange between a vehicle and the structure will be limited by the time that the vehicle is on the bridge. With the present-day tendency for lighter-mass construction the designer is now presented with an added problem.

Mechanical Vibrations and Buildings

The isolation of a building from sources of vibration comes into consideration if the vibration is liable to reach levels higher than is acceptable for the particular use of the building. The criterion of acceptability is usually concerned with the subjective reactions of external disturbance to enable sensitive instruments to be operated in the building, such as in a laboratory or hospital. Besides the conventional structural problems, account must also be taken of the possibility of wind-induced vibrations and of the interaction of the foundation and the ground. For example an isolating clay-bed in a normal season, in drought conditions could become a good acoustic conducting channel. Additional to the usual vibrational problems arising from road and rail traffic there is, in big cities, the specific isolation required for buildings built over underground electric railways. This problem engaged the attention of Lord Rayleigh with reference to the London Underground system in the early twentieth century. In response to complaints of excessive vehicle vibration the Board of Trade set up an investigation. It was found that the vibrational amplitude in the range 10–15 Hz was rarely greater than 0.003 cm and that annoyance was felt when the vehicle acceleration reached 0.04 to 0.05 g where g is acceleration due to gravity. The use of welded rail has helped to minimize vehicle vibration and for different situations short lengths of the full track, including ballast, have been floated on resilient rubber–metal slabs. This also improves the acoustical well-being of dwellings built over railway-cuttings. The investigation also led to an improvement in the rolling stock.

The limiting levels of *particle* velocity (Chapter 1) in building vibrations are of the order of 10^{-6} m/s if the building is being used for such delicate work as optical calibration work, and should not exceed between 10^{-5} and 10^{-4} m/s for road traffic and light winds; in the neighbourhood of 10^{-3} m/s they become perceptible to man, and if reaching 10^{-2} m/s, as for strong winds, the vibration effects become unpleasant to humans. Within another decade of particle velocity, i.e. 10^{-1} m/s, the threshold of structural damage is reached and the conditions are those created by a strong earthquake.

The control of noise in large buildings, when height also enters into consideration, will vary according to the environment and usage but must be planned in detail beforehand, and of course it is essential that the measures are correctly applied subsequently. The existence of any noisy external environment with respect to the proximity of a particular face of the building, and the location of any noisy section within the structure in respect of nuisance to the external community, must be observed in the planning. The overall design must be complete before construction starts as the cost of any subsequent adjustments are economically prohibitive. The technical fields involved may be broadly stated as engineering acoustics and architectural acoustics, although there will be some overlap as for example in the provision of air-conditioning ducts, their incorporation into the structure of the building being the architect's responsibility, while the air-conditioning plant is the concern of the engineer.

The incidence of wind on the face of a building in a more or less normal direction creates an eddy and a suction on the near face. In the case of two buildings close together a channelling effect is produced, leading to severe suction on the sides facing the intervening gap. Most ordinary buildings are relatively stiff with periods less than one second and so are responsive to short gusts if they encompass the building, and a danger hazard may result if a resonance condition is attained.

Vibration Isolation and Transmissibility

As regards vibration isolation the use of passive systems has met the majority of needs concerning cost, simplicity and reliability. However, for certain circumstances active systems would be an improvement for they possess the potential to respond to a complex variation of the input conditions. As quoted in Chapter 1 criteria for the acceptability of the vibration isolation of a building are dependent upon the use for which it was intended and external elements such as winds in general could be disturbing.

In the reduction of transmission, or protection against, periodic vibrations the natural frequency (f_n) of the mounting system must be much lower than the forcing. The calculated efficiency however will be found greater than the operating efficiency due to a number of factors such as the dynamic elastic modulus of the mounting material being greater than the static modulus, etc. In the vibration design criteria for buildings the maximum allowable transmission is a function of the vibrating force and also on the location within the building. *Isolation* efficiencies should be at least 75 per cent in less critical areas, rising to 90 per cent in more sensitive regions. Higher efficiencies are necessary for mountings on wooden floors as compared with concrete and special isolation attention is necessary for rotational equipment, as it is important to avoid imbalance of moving parts.

Forging Hammers and Blasting Operations

Amongst impulsive and percussive types of vibrational sources are forging hammers and blasting operations. The ground vibrations from the latter, apart from the air-blast, can be both annoying to man and sometimes damaging to structures. The threshold for damage is taken as approximately a 'particle velocity' of 12 cm/s with a warning stage at approximately 8 cm/s. Close to the source of a forging hammer its vibrational record can resemble that of a minor earthquake and unless the foundations are adequate there could result a progressive settlement of the hammer due to the large dynamic forces involved. The ground disturbance under favourable ground conditions may be detected more than 0.5 km away but the energy transmission could be greatly reduced by using inertia blocks on springs as mountings for the hammer.

THE OCEAN HABITAT

The possibility of man taking up his abode under the ocean, even if only for short periods in industrial pursuits, would not necessarily mean operating in a silent world as is often supposed. In reality, although little sound can penetrate below the surface from the air, particularly in calm conditions, sound levels exist which are comparable with those in a quiet garden, even in the most secluded parts of the sea. These underwater sounds may arise from natural phenomena, from marine life or from the activities of man. Many of the sounds are random in nature and from the point of view of underwater communication constitute noise and will interefere with information signals.

However, many sounds in the ocean can be regarded as communiction signals or interference sounds according to the interests of the observer. The ultimate lower limit of noise in the water is the thermal noise associated with molecular motion and is normally negligible compared with other noise sources. There is an upper limit to the normal behaviour of water (or other liquid medium such as body fluids) which is set by the value of the excess pressure in the sound wave. When this pressure becomes greater than the ambient static pressure in the system, then during the rarefaction part of the cycle the resultant pressure becomes negative, or in other words the medium is subjected to a tension which can give rise to the phenomenon of cavitation. This generation and subsequent collapse of voids or gas bubbles in liquids leads to development of shock waves, and the medium in fact suffers a form of acoustic pollution; moreover, it is a noisy process. The cavitation threshold at a water–atmosphere surface would be approximately 0.33 watt cm^{-2}. A particular type of cavitation, known as hydrodynamic cavitation, is one of the chief components of ship-propeller noise which in time of war is an indicator of the ship's presence to the enemy. Ultrasonic cavitation is associated with the transducer-generator which is limited in its power output, apart from the nature of the material, by the necessity for operating below the applied threshold voltage for cavitation. The need for operating well below this threshold is particularly important in ultrasonic medical applications to avoid damaging human tissue. In the ocean the movement of water itself represents the minimum ambient noise of practical significance and the breaking of surf on the seashore may be heard several kilometres away, while even the disturbance of the sand on the shore without actual wave-breaking can be heard in the water at distances of several hundred metres. The waves breaking over breakwaters can enclose volumes of air that are set into low-frequency vibration and with the innumerable different-sized agitated air-bubbles the overall wave spectrum forms a good source of 'white noise'. The noise increases with the wave-height but down to about 100 metres below the surface its characteristics are not apparently greatly affected by the depth of the observing point. Until comparatively recently it was not realized that sounds of fish could provide a limiting background to the operation of sound detection systems. The croaker, for example, is typical of the drumfish class who generate sound by striking a gas-filled bladder with a vibrating muscle in a series of blows at a rate of 600 blows per second. Although the acoustical output of a single croaker is small the large number which congregate in certain locations can produce strong interference on sonar detection systems, e.g. in Chesapeake Bay, USA, a number of 300 million has been quoted as the summer population. The normal activity is at a maximum an hour after sunset and has been known to be 65 dB greater than the normal water noise, but as regards aural listening may be distinguished from ships' sounds by suitable filtering circuits. Snapping shrimps if in sufficient numbers can be heard in the air above the water surface. Their frequency is prominently associated with the 10 kHz region, which creates a problem with some sonar-echo ranging equipment. It is also suspected that moving sediments are the origin of noise-bands which have appeared on the records of high-frequency sonar systems and this possibility has received support from laboratory experiments using small glass spheres. The phenomenon of musical sands appears to be a closely allied effect. (*see* Figures I.10 and I.11 for ocean noise).

As regards man-made noise the most common is due to that of ships, and has a certain resemblance to traffic noise on land. The actual sounds created by a ship depend upon type, dimensions and method of operation, so that a given ship could be characterized by its spectrum, which could be important in naval defence.

Finally, as the counterpart in the ocean to infrasonic waves in the atmosphere, are the so-called internal waves. These waves have received a deal of attention during this century and they have been of particular interest to the navies of the world because they influence sound propagation by disturbing the thermocline, which is a steep thermal gradient existing below the so-called isothermal layer that extends to about 50 metres below the ocean surface. It is said that fishermen on the Pacific islands when fishing can often detect the presence of internal waves, which are indicators of the approach of a storm, with its disturbance of the environment.

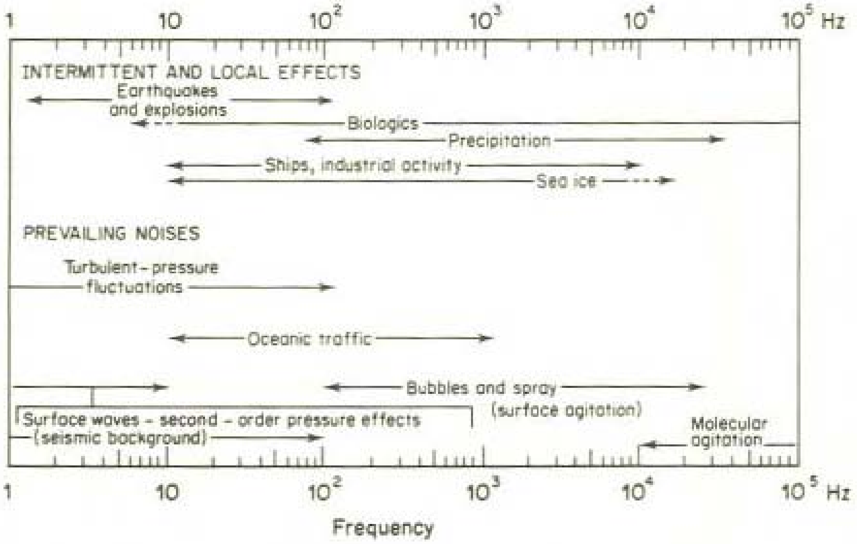


Figure I.10 Summary of ambient ocean noise spectra (after Wenz)

Off-Shore Structures

Off-shore structures have added another dimension to noise problems at sea. There has been a growing concern about the high noise levels on the oil rigs and production platforms which could affect direct aural communication between workers. This interest has also developed with the extension of the Health and Safety At Work Act to cover workers in the off-shore oil and gas industry. Difficulty was found in determining the radiated sound levels from the powerful equipment closely packed in reverberant steel units on the platforms, when employing the normal sound pressure measurements. However, the development of sound intensity measurements with their inherent feature of giving direction as well as the level of sound has made measurement less difficult since extraneous sources can be ignored. Recent research work by Norwegian investigators indicated that it is the only method which can be used to check that a guaranteed level is met by a commercial piece of equipment.

EDUCATION AND PUBLICITY

Professional societies can play an important part in influencing their national governments to appreciate the harmful effect of excessive noise exposure on the health and comfort of their citizens. This awareness of the noise problem

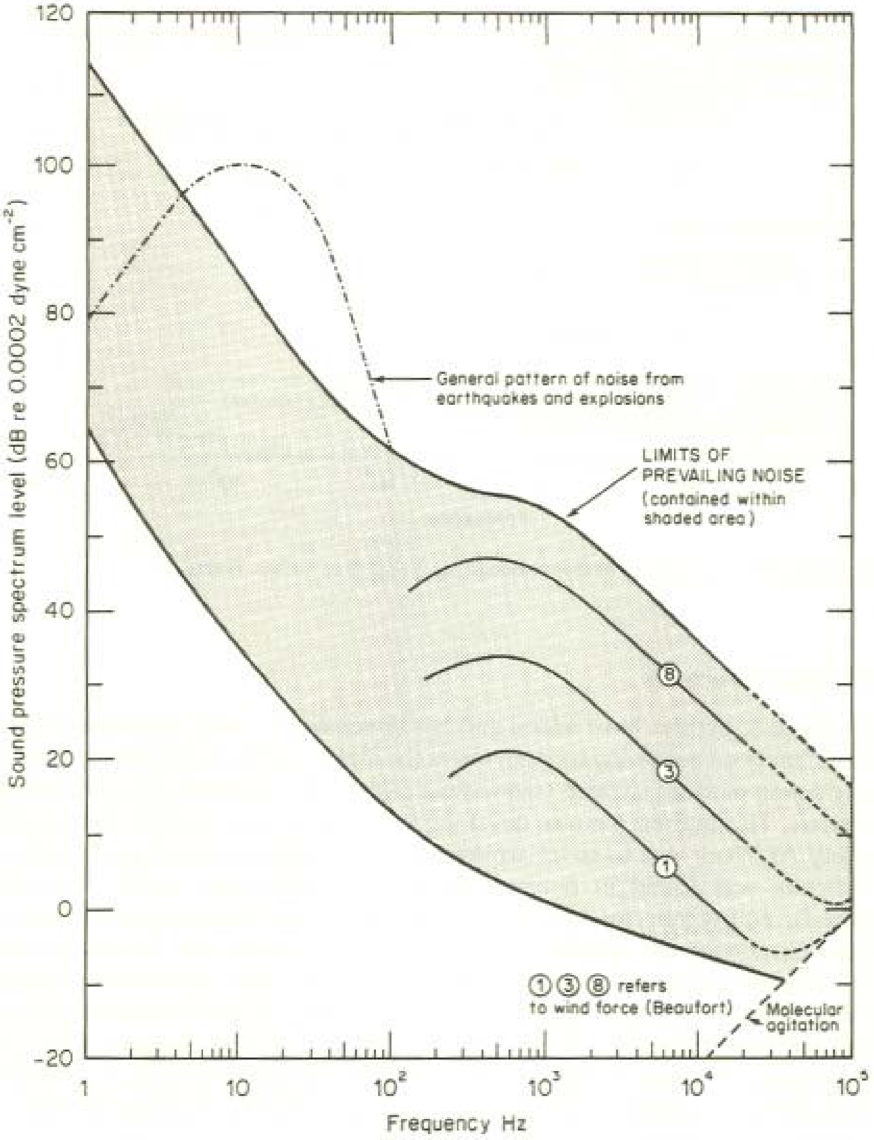


Figure I.11 Noise in the ocean (after Stephens, 1970)

had in fact been appreciated in the USA as early as 1929 by the New York Noise Abatement Commission, who used a noise-measurement truck to make the first comprehensive city-wide noise survey, observations being made at over 130 locations in the city.

Twenty-seven years later the Acoustical Society of America (ASA) at the second International Congress on Acoustics took as the main theme 'Sound and Man'. Again in the early 1970s the ASA arranged a conference to delineate ways in which it might approach acoustical problems affecting human welfare during the ensuing decade. A task team approach was adopted in which individuals were assigned to particular task areas, seven in total, which included interorganizational relations and the diffusion of knowledge, together with various technological sections. Although a society is not a formal educational and training establishment it should bear the responsibility of providing guidance to teaching institutions as to pressing national educational needs in its fields of interest. Such a situation arose in the UK concerning the implementation of noise abatement codes of practice which were to be administered by health and safety officers, whose training had not involved significant attention to acoustics. As a consequence the educational section of the Institute of Acoustics developed a course in acoustics to meet the immediate needs and which was to lead to an examination for a Diploma in Noise Control. The examination is under the administration of the Institute of Acoustics, but the teaching is carried out at the various interested polytechnics and technical colleges who are accredited if they meet an acceptable standard as regards teaching staff, laboratory conditions, library facilities and appropriate apparatus.

The conservation of hearing in industry involves the often difficult problem of making the ordinary worker, particularly the youthful, fully aware of the dangers arising from noise pollution. The existence of trade associations can here achieve a great deal as they can often cover many countries and are engaged in a common topic, as for example that of the Steel Castings Trade Association with its approximately fifty member companies. This association instituted a short training course on the measurement and reduction of foundry noise and which had the advantage of being carried out by its own staff. An additional feature of general value in disseminating information to the public was that the manner of presentation had particular relevance to the educational standard of the listeners.

The last decade has seen a significant change in noise control and research, to a certain extent the result of noise control legislation which has stimulated development in the technology of noise control. Computer usage has led to improvements in acoustic analysis and the need for technicians and others to receive training in the new techniques has made an impact on noise control educational programmes, which has been particularly evident in the USA. In large local urban authorities the acoustical technologist would require an appreciation of many fields additional to a good knowledge of basic acoustics, basic electronics and instrumentation, and such needs can be provided by suitable short courses.

The general public should be informed of acoustical developments by well-designed television programmes and public lectures, in which acoustical society members can play an essential part. Another important function of the professional society is to bridge the gap between the world of technology and the academic sphere by way of conferences, seminars and publications. The multi-disciplinary nature of acoustics makes it easier to choose meeting topics of common interest with other disciplines and so also helps the problem of intercommunication.

At the important level of school education acoustics had become somewhat of a Cinderella subject in the face of seemingly more exotic subjects and a crowded syllabus. The position has been worsened by the fact that few teachers from the university have received any acoustical education. The Institute of Acoustics has endeavoured to create an interest amongst fifth and sixth form scholars by means of lectures at various centres in the UK. Also the Science Museum in London has created a transportable science exhibition for use at schools with the overall title of 'Musical Notes and Vibrations', involving eight separate stands on different acoustical phenomena and applications. There are 40 different experiments which are operable by the scholars themselves. It should also be added that the Schools Council in the UK have introduced more technology into the curriculum at secondary schools and acoustics has been one of the chosen subjects.

Finally, there is the problem of attracting school leavers and university students into thinking about careers involving acoustics. Here again the professional societies should act as informers and to give publicity to the possible areas of recruitment. Although acoustic pollution would seem to be mostly associated with audiometry, bio-engineering and structural engineering, there are many problems to attract the interest of the physicist, such as the various sources of noise in the water-cooling towers of power stations and the water-flow over river weirs. In the latter case the continuous sheets of water enclose volumes of air vibrating at infrasonic frequencies, unless the sheets are broken up by the insertion of wooden baulks.

SOME GENERAL COMMENTS AND THE FUTURE

The need for a more world-wide approach to the noise problem may be desirable but is fraught with many difficulties. A commendable step in this direction are recent developments in a legislation proposal on the protection of workers from effects of noise, which would operate throughout the member states of the European Community. It is hoped that it would include non-auditory hazards as well as the protection of hearing and also the setting up of noise limits for different types of machine such as agricultural tractors, excavators and concrete breakers and other machines used in construction and demolition work. The cost of noise control can be quite considerable and to cover the cost of implementation of the comprehensive laws on noise, inaugurated by the Netherlands government in 1979, 'noise charges' were to be leveled on sound insulation of buildings.

The need for closing the gap between research knowledge and its application has been exemplified in the case of knowledge of the physical mechanisms involved in sound propagation outdoors. Until recently only the simpler models based on average behaviour were used for prediction of noise levels around projected airports and alongside highways. The deeper significance of local conditions is now being incorporated in the schemes of prediction, which should lead to a greater accuracy in forecasting.

Although comprehensive studies have been made of noise levels in industry and the general environment, comparatively little attention has been given to domestic equipment, but more recently the motorized lawn mower has come in for scrutiny in a number of countries and the EEC has introduced a code of noise test for these machines. Even in the domestic kitchen and the canteen there is scope for quieter utensils: there is a basic need for a quiet metal, like lead, but not incurring its undesirable qualities.

Advances in acoustical technology and theory continue and recent developments in statistical room acoustics have been of significance at the higher frequencies where the earlier modal theory became inapplicable due to the enormous number of overlapping vibrational modes which are involved. The use of models in noise control problems is important alike for theoreticians and engineering designers. The degree of simplicity of the modelling will depend on the nature of the questions that are being asked.

A very significant and recent development in noise control engineering has been the growth of interest in sound intensity measurements. In the early 1970's sound power was being established as the primary measure of the noise emission from machinery. In the immediate future acoustic standards will be based on sound intensity, and its direct relation with sound power will make it an obvious procedure for evaluating the noise emission of machines (Chapter 1).

The close relationship of acoustics with medicine is exemplified by a recent development in phonography which is associated with the respiratory track. Skawinska in Canada has based his study of the acoustic phenomena resulting from the presence of disease by analogy with the theory of speech sound production. He has shown how various types of constrictions in the respiratory channel will produce a characteristic stridor. The type of stridor is found to depend on: the location of the constriction in the tract; the shape of the constriction; the nature of the tissue around the constriction; and finally the pressure difference between the two sides of the constriction. A strong relationship was found between particular diseases and the acoustical features of respiratory noise. This effect could act as a warning for example of the development of throat paralysis in bulbar polio.

Acoustics may be of service to man in combating other types of pollution. The discovery in the mid-eighties, almost simultaneously in the USA and the UK, of the photo-acoustic effect led to the development of the spectrophone. In this technique the sample of gas in a suitable glass envelope is subjected to modulated electromagnetic radiation and will suffer absorption if there is even a small amount of carbon dioxide of the order of 1 in 10^5 by volume in the gas sample. The acoustic resonance involved is easily measured. The extent of the 'fouling' of streams may also be monitored ultrasonically. Again in the casting of steel ingots it is important to know the extent of the inclusion of impurities which could impair the strength of the material and their existence may be found by ultrasonic diagnosis.

A positive use of high energy sound is its direct application to the dispersal of coagulation in liquid manufacturing processes or in the precipitation of particles in gaseous systems. This has been achieved by the development of high acoustic intensity sources (Gallego *et al.*, 1978, 1979).

Looking to the future it seems that motor vehicles will continue to be dominant source of noise, and complementary actions such as reduced emission at the source, improved traffic management, use of noise barriers, etc. (Chapter 12) can contribute to noise abatement and it is forecast that reduction of emission at source is likely to make the largest contribution. This gain would probably be at an increased cost of a vehicle and could also involve an increased fuel consumption; moreover this period for mass change-over to the improved vehicle could take between one and two decades, whereas the density of traffic is not likely to decrease in the meantime. The fatigue effects of high-intensity noise upon aircraft panels and electronic equipment has received attention over a number of years, but the effects are now significant in a wider range of equipment and as a result the requirement for a high rise intensity test is being written into many engineering specifications.

It is always very expensive and often impossible to reduce existing noise satisfactorily and so regional and town planners have a key role to play. Their task is helped by the fact that noise levels from sources such as road and air traffic can often be predicted; for example there are four different methods which have been employed for predicting traffic noise: scale model techniques, computer simulation, theoretical methods and empirical analysis. The use of all four procedures has led to the underlying principles on which UK traffic noise prediction is currently based.

The chapters of Part II in this monograph give detailed accounts of how sound can affect man in many ways. Although the information of a given chapter is generally restricted to a particular 'isolated' noise it should be remembered, as mentioned earlier in the survey, that the noise environment in everyday life is usually more complex and can be a mixture of many different sound sources. Moreover there are other environmental parameters, such as temperature and pressure conditions, as well as air and dust pollution, which can contribute to man's nervous reaction. This is a field requiring further investigation. The diversity of the disciplines of the various authors are indicative of the many facets of acoustic pollution, as of acoustics in general.

It seems appropriate to conclude by recording a paragraph from *Scientific American* of July 1928 which stated: 'A growing recognition of the right of the citizen to be protected against offences to his senses of sight, smell and hearing will mark the future of city administration ... but we think the most serious trespass against the comfort of dwellers in cities, and particularly those of great size, is the matter of noise ...' — and still the problem is with us.

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PART I

FUNDAMENTALS OF NOISE AND HEARING

Noise Pollution
Edited by A. Lara Sáenz and R. W. B. Stephens

CHAPTER 1
Physics of Noise

A. LARA-SÁENZ

In this chapter the physical processes involved in the generation, propagation and measurement of sound signals will be discussed so far as they relate to the understanding of noise in its various aspects.

1.1 NOISE GENERATION: MECHANICAL VIBRATION

1.1.1 Introduction

Noise as a sound sensation has its origin in the mechanical vibration of matter, either in the solid or fluid state. The ring of a bell or the escape of a gas in a pressurized system are two simple examples of the mechanical vibration of matter. The transmission of these vibrations through the air are received at the ear to become interpreted as sound by the human sensory system.

1.1.2 Why Does Matter Vibrate?

Two physical properties which control the vibrations of matter are its density and its elasticity (or springiness). Any external force imparted to a system which produces a displacement of the material body will invoke an elastic restoring force and the work done against this force will be stored as potential energy. On release of the external force, this energy will be expended in imparting kinetic energy to the mass of the body and this will accelerate until reaching its original undisplaced boundary, in the absence of damping. The presence of damping would involve an energy loss thus reducing this outward displacement. There will ensue a continuous and reversible interchange between the motion of the body and the elastic deformation thus giving rise to an oscillatory motion of the system about its equilibrium position, i.e. a mechanical vibration.

1.1.3 A Simple Vibrating System

Let us consider a simple non-dissipative ideal model of a vibrating system consisting of a rigid mass m, concentrated at its centre of gravity, and attached to a massless spring of elastic constant, k, the spring being rigidly fixed at its remote end (Figure 1.1).

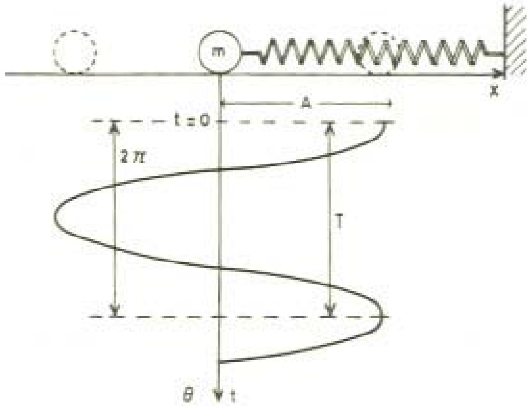

Figure 1.1 Mechanical vibration. Amplitude of displacement A, time of one cycle or Period T. Solid curve is displacement-curve, i.e. waveform of vibration

The mass is constrained to move along a single axis constituting one-degree-of-freedom system and its position at any time may be described by the single coordinate x.

The *free motion* above can be mathematically expressed by the application of the d'Alambert principle, viz Σ forces = 0. In this case, the operating forces are those of inertia and elasticity, so

$$m \frac{d^2x}{dt^2} + kx = 0$$

where k is the linear elastic constant. This second-order homogeneous linear differential equation is satisfied by

$$x(t) = A \cos \omega_0 t$$

$$\text{with } A = x_0 \quad \text{at } t = 0 \quad \text{and} \quad \omega_0 = \sqrt{\frac{k}{m}}$$

The fact that the simplest and basic mechanical vibration corresponds to a sinusoidal oscillation, is of fundamental importance in acoustics; for example, the explanation of the hearing mechanism (Chapters 4–6) is based on the sensation produced by the sinusoidal tones, which are present in any complex sound.

Because the harmonics function sine and cosine repeat themselves, every 2π radians, the time T (or period) of a cycle, is given by $\omega_0 T = 2\pi$ i.e. $T = 2\pi/\omega_0$. The parameter $\omega_0 = 2\pi/T$ has the dimension of radians divided by time, i.e. an angular velocity. The period of vibration may be thus related to that of a particle moving in a circular orbit with constant angular velocity ω_0. Hence the angular displacement θ (in radians) at time t from the initial angular displacement at $t = 0$ is $\omega_0 t$ radians.

$$\omega_0 = \sqrt{k/m} \quad \text{has dimensions of } \frac{1}{\text{Time}};$$

$$\left[\frac{MT^{-2}}{M}\right]^{\frac{1}{2}} = [\mathrm{T}^{-1}] \text{ i.e. an angular velocity}$$

The frequency or number of cycles per second is then given by

$$f_0 = \frac{1}{T} = \frac{\omega_0}{2\pi}\, H_z \quad 1 \text{ Herz} \equiv \text{One cycle of oscillation per second}$$

The complete solution for $x(t)$ to satisfy initial conditions (x_0, v_0) is

$$x(t) = A \cos \omega_0 t + B \sin \omega_0 t, \text{ with } A = x_0 \quad \text{and} \quad B = \frac{v_0}{\omega_0}$$

This expression is to be simplified by introducing the parameters C and θ_0 given by

$$A = C \cos \theta_0, \qquad B = C \sin \theta_0$$

hence $x(t)$ becomes

$$x(t) = C \cos (\omega_0 t - \theta_0)$$

where $C = \sqrt{(A^2 + B^2)}$ and $\tan \theta_0 = B/A$.

Making use of the de expression $e^{jz} = \cos z + j \sin z$, $\cos z =$ Real part of e^{jz}, the harmonic functions can be expressed in exponential form*, what yields to the complete exponential formula for the displacement of the vibrating motion.

$$x(t) = C\, e^{j(\omega_0 t - \theta_0)}$$

This formula in the case of $x_0 = A$ and $v_0 = 0$ $(B = 0)$ reduces to the exponential expression

$$x(t) = A\, e^{j\omega_0 t} \equiv \cos \omega_0 t$$

---

[*] The physical quantities correspond with the real part of the exponential function.

The following relations are readily deducible

	Initial conditions	
	$x(t)_0 = x_0,\ v(t)_0 = v_0$	$x(t)_0 = x_0,\ v(t)_0 = 0$
Displacement	$x = C\cos(\omega_0 t - \theta_0)$	$x = x_0 \cos \omega_0 t$
Velocity	$v = \dfrac{dx}{dt} = -\omega_0 C \sin(\omega_0 t - \theta_0)$	$v = -\omega_0 x_0 \sin \omega_0 t$
Total energy	$E = \frac{1}{2}kC^2$	$E = \frac{1}{2}kx_0^2$

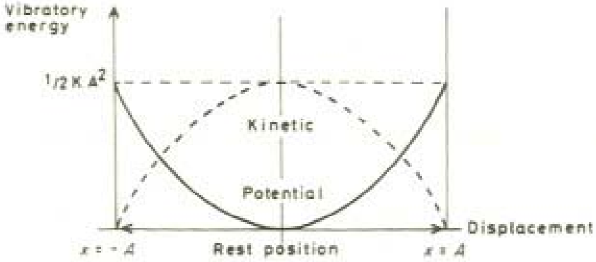

Figure 1.2 Mechanical vibration: kinetic and potential vibrating energy versus displacement along a cycle of oscillation

The energy balance is graphically represented in Figure 1.2.

A modification of the simple model to approach real situations is to include a dissipative force. This resistive force is in general of the viscous type and therefore proportional to the relative speed of motion. The constant of proportionality is defined as the resistive R_m of the system.

By introducing this force in the D'Alambert equation, the frequency of the oscillation slightly reduces to $\omega' = \sqrt{\omega_0^2 - \alpha^2}$ where

$$\alpha = \frac{R_m}{2m} \text{ is the temporal damping coefficient}$$

The amplitude of the motion is damped and decays according to the factor $e^{-\alpha t}$.*

Because in general $R_m \gg m$, $\omega' \sim \omega_0$, then the complete solution for the damped vibration of the isolated system is

$$x(t) = C\,e^{-\alpha t}\,e^{j(\omega_0 t - \theta_0)}$$

---

* For $\alpha = \omega_0$, $\omega' = 0$ (the system does not oscillate); and $R_c = 2m\omega_0$ is called the critical resistance, and the damping factor.

$$D = \frac{R_m}{R_c} = \frac{\alpha}{\omega_0} = \frac{\alpha T}{2\pi} = \frac{\delta}{2\pi} \text{ where the decremental logarithm is measured by}$$

$$\delta = \frac{1}{N} L_n \frac{Ce^{-\alpha t}}{Ce^{-\alpha(t+NT)}} = \frac{1}{N} L_n e^{\alpha NT} = \alpha T$$

1.1.4 Forced Mechanical Vibration

Most sources of noise are based on forced mechanical vibrations, in which the vibration is sustained by an external agency and the ideal model no longer has a single free vibratory damped motion.

The external forces may have a complex time variation pattern which would complicate the solution of D'Alambert's equation. Fortunately by means of Fourier analysis, any complex signal can be analysed (with some mathematical restrictions) in terms of sinusoidal components. This is most favourable in acoustics because any complex mechanical vibration that reaches our internal ear is analysed in terms of its sinusoidal components.

Fourier analysis was first introduced into the theory of hearing by Ohm (1843) who analysed the complex speech acoustical signals into sinusoidal tones. Today, there is evidence that the temporal and spatial sinusoidal tone-patterns produced in the peripheral auditory system by complex acoustic signals are responsible for mecano-electrical transduction into codified nerve impulses. These impulses convey and stimulate sound sensations in the central-auditory system (Chapters 4 and 6).

1.1.5 Mechanical Impedance vs Electrical Impedance

The response to sinusoidal excitation of any vibratory system, the hearing mechanism included, can be represented by its impedance.

The impedance $Z(\omega)$ of a mechanical system relates the sinusoidal components of the excitation force $F(t)$ to the resulting velocity of oscillation $u(t)$, i.e. $Z_m(\omega) = F(t)/u(t)$ as the electrical impedance $Z_e(\omega)$ of an electrical system relates the applied voltage $V(t)$ to the resulting current $i(t)$, i.e. $Z_e(\omega) = V(t)/I(t)$. The term impedance (from the Latin *impedire*), was first used in electrical theory (Heaviside, 1896) is of outstanding importance, because, in general, it relates the excitation with the response and govern the energy transfer between systems.

When the mechanical system model, with its concentrated constant parameters m, k and R_m, is excited by external forces represented by $F_e = F\,e^{j\omega t}$, then the D'Alambert principle enables the equation of equilibrium to be established, at any instant, between the action and reaction forces, i.e.

$$Fe^{j\omega t} = m\frac{d^2x}{dt^2} + R_m\frac{dx}{dt} + kx.\ \text{Trying } x(t) = Xe^{j\omega t}$$

the solution of this equation results in $x(t) = \dfrac{-jFe^{j\omega t}}{\omega[R_m + j\,(m\omega - (k/\omega))}$ and

$$\frac{dx}{dt} = u(t) = \frac{F\,e^{j\omega t}}{Z_m(\omega)}$$

where $Z_m(\omega) = R_m + j\,(\omega m - k/\omega) = R_m + jX_m$ is the mechanical impedance of the system in mechanical ohms, Ω_m, [N.s/m]. The impedance of an electrical circuit with R_e, L, C in series is: $Z_e = R_e + j(L\omega - (1/C\omega)) = R_e + jX_e$. Thus we have the equivalence of the analogous parameters

$$R_e \equiv R_m, \qquad L \equiv m \quad \text{and} \quad C = \frac{1}{k} \equiv C_m$$

L and C are respectively the electrical inductance and capacitance and m and C_m the mechanical inertance and compliance.

1.1.6 Mechanical Resonance

The mechanical impedance $Z(\omega)$ describes the response of a system as a function of the frequency. The larger the impedance the smaller the velocity (response) due to a given applied force. The minimum value of Z_m is at the frequency for which its reactive term X vanishes. This frequency is called the resonance frequency of the system: The condition $X_m = 0$ implies that $\omega_0 m = k/\omega_0$ i.e. $\omega_0 = \sqrt{k/m}$ which is equal to the free oscillation frequency of the system, previously defined, (1.1.3).

When the frequency of the excitation coincides with the free oscillation ω_0 of the system, the impedance presented by the system is a minimum and consequently its response is a maximum. This phenomenon is known as *Resonance*, expression originated in acoustics and borrowed by the electricians in "compensation" to the term *Impedance* borrowed from them.

Resonance has a very important role in all phenomena of system responses. In acoustics there are plenty of situations due to resonance phenomena. Musical instruments are but one of the most common examples. Most mechanical systems exhibit different frequencies of resonance and the designer can make use of them — either to emphasize the response or to reduce it depending on whether a reinforcement or a reduction of sound is desired.

1.1.7 Electromechanical Analogy: Energy transfer vs Impedance Matching

Making use of the electro-mechanical analogy (Olson, 1943), and the well-known Thevenin theorem of electrical circuit theory, it may be shown that any active mechanical system can be represented by a pure force generator F_0 in series with its internal impedance Zi Figure 1.3 shows the analogous electrical and mechanical circuits with the equivalence:

$$\begin{bmatrix} V \\ I \end{bmatrix} \equiv \begin{bmatrix} F \\ u \end{bmatrix}, \; Z_e = \frac{V}{I} \equiv Z_m = \frac{F}{u}$$

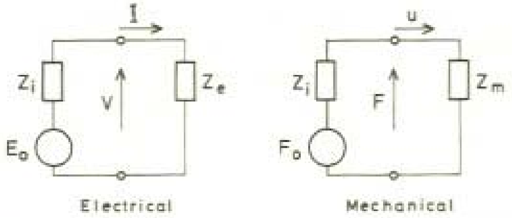

Figure 1.3 Electro-mechanical systems analogy

These circuits enable the transfer of energy between the active (source) and passive (load) systems in terms of their respective impedances to be evaluated

$$W = VI = F \cdot u = \frac{F^2}{Z_m} \quad \text{(paragraph 1.2.9)}$$

but

$$F = \frac{F_0 Z_m}{Z_i + Z_m} \quad \text{therefore} \quad W = F_0^2 \frac{Z_m}{(Z_i + Z_m)^2}$$

This function has a maximum for $Z_m = Z_i$, i.e. when the load impedance Z_m matches the source impedance Z_i.

Impedance matching is very important in all processes of energy transfer. In electro-acoustic systems such as sound-recording and reproducing equipment, all the elements, either active or passive, must have the same impedance to transfer the maximum energy along the transmission chain. In noise control, the large impedance mismatch between most sound sources and air favours the low efficiency of the vibratory energy transmission.

On the contrary, when the reception side is the hearing system, the living species have evolved to match the high-impedance of the mechanical system of its internal ear to the low-impedance of the air. This process was basic in the survival and evolution of the species marked by the transfer from the almost perfect impedance matching in sea life underwater to the high mismatch in the air.

1.2 ACOUSTIC WAVES: PROPAGATION OF MECHANICAL VIBRATIONS

1.2.1 Introduction

The idealized theoretical model of a mechanical vibrating system with lumped parameters of mass, elasticity and viscosity, permits the analysis and evaluation of the basic sinusoidal vibrations that are involved in any generation of sound.

In most cases, the mechanical systems are a continuum matter in either solid or fluid states. Because of the elastic bonds in matter, any local vibration is transmitted to the neighboring elements. The process of vibration transmission through condensed media constitutes the *elastic wave* propagation, which is responsible for the transport of mechanical (acoustical) energy.

1.2.2 Sound Waves

The term *sound wave* is commonly associated with elastic waves in the frequency range of the human hearing, i.e. 20 Hz to 20 kHz. Waves below and above this range are respectively known as *infra-* and *ultra-sounds*.

The propagation of vibrational energy takes a finite time and the distance travelled by the wave front (all points of which are in the same phase of the oscillation), in unit time, is the so-called phase velocity or *speed of sound* c. The value of c depends on the type of wave and on the physical characteristics of the propagation medium (Table 1.1).

1.2.3 Types of Sound Waves

Gases and low-viscosity liquids, when mechanically disturbed can only sustain changes in volume (the restoring force being the consequent pressure changes), so the mass elements in any fluid volume in contact with a vibrating surface will move in unison (i.e., in-phase displacements) creating successively *compressions and rarefactions* in the surrounding volume. These fluctuations of pressure are transmitted as a progressive wave into the fluid by virtue of its compressional or volume elasticity. In addition to these compressional waves solids can resist also changes of shape, and so are able to transmit *shear type deformations* i.e. shear-type waves and *flexural* or bending waves (Chapter 14).

Compressional waves are longitudinal in the sense that the oscillation of matter is in the direction of propagation. On the contrary shear and bending waves are transversal as the deformations take place perpendicular to the direction of propagation.

The geometry of the wave fronts differentiates waves into *plane*, *spherical* or *cylindrical*. For plane waves, the amplitude of the perturbation should ideally remain constant along the propagation path. In spherical and cylindrical waves the amplitude decreases linearly with the distance. These two types of waves are referred to as diverging waves.

1.2.4 Compressional Sound Waves in Air

Although sound waves may be propagated in any condensed medium, the most significant medium is air for noise pollution in the human habitat.

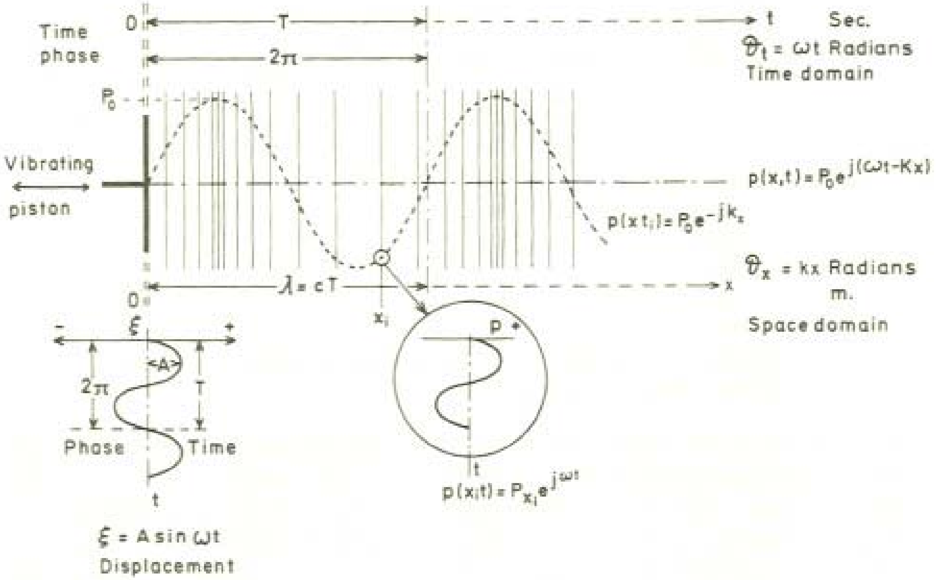

Figure 1.4 Plane compressional sound waves. A, amplitude of sinusoidal vibration of the piston. P_{xi} amplitude of the oscillation of the acoustic pressure in point x_i

Figure 1.4 shows a typical representation of compressional waves in air generated by sinusoidal vibrations of a rigid plane surface, (piston).

The wave profile in space follows the vibration profile in time $\xi(t)$. In the time of one cycle (T) the wave-front will move a distance cT. This distance (λ) defines the wavelength of the propagation. Hence

$$\lambda = cT = \frac{c}{f}$$

general expression that relates, for any type of wave in any medium, the wavelength with the frequency through the speed of propagation.

In linear propagation (valid for most common sounds except for intense ones such as explosions, sirens, etc.) there is no distortion of the wave-front either in time or space. If the vibration profile is any time function $\varphi(t)$, which is propagated in the positive x direction with a speed c it may be represented by the function $\varphi(ct - x)$. This profile repeats itself at distance ct along the propagation path (Figure. 1.5).

In the simplest and fundamental case of sinusoidal vibration, Figure 1.4, at

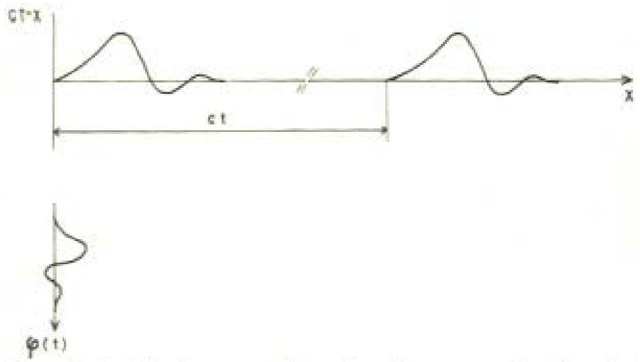

Figure 1.5 Displacement along the axis x at speed c of an elastic perturbation of profile $\varphi(t)$

any point x_i of the propagation path the sound pressure follows a sinusoidal oscillation represented by $p(x_i t) = P_{x_i} e^{j\omega t}$. Correspondingly, at any time t_i, the instantaneous value of the oscillating pressure at points along the propagation path will correspond to a sinusoidal profile represented by $p(x,t_i) = P_o e^{-jkx}$ where k is known as the wave-number and is the angle in radians per unit length of the propagation path, analogous in the space domain to the angular velocity ω in the time domain, k and ω being related by the speed c of propagation:

$$\frac{\omega}{k} = \frac{2\pi/\mathrm{T}}{2\pi/\lambda} = \frac{\lambda}{T} = \lambda \mathrm{f} = c$$

The variation of the sound pressure in points along the propagation path is therefore a sinusoidal function both of t and x given by the expression

$$p(x,t) = P_o e^{j(\omega t - kx)}$$

This expression is of fundamental use in dealing with wave phenomena.

1.2.5 Speed of Sound Propagation

For linear propagation in a homogeneous non-dissipative fluid media the speed of sound is independent of the amplitude and frequency and is given by the general expression $c = \sqrt{B/\rho}$ where $B = -\Delta p/\Delta v/v$ is the bulk modulus of elasticity and $\rho = m/V$ is the density of the medium, therefore $\sqrt{B/\rho}$ has the dimension of a speed $[\sqrt{(ML^{-1}T^{-2}/ML^{-3})} = LT^{-1}]$.

In the propagation of sound waves in a gas like air, the volume changes in free space can be generally considered adiabatic, i.e. there is no exchange of thermal energy between adjacent elements of volume, therefore the adiabatic equation of state for perfect gases $P \cdot V^{\gamma} =$ Constant applies, where γ is the ratio of principal specific heats. This gives for the bulk modulus of elasticity $B = -\partial p/\partial V/V = \gamma P$. P is the total instantaneous pressure, $P = P_0 + p$, which, because of the relative small values of the acoustic pressure, P can be substituted in the air by the atmospheric pressure P_0: therefore $B = \gamma P_0$ and for the same reason $\rho = \rho_0$, and the speed c_0 of sound in dry air at 0° Centigrade is given by

$$c_0 = \sqrt{\frac{\gamma P_0}{\rho_0}} \simeq 330 \text{ m/s}$$

for $P_0 = 1.013$ Pa* (Newton/m^2), $\rho_0 = 1.293$ Kg/m^3 and $\gamma = 1.41$

The speed of sound in gases does not change appreciably for regular changes in pressure as they are accompanied by changes of density so that the quotient P/ρ keeps practically constant. On the contrary, temperature has an appreciable influence on the speed of sound in gases. The quotient P/ρ varies with the temperature according to the equation of state $P/\rho = RT$, where R is the gas constant and T is the absolute temperature.

Therefore

$$\frac{c_t}{c_0} = \sqrt{\frac{T}{T_0}} = \sqrt{\frac{273 + t}{273}}$$

For dry air at $t = 20$ °C, $c_{20°} = c_0\,(1 + 0.037) = 330 + 12 = 342$ m/s.

The speed in water varies with temperature, pressure and salinity. A common value used as a reference is 1,500 m/s which corresponds to ocean surface waters at 0 °C and 35 ppt salinity.

In solids, the longitudinal type of wave travels at a speed $c_L = \sqrt{D/\rho}$ where D is the lonitudinal modulus of elasticity (volume).

For shear waves, the propagation speed is $c_s = \sqrt{G/\rho}$ where G is the shear modulus of elasticity. Table 1.1 gives values of sound speed in different media and structures, as well as the relations between D, G and B with Young's modulus E and Poisson's ratio of contraction μ.

1.2.6 Specific Acoustic Impedance Z_s: Characteristic Impedance of Matter, $Z_o = \rho c$

The impedance of a mechanical oscillatory system defines its reaction to a sinusoidal excitation making it possible to evaluate the transfer of energy to the receiving system. The main difference in acoustics compared with the electrical case is that except for special cases, when the dimensions of the system elements are small compared with the wavelength, the parameters of the system are not concentrated but distributed in a continuous manner.

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* Pa = Pascal.

Table 1.1

Material	Density	Modulus of elasticity (Pa)*				Wave velocity (m/s)				Characteristic impedance	Frequency of coincidence	Loss factor
						Longitudinal			Transversal			
(20° C)	kg/m^3 ρ	Young (Bar) E $\times 10^{10}$	Shear G $\times 10^{10}$	Bulk B $\times 10^{10}$	Poisson's ratio μ	Bulk (C_L) $\times 10^3$	Bars (C_{LB}) $\times 10^3$	Plate (C_{LP}) $\times 10^3$	Shear (C_s) $\times 10^3$	(Pa.s/m)* ρC_{LP} (plates) $\times 10^6$	f_c (Hz) (Plates) d = thickness (m)	(Platelike) η
Aluminium	2,700	7.2	2.7	7.5	0.34	6,400	5,160	5,500	3,160	15.0	12.40/d	10^{-4}–10^{-2}
Iron (cast)	7,800	10.5	4.1	8.0	0.28	4,150	3,670	3,820	2,790	30.0	17.50/d	10^{-4}–10^{-2}
Steel	7,800	21.0	8.0	18.4	0.31	6,100	5,200	5,450	3,200	42.5	12.00/d	10^{-4}–10^{-2}
Brass	8,500	9.5	3.57	9.3	0.33	4,060	3,350	3,550	2,050	30.0	20.00/d	$< 10^{-3}$
Copper	8,900	12.5	4.6	14.0	0.35	4,750	3,750	4,000	2,275	35.6	17.00/d	2.10^{-3}
Lead	11,100	1.7	0.6	4.0	0.43	2,100	1,240	1,370	735	15.2	52.00/d	1.5–2.10^{-2}
Gypsum	1,000	0.35					1,870			~1.9	34.00/d	1–3 10^{-2}
Brick†	1,600	1.4					3,000			~5.0	21.60/d	10^{-2}
Concrete†	2,200	2.5					3,400			~7.5	19.00/d	1–5 10^{-2}
Glass†	2,500	6.5	2.67	3.8	0.22	5,450	5,100	5,230	3,270	13.1	12.50/d	10^{-3}–10^{-1}
Cork†	200	0.0025	0.001	0.002	0.28	400	350	365	225	0.07		0.13–0.17
Wood (pine)	600	0.5	0.21	0.26	0.18	3,000	2,885	2,935	1,870	1.76	22.20/d	1–4 10^{-2}
Rubber (soft)	950	0.0005	0.17×10^{-3}	0.1	0.4992	1,025				~1.0		~ 0.3
Rubber (hard)	1,100	0.25	0.09	0.4	0.4	2,200	1,500	1,640	950	18.0		~ 0.15

$$D = E\frac{1-\mu}{(1+\mu)(1-2\mu)} = B + \frac{4}{3}G, \text{ being } B = \frac{E}{3(1-2\mu)} \text{ and } G = \frac{E}{2(1+\mu)};\ f_c = \frac{6.4 \times 10^4}{d}\sqrt{\frac{\rho}{E}};\ C_B = \sqrt{1.8\,f.d}\,\sqrt{\frac{\rho}{E}}$$

$$\text{(Volume) } C_L = \sqrt{\frac{D}{\rho}} = \sqrt{\frac{E}{\rho}\frac{1-\mu}{(1+\mu)(1-2\mu)}} = 2C_S;\ \text{(Bars) } C_{LB} = \sqrt{\frac{E}{\rho}};\ \text{(Plates) } C_{LP} = \sqrt{\frac{E}{\rho(1-\mu^2)}}\quad C_S = \sqrt{\frac{G}{\rho}} = \sqrt{\frac{E}{2(1+\mu)\rho}}$$

---

*(SI) Pa = N/m^2; N = kg.m/s^2; $\rho = \left[\frac{\text{Pa.s}}{\text{m}}\right] = \frac{\text{N.s}}{\text{m}^3} = \left[\frac{\text{kg m}}{\text{m}^3\text{ s}}\right]$; 1 bar = 10^5 N/m^2.

(CGS) Pa = 10 dyne/cm^2 = 10 μbar; 1 Rayl = 10 Pa.s/m (MKS).

† Average.

Referring to compressional sound waves, the relation between the instantaneous sound pressure p at a point of a medium and the velocity of oscillation u is called the Specific Acoustic Impedance : $Z_s = p/u$. It has the dimensions of a mechanical impedance per unit surface area

$$\left[\frac{Z_m}{S} = \frac{F}{uS} = \frac{p}{u}\right]$$

The analytical expression for Z_s is obtained by applying the second law of dynamics to an element of volume excited by a sound wave.

The force that accelerates a unit element of matter, which is due to the pressure gradient along the propagation path i.e. $\partial p/\partial t$, must be numerically equal to the product of the density and the vibrational acceleration $\partial u/\partial t$ (Newton second law) i.e., $-\partial p/\partial t = \rho\,(\partial u/\partial t)$ (The force and the gradient of pressure opposes each other). This linearized Euler's equation of force is valid for any linear sound propagation in fluids.

For sinusoidal waves,

$$u = U(r)\,e^{j(\omega t - kr)}, \text{ therefore } \partial u/\partial t = j\,\omega u$$

and the Euler's equation simplifies to $-\partial p/\partial r = \rho j\omega u$.

For plane waves, where the peak amplitude P_0 of the sound pressure remains constant along r, $p = P_0\,e^{(\omega t - kr)}$, the gradient of p reduces to a variation of the phase given by

$$\frac{\partial p}{\partial r} = -jkp \quad \text{or} \quad -\frac{\partial p}{\partial r} = j\frac{\omega}{c}p$$

Therefore for plane wave the Euler's equation gives the relation

$$j\frac{\omega}{c}\,p = \rho j\omega u \qquad \text{i.e. } \frac{p}{u} = \rho c = Z_s$$

ρc is a real quantity characteristic of every material and because it has the dimensions of a mechanical impedance per unit surface is called the *Characteristic Impedance of Matter*.

For air at normal conditions (in CGS units).

$\rho c = 1.2 \times 10^{-3}$ g/cm^3. 34×10^3 cm/s $= 41$ dyne.s/cm^3 $= 41$ Rayls (in honour of Lord Rayleigh).

In practical units (MKS or SI), $\rho c = 1.2$ kg/m^3 $\times$ 340 m/sec $= 410$ N.s/m^3 $=$ 410 MKS Rayls, i.e. 1 Rayl = 10 MKS Rayls. Table 1.1 gives values of ρc for different media.

The ratio p/u being a real quantity for planes waves, expresses the fact that the sinusoidal time variation of p and u are in phase at all points along the propagation path.

For diverging spherical waves and because the peak amplitude of the sound pressure varies as $1/r$, i.e. $p = (P_0/r)\, e^{j(\omega t - kr)}$ the gradient of p results $\partial p/\partial r = -p\,[1/r + jk]$, i.e. it includes a variation with the distance to the source (geometrical centre of divergence).

The Euler's equation results in

$$\rho j\,\omega u = p\,(1/r + jk) \quad \text{or}$$

$$Z_s = \frac{p}{u} = \frac{j\rho c k}{(1/r) + jk} = \rho c \frac{kr}{\sqrt{1 + k^2r^2}}\; e^{j\theta} = \rho c \cos\,\theta e^{j\theta} \text{ with } \tan\theta = \frac{1}{kr}$$

This relation shows that for spherical waves Z_s is a complex quantity $Z_s = |Z_s|\, e^{j\theta}$ of amplitude $|Z_s| = \rho\, c \cos\theta = P/U$, θ being the angle of phase delay between p and u, that depends of the product kr. For $kr \gg 1$, θ approaches zero ($\tan\theta = (1/kr) \rightarrow 0$) either for large values of k (high frequencies, $K = \omega/c$) or for large distances (r) to the source. In both cases, the wave-fronts approach plane-wave geometry, and in coincidence with, $|Z_s|$, $= \rho c \cos\theta$, tends to the value ρc for plane waves, i.e. at high frequencies or at long distances to the source the specific acoustic impedance Z_s can be approximated by the real quantity ρc independently of the form of the wave propagation either of constant or diverging geometry.

1.2.7 Acoustic Impedance: Impedance Relations

In a point of the medium excited by a sound wave, the sound pressure p generates a particle velocity u. Consequently the "passing" of wave-front through a surface produces a *rate of volume displacement* $\dot{X} = S\cdot u$, where S is the area of the surface. The ratio between p and $\dot{X}$ defines the acoustic impedance Z_A at the surface s, i.e.

$$Z_A = \frac{p}{\dot{X}} = \frac{p}{Su} = \frac{Z_s}{S}$$

Therefore the following relations between impedances hold:

Mechanical impedance (Mechanical ohm, Ω_m); $Z_m = \frac{F}{u}\left[\frac{\text{N.sec}}{\text{m}}\ \Omega_m \text{ MKS}\right]$

Specific acoustic impedance $\left(\text{Rayl} = \frac{\text{dy.s}}{\text{cm}^3}\right)$;

$$Z_s = \frac{p}{u} = \frac{F}{Su} =$$

$$\frac{Z_m}{S}\left[\frac{\text{N.s}}{\text{m}^3}\ \ \text{Rayl MKS} = 10^{-1}\text{Rayl}\right]$$

Characteristic impedance of matter;

$$Z_0 = \rho c \left[\frac{\text{N.s}}{\text{m}^3} \ \text{Rayl MKS} \right]$$

Acoustic impedance (Acoustic ohm, Ω_A);

$$Z_A = \frac{p}{Su} = \frac{Z_s}{S} = \frac{Z_m}{S^2} \left[\frac{\text{N.s}}{\text{m}^5} = \frac{\text{Rayl MKS}}{\text{m}^2} \right.$$

$$\left. = \Omega_A \ \text{MKS} = 10^{-5} \ \frac{\text{Rayl}}{\text{cm}^2} = 10^{-5}\Omega_A\text{CGS} \right]$$

With this last relation it is possible, for instance, to calculate the acoustic impedance presented by the tympanic membrane, dividing its mechanical impedance by the square of the tympanic area.

The electromechanical analogies can also be extended to acoustics through the respective impedance expressions. These analogies permit the functioning of acoustical systems to be described by means of the well-known theory of electric circuits. It can be applied to complicated systems such as those involved in machinery noise radiation, voice generation or to the mechanism of the middle-ear coupling, etc. The measurements of the impedance of the middle ear has become a valuable diagnostic procedure and source of information in otology.

1.2.8 Specific Types of Sound Field: Free, Confined, Diffuse

The sound field is understood to be the space surrounding a sound source in which its acoustic effects can be practically detected. The principle of the superposition of sound excitations at a given point means that the existence of a close cluster of sources can lead to a very complex sound field.

The particular case in which the boundaries of the volume in which sound is being propagated are sufficiently removed to have insignificant influence is referred to as *Free Field* conditions. These conditions of propagation are seldom found in nature. Even in the case of open-air propagation there is the boundary provided by the ground and this will act as a reflector and absorber of sound energy (Chapter 2) so the free-field conditions would not be fully realized. In addition, obstacles will *diffract* (curve) the sound waves, and climatological conditions may cause *refraction* (change in direction by layers with different speed of propagation).

A. Simulated Free-Field Conditions (Anechoic Chamber)

An attempt to simulate free-field conditions has been the construction of

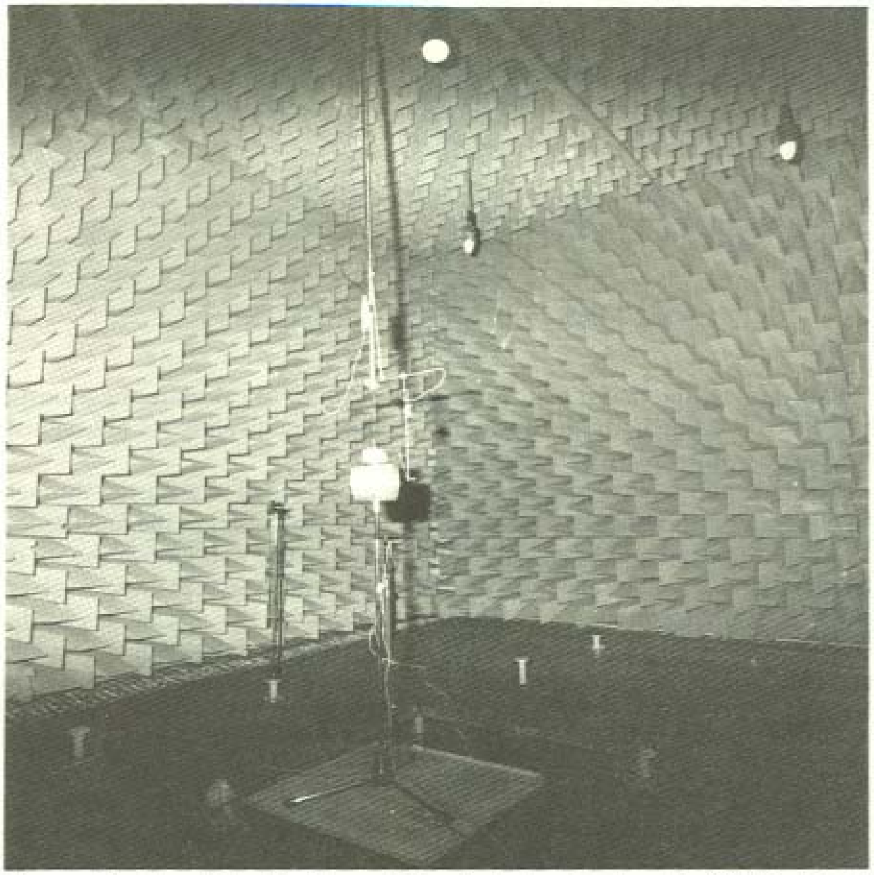

Figure 1.6 Anechoic chamber at the Institute of Acoustic CSIC. Madrid (Lara-Saenz, 1965), cut-off frequency ($R \leqslant 0.1$) 90 Hz., Interior dimensions 7.4 × 5.5 × 5.5 m

so-called anechoic chambers which are enclosures in which all interior surfaces are covered with sound-absorbing material in most cases in the form of wedges, with their flat rectangular bases in contact with each other. The depth of such wedges determines the lower frequencies of close simulation, i.e. a close agreement with the inverse square law for the fall-off of intensity from sources within the room. These confined fields are limited in size by their expense, and are generally used for such purposes as the evaluation of acoustic emission of sources (ISO 3475), calibration of transducers (ASA S1.10.5; IEC 268-5), etc. (Figure 1.6 (Lara Saenz, 1965)).

B. Simulated Diffusion Rooms (Reverberation Chambers)

These rooms are designed to obtain as close an approximation as possible to the condition when there is a uniform value of average sound energy per unit

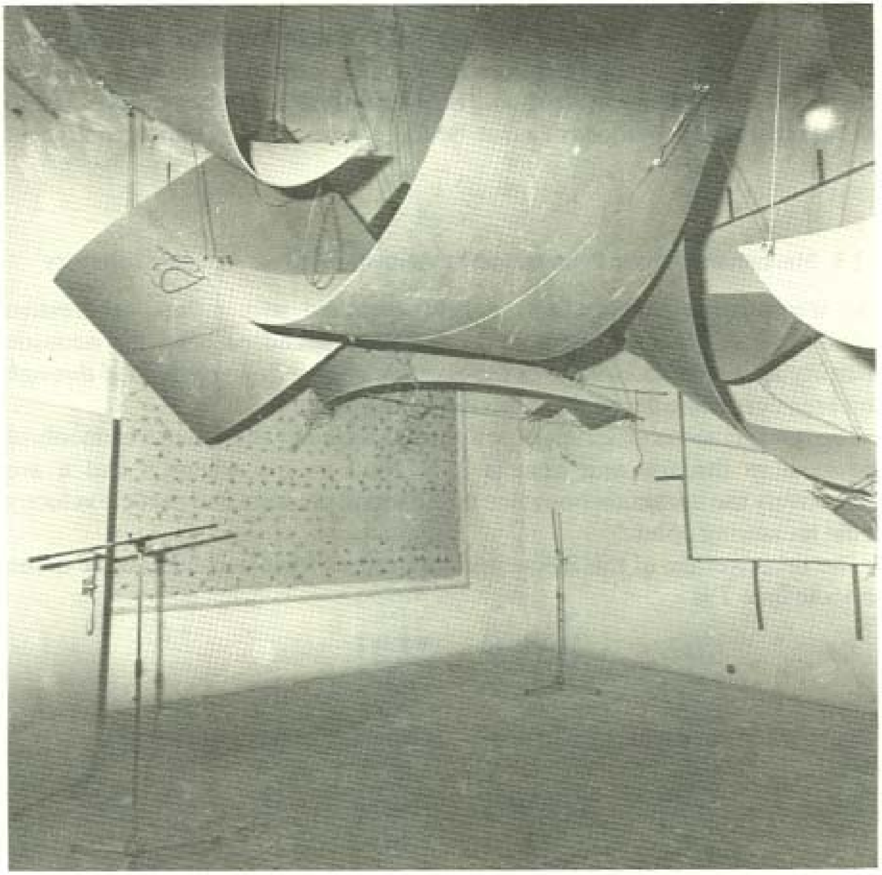

Figure 1.7 Reverberant chamber at the Institute of Acoustic CSIC, Madrid (Lara-Saenz, 1965). Reverberation Time at 500 Hz, 6.8 sec; volume 200 m^3

volume over most of the internal space. This is achieved by choosing the confining surfaces to be strongly reflecting to acoustic waves but also minimizing the existence of standing waves by a slanting of the surfaces with respect to each other. Additional *diffusion* is attained by fixed or movable reflections surfaces within the room volume. This kind of chamber allows the overall power emission of sound or noise sources to be evaluated (ISO 3741) as well as the absorption characteristic (ISO/R 354), of sound materials (Figure 1.7 (Lara Saenz, 1965)).

Due to the complexity of real sound fields, an approximation is made in every case by reference to the well-defined conditions of *Free Field* or *Diffuse Field*.

Thus open air propagation is basically approximated to by free field conditions. In a closed space there is dependence on the distance to the sound source. At short distances, the direct sound (free-field approximation) dominates but it is the reverberant sound (diffuse field approximation) which dominates at greater distances. The simple Sabine formula for the reverberation time in rooms assumes a diffuse field, which is often inconsistent with the real conditions, and therefore should be used only as a rough reference. It also fails to satisfy the conditions of a free-field, i.e. when the absorption coefficient is unity.

1.2.9 Mechanical Power Propagated by Acoustic Waves: Acoustic Intensity

The transmission of vibration energy associated with a free progressive sound-wave is measured in points (x_i) of the sound path by the acoustic intensity $I(x_i)$ or time average of the acoustic energy flow *transmitted through* unit area perpendicular to the direction of propagation.

The instantaneous mechanical power transmitted by the wave to elements of the medium through unit area is $I_i = F \cdot u/S = p \cdot u$ where p and u are respectively the instantaneous value of the sound pressure and particle velocity at the measuring point.*

The time average of this instantaneous product for a sinusoidal wave in the periodic time T is

$$I = \bar{I}_i = \frac{1}{T}\int_0^T p.u \,\mathrm{d}t \left[\frac{N}{\mathrm{m}^2}\cdot\frac{\mathrm{m}}{\mathrm{sec}} = \frac{\mathrm{watts}}{\mathrm{m}^2}\right]$$

For plane waves, p and u are in phase (its ratio is a real quantity ρc) so

$$I = \frac{1}{T}\int_0^T P\cos(\omega t - kx)U\cos(\omega t - kx)\mathrm{d}t = \frac{P.U}{2} = \frac{P^2}{2\rho c} = \frac{p^2_{\mathrm{rms}}}{\rho c}\;^{\dagger}$$

For spherical waves the oscillations of p and u are delayed in time an angle θ

Therefore

$$I = \frac{PU}{2}\cos\theta$$

but for this type of wave

$$\frac{P}{U} = \rho c \cos\theta$$

Therefore $I = p^2_{\mathrm{rms}}/2\rho c$ same expression as for the plane waves.

The expression for the acoustic intensity $I = p^2_{\mathrm{rms}}/\rho c$ is analogous to the power delivered to an electric circuit of electric resistance R by applying a

---

* Without mean flow in the medium.

† In sinusoidal waves, T is one cycle time and $p_{\mathrm{rms}} = P/\sqrt{2}$, P being the peak amplitude of the sine wave.

voltage V (excitation), that produces a current I (response) $W = V \cdot I = V^2/R$ (paragraph 1.1.7).

1.2.10 Acoustic Energy Density *E*

An acoustic field comprises the superposition of waves having in general different pressure amplitudes and propagation directions. The intensity, giving the directional rate of energy flux, is not valid to evaluate the magnitude of the resulting acoustic field because waves from different directions may reduce the net flux through a surface and even to cancel it as in the case of a perfect diffuse field. What counts is the resulting average vibration energy density in points on the field.

For non-dissipative fluids, the instantaneous value $E(t)$ of the acoustics energy density is (as in the case of mechanical vibrating systems) the sum (per unit of volume) of the kinetic energy of the moving masses and the potential energy in the compressed and rarefied volume elements.

It is easy to show that

$$E(t) = \tfrac{1}{2}\rho\left(u^2 + \frac{p^2}{\rho c^2}\right)$$

For sinusoidal waves the time average of $E(t)$ in the period T is obtained throught the specific acoustic impedance $Z_s = p/u$ for each type of wave

$$E = \hat{E}(t) = \frac{1}{T}\int_0^T E(t)\,\mathrm{d}t = \frac{\rho}{2T}\int_0^T p^2\left(\frac{1}{Z_s^2} + \frac{1}{\rho^2 c^2}\right)\mathrm{d}t = \frac{P^2}{2\rho c^2} = \frac{p_{\mathrm{rms}}^2}{\rho c^2}$$

1.2.11 Intensity *vs* Energy Density.

Either in free-field or reverberant situations the field can be considered as comprising free progressive plane waves.

In the free-field, the Intensity I is related to energy by the straight-forward relation

$$I = Ec = \frac{p_{\mathrm{rms}}^2}{\rho c}$$

In the reverberant field, the flux of energy I_D incident on any surface is one fourth* of the flux coming from all directions, therefore

$$I_D = \frac{Ec}{4} = \frac{p_{\mathrm{rms}}^2}{4\rho c}$$

---

* In a diffuse field the flux over one face of a surface is half the total flux and this flux coming from all directions in a semi space reduces by a factor of two compared with the same flux normal to the surface.

where p_{rms} is the resulting value in the field. Because microphones easily detect sound pressure, the sound field is evaluated in terms of its mean square pressure, $\overline{p^2} = p^2_{\mathrm{rms}}$ (1.4.1).

In most cases the reverberant field is not homogeneous and a space average value of E is needed to evaluate the field.

Intensity in a particular direction can be measured in terms of the pressure gradient in that direction. The technique involves the use of two identical microphones facing each other in the direction of the acoustic flux, and it is of particular interest mainly in source localization (Gade 1982).

1.2.12 Evaluation of the Sound Field Level; Decibels Scale

The average normal human ear can perceive pitch sensations corresponding to sinusoidal acoustic waves in a range of frequency between 20 and 20,000 Hz. Because the sensitivity of the ear varies with frequency a middle-range frequency of 1,000 Hz is taken as reference for the average normal threshold of hearing.

The range of acoustic energy density for the human ear between the threshold of hearing and the sensation of pain is as large as 10^{14}. In order to handle this tremendous range (hundred millions of millions!), use is made of a logarithmic scale to compare different values of energy with a reference value. The unit is the Bel, first introduced at the Bell Laboratories (USA) to evaluate the attenuation of sound signals in telephone cables; n Bels corresponding to an energy ratio of 10^n. Consequently, the mathematical expression for the Bels scale is n Bels $= \log_{10} 10^n$ and the unit 1 Bel $= \log_{10} 10$. Using this scale the average human hearing range reduces to a scale of 14 Bels. In actual practice a more convenient unit is that of 0·1 Bel, known as the decibel (dB), so that the human hearing range is given by 140 dB. ($10 \log 10^{14}$).

Because the sound energy density is proportional to the square of the sound pressure, it is possible to evaluate the energy density level range of human hearing in terms of the sound pressure by fixing a reference pressure value p_0, corresponding to the average threshold of hearing. This value has been chosen as the rms sound pressure of a free progressive wave of 1,000 Hz just perceived binaurally by the average normal hearing person facing the source (ISO-R 226), and approximated to $p_0 = 2 \times 10^{-5}$ N/m^2 = 20 μ Pa.

The energy level of the sound field in decibels in terms of the root mean square sound pressure p_{rms} in the air, is given by the relation

$$10 \log \frac{E}{E_0} = 10 \log \frac{p^2_{\mathrm{rms}}}{p^2_0} = 20 \log \frac{p_{\mathrm{rms}}}{p_0} \text{ dB} = \text{SPL}$$

This level is usually known as the *Sound Pressure Level (SPL)*, (it should better be called Sound Mean Square Pressure Level).

For free field propagation the SPL coincides with the *Sound Intensity Level*, (SIL).

$$\text{SIL} = 10 \log \frac{I}{I_0} = 10 \log \frac{p_{\text{rms}}^2}{p_0^2} = 10 \log \frac{E}{E_0} = \text{SPL}$$

$$\text{where } I_0 = \frac{p_0^2}{\rho c} \simeq \frac{4 \times 10^{-10}}{400} = 10^{-12}\ \text{w/m}^2$$

For a diffuse field, the level of the sound intensity I_D $\text{SI}_\text{D}\text{L}$ impinging on any surface differs from the SPL, i.e.:

$$\text{SI}_\text{D}\text{L} = 10 \log \frac{I_D}{I_0} = 10 \log \frac{E/4}{E_0} = 10 \log \frac{1}{4} \frac{p_{\text{rms}}^2}{p_0^2} = \text{SPL} - 6\,\text{dB}$$

(paragraphs 1.3.6 and 1.3.10).

1.2.13 Sound Sources *vs* Wave-front Geometry

A sound source is any device that transmits mechanical vibrational energy to the surrounding medium.

Sound sources can be of many types. For most practical cases of noise radiation it is convenient to refer to the geometry of the generated wave-front as either Plane, Spherical or Cylindrical. This information facilitates the evaluation or prediction of the geometrical spreading of the sound energy along the propagation path.

The generation of plane waves would require, theoretically, an infinite plane vibrating surface. An actual approach to plane waves is the propagation in pipes ($d \gg \lambda$). In real cases, most extended sources, i.e. with large radiation surface in comparison with the wavelength λ of the generated sound wave, radiate approximately plane waves in the vicinity of the source.

In the case of radiating surfaces small in comparison with λ the source can be approximated to a theoretical small pulsating sphere that radiates spherical wave-fronts. This constitutes a point source.

Finally, a third type of common sound source is a line of point sources, or line source, that radiates cylindrical wave-fronts.

1.2.14 Sound Source Power Level — SWL

A main factor for evaluating a sound source is its radiated power. In order to relate this power with the Intensity Level of the radiated free field, it is expressed on the decibel scale by reference to a power value W_0. This is chosen to be that of a spherical radiating source producing the reference intensity $I_0 = 10^{-12}$ W/m^2 over a spherical surface of 1 m^2. Therefore, ($W_0 = I_0 . S$):

$$W_0 = 10^{-12} \text{ watts}$$

The sound power level of a source of sound power W_A watts is then given by

$$\text{SWL} = 10 \log \frac{W}{W_0} \text{ dB}$$

Table 1.2 gives reference values of some common sources.

Table 1.2 Sound Power and Sound Power Level of common noise sources

W (watts)	SWL (dB) 0 dB = 10^{-12} watts	Source
10^3	150	Jet aircraft
10	130	80 instrument orchestra (fortissimo)
10^{-1}	110	Chipping hammer
10^{-3}	90	Shouting
10^{-5}	70	Normal voice
10^{-7}	50	Quiet electric shaver

1.2.15 Source Strength, Q

The source strength is a convenient parameter in defining sound sources. It is a measure of the rate of the volume flow generated by the source, i.e. $Q = S \cdot u$ where S is the radiating surface area and u its instantaneous vibration velocity. In general u may vary along the surface and

$$Q = \int_s u \, \mathrm{d} s$$

The importance of Q is that for any source that can be assimilated to a Simple Source (closed surface with $l/\lambda \ll 1$, where l is a linear dimension) the radiated power is independent of the source shape and only depends on the rate of change of Q.*

$$W = \frac{\rho}{8\pi c}\left(\frac{\mathrm{d}Q}{\mathrm{d}t}\right)^2 \text{ by substituting } \frac{\mathrm{d}Q}{\mathrm{d}t} = \omega Q = \frac{2\pi c}{\lambda} Q; \; W = \frac{\rho \pi c}{2}\left(\frac{Q}{\lambda}\right)^2$$

1.2.16 Geometrical Spreading of Sound Energy

Because the acoustic power radiated by a source spreads into space, the sound intensity falls off with the distance from the source, depending of the shape of the wave-front.

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* This fact used to be strikingly demonstrated by Prof. M. Heckel (Chapter 14) to his pupils by opening two similar bottles of champagne but at different speeds!

In the absence of damping, a plane-wave in free space maintains, theoretically, the same intensity through the propagation path. In real cases, as the radiating surface is limited, the plane-waves gradually diverge with the distance into spherical waves. In this last type, because the surface area of the wave-fronts increases as the square of the distance from the source, every time that the distance doubles the surface increases four times. The total power being the same through any wave-front surface (no dissipation), the intensity, or power per unit area, decreases to one-fourth, i.e. the intensity reduces by 10 log $2^2 = 6$ dB per each doubling the distance (inverse square law).

For cylindrical waves, the surface increases linearly with the distance, so the intensity reduces only by 10 log 2 = 3 dB for each doubling of the distance.

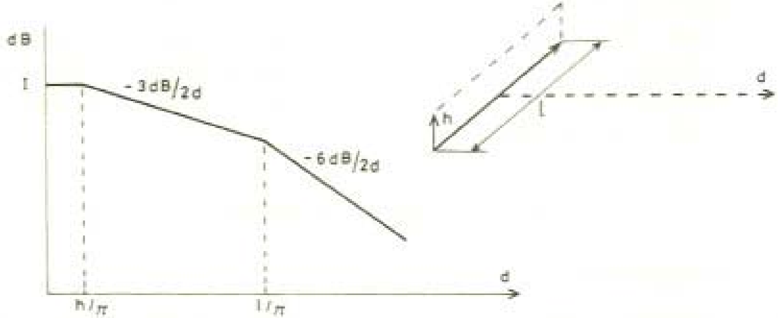


Figure 1.8 Theoretical Sound Level reduction with the distance from a passing rail road train with lateral dimensions $l \gg h$

Figure 1.8 shows a graphical approach to the reduction of sound intensity with the distance due to geometrical spreading for a passing railroad train. At short distance, the sound-waves from the moving carriages can be approximated by plane-waves with no intensity reduction, but subsequently they approach the cylindrical form as corresponds to a line source, with the intensity falling off 3 dB for doubling the distance. At great distances, the line source approach a point source and the cylindrical waves become approximately spherical with a reduction of intensity of 6 dB per doubling the distance.

An isolated car in a road approximates to a point source, while a dense continuous traffic approaches a line source; a flying plane approaches a point source (Chapters 12 and 13).

1.2.17 Radiation Pattern: Directivity and Directivity Index

Real noise sources differ from theoretical types. In most cases they have many vibrating parts with different frequencies and velocities of vibration. While preserving the geometry of the radiated wave-front, the intensity may vary with the direction of propagation. In many cases it is important either for sound propagation outdoors or in interior sound fields to know the radiation pattern of the intensity which in general varies also with the frequency. The *Directivity* is a convenient reference parameter and is given by the ratio of the intensity I_θ in a point at distance r in a determined direction θ as compared to the intensity I_0 in the same point for the case of a spherical radiation, i.e. $D = I_\theta / I_0$ where $I_0 = W / 4\pi r^2$, W being the source sound power. The *directivity index*, DI, is the expression of the Directivity in a decibel scale.

$$DI = 10 \log \frac{I_\theta}{I_0}$$

The directivity is an intrinsic characteristic of the sound source and refers to the radiation pattern in free-field conditions. Extrinsic characteristic to the source such as reflections from boundary surfaces in the proximity may modify the directivity pattern. These are the cases of location of sources on the floor, with a backing wall or in a corner, which theoretically increase the Directivity by a factor of 2, 4 or 8 respectively.

1.3 SOUND IN ENCLOSURES

1.3.1 Standing Waves

When a progressive sound wave encounters a rigid plane surface as can be the case with room walls, there is a *reflection* of energy and a sound-wave comes back in a direction that follows the specular law of reflection.

For a sinusoidal sound pressure wave the addition of the normal incident and reflected waves results in a total sound pressure

$$p = p_i + p_r = P_i e^{j(\omega t + kx)} + |R| P_i e^{j(\omega t - kx + \phi)}$$

the reflection coefficient being

$$R = \left|\frac{P_r}{P_i}\right| e^{j\phi}$$

In the case of a perfect rigid surface $P_r = P_i$, $\phi = 0$, $R = 1$ and

$$p = P_i (e^{+jkx} + e^{-jkx}) e^{j\omega t} = 2P_i \cos kx e^{j\omega t}$$

i.e. at each point x, there is a time varying pressure of angular frequency ω, with a fixed amplitude given by $|2P_i \cos kx|$. This fixed spatial amplitude distribution corresponds to a *stationary wave* with alternate maxima and

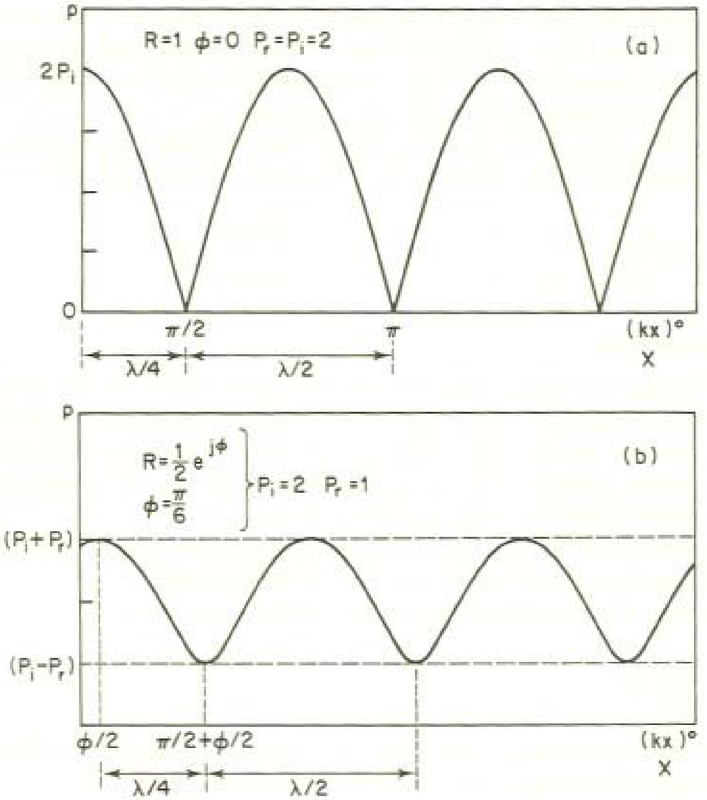


Figure 1.9 (a) Standing wave pattern along x for a complete reflection ($R = 1$) at $x = 0$; (b) Standing wave pattern along x for a partial reflection ($R < 1$) at $x = 0$

minima located at values of x given by $kx = 0, \pi/2, 3\pi/2, 2\pi$, etc. (Figure 1.9(a)). As $k = 2\pi/\lambda$, the maxima or minima are separated by $\lambda/2$ and the stationary wave has a repetition rate twice that of the progressive sound wave.

In the general case of non-perfect rigid surfaces it can be easily deduced that

$$p = (P_i - P_r)\, e^{j(\omega t + kx)} + 2P_r \cos\left(kx - \frac{\phi}{2}\right) e^{j(\omega t + (\phi/2))}$$

i.e. the total pressure is now the result of a progressive wave of amplitude $(P_i - P_r)$ added to a stationary wave of amplitude $|2\, P_r \cos\,(kx - \phi/2)|$.

The resulting amplitude distribution corresponds to a *standing* wave with maxima $(P_i + P_r)$ and 'rounded' minima $(P_i - P_r)$, (Figure 1.9(b)).

In the theoretical case of a perfect rigid plate, the surface does not absorb any energy ($R = 1$), and the resulting stationary wave does not transport energy. In the general case, the surface "absorbs" some energy which is transported by the progressive component of the resulting *standing* wave.

The ratio $P_{\text{max}}/P_{\text{m}}$ is the Standing Wave Ratio (SWR). By measuring the SWR the amplitude of the reflection coefficient R can be deduced:

$$\text{SWR} = \frac{P_{\text{max}}}{P_{\text{m}}} = \frac{P_{\text{i}} + P_{\text{r}}}{P_{\text{i}} - P_{\text{r}}} = \frac{1 + R}{1 - R}\,;\; R = \frac{\text{SWR} - 1}{\text{SWR} + 1}$$

1.3.2 Room Modes

Standing waves are responsible for the *Resonant Modes* of the rooms, or frequencies for which the wavelength are integers of the sound-ray paths. The room emphasizes those frequencies of the signal spectrum which coincide (within a close range) with its resonant frequencies. This phenomenon constitutes the 'frequency response' of the room.

The transitory period after the extinction of the source (like in any vibratory system) depends on the decay of the different room modes.

The number of room modes below a frequency f is given by

$$N \sim \frac{4\pi V}{c^3} f^3$$

From this expression it is deduced that the number of modes in a frequency band increases with the square of the centre frequency

$$\frac{\Delta N}{\Delta F} \sim \frac{4\pi V}{c^3} f^2$$

i.e. the response of the room becomes smoother as the frequency increases.

The shape of the room influences the spatial distribution of the modes, but not the number of them which depends on the volume (Bolt R. H. 1946).

1.3.3 Reflection, Absorption and Transmission Coefficients

In actual situations the limiting surfaces of a sound field are not perfectly rigid and part of the incident energy 'enters' the surface and the rest is reflected. The boundary condition at the surface, for the same type of wave propagation in both media (Figure 1.10(*a*)), requires that the pressure and the velocity on both sides be equal. This leads to the expression for the *Amplitude Reflection Factor R*.

$$R = \frac{P_r}{P_i} = \frac{Z_2 - Z_1}{Z_2 + Z_1}$$

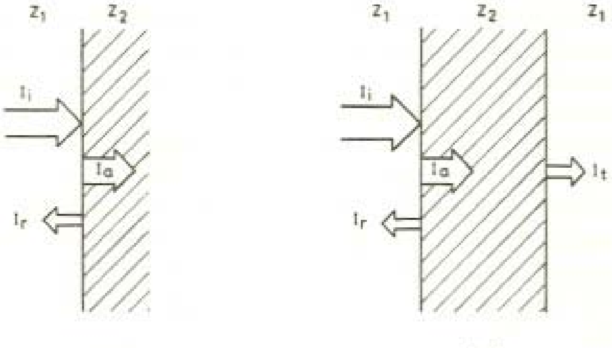
The *Energy Reflection Coefficient* or ratio between the reflected and incident energies is

$$\alpha_r = R^2 = \left(\frac{I_r}{I_i}\right) = \left(\frac{P_r}{P_i}\right)^2 = \left(\frac{Z_2 - Z_1}{Z_2 + Z_1}\right)^2$$

The energy not reflected is 'absorbed through the surface' and defines the *Absorption Coefficient* at the interface at normal incidence

$$\alpha_a = \alpha_\perp = \frac{I_i - I_r}{I_i} = 1 - \alpha_r = I - R^2 = 1 \left|\frac{Z_2 - Z_1}{Z_2 + Z_1}\right|^2$$

For $Z_2 = Z_1$, $R = 0$ and $\alpha_a = 1$, i.e. all the incident energy is 'absorbed' through the surface.



(a) (b)

Figure 1.10 (a) Plane wave reflection and absorption at the interface of two infinite media of impedances Z_1 and Z_2; (b) Plane wave reflection, absorption and transmission by a finite size medium of imput impedance Z_2

In most cases, the depth of the material backing the interface $Z_1 | Z_2$ is finite, (walls, floors, etc.) delimiting a second interface $Z_2 | Z_1$, (Figure 1.10(b)). Not all the energy passing through the first surface may be dissipated in the material. The remaining energy is transmitted by the intermediate medium defining a *Transmission Coefficient*:

$$\alpha_t = \frac{I_t}{I_i} = \frac{I_i - I_r - I_d}{I_i} = 1 - \alpha_r - \alpha_d \quad \text{hence} \quad \alpha_r + \alpha_d + \alpha_t = 1$$

is the power balance equation.

The dissipated energy I_d is degradated by the mechanism of wave propogation inside the material.

1.3.4 Sound Absorbing Materials: Sabine Absorption Coefficient, Equivalent absorption area, A

All building materials, even those considered highly reflective such as solid concrete, glass and steel absorb some energy from the sound field when they form the bounding surfaces of an acoustic space. At specific frequencies, considerable energy may be absorbed by mechanical resonance (e.g. vibration plates) or acoustical Helmholtz resonators.

However, the absorption of a significant amount of sound energy over a broad range of frequencies requires specific materials, known as Acoustic Absorbing Materials. They generally have a fibrous or porous structure which facilitates the degradation of acoustic energy into heat through viscous and thermal damping processes in the air filling the pores.

Because such absorption depends on the angle of incidence of the sound-wave, a statistical absorption coefficient is defined: the ratio of the absorbed to the incident energies in a diffuse sound field. In practice, this absorption coefficient is measured in specially constructed Reverberation Chambers installed in specialized laboratories. Since the accuracy of this method is limited by many imperfections such as a finite sample size, the measurements are made under standard conditions and the absorption coefficient is calculated from the Sabine formula. This absorption coefficient is described as alpha Sabine or α_s. As the coefficient α_s varies with frequency it is usually measured at a few standard frequencies (e.g. 250, 500, 1 kHz, 4 kHz). Use is sometimes made of the NCR (Noise Reduction Coefficient) which corresponds to the average absorption at only three frequencies (500, 1,000 and 2,000 Hz).

For a whole room, the *Average Absorption Coefficient* $\bar{\alpha}_s$ is defined as the coefficient that multiplied by the total surface area of the room will give the same total absorption as the sum of the partials formed by multiplying each element of surface area by its corresponding absorption coefficient,

$$\alpha_1 S_1 + \alpha_2 S_2 + \ldots \alpha_n S_n = \bar{\alpha} \sum_{i}^{n} S_i = A \, [\mathrm{m}^2]$$

i.e., A is the equivalent area of a surface with 100% absorption. Volume elements may add equivalent units of absorption, (e.g. ~ 0.4 m^2 per person).

1.3.5 Decay of Energy in Reverberant Fields: Reverberation Time

Since speech and music are transient in nature, the reverberant decay of sound energy is a highly definitive acoustic characteristic of any room. Such reverberation determines the masking effect of decaying sounds in presence of succesive sounds, as well as the overall level of sound in the room. When the source of sound is switched off, the energy E_D of the diffuse field decays exponentially in accordance with the expression $E_t = E_D \, \mathrm{e}^{-(Ac/4V)t}$

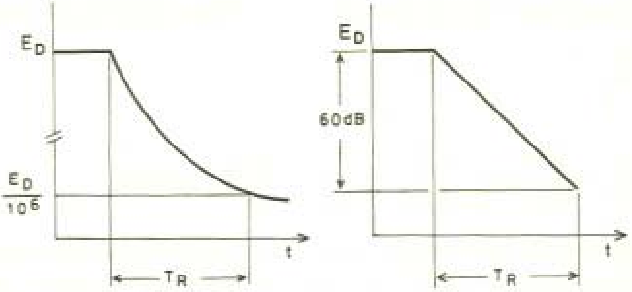


Figure 1.11 Qualitative decay of energy of a reverberant field: Reverberation Time T_R

(Schroeder, 1966). where V is the volume of the room in m^3, A is the total equivalent surface absorbing area in the room in m^2, c the speed of sound in air in m/s and E the acoustic energy density in Joules/m^3 (see Figure 1.11).*

The *Reverberation Time* T_R as first defined by Sabine (1922) ($T_R = k(V/A)$) is the time required for the energy density to fall by a factor of one million, (60 dB). This time can be measured or predicted through the decay curve (Figure 1.11) and can be calculated as follows

$$\frac{E_D}{E_{T_R}} = 10^6 = e^{(Ac/4V)T_R}$$

hence

$$T_R = \frac{4V}{Ac} \log_e 10^6 = 0.163 \frac{V}{A} \text{ seconds}$$

in agreement with the empirical formula deduced by Sabine. The coefficient $Ac/4V$ is the *time constant of the room.*

Subjective tests have shown that there are optimum reverberation times for music and speech as expressed in well-known abacus (Knudsen, 1932).

1.3.6 Energy Density Level in Reverberant Fields: SPL

The energy level in a room due to one or more sound sources is a function of the units of absorption. If W is the total steady-state acoustic power of the sources in a room of volume V and A units of equivalent absorption area, the equilibrium between the input and absorption of energy requires that

$$W = I_D \cdot A$$

---

* As the absorption is frequency dependent the decay curve is not smooth, it is the resultant of the different decay of each room mode.

I_D being the intensity *over* the surfaces in the diffuse field (paragraph 1.2.11)

$$I_D = \frac{E_D \cdot c}{4}$$

therefore $E_D = \frac{4W}{Ac} = \frac{4WT_R}{0.163cV} = \frac{7.2}{100}\frac{W_A T_R}{V}$, Julius/m^3

i.e. the energy density per unit power is proportional to the quotient T_R/V.

This explains how to reduce the level of a noise in a room. Since T_R is proportional to volume, varying the volume will not change E_D. Only an increase in absorption will help, as is the common case of installing a false acoustic ceiling.

The Energy Level, or SPL, is a function of W and A, SPL $= 10 \log \frac{4W/A}{10^{-12}}$ dB.

1.3.7 Interaction of Sound Waves with Solid Structures: Forced Bending Waves, Coincidence Effect

A dynamic elastic deformation in an infinite plate or panel generates in it free progressive bending waves with transversal displacement perpendicular to the surface, so that sound is radiated from both faces into the surrounding fluid media.

The speed of propagation of sinusoidal bending waves is not independent of the frequency as in the case of compressional and shear waves and is given by

$$c_B = \sqrt{\omega}\ \sqrt[4]{\frac{B}{m}}$$

i.e. the plate is a dispersive propagating medium for bending waves.

Plane sinusoidal sound-waves in a fluid can give rise to bending waves in a plate provided that the *trace-speed* of the fluid waves over the surface of the plate coincide with the speed of propagation of the bending waves at each particular frequency (Figure 1.12), i.e. $c_a/\sin\theta = c_B$ (or the trace wavelength $\lambda_a = \lambda_B \sin\theta$) so as to reinforce the bending wave by a progessive in phase excitation (i.e. resonance) along its propagation path.

This phenomenon was first reported by Cremer (1942) and was called the *coincidence effect* and later '*trace-matching*'.

At each angle of incidence there is a corresponding frequency for which there is 'trace-matching'. At $\theta = \pi/2$ or grazing incidence, the frequency at which the speed of the bending waves is equal to the sound speed in air [$c_B = c_a$ *at* $(\theta = \pi/2)$] is called the *grazing* frequency f_g. Below this frequency $c_B < c_a$ bending waves cannot be excited. The panel behaves like a 'limp' panel with masses without elastic bounds. (This corresponds to the so-called 'mass law' region.) At grazing frequency and above, the bending waves are faster than sound in air ($c_B = c_a \sqrt{f/fg}$), there is always one angle θ for which the relation $c_a/\sin\theta = c_B$ holds. This frequency region is called the coincidence region (Figure 1.14). The energy of the incident wave, in a great part reflected in the solid surface, generates bending waves in the panel that radiate sound from both faces (Figure 1.12)

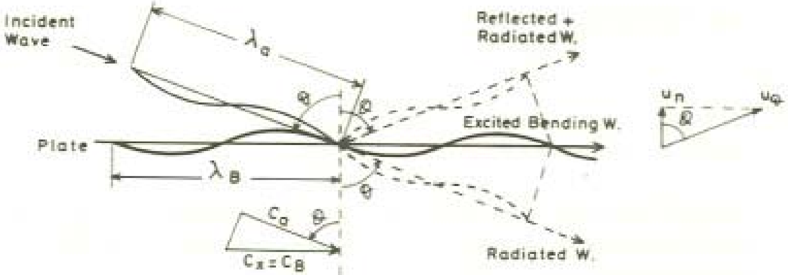


Figure 1.12 Excitation of bending waves in plates by sound air waves: coincidence effect

Because the sound transmission is maximum at f_g this frequency is called in room acoustics the *critical frequency* f_c of the panel and is deduced from

$$c_B = \sqrt{\omega_c}\sqrt{\frac{B}{m}} = c_a \quad \therefore \quad f_c = \frac{\omega_c}{2\pi} = \frac{c_a^2}{2\pi}\sqrt{\frac{m}{B}}$$

For a non-dissipative plate of thickness d and Young modulus E, [N/m^2]

$$B = E \cdot I^* = \frac{Ed^3}{12}, \; m = \rho d, \; [\mathrm{kg/m^2}]$$

and the *critical frequency* of real panels can be approximated by

$$f_c = \frac{c^2}{1.8d}\sqrt{\frac{\rho}{E}} \simeq \frac{6.4 \times 10^4}{d}\sqrt{\frac{\rho}{E}}\ \mathrm{Hz}$$

Materials with high ratio ρ/E like sheets of lead, steel, etc. with a thickness of few millimetres have a high value of f_c. Masonry structures on the contrary have a lower ratio ρ/E and larger width that usually places f_c in the low-frequency range with danger of high-sound transmission of bass frequencies. (Table 1.1).

1.3.8 Radiation Ratio σ ($f \geq f_c$).

A radiation ratio σ is defined by comparing the energy radiated by the bending waves in a direction perpendicular to the panel surface, with the theoretical

---

* I = moment of inertia of the cross section per unit width, [m^3].

plane wave radiation of a rigid surface with the same normal velocity of vibration, i.e.

$$\sigma = \frac{Z_0 u_\theta^2 \cos\theta}{Z_0 u_n^2}$$

but

$$u_n = u_\theta \cos\theta \text{ (Figure 1.12)}$$

therefore

$$\sigma = \frac{1}{\cos\theta} = \frac{1}{\sqrt{1 - \sin^2\theta}} = \frac{1}{\sqrt{1 - (f_c/f)^2}}$$

at $f = f_c$, σ goes theoretically to ∞ but in actual cases the panels are finite and have losses, consequently σ follows a curve similar to the one in Figure 1.13 with a maximum value of the order of 5.

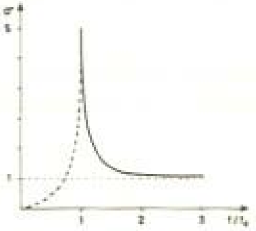


Figure 1.13 Radiation ratio of plate-like structures

1.3.9 Acoustic Isolation — Sound Level Difference, D* and D_n, (ISO 140/$_{\text{IV}}$)

The *Acoustic Isolation between two rooms* is defined by the *Level Difference D* between the *emitter* and *receiver* fields:

$$D = L_1 - L_2$$

Because for the same emitter level L_1, the level L_2 varies with the absorption units A in the receiving room, a Normalized Acoustic Isolation D_n is defined in Room Acoustics corresponding to an absorption of 10 m^2 (for average living room):

$$D_n = L_1 - L_2 + 10 \log \frac{10}{A}$$

D_n can be normalized in terms of the reverberation time T_R for an average

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* **D** is also known as *Noise Reduction* (ASTM: E90-70).

receiving room with a volume $V = 30\,\text{m}^3$ and $A = 10\,\text{m}^2$ which results in $T_R = 0.16\ V/A = 0.5$ sec. Therefore

$$D_n = L_1 - L_2 + 10 \log \frac{T_R}{0.5}$$

The Acoustic Isolation is frequency dependent therefore it must be expressed at normalized frequencies.

1.3.10 Acoustic Insulation: Transmission Loss (TL) of Plate-like Elements, or Sound Reduction Index (R), (ISO 140/$_{\text{III}}$)

The acoustic isolation between two rooms is mainly due to the insulation characteristics of the limiting surface elements (walls and floors).

The Acoustic Insulation of a panel is characterized by its energy transmission coefficient $\tau = E_t/E_i$ or ratio of the transmitted to the incident sound energies, and is given in terms of its *Transmission Loss TL* i.e. difference in dB between the incident and the transmitted energies, hence $TL = 10 \log \mathrm{E_i} - 10 \log \mathrm{E_t} = 10 \log \mathrm{E_i}/E_t = 10 \log 1/\tau = R$.

The Transmission Loss of a separating element of surface S can be related with the Level Difference D between two adjacent rooms. The rate of transmitted energy must be equal to the rate of absorbed energy in the receiving side, $W_2 = I_2 \cdot A$, and the incident energy W_1 equal to the product $I_1 \cdot S$. Therefore

$$TL = 10 \log \frac{W_1}{W_2} = 10 \log \frac{I_1 S^*}{I_2 A} = 10 \log I_1\ I_0 - 10 \log I_2\ I_0 + 10 \log \frac{S}{A}$$
$$= L_1 - L_2 + 10 \log \frac{S}{A}$$

1.3.11 Transmission Loss of Solid Panels as a Function of their Physical Characteristics

The geometry and physical characteristics of a panel defines the frequency of coincidence.

In the region below coincidence the *mass law* applies according to the approximate expression

$$TL \sim 10 \log (\omega\, \mathrm{M} \cos \theta)^2 + \text{Const.}$$

where M is the mass per unit surface (Kg/m^2).

This expression gives an increase in TL of approximately 6 dB for each doubling of the frequency or the mass.

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[*] The sound field conditions (free or diffuse) has to be the same on both rooms to be valid that $10 \log I_1/I_2 = L_1 = L_2$, otherwise I_1/I_2 will include a factor 4 or ¼ that will add ± 6dB to the level difference (1.2.12).

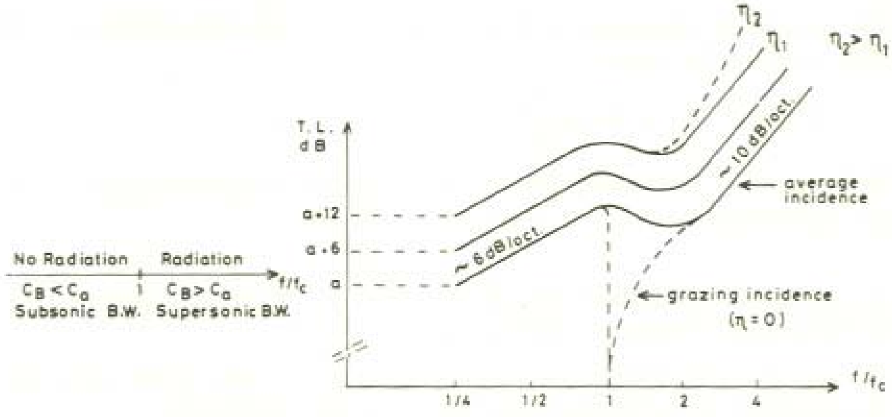


Figure 1.14 Sound Transmission Loss of plate-like structures

At and above the frequency of coincidence, *TL* has a dip the extension of which, as well as its later increase with frequency, depends on the loss factor η* of the panel (Table 1.1).

Figure 1.14 is a qualitative representation of this process.

Practical design charts for the evaluation of *TL* for single panels can be found in (Watters, 1959).

1.3.12 Sound Transmission Class (STC), (ASTM 413), or airborne sound insulation Index, Ia, (ISO/R 717)

In order to characterize the Transmission Loss of panels by means of a single-number the measured spectral curve of *TL* in ⅓ octave bands from 125 to 4,000 Hz is properly compared with normalized curves (designed for common multi-family dwelling noise) rated in STC or Ia by the number of dB at 500 Hz. Overall dBA ratings are also used, (Gösele 1965, Moreno *et al* 1983).

1.3.13 Global Sound Insulation (a_G)

In buildings it is common to have in the same surface, for instance, the facade, elements with different acoustic insulation such as walls and windows.

These situations ask for the definition of a global insulation a_G of the whole surface evaluated in terms of its average energy transmission coefficient $\bar{\tau}$.

$$\bar{\tau} = \frac{S_1\tau_1 + S_2\tau_2 + \dots S_n\tau_n}{S}$$

$$a_G = 10 \log \frac{1}{\bar{\tau}} = 10 \log \left[\frac{S}{\tau_1 S_1 + \dots \tau_n S_n}\right] = 10 \log S / \left(\frac{S_1}{10^{a_1/10}} + \cdots \frac{S_n}{10^{a_n/10}}\right)$$

---

* *Loss factor* is a measure of the fraction of the stored energy lost per radian (m). For common solid materials can be considered constant in the audio range, Table 1.1.

where $a_n = 10 \log 1/\tau_n$ is the acoustic insulation or Transmission Loss of the surface element S_n.

In the common case of only two elements (room with a window), simple abacus permit the calculation of a_G in terms of the (wall and window) surfaces and their respective specific insulations.

1.3.14 Insertion Loss (IL)

It is a measure of the effectiveness of a sound insulating element by comparing the sound levels before (L) and after (L') the intersection of the element

$$IL = L' - L \text{ dB}$$

It is an appropriated index to evaluate the influence of sound barriers and enclosures etc., in bands of frequency either in free or reverberant field situations.

1.3.15 Vibration Isolation, Transmissibility of Insulating Systems

Because a building structure consists mainly of beams and plates, the geometrical spreading of sound-waves along the structure is much less than in open space, so that the acoustic energy can be transmitted far from the excitation point. The large surface of floors and walls can act as sound sources of relatively high strength, the main radiation being due to bending waves. An important section of noise control is related with the reduction of the directly transmitted vibratory energy to the supporting structure.

The general principle of vibration isolation is based on the interposition of an insulating mounting between source and structure. A simple model for analysing insulating systems (mass, elasticity and resistance concentrated in 'pure elements') is given in (Figure 1.15).

An insulating system is characterized by its transmissibility which is the ratio of the transmitted force (or displacement) to the exciting force (or displacement), the transmission being controlled by the elastic and resistive elements.

For a system without dissipation (loss factor* $\eta = 0$), the transmissibility is given by $|\varepsilon| = |1/1 - \Omega^2|$ where Ω is the ratio of the excitation frequency to the resonance frequency (f_0) of the system (dotted curve Figure 1.15). In real systems the value at resonance ($\Omega = 1$) is reduced as a function of η, $|\varepsilon| = [1 + \eta^2/(1 - \Omega^2)^2 + \eta^2]^{1/2}$ For viscous damping $\eta = \omega R/k = 2D\Omega$ (Figure 1.15). For other damping mechanisms, $\eta \simeq c^{re}. \ll 1$, (Table 1.1) $|\varepsilon| \simeq |1/1 - \Omega^2|$, with values at resonance ($\Omega = 1$) given by the equivalent viscous damping ratio curve (Figure 1.15).

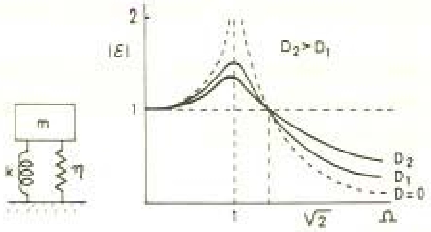


Figure 1.15 Transmissibility curves versus frequency with damping ratio D as parameter

For a given mass and excitation frequency the noise control designer may select K and η so that the region of low transmissibility i.e. the region above $\Omega = \sqrt{2}$ includes the frequencies to be attenuated. Acceleration limits of vibration levels in man are given in ISO 2631.

1.3.16 Impact Sound Insulation in Buildings (ISO $140/_{\mathrm{VII}}$)

The impact noise transmitted through the structure to the room below can be reduced by interposing a resilient layer between the supporting structure and the floor finishing. This technique is referred to as *Floating Floors*. An alternative or additional reduction can be obtained by 'soft' *floor coverings*. (Plastics, Rubber, Carpets, etc.)

The transmission is evaluated in terms of the Normalized Impact Sound Level L_n in the receiving room, generated by a standard tapping machine in the room above, (ISO $140/_{\mathrm{VI\text{-}VII}}$).

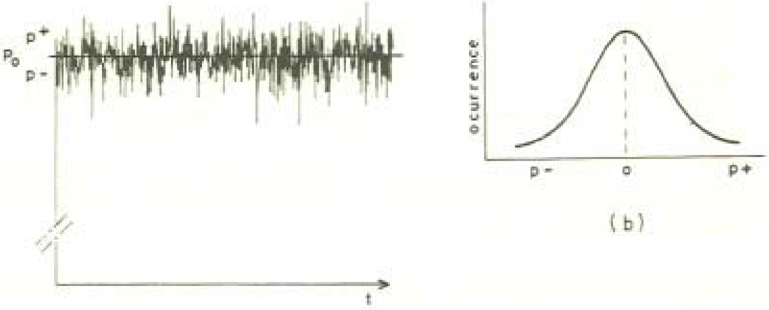
$$L_n = L_i + 10 \log. {}^{\wedge}2/10$$

A single Impact Insulation Index I_i can be obtained by properly camparing the i/3 octave spectrum of L_n with normalized transmission curves. (ISO 717).

1.4 MEASUREMENT OF NOISE

1.4.1 Introduction

Sound waves in fluids are of compressional in nature. Of the different physical variables that may characterize the wave, the sound pressure is the easiest to measure, by means of microphones. For most noises, when pressure is plotted against time, the pressure amplitude p is randomly distributed around the



(a)

(b)

Figure 1.16 (a) Sound pressure variations around the atmospheric pressure due to the presence of noise; (b) Statistical distribution of random sound pressure

atmospheric static pressure P_0 (Figure 1.16(a)) (for community noise levels, p is of the order of $0.1\ P_a \sim P_0 \cdot 10^{-6}$), with zero average.

$$P_0 = 1\ \mathrm{K/cm^2} \simeq 10^5\ \mathrm{Newton/m^2} = 10^5\ \mathrm{Pa}$$

The pressure amplitude tends to follow a gaussian distribution as shown in Figure 1.16(b).

The effective, or root mean square, pressure, is a good measure of the pressure variations over a short period of time T The squaring avoids cancelation)

$$p_{\mathrm{rms}} = \sqrt{\frac{1}{T}\int_0^T p(t)^2\, \mathrm{d}t} =$$

1.4.2 Sound Level Meters (I.E.C. 651)

Most noise sources generate waves of complex shape comprising several sinusoidal frequencies with different time-varying amplitudes and phase. Also, it is commonly the case that sound fields are composed of simultaneous radiation from several sources. The simplest and direct measurement of the sound field at any given point is the overall mean square sound pressure $\overline{p^2}$ which is equal to the average of the contributions p_i^2 from the individual sources.

$$\overline{p^2} = p_{\mathrm{rms}}^2 = \frac{1}{T}\int_0^T \sum p_i^2\, \mathrm{d}t$$

This is accomplished by the Sound Level Meter (Figure 1.17) which with the aid of a microphone (1) transforms the overall pressure amplitude variations $p(t)$ into the corresponding electric signals $V(t)$.

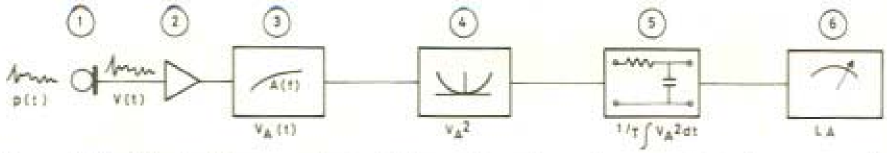


Figure 1.17 Block diagram of the different functions of a sound level meter: (1) Electro-acoustic transduction (microphone); (2) Electrical amplification; (3) Filtering; (4) Squaring; (5) Mean-squaring; (6) Level read-out

The electrical system includes amplification (2), filtering (3), square low detection (4), averaging (5) and complementary attenuators and switches. The sound-field level is indicated by the read-out apparatus (6) which may be analogue or digital, visual or printed. The rms rectifier and the read-out circuit introduce a time constant specified in the international standards (I.E.C.* 651).

The read-out apparatus has a logarithmic scale so as to give directly the value of the Sound Pressure Level in decibels referred to $p_0 = 2 \times 10^{-5}$ N/m^2 = 20 μ Pa: (1.2.12)

$$\mathrm{SPL} = 10 \log \frac{p_{\mathrm{rms}}^2}{p_0^2} \ \mathrm{dB}$$

It is customary to calibrate the entire system with a pistonphone which generates predetermined sound pressure levels.

Many instruments provide for the measurement of the overall sound pressure level without filtering (i.e., linear frequency response). To improve the correlation between sound sensation and instrument reading, all sound-level meters contain filtering networks that mainly reduce the response in the low frequency range in accordance with the reduced sensitivity of the human hearing in that range. Perhaps inspired by the original equal loudness contour curves of Fletcher and Munson (1938), three weighting curves A, B and C are found in many instruments.

The weighting curve used in a measurement of sound level is often indicated by a letter following the decibel symbol, e.g. dBA, dBB or dBC. After many years of research and experience, there is general agreement that for most common steady noises there is reasonable correlation between sound level measurements made with A-weighting and the effects of noise on man (hearing damage, annoyance and sound sensation). Presently most units and indexes for noise evaluation are based on dBA measurements. A fourth weighting, curve D, has been added to improve the better correlation with the sensation produced by high pitched noises like those related with aircraft noise (ISO 1999; 2204; 1966; 226; 532).

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* I.E.C. = International Electrotechnical Commission.

1.4.3 Noise Spectrum

In dealing with the evaluation of noise and noise control it is neccesary in most cases to know not only the overall noise level but how the energy is distributed over its frequency components. This is accomplished by filtering the noise in bands of frequency and measuring the sound level in each band.

Each band is characterized by its *bandwidth*, $\Delta f = f_2 - f_1$, and centre frequency f_c. The bandwidth can be of *constant width* (e.g. a few Hz) to separate discrete frequencies, or a *constant percentage* of the centre frequency. The latter type is most convenient to analyse noises that have a broad and quasi-continuous frequency spectrum. Octave band and one-third octave band filters with normalized frequencies (ISO 266–1975 (E)) are of this type. There are also constant-percentage bandwidth filters with bandwidths of 1/10, 1/12, 1/15, 1/30 of an octave, or even 1% of the centre frequency.*

1.4.4 Power Spectrum — White, Pink and Magenta Noises

The power spectrum of a sample of noise shows the power per unit band of frequency. It serves to define special types of noises and to compare noise spectra. White Noise, Pink Noise, and Magenta Noise are useful descriptions of artificial noises with definite spectra.

White Noise has a constant power spectrum (Figure 1.18(a)). When analysed with constant percentage band-width filters such as octave-band filters, its band levels increases at the rate of 3 dB/octave. (Note that the bandwidth doubles for each octave increase in frequency, hence 10 log 2 = 3 dB.) When White Noise is passed through one-third octave band filters, the band levels lie on a parallel line which is 4.8 dB (10 log 3) below the line of octave band levels.

Pink Noise has equal power levels in each octave band (see Figure 1.18(b)). Consequently, the power spectrum has a slope of −3 dB per octave. Magenta Noise has an octave-band power levels which decrease at −3 dB per octave which corresponds to a power spectrum with −6 dB per octave slope. White, Pink and Magenta Noise sources are frequently use to measure the performance of acoustical systems, specially where resonances at discrete frequencies are considered unimportant. Examples include measurements on transducers such as microphones and loudspeakers and measurements of sound absorption, sound insulation and reverberation time.

1.4.5 Statistical Percentiles of Noise: L_n

Many noises as traffic noise, community noise, etc., are not only complex in nature but have time-varying level. Despite this variability, some common types

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* $f_2/f_1 = k$ $(k = 2, {}^{2}/_{3}, {}^{2}/_{10}, {}^{2}/_{12} \cdots)$ $f_c = f_1\sqrt{k} = f_2/\sqrt{k} = \sqrt{f_1 \cdot f_2}$

$$\frac{(\Delta f)_{i+1}}{(\Delta f)_i} = \frac{(f_c)_{i+1}}{(f_c)_i} = k \quad \Delta f = f_2 - f_1\,(k-1) = f_c\,\frac{k-1}{\sqrt{k}} = f_c c^{n}.$$

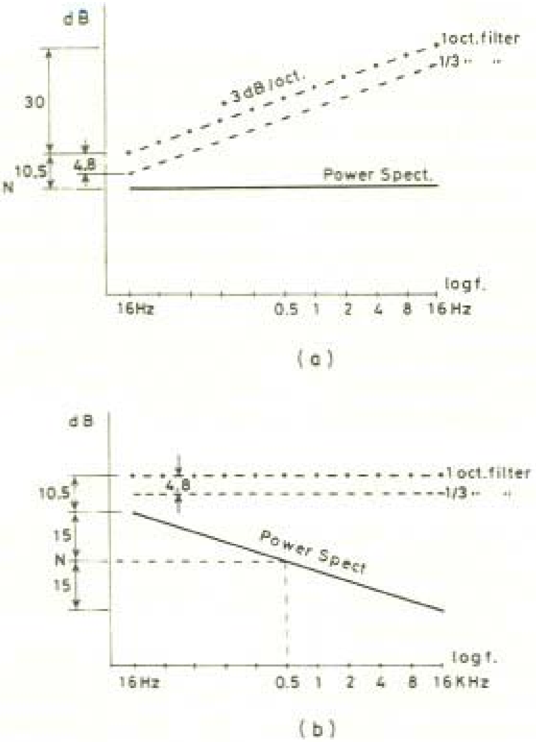

Figure 1.18 Power spectrum of artificial noise signals. (a) White noise; (b) Pink noise

of noise have characteristic frequency spectra. Hence, the evaluation of the overall time-varying level requires a statistical approach.

Instruments are available to measure the noise level in finite steps (e.g. 5 dB). Sound instruments accumulate the total time that each level is present during a given measurement period (e.g. 8 hours when evaluating noise exposure at work). With such data a histogram can be plotted of the level distribution. Many random noises have a bell-shaped distribution of levels which corresponds to the analytical Gaussian or Normal mode distribution, (Figure 1.19a).

Another and useful way of presentating data is the cumulative level distribution shown in Figure 1.19b. It shows the percentage of the total time during which each level is attained or exceeded.

The percentile levels are very much used in noise evaluation and are referred to as L_n, n being the percentage of time that the corresponding step of level has been attained during a total period T. The most common percentiles are L_{90} (a good reference for background level) L_{50} (approximate average), L_{10} (intense level periods), L_1 (peak levels), etc.

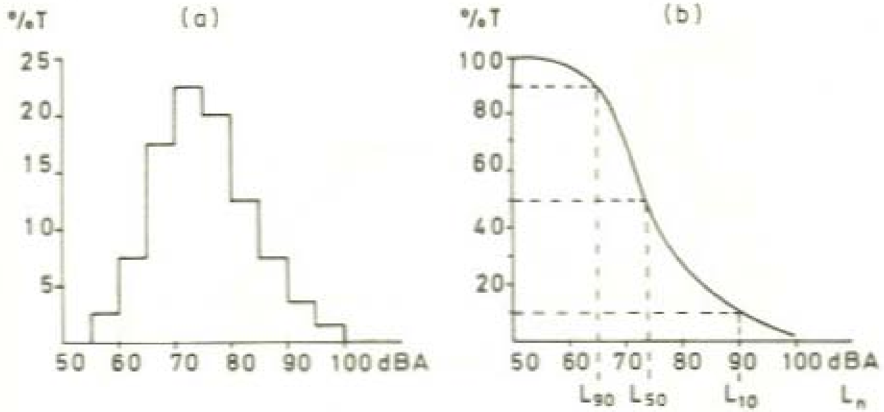

Figure 1.19 Urban traffic noise level distribution: (a) Histogram; (b) Percentile levels.

1.4.6 Traffic Noise Index TNI (Langdon and Scholes, 1968) — Noise climate

This rating is based on statistical analysis of out-door road traffic A-weighted levels, and takes into account the background level L_{90} and the level fluctuations in terms of the so called Noise Climate $(L_{10} - L_{90})$

$$\text{TNI} = L_{90} + 4\,(L_{10} - L_{90}) - 30^*$$

1.4.7 Equivalent Continuous Sound Level L_{eq} or Time Average A-weighted Sound Level $\bar{L}_A$ (U.S. E.P.A., 1974)

After many attempts to simplify the long term measurement of random noises, it has been found that most of the effects of noise on man can be correlated with the noise energy 'dose'. In line with this view, various indexes have been established that are based on L_{eq} which is the level of a theoretical steady noise equivalent in energy (or properly speaking, mean square sound pressure) to the real fluctuating noise over a given period of time, such as one day. Because of the general acceptance of A-weighting, L_{eq} is generally understood to be A-weighted (i.e. $L_{eq} \equiv \bar{L}_A$). The mathematical expression is

$$L_{eq} \equiv \bar{L}_A = 10 \log \left[\frac{1}{T}\int_0^T \left(\frac{p}{p_o}\right)^2 dt\right] = 10 \log \left[\frac{1}{T}\int_0^T 10^{(L_{(t)}/10)}\, dt\right] \text{dBA}$$

where $L_{(t)}$ is the time varying level.
For practical purposes, it can also be expressed in terms of the intervals of time $\Delta\tau_i$ that each discrete value L_i is present:

$$L_{eq} \equiv \bar{L}_A = 10 \log \left[\frac{1}{T}\sum_{i=1}^{n} \Delta\tau_i\, 10^{(L_i/10)}\right] \text{dBA}$$

[*] Constant to bring the index into conventional range.

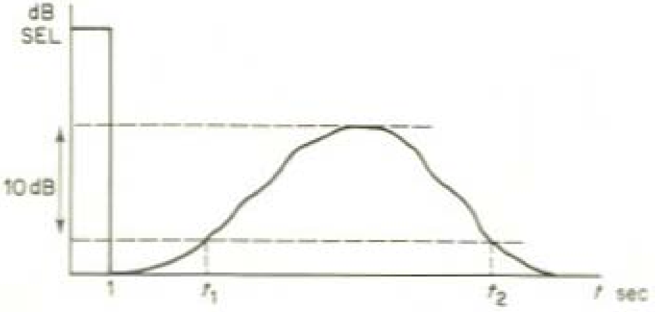

Figure 1.20

When the noise is a result of single events, as with air traffic, an alternative way of evaluating the L_{eq} is by means of the so-called Single Event Level (SEL), which is the average energy level of the noise event referred to a period of one second. The energy is integrated over an interval $(t_1 - t_2)$ defined by a line 10 dB below the maximum level attained by the event (Figure 1.20). In the case of n single events in the period T

$$L_{eq} = 10 \log \frac{1}{T} \sum_{i=1}^{n} 10^{(\mathrm{SEL}/10)} \text{ dBA}$$

For a Gaussian distribution of levels the calculus of L_{eq} can be reduced to

$$L_{eq} = L_{50} + 0{\cdot}021\,(L_1 - L_{50})^2$$

There is much experimental evidence indicating that L_A is well-correlated with the annoyance caused by community and road traffic noise. It can be said in general that for this reason most noise criteria refering to community annoyance are based on L_{eq} or $\overline{L}_A$.

1.4.8 Day–Night Equivalent Level L_{dn}

This is a modified version of $\overline{L}_A$ for 24 hours to take into account the greater annoyance produced by noise at night periods. It includes a penalty of 10 dB for the period from 2200 to 0700 hours. Its mathematical formula for discrete values of day (L_d) and night (L_n) levels is

$$L_{dn} = 10 \log \frac{1}{24} \left[\sum_{0700}^{2200} 10^{L_d/10} + \sum_{2200}^{0700} 10^{(L_n+10/10)} \right] \text{dBA}$$

(Note that day–night penalties ranging from 2 to 10 dB have been proposed.)

1.4.9 Yearly Day–Night Equivalent Level L_{ydn}

This average level takes into account differences that may occur from season to season when evaluating the average L_{dn} for the whole year.

The relation between the average level for a fraction $k \cdot y$ of a year, and the whole year is given by the straight-forward formula

$$L_{ydn} = L_{kydn} + 10 \log k$$

Thus, a value of L_{dn} of 90 dB in a 3 months period ($k = 1/4$) corresponds to a L_{ydn} given by

$$L_{ydn} = 90 + 10 \log 1/4 = 84 \text{ dB}$$

provided that the contributions from other periods of the year are negligible.

1.4.10 Noise Pollution Level L_{NP} (Robinson, 1969)

This index is intended to take into account the additional disturbing or annoying influence of level fluctuations. An approximate expression for L_{NP} for most community situations is

$$L_{\mathrm{NP}} = L_{\mathrm{eq}} + (L_{10} - L_{90})$$

where $(L_{10} - L_{90})$ evaluates the difference between the intense levels and the background level (Noise Climate).

1.4.11 Perceived Noise Level L_{PN} (PNL) and Tone Corrected Perceived Noise Level (TPNL)

This index is a measure of aircraft noise (used for aircraft qualification tests in USA). The noisiness of a broad-band noise is evaluated, by the maximum level in each frequency band in a 'fly-over', and expressing that level as 'noisiness' in noys (Kryter, 1959). A simple summation of the weighted contribution from the various bands gives the total Perceived Noisiness PN (in noys). This is converted into Perceived Noise Level L_{PN} in PN dB using an abacus which corresponds to

$$L_{\mathrm{PN}} = \log_2 \mathrm{PN} + 40 \text{ dB}$$

To take into account the annoyance caused by the presence of pure tones a correction is included which depends on the frequency of the tone and the tone-to-noise level difference. The tone-corrected index is called L_{TPN}

1.4.12 Effective Perceived Noise Level L_{EPN}

To obtain better correlation with the community annoyance produced by aircraft flyovers a correction term is added to PNL, to allow for the dependence of sensation with noise duration. This modified Index is the L_{EPN} measured in Effective Perceived dB. For a series of events the L_{EPN} is obtained by summing the energies of all the L_{TPN_i} included in a marging of 10 dB of the maximum values in intervals of half second

$$L_{\mathrm{EPN}} = 10 \log \sum 10^{((L_{\mathrm{TPN}_i})/10)} \text{ EPN dB}$$

1.4.13 Noise Exposure Forecast, NEF (Galloway and Bishop, 1970)

This index was established to evaluate noise exposure in the vicinity of airports. It is based on L_{EPN} with additional terms depending on the number of aircraft operations and their times of occurrence during a typical 24–hour period.

For a given aircraft type and flight path

$$\mathrm{NEF}_i = L_{\mathrm{EPN}_i} + 10 \log \left[\frac{n_D}{K_D} + \frac{n_N}{K_N}\right] - 75$$

where n_D and n_N are the number of day and night flight operations. $K_D = 20$ and $K_N = 1, 2$.

The total noise exposure at a given location is obtained by combining the individual values of NEF as follows

$$\mathrm{NEF} = 10 \log \sum_{i=1}^{n} 10^{(\mathrm{NEF}_i/10)}$$

Contours of equal NEF ('footprints') show the impact of aircraft noise on the community living in the vicinity of the airport (see Figure 1.21).

1.4.14 Noise and Number Index, NNI ('Wilson Report', 1963)

This is a composite measure used to evaluate the annoyance due to aircraft operations which combines the average peak noise level L_{peak} expressed in PN dB with the number N of noisy events occurring during a 24-hour period.

$$\mathrm{NNI} = \bar{L}_{\mathrm{peak}} + 15 \log N - 80$$

where $\bar{L}_{\mathrm{peak}} = 10 \log 1/N \Sigma_1^N 10^{(L_{\mathrm{peak}}/10)}$. Unlike NEF, NNI does not include any weighting-factor for night-time operations.

Figure 1.21 (Pons *et al.*, 1982) shows the NNI and NEF contours lines for Barajas International Airport (Madrid) corresponding to a particular period of time, during day hours. (Acceptable values of NNI for night hours use to be 20 units below).

1.4.15 Prediction of Noise-Impact on Society — Hearing Loss Impact

Guidelines based on L_{dn} have been developed to estimate the effects of noise on communities in the vicinity of major projects such as new highways and airports (CHABA, 1978). These guide-lines link L_{dn} with the percentage of population which is likely to be highly annoyed by the noise associated with the project.

To describe the magnitude of annoyance impact by a single number, use is made of the so-called *Fractional Impact Method*, the main assumption being that the impact of high-level noise on a few people is equivalent to the impact of a lower level of noise on a greater number of people. Then the impact on the total population can be expressed as the 'equivalent totally impacted population', the so-called *Sound Level Weighted Population* (LWP).

To evaluate the impact use is made of a curve due to Schultz (Schultz, 1978) that is based on a synthesis of several sets of previous survey data correlating the percentage of 'Highly Annoyed' people in a community with the average outdoors L_{dn} noise level as shown in Figure 1.22.

Assuming that a population can be considered 'totally impacted' when 40% of the people are highly annoyed, an impact factor $W = 1$ can be asigned to an L_{dn} of 75 dB. Thus the Schultz curve serves to provide a weighting function that gives directly the impact factor W_i corresponding to each given value of $L_{(dn)_i}$.

This curve fits a trinomial equation that can be approximated by the simple expression

$$W_{(L_{dn})} = \frac{HA}{40}$$

Given this 'level weighted impact factor', the equivalent totally impacted population LWP can be calculated by adding the products of the population groups $P_{(L_{dn})_i}$ and the corresponding impact factors $W_{(L_{dn})_i}$, i.e.

$$\text{LWP} = \sum P_{(L_{dn})_i} \cdot W_{(L_{dn})_i}$$

where i advances in steps of 5 dB.

By dividing the number of totally annoyed people by the total exposed population a *Noise Impact Index* (Nii) is defined which can be used to compare relative impacts.

$$\text{Nii} = \frac{\text{LWP}}{\text{P}_{\text{total}}}$$

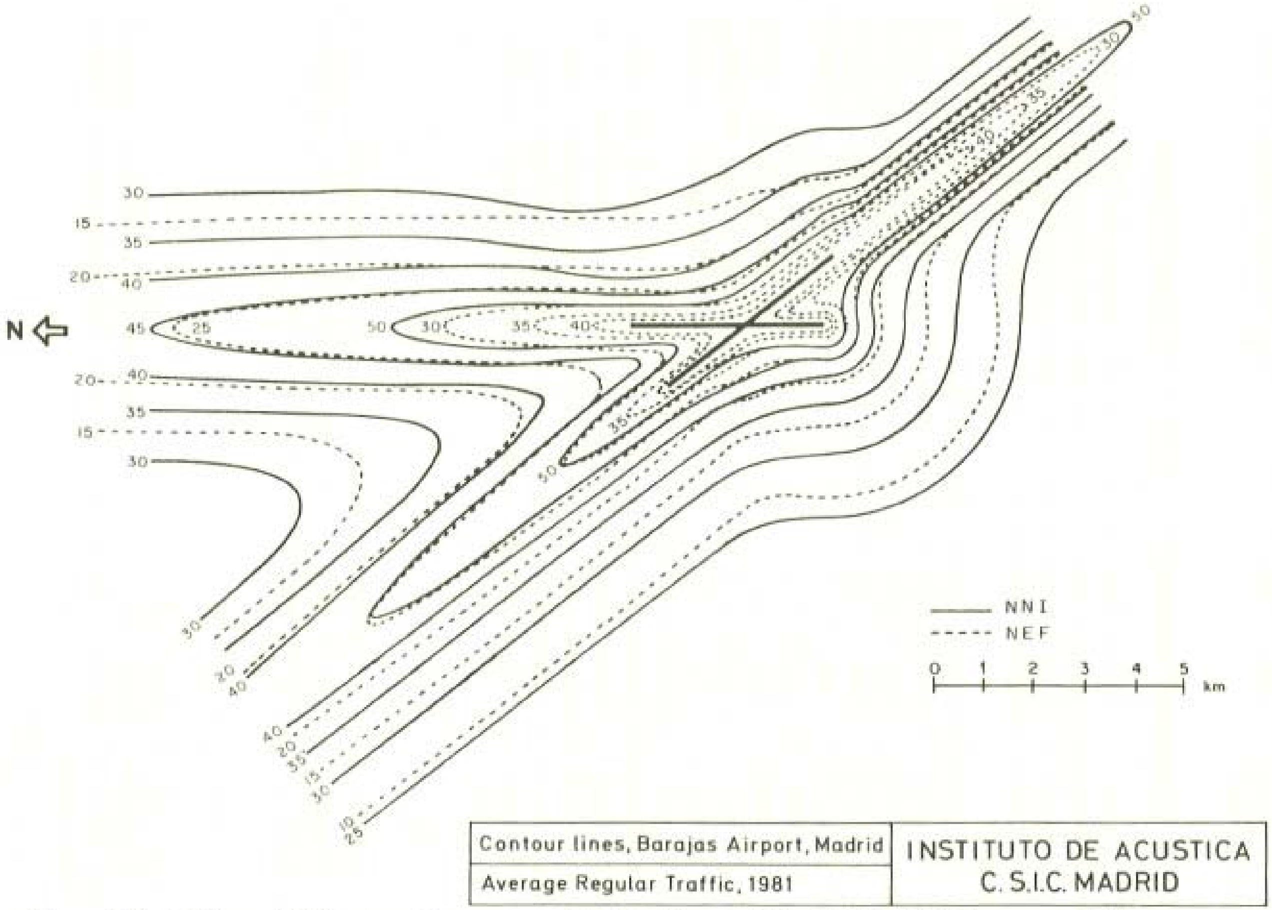

Figure 1.21 NNI and NEF contour lines measured in the Airport of Barajas, Madrid (Pons *et al.* 1982)

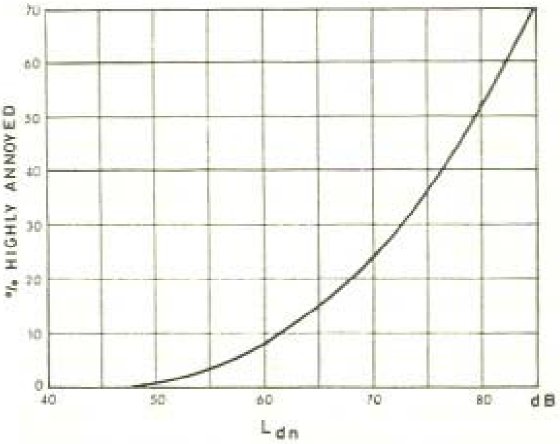

Figure 1.22 Percentage of highly annoyed people versus out-doors community noise in L_{dn} (after Shultz, 1978)

Hearing Loss Impact

Values of L_{dn} over 75 dB imply a severe noise exposure, the impact is predicted by an index called *Population Weighted Loss of Hearing* (PHL).

The level weighting function in this case is a curve of the Noise Induced Permanent Threshold Shift (NIPTS) produced by 8 hours of daily exposure (or L_{dn}) during a life working period of 40 years (Robinson, 1971).

The analytical function derived from the experimental curve can be approximated by

$$\mathrm{WHL} = \frac{(L_{dn} - 75)^2}{40}$$

and therefore

$$\mathrm{PHL} = \frac{\sum_{75}^{x} P_{L_{dn}} \, \mathrm{WHL}}{\sum_{75}^{x} P_{L_{dn}} \, d_{L_{dn}}}$$

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CHAPTER 2

Review of Noise Propagation in the Atmosphere[*]

J. E. Piercy, T. F. W. Embleton and L. C. Sutherland

ABSTRACT

A general review is presented of most areas of sound-propagation outdoors that are of interest for the control of community noise. These areas are geometrical spreading, atmospheric absorption, ground effect, (near horizontal propagation in a homogenous atmosphere close to flat ground), refraction, the effect of atmospheric turbulance, and the effect of topography (elevation, hillsides, foliage, etc.). The current state of knowledge in each area is presented and suggestions made concerning research activities, applications of existing research, and practical problems which arise in the prediction of noise levels.

2.1 INTRODUCTION

The study of sound propagation in the atmosphere has a long and intriguing history. Between 1850 and 1950 there were a number of isolated investigations of good quality in response to specific needs of the times, such as fog signaling, the location of artillery pieces, etc. (see Wescott and Kushner (1965) for an annotated bibliography of work done prior to 1965). When the noise from jet aircraft and the testing of rockets became a social problem in the 1950's, there was a resurgence of research activity, adapting existing knowledge from other fields of physics to the problem of noise propagation, and several excellent reviews of sound propagation in the atmosphere appeared at this time (Ingard, 1953; Ingard, 1955; Nyborg and Mintzer, 1955; Rudnick, 1957). The field then returned to its previous state of sporadic isolated activity, although at a substantially higher level. In recent years increased concern over noise has led once again to advances in the understanding of outdoor propagation by the

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application of knowledge from other fields of physics, which this time has been gained since the 1950's.

This review is an attempt to document the advances for most areas of sound propagation in the atmosphere which are relevant to the control of community noise. It was undertaken at the request of the Coordinating Committee on Environmental Acoustics of the Acoustical Society of America, and is part of the output of the working group on outdoor propagation (see also Lyon, 1974; Kurze, 1974). The review aims to summarize the current state of knowledge in each area and to suggest research activities, applications of existing research, and practical problems which arise in the prediction of noise levels. Because the field is so diffuse, each subject area is treated separately, accompanied by most of the suggestions of relevant to the particular area. To add perspective, however, problems in predicting noise levels are discussed generally at the end (Section 2.6) with recommendations for reserch.

The first two areas covered in the review are geometrical spreading (Section 2.2.1) and atmospheric absorption (Section 2.2.2). Together, these are the dominant mechanisms determining sound levels in air-to-ground sound propagation. Near-horizontal propagation in a homogeneous atmosphere close to flat ground (the ground effect) is then treated in Section 2.3 and the effect of surface meteorology in Section 2.4. The latter includes the effects of refraction and atmospheric turbulence. The role of topography — elevation, hillsides, foliage, obstructions, etc. — is then discussed briefly in Section 2.5.

There is much useful material in the earlier reviews of a general nature (Ingard, 1953; Ingard, 1955; Nyborg and Mintzer, 1955; Rudnick, 1957) which has been excluded here for brevity. Furthermore, specifically excluded are multipath propagation in cities, and noise reduction by barriers, which have been the subjects of recent reviews (Lyon, 1974; Kurze, 1974).

2.2 PROPAGATION AWAY FROM BOUNDARIES (AIR TO GROUND)

2.2.1 Geometrical Spreading

The geometrical spreading of sound from a coherent source is normally well covered in textbooks — an attenuation of 6 dB per doubling of distance for spherical expansion from a point source, 3 dB per doubling of distance for cylindrical expansion from an infinite line source, and parallel loss-free propagation from an infinite area source. For sources of finite size there is a nearfield where the above is approximately true and a farfield where the expansion is spherical. In community noise, however, incoherent sources are often more important and the treatment of geometrical spreading from incoherent sources has been extended in recent years to cope with multivehicle problems, particularly road traffic and railway noise.

The description above of the spreading from coherent sources remains true for sources which are incoherent, but the size of the nearfield is much more restricted, and the propagation much less directional (compare as an illustration, the light from a light bulb to that from a laser). Treatments of the incoherent acoustic line source which are useful for highway or railway design are given in Rathe (1969) and Kurze (1971).

The background noise in a city may be modelled as an incoherent area source (Shaw and Olson, 1972; Tatge, 1972; Sutherland, 1975). The effect of city boundaries — streets, barriers, and open areas — in channeling or attenuating this propagation is reviewed elsewhere (Rathe, 1969; Kurze, 1971; Shaw and Olson, 1975). A point of relevance to noise control is that the geometric spreading of different percentiles of noise from an (isolated) incoherent line source varies with the percentile (Thiessen, 1973). There is a considerable conceptual and economic benefit in specifying noise criteria for the design of roadways in such a way that the spreading loss can be accounted for in a simple manner, such as a loss of 6 dB/doubling of distance for the maximum level of individual vehicles (i.e., levels close to L_1, the level exceeded only 1% of the time), or a loss of 3 dB/doubling of distance for the equivalent continuous sound level (L_{eq})

2.2.2 Atmospheric Absorption

Present knowledge of the rate at which acoustic energy is absorbed during propagation through the atmosphere comes from three sources — direct measurements in the field, measurements of air absorption in the laboratory, and general knowledge of the mechanisms. The current state of the latter two may be examined using Figure 2.1. In this figure (Piercy, 1972), the frequency dependence of the absorption in a distance of one wavelength is shown for four different values of relative humidity (RH). The measurements are from four different investigations (Pohlman, 1961; Evans and Bazley, 1956; Harris, 1966; Harris and Tempest, 1964), and the first point to note is the close similarity between the measurements by the different investigators. The second is the agreement for each value of relative humidity between the measurements and the top curve T, which is the theoretical curve representing the sum of the contributions from the different mechanisms of absorption (identified by the curves marked C, O and N).

Line C gives the classical absorption caused by the transport processes of classical physics (shear viscosity, thermal conductivity, mass diffusion, and thermal diffusion), together with the absorption caused by rotational relaxation of the molecules in air. Curves O and N represent the contributions from the vibrational relaxation of oxygen and nitrogen molecules, respectively. The fit of curve T to the measurements shown in the figure has been achieved by the adjustment of two constants in the theory, but the basic theory (Evans *et*

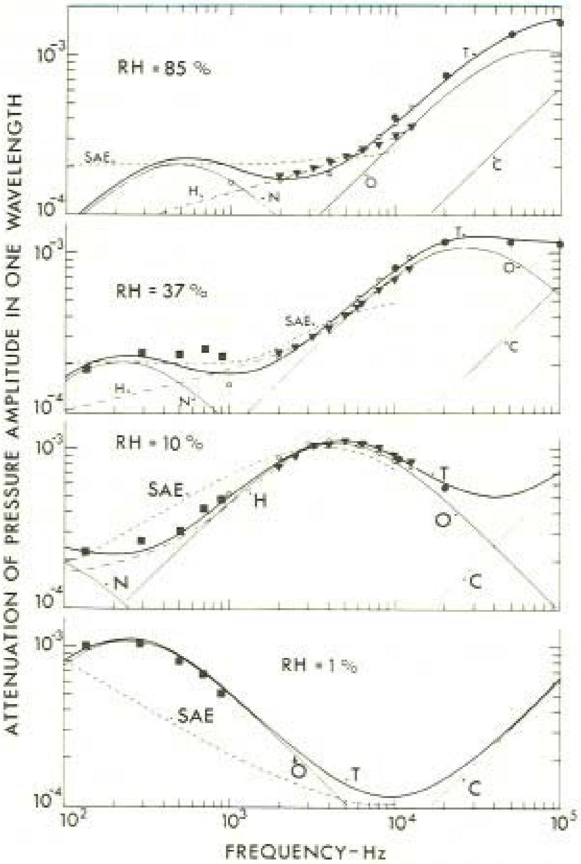

Figure 2.1 The absorption of sound in a distance of one wave-length for four values of relative humidity RH, a temperature of 20 °C, and a pressure of 1 atm (Piercy, 1972). Line C gives the classical and rotational absorption, curves O and N the contributions from the vibrational relaxations of oxygen and nitrogen, respectively, and curve T is the sum of these three contributions. Experimental points ● are from Pohlman, (1961), ○ from Evans and Bazley (1956), ▼ from Harris (1966), and ■ from Harris and Tempast 1964. The absorption predicted by SAE Committee (1964) is curve SAE, by Harris (1966) is curve H, and by Sutherland *et al.* (1974) is curve T

al., 1972) is now sufficiently firm to achieve a fit with an accuracy of approximately 25% without using any adjustment.

It is useful to compare the different methods available for predicting atmospheric absorption with the measurements shown in Figure 2.1. Kneser first developed a theory based only on contributions C and O. While predictions with his original method (Kneser, 1940) are substantially different from curve C and O shown in the figure, a later version by Evans and Bazley (1956) gives positions for these curves which are close to those in the figure. Evans and Bazley's method provides, therefore, a fairly good approximation to experimental data for higher frequencies. At the higher humidities represented by the top two sets of measurements in Figure 2.1, however, the vibrational relaxation of nitrogen (Piercy, 1969) (curve N) is the principal mechanism of absorption for the range of frequencies below about 1–2 kHz which are of major importance for community noise: both the Kneser, and Evans and Bazley methods therefore grossly underpredict the absorption in this low-frequency range.

Two similar methods of calculating atmospheric absorption were proposed before the role of the nitrogen relaxation was understood, that of Committee A21 of the Society of Automotive Engineers (1964) and Harris (1966), both of which produced a decided improvement in the low-frequency range, and these two essentially empirical methods have seen widespread use. Curves marked H and SAE in Figure 2.1 show the predictions of the method of Harris, and the SAE Committee, respectively. Major difficulties using these empirical methods for predicting absorption appear mainly for abnormal measurement conditions, due to extrapolation with an incorrect dependence on the variables, as shown in the figure, for example, for low frequencies or dry air.

It is now possible to generate curve T in Figure 2.1 using simple algorithms with a firm theoretical base, which can be handled easily, for example, by a programmable hand calculator. A new (draft) standard method for calculating atmospheric absorption has recently been proposed on such a basis (Sutherland *et al.*, 1974). The predictions of this new method have been compared with a large assembly of both laboratory and field data from the literature (Sutherland, 1975). The comparison of over 850 laboratory measurements with predictions shows that near 20 °C the predicted values agree within about 5%, with the average of the measurements throughout the audio frequency range and over a wide range of humidity. Although laboratory data at other temperatures are limited, the prediction model is estimated to be reliable within ± 10% from 0 to 40 °C. The field data included analyses of more than 750 measurements of aircraft flyover noise over wide ranges of frequency, temperature, and humidity from a number of different investigators. Although the scatter in the field results was much larger than that in the laboratory measurements, because the weather cannot be controlled, the agreement between predicted and measured absorption was good on the average, as shown in Figure 2.2.

The absorption predicted by the new method, in the practical units of dB/100 m for a pressure of 1 atm, a temperature of 20 °C, and a relative humidity of 70%, is shown in Figure 2.3. Note that the attenuation by

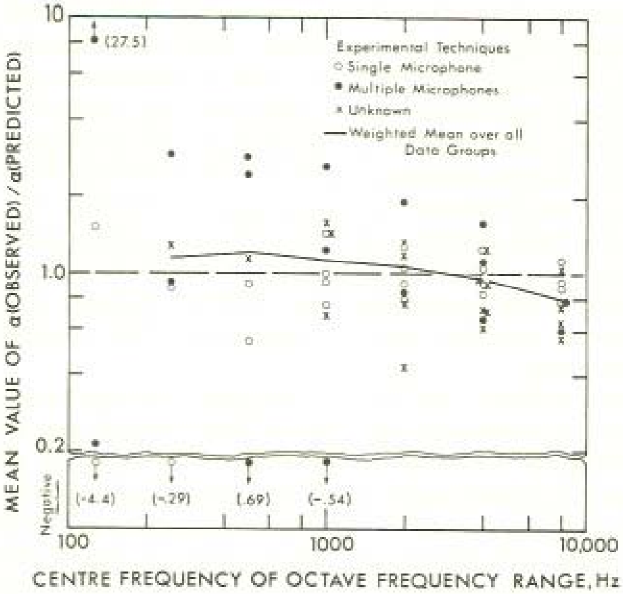

Figure 2.2 Ratio of air-to-ground (aircraft sound propagation) measurements of air absorption loss coefficients to predicted values as a function of frequency (Sutherland (1975). Predicted values were based on weather conditions on the ground, or when data were available on average weather conditions along the propagation path

absorption is constant for a given difference in propagation path lengths unlike geometrical spreading, where it is constant for a given ratio of propagation path lengths. Thus atmospheric absorption tends to become more important with increasing distance between the source and receiver. Note also from Figure 2.3 that the total absorption increases sharply with increasing frequency.

With the new proposed method of predicting atmospheric absorption, the lag between current practice and knowledge has been largely eliminated. Recently, also, this method has been confirmed by extensive measurements at high frequencies (Shields and Bass, 1976; Bazley, 1976) (4–100 kHz), and a few measurements at, in effect, very low frequencies (Lee and Sutherland, 1976) (down to 4 Hz). Nevertheless, there is still need for more data at low frequencies over a substantial range of temperature, and at low humidities. Continuing support is also needed for fundamental work on the mechanisms of air absorption. The measurements would provide needed understanding of the temperature dependence of the relaxation frequency of nitrogen, and lead in due course to the calculation of atmospheric absorption directly from fundamental knowledge (Evans *et al.*, 1972) with enhanced accuracy.

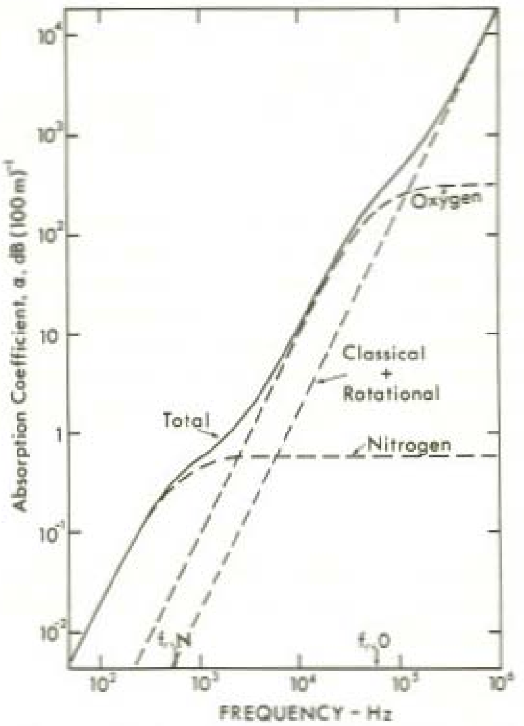

Figure 2.3 Predicted atmospheric absorption in dB/100 m for a pressure of 1 atm, temperature of 20 °C and relative humidity of 70% (Sutherland *et al.*, 1964)

It should be noted that many of the best measurements of outdoor propagation have appeared in the literature in corrected form, with the attenuation calculated for atmospheric absorption removed. The correction for absorption should now be recalculated using the new method, before the original interpretation of these measurements is accepted. In particular, the failure to recognize earlier the contribution from the nitrogen relaxation has led to a number of difficulties some of which will appear in later sections.

2.3 PROPAGATION NEAR THE GROUND

The theory of sound propagation near or along the ground has been treated analytically in the literature, with at least three levels of complexity for the ground surface:

(a) The ground is treated as a locally reacting surface, and waves within the ground are not considered.

(b) The ground is treated as an isotropic fluid medium capable of transmitting dilatational waves in any direction as the result of an impinging wave on the surface.

(c) The ground is treated as an elastic solid medium capable of transmitting both dilational and shear waves resulting from an impinging wave on the surface.

While theoretical models are available in the literature for the latter two (Mackenzie, 1960; Officer, 1958) and other more sophisticated models (Pao and Evans, 1971), there is very little evidence available as yet to show that propagation of sound over the ground is not adequately predicted by the use of the first, much simpler, 'locally reacting' model for the ground surface. Therefore, this is the only model which will be treated in detail in this review. One exception to this general applicability of a 'locally reacting' model will be covered only briefly.

2.3.1 Plane Waves

The amplitude reflection coefficient R_p for a plane wave of sound incident obliquely on a plane locally reacting surface may be conveniently represented by the formula (Morse, 1958)

$$R_p = \frac{\sin\psi - Z_1/Z_2}{\sin\psi - Z_1/Z_2}$$

where ψ is the grazing angle (Figure 2.4), $Z_1 = \rho c$ is the characteristic impedance of air, and Z_2 is the acoustic impedance of the surface (i.e., the ratio of pressure to the normal component of velocity at a point on the surface). In order to include the change of phase as well as amplitude on reflection, complex notation is used for both R_p and Z_2. The characteristics of a particular locally reacting surface may then be represented completely by a complex impedance, $Z_2 = R_2 + jX_2$, which may be dependent on the frequency but not on the grazing angle.

For a perfectly reflecting hard surface, the phase change on reflection is zero, R_p, is 1, and Z_2 must be infinite. In practice, however, Z_2 may be very large, but must always remain finite. For normal incidence in this case $\sin\psi = 1$, and R_p is effectively 1. It is always possible, however, to choose ψ sufficiently small to make the term $\sin\psi$ in Equation (1) small compared to the fixed parameter Z_1/Z_2, and hence make R_p effectively -1. This value signifies a phase change of 180° on reflection and a cancellation of incident and reflected waves at grazing incidence, even though their path lengths are equal. Plane waves at grazing incidence over a plane surface with a finite acoustic impedance thus represent a forbidden mode of propagation.

The rest of Section 2.3 is a description of the implications of this statement for the propagation of noise over the ground, where values of the grazing angle less than 5° have primary importance. The cancellation for small ψ will be shown to represent, in practice, a shadow zone whose acoustical depth is related to the value of the ground impedance.

2.3.2 Spherical Waves, Direct and Reflected

The propagation of spherical waves from a point source near a reflecting plane is an intricate and rambling subject, both mathematically and conceptually. In electromagnetics it has a long history, well chronicled by Baños (1966), from its start by Sommerfield (1926) in 1909 to its present state, as reviewed by Wait (1970). In acoustics there is also a substantial history, from Rudnick (1947) to Wenzel (1974) and Donato (1976), which is chiefly one of adoption of the ideas and solutions from electromagnetic theory. The portion of this history most relevant to the propagation of noise over the ground has recently been surveyed by Embleton *et al.* (1976). The treatment here will follow the latter study, to which the reader is referred for details.

A. *Shadow Zone — Source or Receiver on the Ground*

Consider, again, the basic configuration shown in Figure 2.4. There is a point source S and receiver R situated above a plane boundary with acoustic impedance Z_2. The pressure amplitude p at point R may be represented as follows (Lawhead and Rudnick, 1951; Ingard, 1951):

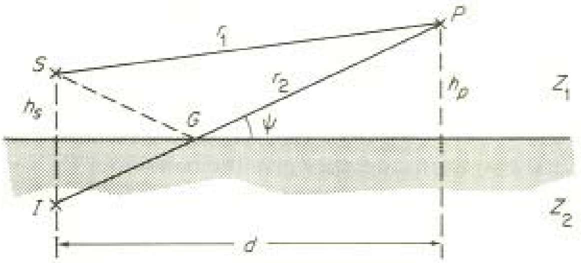

Figure 2.4 Reflection of sound from flat ground with impedance Z_2

$$p/p_0 = (1/r_1)\exp(-ikr_1) + (R_p/r_2)\exp(-ikr_2) + (1 - R_p)(F/r_2)\exp(-ikr_2) \qquad (2)$$

Parameter p_0 is the amplitude of the pressure at unit distance from point source S in the absence of the ground surface. Equation (2) is one form of what is often referred to as the Wey–Van der Pol solution.

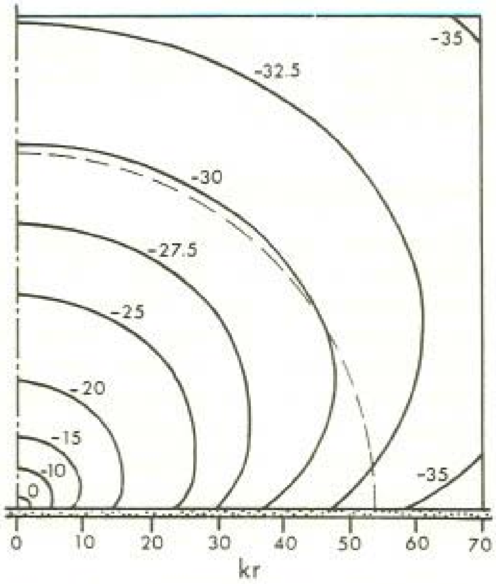

Figure 2.5 Pressure distribution around a point source located on a plane with impedance ratio $Z_2/Z_1 = 10$ (Ingard, 1951). The dashed line gives, for comparison, spherical expansion over a rigid plane

The first term on the right of Equation (2) expresses, in complex notation, the contribution from the wave proceeding directly from S to R. It is only necessary to recognize that the distance r_1 in the denominator is an expression of the inverse square law. The second term is the familiar one for the reflected wave, which appears at point R to have come a distance r_2 from the image source I. The first two terms together give the behaviour shown in Figure 2.5, which is essentially as described in the previous section for plane waves, since R_p is the plane wave reflection coefficient given by Equation (1). [The significance of the third term in Equation (2), and in particular the amplitude factor F, which gives the behaviour of ground and surface waves, will be described later in Section 2.3.4.] Propagation upwards in Figure 2.5, away from the point source on the surface [large ψ in Equation (1)], is spherical expansion: compare, for example, the 30-dB contour to the dashed circle in the figure. Along the surface, however, a shadow zone forms gradually as the sound propagates outward. In this region ($\sin\psi \ll Z_1/Z_2$), Equation (1) and the first two terms in Equation (2) indicate an attenuation A_e in excess of that from inverse square law and atmospheric absorption (and called hereafter just excess attenuation) given by Embleton *et al.* (1971)

$$A_e = 20\log_{10}[2\sin\psi(Z_2/Z_1)],\ \mathrm{dB} \tag{3}$$

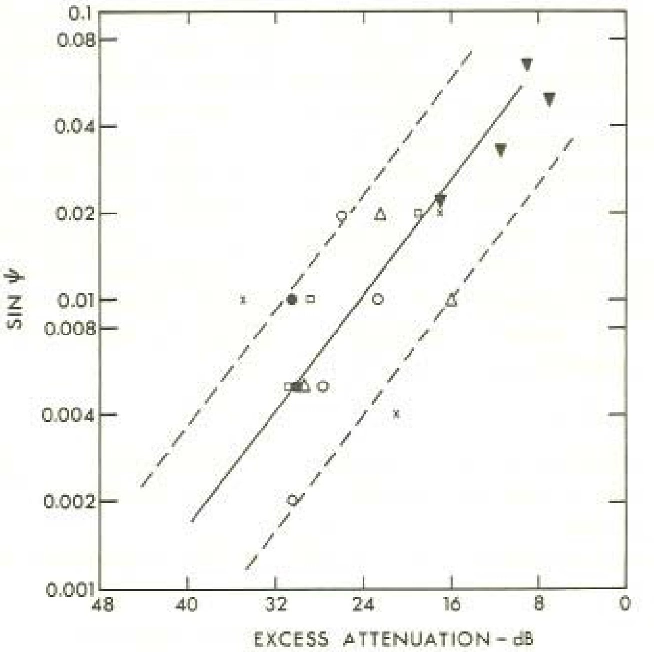

Figure 2.6 Measured excess attenuation for a point source on the surface ($h_s = 0$) of a flat grassy site and the receiver at various heights ($0 \leqslant h_r \leqslant 5$ m) and distance ($d = 5$ m for ▼, 15 m for X, 30 m for ○, 60 m for △, 120 m for □, and 240 m for ●) for a frequency of 3 kHz. There was a brisk crosswind to eliminate the gradients of wind and temperature which cause refraction. The measurements are compared to the attenuation predicted (solid line) via Equation (3) from the value of the ground impedance determined from measurements at short range. The dashed lines encompass 90% of the measured values (Embleton *et al.*, 1976)

A comparison of this prediction with measured levels at distances out to 240 m for one well-chosen example is shown in Figure 2.6. Note that the excess attenuation in the shadow zone is dependent only on ψ and the magnitude of the ratio Z_2/Z_1, and reaches values of ~ 30 dB. It is the result of cancellation between direct and reflected waves in the immediate vicinity of the souce, produced by the phase change of nearly 180° upon reflection, as described previously for plane waves.

B. *Effect of Path-length Differences-Source and Receiver both above a Hard Ground*

When both the source and receiver are above the ground there is a phase change caused by the difference in length between propagation paths r_1 and r_2

in Figure 2.4, in addition to the phase change on reflection described in the previous section. To show the effects of the former, free from the latter, consider propagation in the configuration of Figure 2.4 above a hard, smooth surface, whose reflection coefficient R_p is effectively 1. Spectra of excess attenuation measured (Piercy *et al.*, 1976) for two specific configurations relevant to standard vehicle tests are shown in Figure 2.7. The major dips in the spectra (of ~ 20 dB) are the result of cancellation between direct and reflected rays for path-length differences (PLD's) of an odd number of half wavelengths. The interference between direct and reflected sound over the rest of the spectra is approximately coherent addition. (Note that the minor dips and peaks are caused by turbulence, and will be considered later.) An elementary geometric calculation shows

$$\text{PLD} \approx 2h_s h_r/d \tag{4}$$

for small values of ψ. Note therefore that the frequency $f_{\min}$ of the first minimum will increase with increasing d, as shown in Figure 2.7, and also decreasing h_s and h_r.

Spectra such as those shown in Figure 2.7 for propagation over a hard

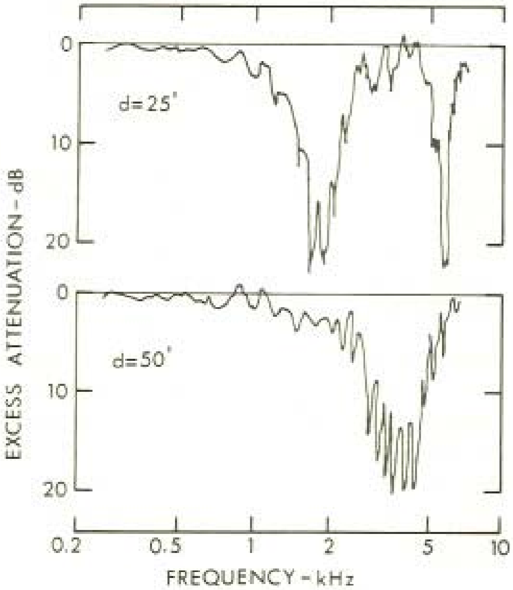

Figure 2.7 Measured excess attenuation for propagation from a point source over asphalt, $h_s = 0.3$ m, $h_r = 1.2$ m. The excess attenuation is relative to that for the point source placed on a perfectly hard surface (Piercy *et al.*, 1976)

surface may be divided into two regions: $f < \sim \frac{1}{2} f_{\min}$ where the transmission characteristic is reasonably uniform, and $f > \frac{1}{2} f_{\min}$ where it alternately shows the effects of constructive and destructive interference. The former is highly desirable for testing noise sources (see Section 2.6.1) and the importance of both regions for outdoor propagation in general will be discussed later in Section 2.3.5.

2.3.3 Ground Impedance

Measurements of the acoustic impedance of the surface of the ground are scarce; only for mown grass, as found on airports and around public highways and buildings, is a substantial amount of data available (Embleton *et al.*, 1976; Dickinson and Doak, 1970; Jonasson, 1972). The most detailed information on the impedance of mown grass (Embleton *et al.*, 1976) is shown in Figure 2.8. It was obtained from measurements either with a vertical impedance tube, or from interference phenomena, at oblique angle of incidence, similar to those described in the previous section. The values of impedance shown in Figure 2.8 confirm the grassy surface to have the acoustic properties of a locally reacting porous medium, which are well understood from the study of acoustic building materials. The impedance is determined by the presence of a thin porous layer on the surface that must have holes small enough to offer substantial resistance to the flow of air. Thus the impedance of short grass as in a lawn is not changed appreciably by mowing, as the main resistance to flow appears to be either in the turf itself or, more likely, in the soil near the surface kept loose by the roots. Different stretches of institutional or mowed airport grass are found to have similar values of impedance, and this impedance was not very sensitive to weather (Dickinson and Doak, 1970). It is important to note that the reactive component corresponds to a stiffness and not to a mass.

There is little information about the acoustic impedance of other ground surfaces. A stubble field (Jonasson, 1972), or the ground under a pine plantation (Aylor, 1972) both appear to have an impedance similar to that of grass, presumably because of the roots loosening the soil. Snow (Parkin and Scholes, 1965) and ground recently loosened by discing (Aylor, 1972) appear to have a much lower impedance at low frequencies. The impedance of asphalt (Parkin and Scholes, 1965), although much higher than grass, is by no means infinite.

2.3.4 Ground and Surface Waves — Source and Receiver Both on the Ground

The third term in the Weyl–Van der Pol solution of the wave equation for spherical waves (Equation (2)] arises mathematically from the need to match the boundary conditions, in particular the variation of the curvature of the wavefronts with distance along the boundary. Parameter F in this term

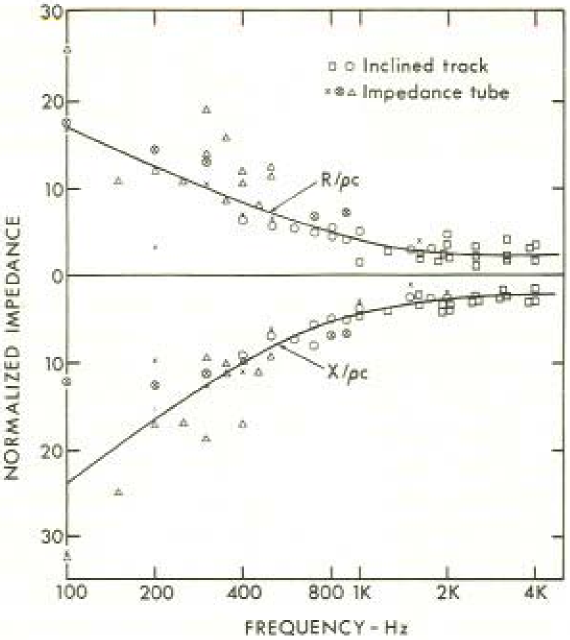

Figure 2.8 Real component R_2 and imaginary component X_2 of the acoustic impedance of grass-covered flat ground (different areas of two different sites) obtained from measurements either with an impedance tube or of interference at oblique incidence (Embleton *et al.*, 1976). (Note that the imaginary component corresponds to a stiffness reactance)

represents a complicated mathematical function (Rudnick, 1947; Lawhead and Rudnick, 1951) of a variable w called the numerical distance. This function is plotted (Wait; 1970) versus w in Figure 2.9 for various values of the phase angle $\phi = \tan^{-1}(X_2/R_2)$ of the surface impedance Z_2. The numerical distance is given by the expression (Embleton *et al.*, 1976)

$$w = (\tfrac{1}{2}ikr_1)(\sin\psi + Z_1/Z_2)^2 \tag{5}$$

where $k = 2\pi/\lambda$ is the propagation constant in air, and the other variables are defined in Sections 2.3.1 and 2.3.2. It is useful to consider the numerical distance w to represent the propagation distance r, scaled for a given value of frequency f, and grazing angle ψ, by the impedance Z_2, according to Equation (5).

The physical interpretation of the third term in Equation (2) is more elusive than that of the first and second terms which are the direct and reflected waves discussed in Section 2.3.2. The physical interpretation is most clear for both

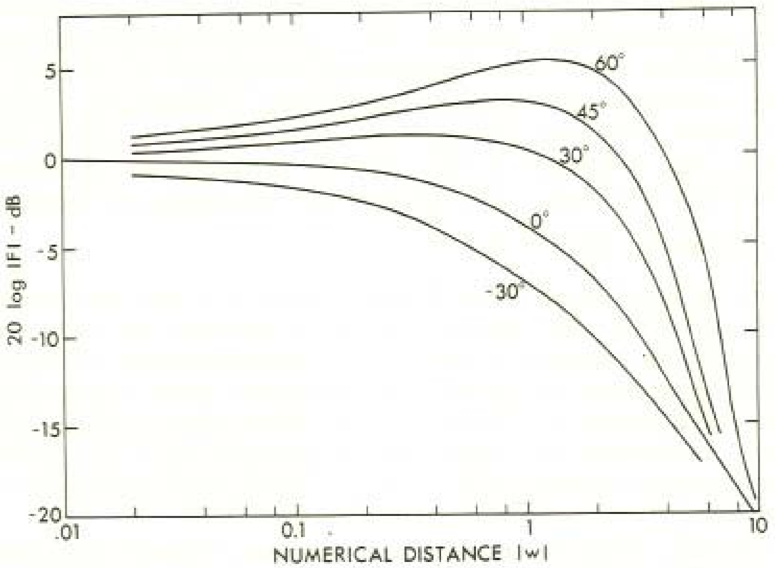

Figure 2.9 Amplitude factor $F(w)$ of the ground sand surface waves vs numerical distance w for various values of the phase angle ϕ of the surface impedance (Wait, 1970)

source and receiver on the boundary ($h_s = h_r = 0$ in Figure 2.4, and $\psi = 0$) and the boundary resistive ($\phi = 0$), because of the direct analogy to the propagation of electromagnetic waves above the earth (for which the Weyl–Van der Pol solution was originally derived). Under these conditions the direct and reflected waves cancel completely to form a shadow zone, as described earlier in Section 2.3.1 and 2.3.2A. This shadow zone is penetrated by the ground wave which is represented by the third term in Equation (2) for $\phi = 0$. The amplitude of this ground wave is indicated by the curve for $\phi = 0$ in Figure 2.9. Althought the ground wave is important for radio communications, carrying the electromagnetic energy from the antenna of the local AM station to one's radio, its exact physical nature is still obscure (Baños, 1966). The dependence on the variables, however, is well defined. The curve for $\phi = 0$ in Figure 2.9 indicates that at short distances ($w \ll 1$) the ground wave suffers no excess attenuation compared to propagation over an infinitely hard surface, but for longer distances ($w \gg 1$) exhibits a loss of 6 dB per doubling of distance in addition to that provided by the inverse square law.

The data in Figure 2.8 indicate, however, that the phase angle ϕ for the acoustic impedance of a grassy surface varies between approximately 45 and 60° over the audible range of frequencies. (By the sign convention used in this paper, a positive imaginary term for impedance corresponds to a stiffness reactance.) The amplitude of the function F for this range of ϕ in Figure 2.9

differs from that for $\phi = 0$ (and hence differs also from the values used for radio wave propagation in the atmosphere) by the presence of a substantial increase in the vicinity of $w = 1$. This increase in the function F we now know to be mainly the contribution of a surface wave (Wenzel, 1974; Donato, 1976) in the air: this wave is coupled to the ground surface owing to the latter's stiffness reactance but propagates in the air, with an amplitude that decreases exponentially with height z above the boundary according to the formula

$$p = p_b \exp[-X_2^2(R_2^2 + X_2^2)^{-1} kz] \tag{6}$$

where p_b is the amplitude at the boundary. For $w \ll 1$, e.g., for d small, the contribution of the surface wave in Figure 2.9 is relatively smaller than that of the ground wave because the surface-wave amplitude decreases at only 3 dB per doubling of distance (cylindrical expansion from a point source) compared to 6 dB for the ground wave. For $w \gg 1$ the amplitude of the surface wave again becomes smaller than the ground wave because of its attenuation by viscous losses in the pores of the boundary, which is exponential with distance r along the boundary.

In summary, theory indicates that the propagation of sound energy between a point source and receiver which are both placed on a grassy surface ($h_s = h_r = 0$) is by a ground wave, as in electromagnetic propagation, augmented by a surface wave. The scale of the distances and heights of these waves is given in Table 2.1 for a grassy surface whose impedance is that shown in Figure 2.8. Some of the properties of these waves have been verified directly by measurements over grass (Donato, 1976; Embleton *et al.*, 1976) at short distances, where disturbing phenomena such as turbulence and refraction are absent, and by model experiments indoors (Lawhead and Rudnick, 1951; Ivanov-Shits and Rozhim, 1960). The relevance of ground and surface waves to long range propagation when both source and receiver are above the ground will be discussed in the following section.

Table 2.1. The propagation distance d_w for numerical distance $=1$, and height z_{sw} for the amplitude of the surface wave to decrease by $1/e$ from its value at the boundary, calculated by Equation (5) and (6), respectively, from the impedances shown in Figure 3.8 for mown grass

f(Hz)	d_w(m)	z_{sw}(m)
50	4,000	58
100	1,500	23
200	270	7.3
500	24	0.9
1,000	3.6	0.5
2,000	1	0.15

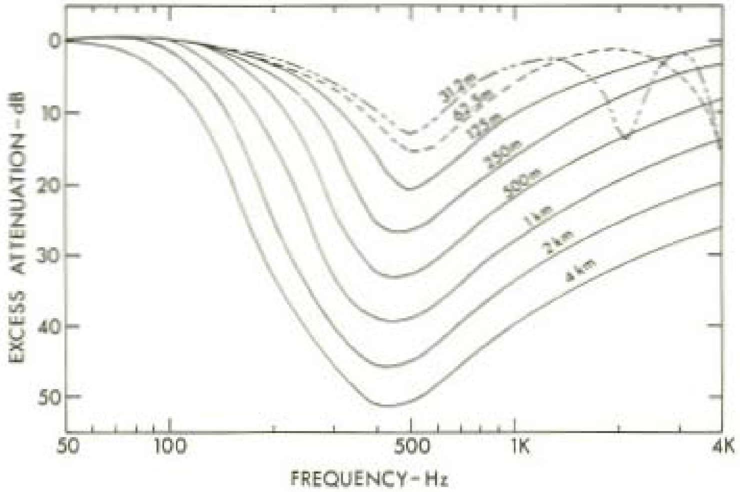

Figure 2.10 Excess attenuation calculated for propagation from a point source over mown grass for h_s = 1.8 m, h_r = 1.5 m, and the distances of propagation d indicated. The attenuation is calculated for values of impedance given in Figure 2.8. The excess attenuation is relative to that for the point source placed on a perfectly hard surface (Piercy *et al.*, 1976)

2.3.5 All Phenomena Together — Source and Receiver both above the Ground

All the phenomena described previously in Sections 2.3.1–2.3.4 must be considered when both point source and receiver are above the ground. The curves shown in Figure 2.10, for propagation in the configuration of Figure 2.4 with h_s = 1.8 m, h_r = 1.5 m, and various values of d, have been calculated (Piercy *et al.*, 1976) using the theory of Donato (Donato, 1976) with values of impedance taken from the curves for mown grass in Figure 2.8. The individual contributions to these curves from direct D, reflected R, ground G, and surface S waves are illustrated (Piercy *et al.*, 1976) for three of these distances in Figure 2.11, together with measurements of the propagation of jet noise for the same values of h_s and h_r and comparable d (110 and 615 m) under neutral atmospheric conditions at an airport (Parkin and Scholes, 1965). (These measurements will be described in greater detail in Section 2.4.2B.)

Consider first the curves for a distance of 31.2 m in Figure 2.11.Here the grazing angle ψ is sufficiently large for D and R waves alone [first two terms in Equation (2)] to be a good approximation to the complete solution. Note that the latter includes contributions from D, R and G waves only, because the angle ψ is too large for an S wave to be significant. For frequencies greater than about 1 kHz there is a series of maxima and minima caused by path length differences (PLD's) between direct and reflected waves, that is an interference

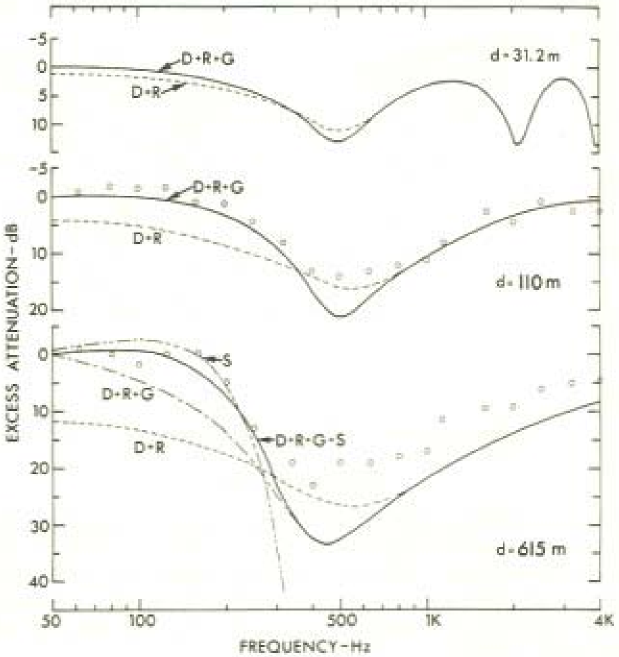

Figure 2.11 Excess attenuation for propagation from a point source over mown grass, $h_s = 1.8$ m, $h_r = 1.5$ m. The calculated curves show the contributions from the various waves—direct D, reflected R, ground G, and surface S. The points are measurements of jet noise from Parkin and Scholes (1965) at comparable distances. The excess attenuation is relative to that for a point source placed on a perfectly hard surface (Piercy *et al.*, 1976)

pattern similar to that described in Section 2.3.2 for a hard surface (see Figure 2.7). Unlike the pattern for a hard surface, however, the minima are for PLD's which are approximately even multiples of $\frac{1}{2}\lambda$, indicating that the surface is effectively soft for this configuration and frequency range. As the frequency decreases, however, the ground impedance increases (see Figure 2.8) causing the surface to give a response which is effectively hard for low frequencies ($f < \sim 150$ Hz) as in Figure 2.7. Unlike the response of the hard surface shown in Figure 2.7, however, there is a broad minimum between these two ranges centred at about 500 Hz, which is characteristic of the propagation for short distances over soft ground. It is the result of cancellation between direct and reflected waves caused primarily by the phase change on reflection. The dip shown in Figure 2.11 for a distance of 31.2 m, therefore (for source and receiver now both raised above the surface), is the remains of the shadow zone described previously in Section 2.3.2, for the source (or receiver) on the ground. It has caused major problems for the testing of noise sources such as snowmobiles at short ranges, because the cancellation and hence the noise, is dependent on the impedance of the surface of the particular site (Piercy and Embleton, 1974).

Because the curvature of the wave-front from a point source decreases with increasing distance, the behaviour for long ranges must be asymptotic to that described in Section 2.3.1 for plane waves. The curves in Figure 2.10 indicate that the dip broadens and deepens with increasing distance until most of the audible frequency range is included in the shadow zone in accordance with this principle. Comparison of the curves in Figure 2.11 for a distance of 125 m with those for 31.2 m shows how this broadening comes about. The interference pattern, which occurs at high frequencies for $d = 31.2$ m, has, for $d = 110$ m moved upward in frequency beyond 4 kHz, by virtue of the d^{-1} term in Equation (4), leaving only the rising slope to the first maximum in Figure 2.11. At the low-frequency end, the increasing cancellation between D and R waves produced by decreasing ψ [as in Equation (1)] has revealed a substantial contribution from the ground wave. The measurements are in reasonable agreement with theoretical prediction for 125 m, using impedances obtained from a different site.

Consider now the curves for 615 m in Figure 2.11. The broadening of the shadow zone to higher frequencies evident in the curves for 125 m has continued with increasing distance. There has also been a broadening to the lower frequencies, which leaves most of the energy in the frequency range 50–200 Hz in the surface wave, and the latter fact remains true for longer distances. The measurements for 615 m at low frequencies closely follow theory, showing a small enhancement (negative excess attenuation) due to the surface wave (Wenzel, 1974). There is, however, a tendency at the high frequencies for the measured excess attenuation to be consistently less than predicted.

The reason for the high-frequency discrepancy probably has to do with the use of coherent acoustic theory for the predicted curves. Turbulence in the atmosphere is known to reduce coherence between different propagation paths. While it would be premature to attempt to predict the size of this effect from existing knowledge, to be realistic one must expect significant departures from the curves shown in Figure 2.10 due to turbulence (see Section 2.4.2) particularly at higher frequencies, longer distances, and when the excess attenuation due to interference between direct and reflected waves would otherwise become large (greater than ~ 20 dB, see Section 2.4.3).

In practice, for broadband noise sources, such as a jet engine, and for distances greater than about 1 km, the high frequencies will be attenuated sufficiently by atmospheric absorption, as shown in Figure 2.3, and the midfrequencies will be attenuated by the ground shadow, as shown in Figure 2.10, so that the main contribution to the measured *A*-weighted sound level will come from the surface wave at frequencies below 200 Hz, as illustrated in Figure 2.11. It is likely also that the background roar from distant traffic, is transmitted mainly via this surface wave. It is interesting to note that the attenuation of the surface wave is mainly by the viscous flow of air in the pores of the ground.

2.3.6 Summary

In the preceding Sections 2.3.1–2.3.5, the present understanding of the near-horizontal propagation of sound in an acoustically homogeneous atmosphere close to flat ground has been outlined. The primary effect is a shadow zone caused by the finite acoustic impedance of the ground surface. This shadow zone is penetrated at low frequencies by the ground and surface waves. For both source and receiver above the boundary, the shadow zone is also penetrated at high frequencies by constructive interference between direct and ground-reflected waves. Sound levels can be calculated with reasonable precision using known theory within the constraints imposed by the present knowledge of the ground impedance and the use of coherent wave theory. The effect of inhomogeneity of the atmosphere produced by surface meteorology, as well as surface topography, will be discussed in Sections 2.4 and 2.5.

2.3.7 Prediction Schemes

It appears from the analysis in Section 2.3.5, that the modern theory of the propagation of sound from a point source has good potential for predicting the excess attenuation of noise produced by the ground surface within the constraints reviewed in Section 2.3.6 above. There are two equivalent formulations, by Wenzel (1974) and Donato, (1976), with the latter more suitable for computation. The theory and the mechanisms of propagation are complicated but the solutions are programmable, so that this method appears worthy of development.

A useful but less general approach has been suggested by Delany and Bazley (1970, 1971). They adapted the limited exact mathematical solution of Wisse (1929) for electromagnetic propagation to the propagation of sound. This solution is equivalent to taking only the first two terms in Equation (2). The simplified method of Delany and Bazley has the additional constraint, therefore, to regions where the contributions from the ground and surface waves may be neglected. It appears from the discussion in Sections 2.3.4 and 2.3.5 (and Figure 2.11) that this simplified scheme should not be used for low frequencies at small grazing angles. It should, however, be useful for evaluating the noise from aircraft in flight, the purpose for which it was designed, because here two of the other major constraints (weather and topography) are often not a problem.

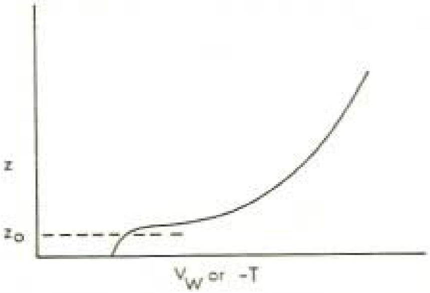

Figure 2.12 Variation of wind velocity and temperature in the vicinity of a flat ground surface ($z < \sim 10$m)

2.4 EFFECT OF SURFACE METEOROLOGY

2.4.1 Relevant Meteorological Phenomena

The variation of the average speed of the wind V_w with height z in the vicinity of the ground for a large flat open area is approximately as shown in Figure 2.12 (Wiener and Keast, 1957; Lumley and Panofsky, 1964; Sutton, 1953). For heights greater than z_0, V_w may be represented by the formula

$$V_w = K_v \log (z/z_0) \tag{7}$$

Parameter z_0 is determined by the roughness of the surface, and is often very approximately the height of a consistent obstacle, such as grass or corn. The region of logarithmic variation shown by Equation (7) is caused by the viscous drag of the surface and is known as the viscous boundary layer. The constant K_v is determined by the roughness of the surface, and the wind velocity above this boundary layer, which is usually not greater than ~ 10 m thick, the height at which wind is normally measured at an airport. In practice it is often necessary to consider deviation from the velocity profile given by Equation (7) caused by the buoyancy introduced by the temperature profile.

In the vicinity of the ground, the variation in average temperature T with height for a large flat area may be represented during the daytime by the analogous expression

$$T = T_0 - K_t \log (z/z_0) \tag{8}$$

where T_0 is the temperature for $z < z_0$. The thermal boundary layer given in Equation (8), which normally has a thickness and value of z_0 similar to that of the viscous layer, is caused by the heating of the surface by the sun. It normally coincides with a condition known to meteorologists as lapse from measurements well above the boundary layer, an example of which is given (Munn, 1966) in Figure 2.13. Shown also in Figure 2.13 is an example of an inversion

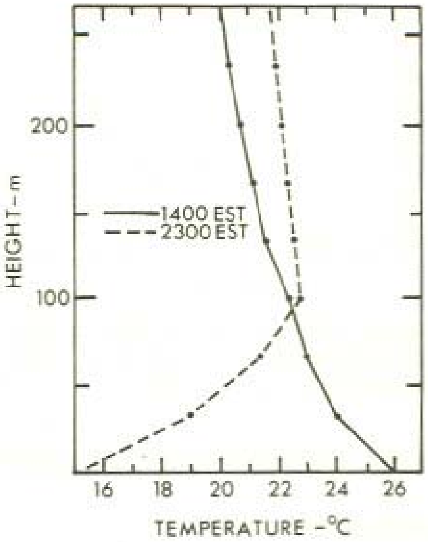

Figure 2.13 Variation of temperature aloft—examples of lapse (afternoon) and inversion (evening) conditions from Munn (1966)

caused by the cooling of the surface of the ground through radiation to the night sky. The term 'neutral' will be used later in the discussion to signify a third meteorological condition, where the dependence of temperature with height is small: This condition may arise typically under heavy clouds.

2.4.2 Refraction

A. Basic Forms

Forms of refraction produced by different meteorological conditions are shown in Figure 2.14. While the effects of wind and temperature gradients appear similar in the figure, the following differences should be noted. Because temperature is a scalar quantity the refraction of sound produced by lapse or inversion conditions is the same in all horizontal (compass) directions. Wind, however, produces refraction nonuniform in direction according to the vector component in the direction of propagation. Thus the refraction produced by the wind is zero when the sound propagates directly crosswind, and increases progressively as the direction of propagation deviates from this condition.

The major acoustic effect in refraction upwards as shown in Figure 2.14(b) is the production of a refractive shadow zone, shown crosshatched in the figure, where, according to the ray picture (geometric accoustics) no sound may enter. Refraction downwards, as shown in Figure 2.14(a) tends in practice to

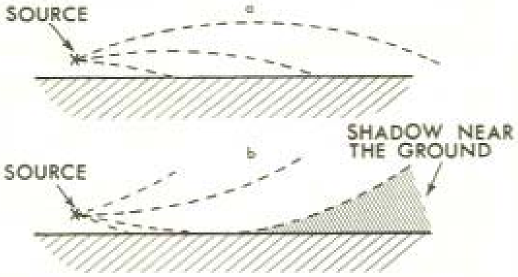

Figure 2.14 (a) Refraction downward—inversion or downwind propagation; (b) Refraction upwards—lapse or upwind propagation

enhance the sound level, by mechanisms which will be discussed in the next section.

B. Refraction Effects for Distances Less than 1500 m

The work of (Ingard (1955), Parkin and Scholes (1965), Wiener and Keast (1957,1959), Delany (1969), Parkin and Scholes (1964), Scholes and Parkin (1967), Scholes *et al.*, (1971), Dean (1961), Baron (1954), Goydke *et al.*, (1968), Franken and Bishop (1967)) may be fitted together to provide a consistent picture of the effect of refraction on the propagation of sound over distances up to 1.5 km using the meteorological and refraction phenomena described in the two previous sections and the propagation phenomena described in Section 2.3. These phenomena will be described with the help of the detailed measurements of Parkin and Scholes (Parkin and Scholes, 1965) shown in Figure 2.15 for the propagation of jet noise over mown grass on a reasonably level airport.

Measured spectra of attenuation in excess of that caused by spherical spreading and atmospheric absorption are shown in Figure 2.15 for two different distances and a number of different meteorological conditions. The source height is 1.8 m and the receiver height 1.5 m. The curves each represent the average of a number of measurements on different days. The dotted, dashed, and solid curves for each distance are designated +5, 0 and −5 to indicate the vector component of wind velocity in the direction of propagation in metres per second. For these three curves the temperature conditions are classed as neutral, as described in Section 2.4.1. Curve 0 for each distance therefore indicates the attenuation produced by the ground effect, as described in Section 2.3.5, and in fact is composed of straight lines joining the experimental points in Figure 2.11. Curve −5 (in Figure 2.15) indicates the additional attenuation produced by a wind shadow zone, and curve +5 the enhancement during downwind propagation.

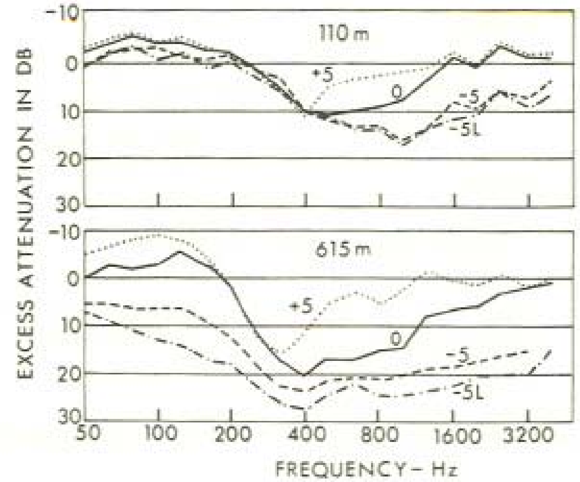

Figure 2.15 Observed attenuation of aircraft noise in a ground-to-ground configuration under a variety of weather conditions (Parkin and Scholes, 1965). Calculated losses from atmospheric absorption and spherical spreading have been subtracted from the attenuation measured in ⅓-octave bands for distances of 110 m and 615 m. These numbers on the curves indicate the vector component of the wind velocity in the direction of propagation in m/sec. All curves are for neutral conditions of temperature except for those marked *L*, which are for lapse

Parkin and Scholes resolve their measurements into two further categories according to the gradient of temperature — either lapse or inversion. The result is generally to change the labels on their curves for all distances by one step (exceptions will be discussed later). Thus their lapse +5 curve is close to the neutral zero curve in Figure 2.15, and the lapse zero curve is equivalent to the neutral −5 curve. The lapse −5 curve, which is the bottom curve (−5*L*) in the figure, represents one of the exceptions. Inversion conditions could only be attained for light winds, and their inversion zero curve is very close to the neutral +5 curve in the figure.

The first conclusion to note, therefore, from the measurements of Parkin and Scholes is that refraction due to vertical gradients of wind and temperature in practice produces equivalent acoustic effects; these are additive, moreover, within the limits imposed by a saturation phenomenon to be described presently. To understand the physical nature of these effects it is useful to divide the frequency range for the spectra shown in Figue 2.15 into three parts: a small central region from about 200–500 Hz where the effect of refraction is smallest, and separate regions for frequencies above and below this central region.

(*a*) *High-frequency region* (*f* > *500 Hz*). In this region the measurements show a strong tendency towards two extreme values for the excess attenuation, approximately 0 dB in conditions of downward refraction (inversion or downwind propagation) and −20 dB in conditions producing upward refraction (lapse or upwind propagation), seemingly independent of frequency or distance (when the latter is sufficiently large). This pattern is reasonably clear in the measurements for a distance of 615 m shown in Figure 2.15, and obvious in the measurements for a frequency of 1.2 kHz over a range of distances shown in Figure 2.16.

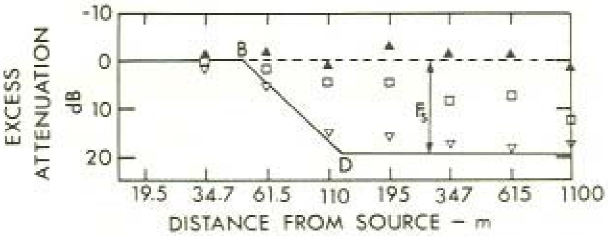

Figure 2.16 Excess attenuation measured for aircraft noise in the 1.2-kHz ⅓-octave band for the ground-to-ground configuration (Parkin and Scholes 1965). The vector component of the wind velocity in the direction of propagation for ▲ is +5 m/sec, □ is 0 m/sec, and ▽ is −5 m/sec. The temperature profile is neutral. F_s is the shielding factor, *B* is the shadow boundary

The pattern for conditions of upward refraction is idealized by the solid lines shown in Figure 2.16. There is effectively no excess attenuation in propagation out to the shadow boundary B in the figure, which is typically 50 m away from the source. The excess attenuation then increases rapidly to position D, but then stays independent of further increases in distance. In effect the signal well within the shadow zone follows the inverse square law but it also reduced in level by a fixed attenuation given by the shielding factor F_s in Figure 2.16.

It should be noted that the pattern of behaviour described above is independent of the magnitude of excess ground attenuation. Thus the measurements for a distance of 615 m in Figure 2.15 indicate at a frequency of 3–4 kHz, where the ground effect is small, there is effectively no enhancement of the signal during downwind propagation, and for a frequency of ~600 Hz, where the ground effect is large, the increase in attenuation in upwind propagation indicated by the −5 curve is small. Furthermore, the −5*L* curve indicates that the additional refraction produced here by adding a temperature gradient is also small. This effect has been described previously as a saturation.

To explain these saturation characteristics, the following mechanism has been proposed for the solid line in Figure 2.16 (upward refraction). The behaviour well within the shadow zone is as if the signal were from a flanking path. The refractive shadow boundary is known to make a small angle, typically < 5°, with respect to the ground (see Section 2.5.1), and it has been widely suggested (Ingard, 1955; Shaw and Olson, 1972; Parkin and Scholes, 1965; Delany, 1969) that the flanking signal is energy scattered down across this boundary by atmospheric turbulence, as indicated by the dashed arrows in Figure 2.17. However, this model for the mechanism of the shielding factor remains untested by experiment or quantitative analysis.

Figure 2.17 A mechanism for the shielding factor, F, in Figure 2.16. The dashed lines represent the continuous scattering of energy down from the sky wave, which propagates without excess attenuation from source S

The method by which the excess attenuation becomes 0 dB for downward refraction, as given by the dashed line in Figure 2.16, is also not clear. The only *a priori* likely way is by destruction of the ground effect. The curvature in the ray path increases the grazing angle ψ in Figure 2.4, hence reduces the cancellation which causes the ground effect (Embleton *et al.*, 1976)

(*b*) *Low-frequency region* ($f < 200$ *Hz*). The curves for $d = 110$ m in Figure 2.15 indicate that the effects of refraction are much smaller for low frequencies than for high: the physical reason is that the scale of the strong gradients in wind and temperature which occur close to the ground (see Figure 2.12 and Section 2.4.1) become small compared to the wavelength of sound at the lower frequencies (Ingard, 1955; Delany, 1969; Dean, 1961). Refraction still occurs for the low frequencies but at much larger distances. The curves marked -5 and $-5L$ for $d = 615$ m in Figure 2.15, for example, indicate that at this distance the shadow zone is still only partially formed, i.e., the excess attenuation falls part way along line BD in Figure 2.16, similar to the curves for -5 and $-5L$ at high frequencies and a distance of 110 m in Figure 2.15.

The +5 curve for a distance of 615 m in Figure 2.15 indicates that during downwind propagation or in an inversion only low-frequency signals are enhanced well above that expected by inverse square law. A likely mechanism for this enhancement is provided by the unique mode of propagation at these frequencies, as described in Section 2.3.5. The surface wave may be attributed to the porosity of the ground retarding the velocity of propagation in the atmospheric layer immediately above the surface. This retardation is enhanced by the vertical gradient of wind velocity during propagation downwind, or the vertical gradient of temperature during an inversion.

(*c*) *Central frequency region* ($f = 350 \pm 150$ *Hz*). A study of curves similar to those in Figure 2.15 for other sites (Parkin and Scholes, 1964; Scholes *et al.*, 1971) and geometrical configurations (Scholes *et al.*, 1971) (h_s, h_r, d) shows the position of this limited region, where the effects of refraction are small, to be in the vicinity of the frequency of maximum ground attenuation, which is somewhere in the range 200–500 Hz. The −5 and $-5L$ curves in Figure 2.15 for a distance of 615 m indicate that the small effect of upward refraction in this region is the result of saturation in the shadow zone, as described above for high frequencies.

The persistence of the ground shadow indicated by the coincidence of curves 0 and +5 for a distance of 615 m is remarkable, however, and almost certainly reflects the unusual mechanism of propagation described in Sections 2.3.4 and 2.3.5. Thus, the sharp increase in excess attenuation with frequency between 200 and 300 Hz at a distance of 615 m was shown to be caused by the absorption of energy in the surface wave by the viscous flow of air in the pores of the ground. The coincidence of the +5 curve with the zero curve in Figure 2.15, therefore, signifies that this loss cannot be replaced by refraction.

C. *Prediction Schemes*

Wiener and Keast (1959) have provided an empirical prediction scheme for the effects of refraction by wind and temperature which is applicable to the high-frequency region described above. In this scheme the distance to the shadow boundary B in Figure 2.16 is calculated assuming linear vertical gradients of wind and temperature. Delany (1969) has improved this scheme by calculating the distance for the logarithmic profiles in the boundary layer indicated by Equation (7) and (8). Kriebel (1972) has also provided an interesting analysis of the propagation in the boundary layer.

It should be noted, however, that measurements in the low-frequency region described above show the excess attenuation to depend on the surface impedance, which is outside the scope of Wiener and Keast's method.

It should also be noted that for propagation over distances much greater than 1.5 km, different factors become important. There are scattered measurements (Ingerslev and Svane, 1968; Dneprovskaya *et al.*, 1963) which indicate a much higher attenuation in the shadow zones than predicted by Wiener and Keast. In downward refracting conditions the relevant portion of the vertical profiles of wind and temperature become higher than the logarithmic boundary layer given by Equation (7) and (8). Inversions then become more important (see Figure 2.13) and a theoretical analysis of the excess attenuation during propagation in inversions is available (Embleton *et al.*, 1976).

Empirical models have also been developed (Polly and Tedrick, 1975) to explain systematic trends observed during a very large number of measurements of low-frequency sound propagation over flat wooded terrain at distances up to 8 km. The average observed excess attenuation was primarily determined by the sign and magnitude of the vertical gradient in the speed of sound, and secondly by the wind speed.

2.4.3 Turbulence

Large eddies are formed in the atmosphere by instabilities in the thermal and viscous boundary layers at the surface of the ground, described in Section 2.4.1. Further instability causes these eddies to break down progressively into smaller and smaller sizes until the energy is finally dissipated by viscosity in eddies approximately 1 mm in size. A statistical distribution of eddies, which we call turbulence, is therefore present in the atmosphere at all times (Lumley and Panofsky, 1964; Tatarski, 1971). The intensity of the turbulence, however, is strongly dependent on meteorological conditions (and also height above the ground), being high, for example, on a windy summer afternoon, and low under nocturnal inversions.

The effect of atmosphere turbulence on wave propagation has been studied extensively during the last twenty years (Tatarski, 1971) most notably on the propagation of light and microwaves, but also of sound (Tatarski, 1971; Mandics, 1971). For sound, the condition most studied is near-vertical propagation, well away from the surface of the ground, to permit the 'acoustical sounding' of meteorological conditions (Little, 1969). There are a small number of investigations of near-horizontal propagation of sound close to the ground (Ingard and Maling, 1963; Embleton *et al.*, 1974) which are of direct relevance to noise problems, but for most questions concerning the effect of turbulence on noise propagation it is necessary to fall back on knowledge accumulated in these related areas.

It is known that atmospheric turbulence produces fluctuations in the amplitude and phase of a pure tone during propagation which increase with increasing distance until a point is reached where the phase fluctuations have a standard deviation comparable to 90°. At this point the signal effectively becomes uncorrelated with the source and the amplitude fluctuations are limited to a standard deviation (Embleton *et al.*, 1974) of ~6 dB. The distance to this point for horizontal propagation of sound near the ground on a summer day is very approximately 700 λ, for frequencies in the range 500–5,000 Hz (Embleton *et al.*, 1974). An effect of this magnitude brings into question the common use of coherent acoustic theory for predicting noise propagation in a number of critical regions, some of which have already been mentioned (Sections 2.3.5 and 2.4.2)

Perhaps the condition most sensitive to atmospheric turbulence is interference phenomena: the sharp spikes clearly visible in the minima of the interference patterns shown in Figure 2.7, for example, are caused by fluctuations in the phase difference between direct and reflected waves, and the effective depth of the minima is determined by the fluctuations (Ingard and Maling, 1963). While a good start has been made on the theory of interference in a turbulent medium (Ingard and Maling, 1963), much more work will be needed on partially coherent propagation before a satisfactory method is achieved for predicting the ground effect at the longer ranges and higher frequencies shown in Figure 2.10.

Another role of atmospheric turbulence which is important for the prediction of noise levels, is in determining the saturation effect in shadow zones, as described in terms of a shielding factor in Sections 2.4.2. The role is, in fact, even more general than described there: it should be expanded to include the acoustic shadow provided by walls (Kurze, 1971, 1974), buildings (Lyon, 1974), the ground effect (Shaw and Olson, 1972), etc. We are very limited at present in our ability to predict levels in shadow zones because of an almost complete lack of understanding of the basic phenomena which determine the shielding factor.

A less profound aspect of atmospheric turbulence, but still a nuisance, is the need to cope with amplitude fluctuations in specifying noise levels (Embleton and Piercy, 1975) from relatively distant sources such as aircraft. One recent experimental study of sound propagation to the ground from a 152 m tower indicated the potential significance of the Richardson's number on the magnitude of these fluctuations (Kasper *et al.*, 1975).

There is one role of atmospheric turbulence which used to be considered important (Ingard, 1953) in predicting noise levels, but now is generally believed to be minor (Deloach, 1975) — that is the direct attenuation of sound by turbulence. If the sound is in a highly directed beam, as for example a vertical atmospheric sounder (Little, 1969) then turbulence attenuates the beam by scattering energy out of it (a phenomena converse to the filling of the narrow shadow zone by scattered energy described in Section 2.4.2). This attenuation can now be calculated with reasonable certainty (Brown and Clifford, 1976). In practice, however, the propagation of noise is usually much closer to spherical expansion from a point source. Because the scattering from turbulence is elastic, and mostly forward through a small scattering angle, the attenuation presented to a spherically expanding acoustic field is negligible. The attenuation of sound due to scattering from a moderately directional source, such as a jet or rocket engine, must lie between these two extremes, but has never been evaluated thoroughly. It is generally believed to be negligible (Sutherland, 1975; Parkin and Scholes, 1965; Wiener and Keast, 1959; Delany,

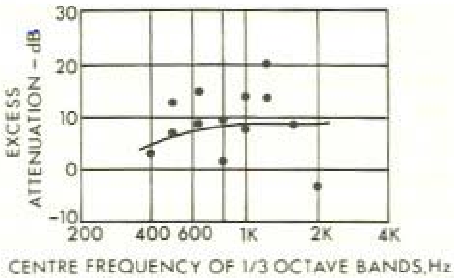

Figure 2.18 Excess attenuation derived from hilltop to hilltop transmission measurements over a distance of about 3 km. The points are measurements which were corrected for inverse square law and molecular absorption using the method of Evans and Bazley (1956) by the original investigators (Wiener and Keast, 1959). The curve is molecular absorption from the nitrogen relaxation, calculated by the method of Sutherland *et al.* (1974), which was neglected in the method of Evans and Bazley (1956)

1969) for most applications. However, where very low frequencies are of importance, for example, in the case of rocket noise, the attenuation by scattering may be significant (Sutherland, 1971) compared to the very low attenuation produced by atmospheric absorption.

2.5 EFFECT OF TOPOGRAPHY

The acoustic phenomena considered previously in Sections 2.3 and 2.4 have all been described for a particular topography, primarily large flat areas covered with short grass, such as an airport, with a receiver placed approximately ear height for a human being standing on the ground. In practice, noise levels need to be predicted for different heights above the ground, for hillsides, for various types of foliage, houses, walls, etc. The data available for such sites is generally much less extensive than for flat ground, and present knowledge is therefore more sketchy. The aim of this section, however, is to outline briefly what is known about the effects of topography. Propagation in city streets, and the attenuation due to barriers will be specifically excluded because these subjects have been covered in recent reviews (Lyon, 1974; Kurze, 1974) which this article is designed to accompany.

2.5.1 Elevation

As an extreme case, consider the propagation from hilltop to hilltop with most of the propagation path several hundreds or thousands of feet above the valley floor. Several sites of this nature have been investigated (Weiner and Keast, 1959; Delasso, 1953), and the measured attenuation is in reasonable agreement with that predicated by inverse square law and atmospheric absorption, when the latter includes the vibrational relaxation of nitrogen (see, for example, Figure 2.18 and the discussion on this point in Section 2.2.2). This attenuation is found to be independent of wind and temperature except in so far as the latter enters into the calculation of absorption.

Studies of noise from low-flying aircraft — effectively sources at low glancing angles ψ (Figure 2.4) — over flat ground are informative (Benson *et al.*, 1958, 1960, 1961). They indicate, for example, that refraction by wind gradients is negligible for $\psi > 5°$ out to a distance of about 6,000 m. There is currently a controversy, however, over a prediction of aircraft noise levels for small ψ, and this problem would probably be well served by an assembly of existing data from many investigators and a fit to the principles out-lined in Section 2.3.

Calculations for the effect of elevation produced by a shallow hillside ($\psi < 1°$) bordering an airport (Embleton *et al.*, 1976; Piercy and Embleton, 1974) have indicated a significant reduction of the ground shadow for aircraft on the ground. There were no supporting measurements but the results correlated well with subjective observations (the structure of complaints).

2.5.2 Foliage

The effect of stands of trees, corn, reeds, etc. have been documented in several studies (Aylor, 1972; Wiener and Keast, 1957; Eyring, 1946; Embleton, 1963; Aylor, 1972; Dobbins *et al.*, 1966). Apparently the main effect at low frequencies is to enhance the ground effect (Aylor, 1972), the roots making the ground more porous, as described in Section 2.3.3. At high frequencies, where the dimensions of leaves become comparable with the wavelength, there is also a significant attenuation caused by scattering (Embleton, 1963; Aylor, 1972). A formula for the latter effect has been developed (Aylor, 1972). The propagation in a vegetative layer over the ground has also been investigated theoretically (Pao and Evans, 1971), but there were no measurements by which to judge the significance of this theory.

In a forest, the vertical gradients of wind and temperature are small (Munn, 1956), the foliage making z_0 in Equations (7) and (8) approximately the height of the trees. Presumably, therefore, the effects of refraction are small also.

2.5.3 Obstructions (Walls, Houses, Bushes, etc.)

The effect of refraction on the propagation of sound in city streets (Wiener *et al.*, 1965) as within forests, is small, and for the same reason: the obstruction to the flow of air is sufficient to raise the viscous and thermal boundary layers to the vicinity of the tops of the obstacles (buildings) (see Section 2.4.1). The attenuation of sound by the ground effect in the city (Lyon, 1974) is also much smaller than in the country (Parkin and Scholes, 1965), partly because of the paved ground, but more importantly because obstacles to the propagation of sound produce an interference pattern much different from the simple interference between direct and ground reflected waves described in Section 2.3. These effects have been studied both for cities (Lyon, 1974; Wiener *et al*, 1965) and open flat land, (Parkin and Scholes, 1965; Wiener and Keast, 1959) with results that are very different. There has been very little work, however, on intermediate sites such as suburbs. Questions such as how many obstacles are needed to destroy the effect of the ground, or refraction, as measured for flat land, cannot be answered at present. As a result the prediction of the propagation of noise from airports, freeways, etc., out into the suburbs is based largely on empirical methods not well founded on either analytical models or extensive experimental data.

2.6 PROPAGATION PROBLEMS SPECIFIC TO COMMUNITY NOISE

2.6.1 Testing and Certification of Sources

A. Vehicles and Other Ground Based Sources

There are several propagation problems in the testing of ground based noise sources such as road vehicles, lawn mowers, snowmobiles, etc. (Bettis and Saxton, 1973; Piercy and Embleton, 1974). The noise is usually measured with a microphone 1.2 m above the ground at a distance of 7–16 m with the propagation path over the surface on which the machine is designed to operate. If the surface is porous, for example, grass or snow, then there can be a problem of variability as a result of the incipient ground shadow described in Section 2.3.5. The solution here is a compromise between measurement configurations, a surface of predictable impedance, and relevance to the use of the machine. If the source is stationary, most of the relevant scientific knowledge (Embleton *et al*., 1976; Piercy and Embleton, 1974) is available, with the exception of good data on the impedance of relevant surfaces. A convenient method of measuring the impedance of surfaces over a range of grazing angle (ψ in Figure 2.4) and frequency is badly needed.

If the surface is hard, there are problems of repeatability for sources with large-amplitude pure-tone components when the transmission path introduces interference maxima and minima at similar frequencies. This phenomenon is reasonably well documented (Bettis and Saxton, 1973; Piercy and Embleton, 1974) (see also Section 2.3.2). Variability due to atmospheric turbulence has also been recorded (Piercy *et al*., 1976; Hemdal *et al*., 1974).

There is also an unresolved problem of variability for moving sources such as vehicles (Piercy *et al.*, 1976). There is a systematic variation in A-weighted pass-by levels with ambient temperature (Piercy *et al.*, 1976; La Breche, 1974) of −1 dB/10 °C, and a run-to-run variation of approximately 1 dB, both of which appear to be associated with the movement of the vehicle. The most obvious mechanism here is refraction by the movement of air in the wake of the moving vehicle (La Breche, 1974).

B. Aircraft

The new method for calculating atmospheric absorption (Sutherland *et al.*, 1974; Sutherland, 1975) described in Section 2.2.2 should bring the physics of the propagation from overhead aircraft under reasonable control. However, the factors which influence sideline propagation are much less well understood. A substantial amount of work has been done on the acoustic effects of the ground plane during ground tests of jet engines, for which a recent review is available (SAE, 1976).

2.6.2 Prediction of Environmental Impact

The basic physics underlying the propagation of noise at long range close to the ground described in Sections 2.2–2.5 is obviously intricate, and current knowledge of it patchy. As a result it is usually not possible in practice to predict noise levels with reasonable reliability at sites distant (hundreds or thousands of metres) from a strong source near the ground using basic knowledge alone. It is possible for a specific site, however, to take a completely empirical approach, measuring the noise from a source at positions of interest under various weather conditions, and predicting, for example, the levels to be expected at these positions from a highway or airport proposed for this site with tolerable precision (Ingerslev and Svane, 1968; Piercy and Embleton, 1974. After several of these individual investigations, it is tempting to generalize the empirical results for average levels and apply them to other sites. This procedure has been popular in recent years, through the development and use of empirical design guides for highways and airports. These prediction methods generally ignore conditions of topography and weather which are known to have a strong influence on sound propagation, as described in Sections 2.2–2.5. Such design guides may be expected to provide reasonable predictions on the average, but for a specific site their unaided use may well result in serious error. Consider, for example, the problems in the prediction of noise from airports reported by Piercy and Embleton (1974) and Dickinson (1976) and also the considerable difference between empirical rules for predicting noise levels from highways based on different (but large) sets of data reported by King and Oliver (1975, Hajek (1975), and Plotkin and

Kunicki (1976). In a field which is physically complex and only partly understood, such as outdoor sound propagation, there is still a decided need for human judgement based on specialist's knowledge of the current state of the art.

2.6.3 Recommendations

It is recommended, in the light of the analysis in the preceding section, as well as the history of research outlined in the introduction, that long-term support be developed at a modest level for the field of outdoor sound propagation. The aim should be to obtain the depth of understanding required to gradually improve the basic knowledge in this complex field. Attainment of the necessary depth of understanding is not compatible with short-term research studies.

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CHAPTER 3

Acoustic Shielding: Noise Reduction by Thin and Wide Barriers

Z. MAEKAWA

3.1 INTRODUCTION

In controlling noise in the open air, it is very common and important to build a screen or solid fence between a noise source and observers to reduce the noise received. This effect is called 'acoustic shielding'. The acoustic shielding may be achieved not only by a screen but also by many obstacles or barriers such as buildings, earth berms, or terrain that blocks the 'line of sight' from the observer to the source.

Figure 3.1 shows the pattern of a diffracted wave-front caused by a half-plane screen. In the shadow zone of the screen, a cylindrical wave is radiated from the edge of the screen according to the Huygens' Principle, though the incident wave upon the other side of the screen is blocked by the screen. The sound intensity in the shadow zone, however, is not explained by Figure 3.1.

The acoustical design of a barrier is not easy due to the difficulty in the calculation of sound diffraction around the barrier. In order to obtain the sound field, many authors have presented their own theories with various accuracy for various types of sound-wave and shapes of barriers. Theoretical work giving the foundations of this problem have been reviewed in the text by Bowman *et al*. (1969). There remains the problem of how to simplify and apply the solution to an existing barrier of complicated shape for the purpose of noise control. The rigorous exact solution is generally applicable only for a very simple and pure condition, which is not likely to exist. On the other hand, some approximations are convenient for practical calculations and are suitable for the design of a barrier for noise reduction.

In this chapter, the discussion is limited to a practical process with minimum mathematical analysis, and the results of recent research are conceptually reviewed.

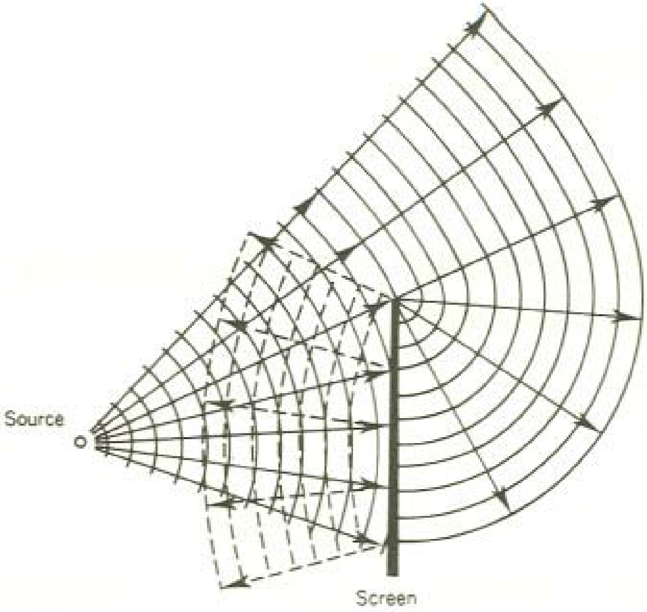

Figure 3.1 Cross-section of a half-infinite screen and wave fronts incident on the screen

3.2 SIMPLE DESIGN METHOD FOR A NOISE BARRIER

3.2.1 Half-Infinite Thin Screen for a Point Source

For the diffraction of a plane wave by a half-infinite plane in free space, the well-known rigorous solution was given by Sommerfeld (1896). Furthermore, a rigorous solution for a spherical wave in the same condition was given by Macdonald (1915). Although an example of the calculated result of the exact solution is shown later, the well known 'Kirchhoff's diffraction theory', which embodies the basic idea of the Huygens–Fresnel principle (Born and Wolf, 1959), is more suitable in the practice of noise-shielding. The formula is

$$[\mathrm{Att}]_{1/2} = -10 \log_{10} \frac{1}{2} \left[\left\{ \frac{1}{2} - \mathrm{C}(v) \right\}^2 + \left\{ \frac{1}{2} - \mathrm{S}(v) \right\}^2 \right] \mathrm{dB} \tag{1}$$

where $[\mathrm{Att}]_{1/2}$ denotes the diffraction through a half-infinite open space. $\mathrm{C}(v)$ and $\mathrm{S}(v)$ are Fesnel's Integrals for variable v, and

$$v = 2 \cdot \sqrt{\frac{\delta}{\lambda}} \tag{2}$$

where λ is the wavelength of sound, and δ is the path difference from a source S to an observer P with and without the screen, as shown at the bottom of Figure

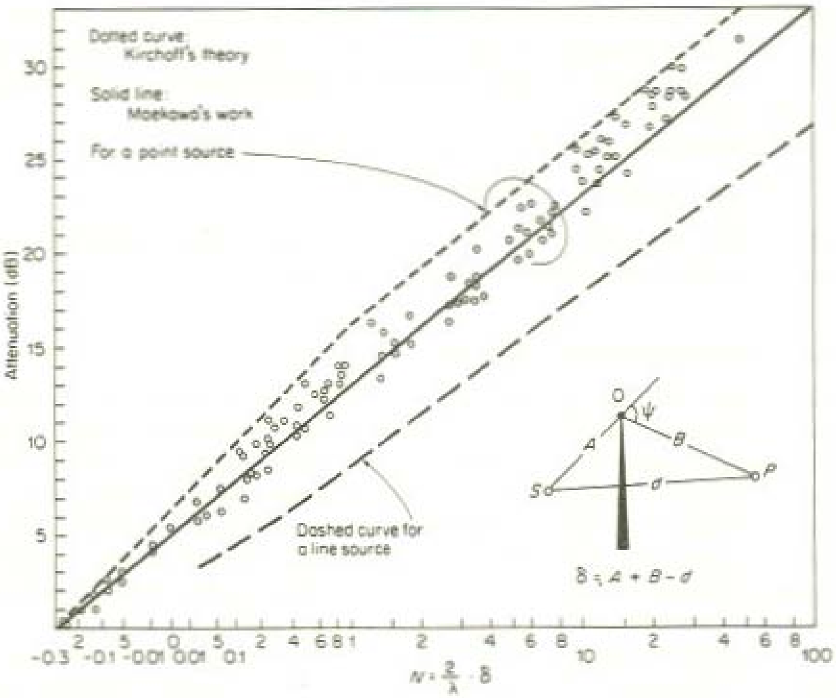

Figure 3.2 Sound attenuation by a half-infinite screen in free space: dotted line ...., theoretical values by Kirchhoff's approximation; solid line —, experimental values by Z. Maekawa; dashed line ----, measured and calculated values for an infinitely long line source parallel to the screen-edge. Attenuation is relative to propagation in free space and valid in region $\psi \leq 90°$; ψ: diffraction angle (Maekawa, 1968)

3.2. This theory was originally developed in optics, and a good approximation in optical diffraction does not guarantee the same accuracy in an acoustical problem, because in optics the wave length is very small, whereas the distances from the obstacle to the source and the observer are very long with the opposite conditions existing in acoustics. Figure 3.2 shows the discrepancy between the attenuation values measured by a model experiment (Maekawa, 1968) and the values calculated by Kirchhoff's Formulae (1) and (2) by converting the variable v to N by the relationship

$$N = \frac{v^2}{2} = \frac{2}{\lambda}\delta \qquad (3)$$

where N is the so-called 'Fresnel Number'. Depending on whether $N < 0$ or $N > 0$, the observer P lies in the bright zone or in the geometrical shadow, respectively. The scale of the abscissa in Figure 3.2 is adjusted so that the experimental curve becomes a straight line. This is done in order for it to be more convenient in using this figure as a design chart, since the experimental curve shows improved approximation of Kirchhoff's theory of diffraction in acoustical problems.

The experimental curve is also expressed by the formula

$$[\mathrm{Att}]_{1/2} \simeq 10 \log (3 + 20\mathrm{N})\ \mathrm{dB}, \qquad \mathrm{N} > 0 \tag{4}$$

in the shadow-zone of the screen (Kurze, 1974). This formula is suitable for the design of a noise-barrier with the aid of a computer.

3.2.2 Large Extended Noise Sources

It is a more difficult problem to obtain a solution of sound diffraction theoretically with a large source, because the wave-front from the large source cannot be expressed exactly. There is a conventional method, however, if the large source can be replaced by one or more point sources. When noises are emitted incoherently from virtual point sources, the sound energy received from each point source, which can be obtained as mentioned above, should be summed up at the receiving point. This conventional method has been verified by many case-studies.

For the special case of a street or a highway, noise is often treated as an incoherent line-source. The performance of a barrier against highway noise should be considered with a line-source parallel to the edge of the barrier. The results of the theoretical computations and also of the experimental studies are shown by a dashed-curve in Figure 3.2. It is more useful in practice to estimate the attenuation by a barrier for road traffic noise.

3.2.3 Finite-Size Screen

There is no such thing as an infinitely long screen but only finite-size screens of limited length. In order to obtain the sound level in the shadow-zone of such a screen, all contributions from the open surface, diffracted sound not only over the top edge but also over the side-edge of the end of the screen, must be integrated at the receiving point.

In the simplest case, if the length of a half-infinite screen is limited at one end, the open surface should be divided into two zones [A] and [B] as shown in Figure 3.3. Zone [A] is a half-infinite empty plane, and [B] is a quarter-infinite one. The contribution of zone [A], denoted by $\mathrm{L_A}$, is obtained by the method mentioned above, using the path difference $\delta_1 = (\overline{\mathrm{SO_1}} + \overline{\mathrm{O_1P}} - \overline{\mathrm{SP}})$ and the Fresnel number $N_1 = \delta_1 \cdot 2/\lambda$. The value of attenuation denoted by $[N_1]$ is given in Figure 3.2. Then $L_\mathrm{A} = -[N_1]$ dB. In order to obtain the contribution of zone [B], denoted by L_B, after calculating N_2 in the path S–$\mathrm{O_2}$–P, the value of attenuation $[N_2]$ is given

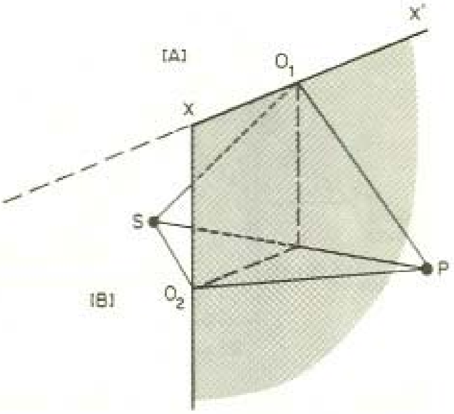

Figure 3.3 Sound diffraction at a corner of a quarter infinite thin screen

in Figure 3.2. The limiting effect caused by the edge of *xx'*, denoted by $[-N_1]$, is also given in Figure 3.2. Then $L_B = -\{[N_2] + [-N_1]\}$ dB.

The sound level at P is obtained by summing L_A and L_B.

When the screen has another end, the contribution of another open surface of a quarter-infinite empty plane should be added to the sound level at P in the same way as mentioned above.

3.2.4 Simple Estimation for a Wide Barrier

According to much experimental data, the effect of the thickness of a screen should be negligible as long as the thickness is smaller than the wavelength. However, there are many occasions when the thickness of the barrier, such as that of a building, must be considered.

The simplest way is to find the effect of thickness '*b*' of the wide barrier, $[\mathrm{ET}]_b$, which must be added to the value of attenuation by an imaginary thin, half infinite screen shown in Figure 3.4. Though the result of theoretical computation shows the resonance effect related to the thickness *b*, with reasonable approximation, the effect of thickness for a noise having a considerable bandwidth is presented by

$$_n[\mathrm{ET}]_b = K \cdot \log_{10} kb \tag{5}$$

where K is the value given by a single chart of Figure 3.5, and $k = 2\pi/\lambda$ (Fujiwara, *et al.*, 1977).

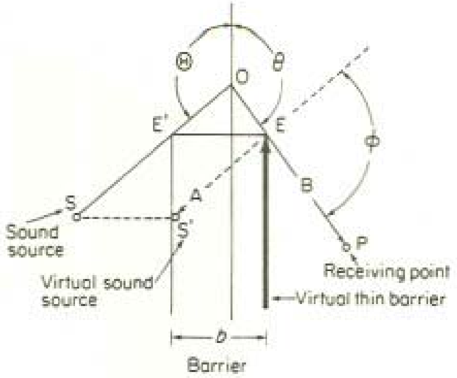

Figure 3.4 Geometry of a thick barrier and a virtual thin barrier

3.3 APPLICATION OF EXACT SOLUTIONS OF SOUND DIFFRACTION

3.3.1 Half-Infinite Thin Screen

The rigorous solution for spherical wave diffraction with a half-infinite thin screen was given by H. M. Macdonald (1915) and several other authors.

The theoretical solutions for the sound field at the receiving point P are generally expressed by Equation (6) as the sum of two terms:

$$U_{SP} = \varphi_{SP} + \varphi_{S'P} \qquad (6)$$

where the first and the second term express the diffracted sound fields from the real source S, and from the image source S′ in the screen, respectively, assuming perfect reflection at the surface of the screen.

In Figure 3.6, an example of the numerical calculation of this rigorous solution is compared with the experimental results and also with the approximate values obtained in Figure 3.2 (Kawai *et al.*, 1977). It can be seen that the exact solution can give the sound-pressure distribution not only in the shadow zone of the screen but in the bright zone of the sound source.

The calculation of the solution is very complicated, but some good approximations suitable for numerical computation are also given in the literature (Kawai *et al.*, 1977).

3.3.2 Infinite-Long Wide Barrier

When the thickness of a barrier is large, it generally has two or more straight edges, as in the case of a building or an earthen bank. Multiple-edge diffractions occur at every edge of the barrier. An exact solution of this case was given based on the single wedge diffraction solution and on concepts

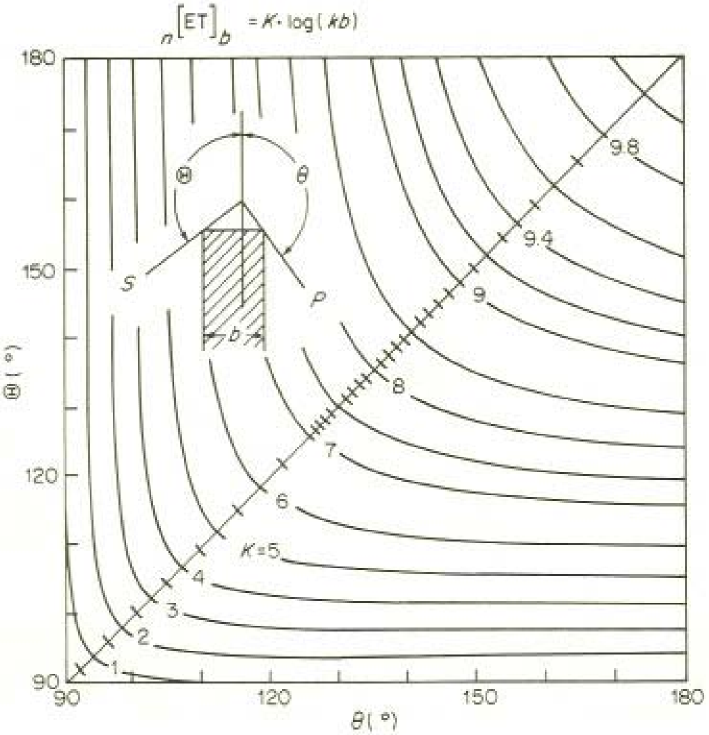

Figure 3.5 The values of K to calculate the effect of thickness $_n[\mathrm{ET}]_b = K \cdot \log(kb)$, which must be added to the attenuation by the imaginary thin screen shown in Figure 4 of a wide noise barrier (Fujiwara *et al.*, 1977)

inherent in Keller's geometrical theory of diffractions (Pierce, 1974). Though the calculation is very comprehensive, several approximations giving good results are presented for various shapes of barriers. Figure 3.7 shows an example of the calculated results compared to values measured by using an experimental model (Kawai, 1980).

3.4 EFFECT OF SURFACE ABSORPTION OF THE BARRIER

The surface condition of the barrier mentioned above is regarded as rigid and assumed perfect reflection. However, walls or screens heavily treated with absorptive materials are widely used as noise barriers.

For the effect of the surface absorption of a half infinite screen, the second term of Equation (6), which expresses the sound field by reflection from the barrier surface, must be multiplied by the reflection coefficient R, of the surface. Strictly speaking, the reflection coefficient must be the one for a

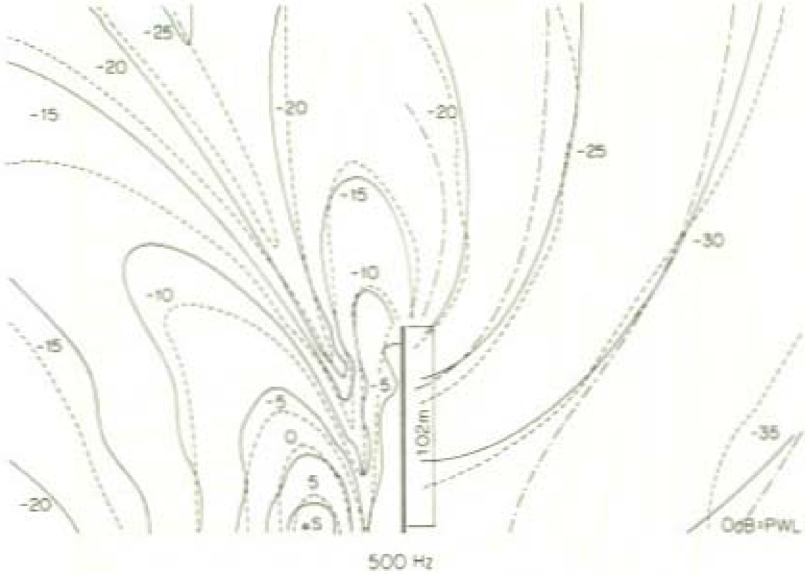

Figure 3.6 Equal sound-pressure level contours of 500 Hz around a half-infinite thin screen: solid curve —, calculated by Macdonald's exact solution; dash-dotted curve -·-·-, by Maekawa's experimental curve in Figure 3.2; dotted curve ...., measured values (Kawai *et al.*, 1977)

spherical sound wave as mentioned in the next section, but it is often approximated, by the coefficient for a plane wave as practical convenience. By means of further simplification in neglecting the imaginary part of the complex acoustic reflection coefficient of the surface, the result of the theoretical derivation is given by Figure 3.8 (Fujiwara *et al.*, 1977). From the practical point of view, we can quickly estimate the effect of the surface absorption only by adding the value of Figure 3.8 to the values of attenuation obtained by the method mentioned above.

3.5 EFFECT OF SOUND REFLECTION FROM THE GROUND

Most of the barriers are built on the ground, and we must consider the effect of sound reflection from the ground as well as the surface of the barrier. In Figure 3.9, assuming specular reflections at the surfaces of the screen and the ground, S′, T and T′ are the images of the point source S, and P′ is the image of the observer P.

3.5.1 Simple Design Method for a Barrier on the Ground

As the simplest treatment of those sound reflections, the source side images T,

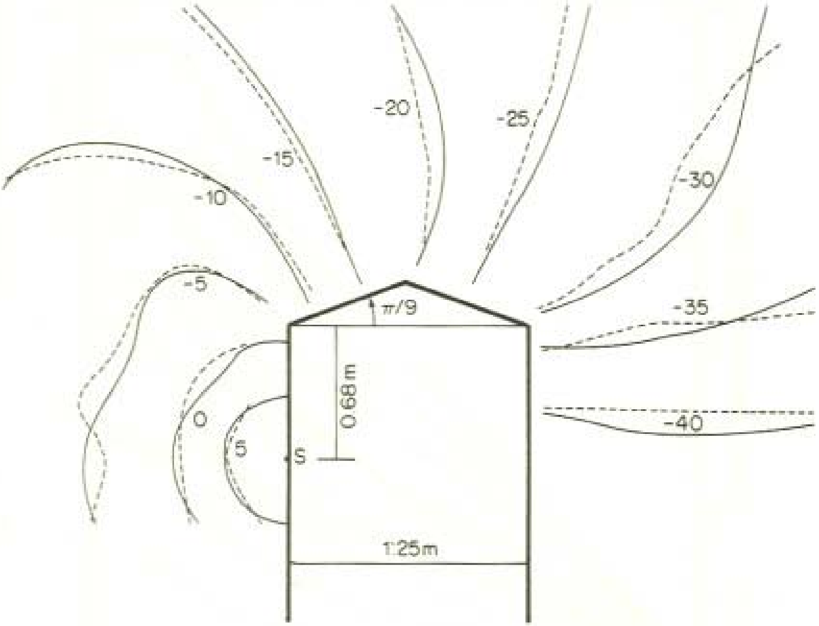

Figure 3.7 Equal sound pressure level contours of 500 Hz around a many-sided long barrier: solid curve —, calculated by Kawai's approximation; dotted curve ...., measured values (Kawai, 1974)

T′ and S′ are neglected, and instead, the sound-level at the top of the screen, including the sound reflections from those images, is selected as the reference value of the sound level in the shadow-zone of the barrier. In this way, we can ignore not only the directivity of the source but also the reflectivity of the ground. Then at the receiver's side, the ground reflection is calculated by means of the same method for the image point P′, assuming perfect specular reflection on the ground. This approximation can be useful for the practice of designing a noise screen erected on hard ground.

3.5.2 Insertion Loss of a Barrier on the Ground

Strictly speaking, the total sound field at the receiving point P consists of eight fields as follows:

$$\begin{aligned} U = {} & \phi_{SP} + \phi_{S'P} + \phi_{TP} + \phi_{T'P} \\ & + \phi_{SP'} + \phi_{S'P'} + \phi_{TP'} + \phi_{T'P'} \end{aligned} \tag{7}$$

where each term is defined similarly to Equation (6) according to their subscript. Furthermore, the sound reflectivity should be considered at the surface of the ground as well as at the screen.

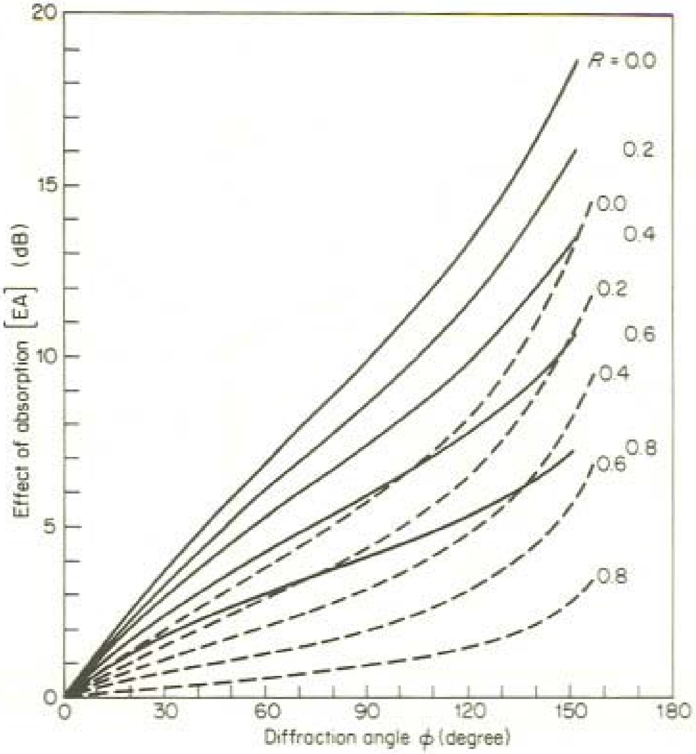

Figure 3.8 Effect of surface absorption of a barrier calculated for a thin half plane, solid curves: for a line source, dotted curves: for a point source. R: sound pressure reflection coefficient (Fujiwara *et al.*, 1977)

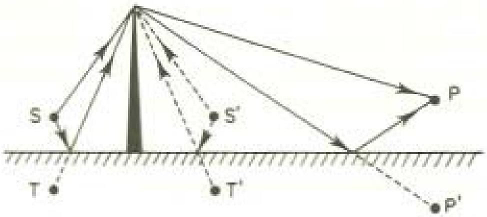

Figure 3.9 Section of a barrier on the ground showing locations of a source, image sources, a receiving point and its image

When the screen has perfect reflection, we can apply the rigorous solution of Equation (6). Then Equation (7) becomes

$$U = U_{\mathrm{SP}} + U_{\mathrm{TP}} + U_{\mathrm{SP'}} + U_{\mathrm{TP'}} \tag{8}$$

The total sound-field consists of the four fields in Equation (8). Also, the sound reflectivity of the ground must be taken into account.

The coefficient of ground reflection Q for a spherical sound wave is presented as follows:

$$Q = R + (1 - R)F \tag{9}$$

where R is the reflection coefficient for a plane wave at the ground surface, and F is a complicated mathematical function of the distance from S to P, of the grazing angle ψ and also of the surface impedance Z_2, as shown at the top of Figure 3.10.

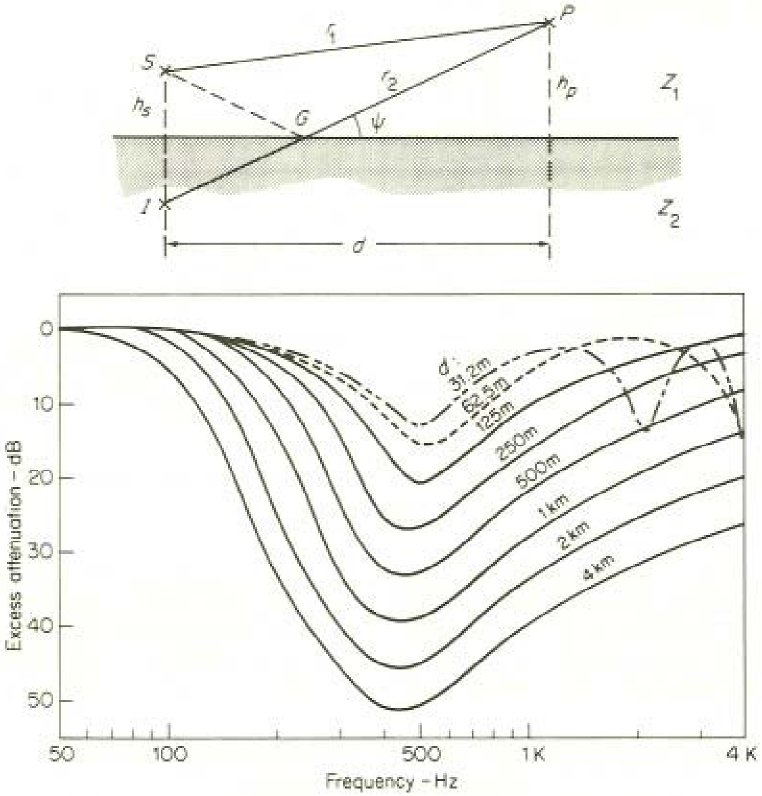

Figure 3.10 Excess attenuation calculated for propagation from a point source over mown grass for h_s = 1.8 m, h_p = 1.5 m, and the distances of propagation d indicated. The excess attenuation is relative to that for the point source placed on a perfectly hard surface, (Piercy *et al.*, 1977)

The curves in Figure 3.10 show excess attenuations calculated for propagation over mown grass in the configuration shown at the top of the figure. These results show good agreement with field measurements. It is clear that the excess attenuation grows unbelievably by distance at some frequency with no barrier.

When a screen is erected on the ground, the effect of the screen on noise reduction is defined as 'Insertion Loss', i.e., the difference in sound-pressure levels caused by the same source with and without the barrier at the observer P. It is possible for the excess attenuation caused by a barrier on the ground to be smaller than that caused only by the ground without the barrier, since it is possible for the latter to be very significant as shown in Figure 3.10. It disappears after the erection of the barrier.

Figure 13.11 shows an example of the insertion-loss of a theoretical calculation compared with the simple approximation mentioned at the beginning of this Section (Isei *et al.*, 1980).

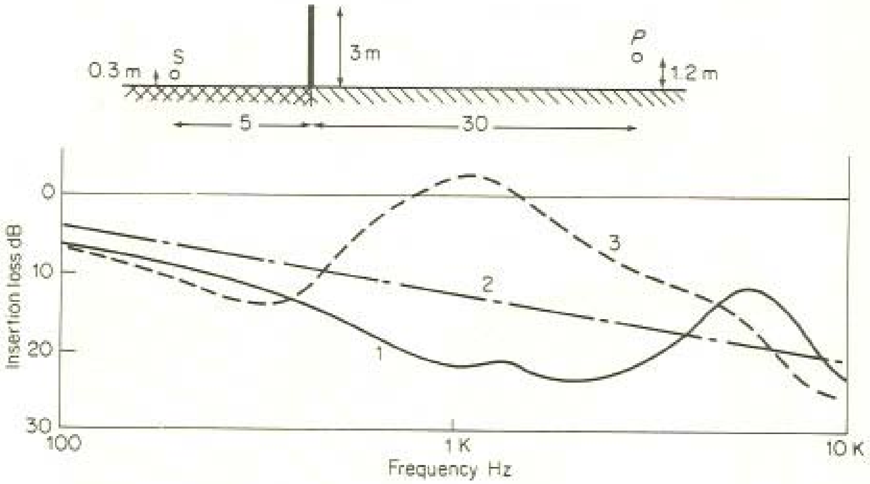

Figure 3.11 Insertion loss of a barrier on the ground for the geometrical configuration shown at the top of the figure. The line source is above a hard surface, and the ground on the receiver side of the barrier is hard for Curve 1 and 2, but soft, grass-covered, for Curve 3. Curve 2 is the prediction from Figure 3.2, though the others are calculated by exact solutions (Isei *et al.*, 1977)

3.6 CALCULATION OF SOUND FIELDS BY INTEGRAL EQUATION METHODS

The problem of determining reflected or diffracted sound-fields has often been treated by using Helmholtz–Kirchhoff's integral formula for objects of simple shapes. The mathematical solutions, however, were not suitable for practical application.

Recently, new techniques for numerical calculations of the integral equation solutions have been developed as derived from Green's formula. The numerical results are found to be in very good agreement with the measured values as shown in Figure 3.12 (Terai, 1980).

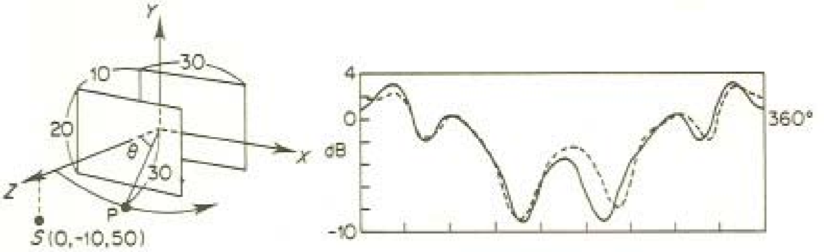

Figure 3.12 Sound field around two rigid rectangular planes: solid curve —, calculated by the integral equation method; dotted curve ..., measured values, (Terai 1980)

The advantages of this method are related to its possible application to all barriers of any complex shape, and for all rigid or absorptive materials. But, it is necessary to consider how many divisions in the given barrier-shape are suitable for calculation, and how to treat the surface absorption characteristics of the material and of the ground.

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CHAPTER 4

Psychophysics of Hearing

EBERHARD ZWICKER

4.1 INTRODUCTION

Physical sound stimuli are analysed by the auditory system and converted into auditory sensations. The total process of the reception of auditory information can be divided into two regions with fundamentally different processing: In the first, oscillations retain their original character, are preprocessed, and then delivered to the nerve endings of the sensory cells. These encode the mechanical stimuli as electrical action potentials. There, the second region begins, containing the neural processing which finally leads to auditory sensations.

In lay terms, 'ear' means in fact the outer ear. There are, however, two more parts which play an important role: the middle ear and the inner ear (Figure 4.1(a)). It is the inner ear, at which — in addition to a sharp hydromechanical frequency selectivity and a strong non-linearity — the transformation of mechanical oscillations into neural activity takes place. The further processing of information in the nervous system, which first takes place in the inner ear and becomes more and more complicated with higher neural levels, is rather complex and to a large extent still unknown.

In this situation, psychoacoustical experiments, the results of which relate physically determined sound stimuli to the corresponding auditory sensations, are very helpful. Such results are based on quantitative statements from subjects about their sensations. The most important sensations, pitch and — especially important in our case — loudness will be discussed in this chapter together with the fundamental effect of masking. Its quantitative description is the basis for some psychophysical models, for example, the model of loudness formation. Finally, a few applications of the corresponding loudness calculation procedure and the loudness meter will be discussed.

4.2 STRUCTURE OF THE EAR

The outer, middle and inner ear of man are shown schematically in Figure 4.1(a). The outer ear collects the sound and passes its energy through the outer-ear canal

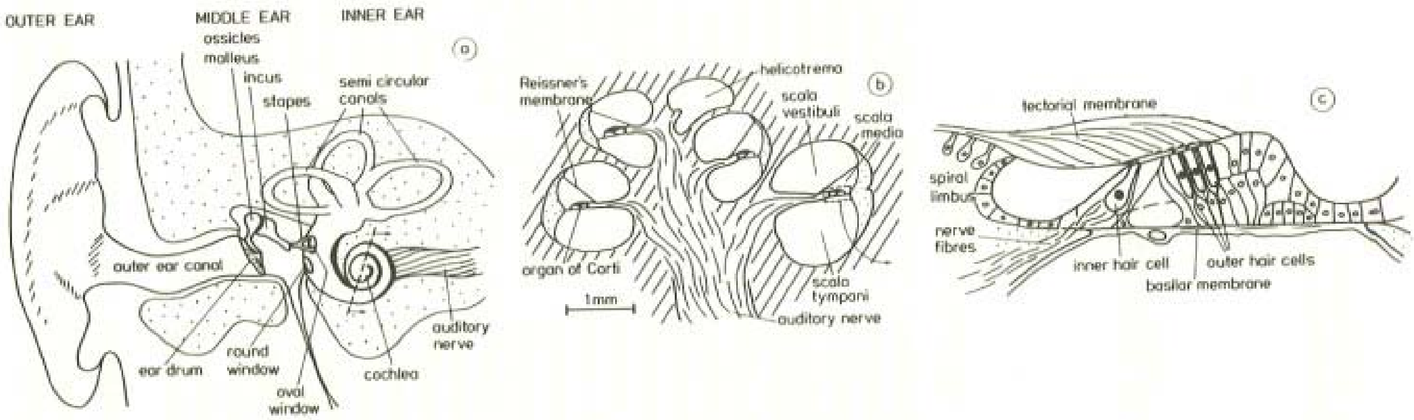

Figure 4.1(a) Schematic drawing of the outer, the middle and the inner ear; (b) Cross-section through the cochlea (schematically); (c) Enlarged schematic drawing of the organ of Corti

to the eardrum. The outer-ear canal has a length of about 2.5 cm which leads to high sensitivity but also to high damage susceptibility in the region near 4 kHz.

The middle ear transfers the oscillations of air particles (large displacement, small force) into motion of the water-like fluid of the inner ear (small displacement, large force). The transformation takes place through the lever ratio produced by the different length of the arms of the middle-ear ossicles malleus (hammer) and incus (anvil) and through the ratio of the area of the large eardrum to that of the small footplate of the stapes (stirrup). This way, an almost perfect impedance matching is produced in the middle frequency range around 1 kHz. The stapes footplate is surrounded by a ring-shaped membrane of the oval window, the entrance to the inner ear.

Two parts make up the inner ear: the vestibular apparatus with the semicircular canals and the cochlea, which is coiled like a snail shell in a flat spiral of two and a half turns (Figure 4.1(a)). The cochlea is embedded in the very hard temporal bone. The cross-section (Figure 4.1(b)) shows three canals or scalae, which run together from the base (oval window) to the apex (helicotrema). The stapes is in contact with the scala vestibuli which is separated from the scala media only by the very thin Reissner's membrane (which for hydromechanical purposes can be ignored). The basilar membrane, however, separating scala media from scala tympani, is loaded with the organ of Corti with the sensory cells (hair cells) and is hydromechanically responsible for the travelling waves. This special kind of oscillation was discovered in the cochlea by the Nobel prize-winning scientist Georg von Békésy. The travelling wave, the vertical displacement of the basilar membrane, begins with small amplitude near the oval window, grows slowly, reaches its maximum at a certain location and then rapidly dies out in the direction of the helicotrema. As the fluids in the cochlea and the surrounding bone are incompressible, the displacement of the oval window must be equalized. This occurs through the basilar membrane (or for very low-frequencies, through the helicotrema, a connection between scala vestibuli and scala tympani at the apex of the cochlea) and the round window at the tympanic side of the cochlea (see Figure 4.1(a)). The travelling waves produce a clear separation of different stimulus frequencies according to the different regions of their maximum displacement. Thus, the inner ear performs frequency separation according to the place principle: if the cochlea is thought of uncoiled and stretched out, the frequencies can be arranged according to the location of their maximal displacement between the oval window and the helicotrema as indicated in Figure 4.2.

The displacements of the basilar membrane are very small. For normal conversation (60 dB SPL), the displacement is only of the order of tenths of a nanometre, corresponding to the diameter of a hydrogen atom. There are still many open questions about this extraordinary sensitivity but the fine structure of the scala media which contains endolymph instead of perilymph seems to be responsible for it.

The organ of Corti (Figure 4.1(c)) contains, besides various supporting cells, the hair cells, which are characteristically arranged: one row of inner hair cells and three rows of outer hair cells. The tectorial membrane, which partly covers the organ of Corti, is attached to the spiral limbus at the inner side of the scala media. According to recent anatomical findings, the hairs of the outer hair cells seem to have relatively strong connections with the tectorial membrane, whereas the inner hair cells are only weakly, if at all, attached. The two kinds of hair cells show quite a different fine structure. These differences indicate that the inner and the outer hair cells have different functions, which, however, are not yet clear.

The complicated and varied innervation of inner and outer hair cells by not only afferent but also efferent nerve fibres becomes even more complicated if one tries to follow the entire flow of information from the inner ear to the brain through the approximately 30,000 afferent auditory nerve fibres. However, a tonotopic organization is found throughout, up to the auditory cortex, i.e. the nerve fibres tend to maintain their local relationship and thereby their frequency response in a systematic arrangement. It should be noted that the frequency selectivity for low-intensity levels is so perfect that only a small group of fibres is activated. For high levels, however, the fibres are less selective, i.e. a single tone activates many fibres.

At higher processing levels of the auditory system, the cells and the cell responses become more and more specialized and more and more complex. This increasing complexity can be traced to the recombination of the various separated components. In this way, the brain can analyse, for example, relatively simple details of the information, such as loudness or interaural time difference, i.e. location of sound source, while in other areas the possibly even more complex coded melody is analysed. In this area, our knowledge about information processing is still very incomplete.

4.3 PITCH AND CRITICAL BAND-RATE

The physiological fact that frequency is tonotopically transferred into specific places creates psychoacoustical counterparts: The sensation of pitch produced by pure tones and the subdivision of the frequency scale into psychoacoustically measured critical bands.

Pitch of pure tones, the so-called frequency pitch, is measured by magnitude estimation or by halving and doubling the sensation by changing the frequency of a nonsimultaneously presented comparison tone of the same loudness but different frequency. The results of such measurements have led to the discovery of a relationship between frequency of a pure tone and the pitch sensation produced by it. This relationship can be defined from an arbitrary

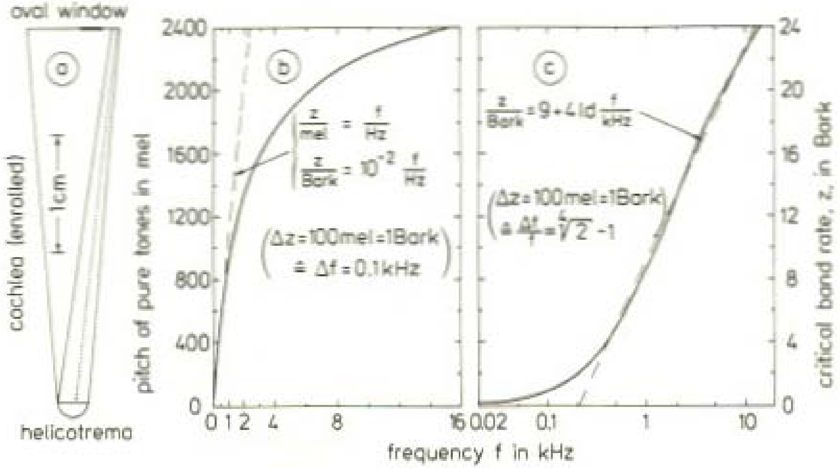

Figure 4.2 Enrolled cochlea: (a) shows a strong relationship between frequency and place of maximal displacement. Corresponding psychoacoustical relations relate the pitch of pure tones to frequency (b) and the critical band rate scale (c). Mathematical approximations are indicated

fixed point. Since this relationship shows proportionality at low frequencies, it seems to be appropriate to choose the fixed point in the low frequency range, i.e. 131 Hz corresponding to the musical note C° or 125 Hz corresponding to a standardized frequency. For frequency and pitch plotted linearly, Figure 4.2(b) shows the proportionality at low frequencies (dashed straight line), where the frequency (in Hz) is equal to the pitch (in mel). Thus pitch sensation increased linearly up to frequencies of about 500 Hz. For higher frequencies, pitch increases less quickly and, at the very high frequency of 16,000 Hz, a pitch of only 2,400 mel is reached. The behaviour at frequencies above 500 Hz becomes clear if frequency is plotted on a logarithmic scale and pitch on a linear scale as in Figure 4.2(c): pitch increases with the logarithm of frequency (dashed straight line).

As described above, a single tone stimulates a certain area in the inner ear along the basilar membrane. Another tone with somewhat higher frequency stimulates an area nearer the oval window. The critical bands are the idealized counterparts of these areas along the frequency scale and may be understood as bandfilters with infinitely steep slopes and a bandwidth CB which depends on frequency. Keeping in mind that such a rectangular filter is only a very first approximation (see also Section 4.4.1), the critical band concept is nevertheless very useful in many cases. There exists quite a number of psychoacoustical experiments which have been used to estimate the width of the critical band, most of which lead to similar values, at least for low and medium levels. For higher levels, the approximation may be too simple.

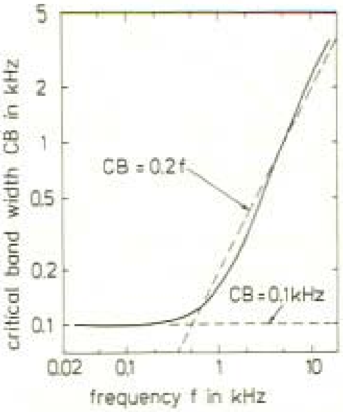

Figure 4.3 Critical bandwidth as a function of frequency. Mathematical approximations are indicated

The critical bandwidth, CB, is plotted in Figure 4.3 as a function of the frequency. It is nearly constant and equal to 100 Hz for low frequencies up to 500 Hz. For frequencies above 500 Hz, the critical bandwidth is nearly proportional to the frequency. The two approximations given as dashed straight lines in Figure 4.3 describe these dependencies in the respective regions.

When adjacent critical bands are ordered so that the upper limit of one is the lower limit of the next, and when each critical band is assumed to have a certain constant psychoacoustical value, viz. 1 Bark, the unit of the critical band-rate, a psychoacoustical scale can be calculated. Such a scale corresponds very closely to the pitch scale, only the units are different: 1 mel for frequency pitch and 1 Bark for critical band-rate. Since the critical band has a width CB = 100 Hz at low frequencies, where f and z have the same number, it follows that 1 Bark = 100 mel. Using this relation an additional ordinate scale is given for Figure 4.2(b) and 4.2(c) on the right-hand side. This scale, the critical band-rate scale, is very useful because it relates the physical frequency scale to the corresponding psychophysical scale which is closely related to the distance along the basilar membrane (Figure 4.2(a)). Since one critical band may be understood as the distance over which the ear is able to integrate intensity, the unit of 1 Bark seems to be more natural than that of 1 mel when the effects of masking or loudness are to be discussed.

4.4 MASKING AND EXCITATION

That sound pressure level, L_T, of a sinusoidal test tone which in silence is necessary to reach audibility is called the threshold in quiet. Plotted as a function of frequency, this threshold marks the boundary between the area of audible tones and that of inaudible tones and therefore is the boundary of masking as well. The dashed lines in Figure 4.4 indicate the threshold in quiet: It slowly decreases as frequency increases, shows a minimum near 3 kHz and rises very steeply with high frequencies.

4.4.1 Steady State

If an audible sound — for example, a noise called the masker — is added continuously, the threshold in quiet is raised to a higher value, the masked threshold, especially in that frequency range in which the masker contains most of its spectral intensity. Using White Noise, a special noise with frequency independent intensity density with no pitch and no rhythm, the masked threshold is elevated more and more as the level of the masker increases (Figure 4.4(a)). The masked threshold is flat at low frequencies, rises with higher frequencies, and increases by the same number of decibels with which the level L_{WN} of the white noise masker is raised. The increment of the white-noise masked threshold towards high frequencies amounts to 10 dB per decade. Thus, the frequency selectivity of our hearing system, i.e. the critical bandwidth, increases proportionally with frequency in that region.

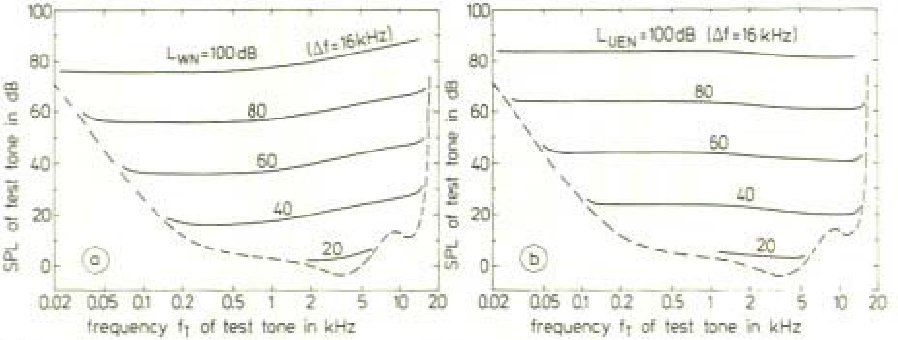

Figure 4.4 Threshold of tones in quiet (dashed) and threshold of tones masked by White Noise (a) and by Uniform Exciting Noise (b). Parameter is the total sound pressure level (bandwidth 16 kHz) of the masker noises

Another often-used broadband noise is the Uniform Exciting Noise. This is a noise which contains the same sound intensity in each critical band. Such a noise produces almost flat masking thresholds as indicated in Figure 4.4(b).

Broadband maskers elevate the threshold in quiet over almost the total audible frequency range. Narrowband maskers, for example noises of one critical bandwidth or tones, shift the threshold in quiet towards higher levels only near and above the centre frequency of the masker. Figure 4.5(a) shows masked thresholds produced by critical band noises at 0.15, 1, and 7 kHz with

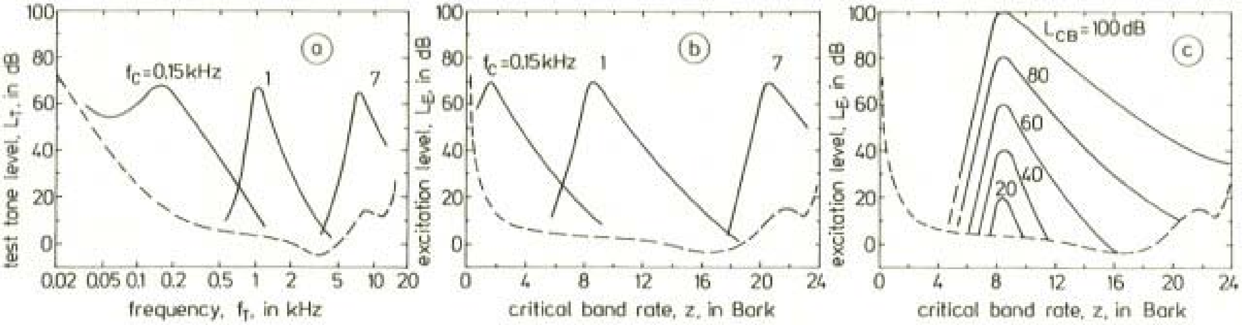

Figure 4.5(a) Threshold of tones in quiet (dashed) and threshold of tones masked by critical-bandwidth maskers at centre frequencies of 0.15, 1 and 7 kHz and SPL's of 70 dB; (b) Excitation level—critical-band rate patterns produced by the same narrow band maskers used in (a); (c) Same patterns as in (b) but for maskers at 1 kHz with different levels

masker level L_M = 70 dB. The shape of the masked threshold for 1- and 7-kHz noises looks very similar, that at 0.15 kHz, however, is broadened. Whether this is a consequence of the frequency dependend selectivity (critical bandwidth) of the ear has to be determined.

Excitation-level critical band-rate patterns are produced from masked threshold-frequency patterns as follows: (a) the frequency scale of the test-tone is transferred into the corresponding critical band-rate scale; (b) the whole masking pattern is shifted a few dB upward until the critical band level is reached for frequencies where it is defined physically, i.e., 70 dB at their peaks in Figure 4.5(a). Such a transformation is drawn in Figure 4.5(b). Now, all three patterns, including the one for 0.15 kHz look very similar indicating almost constant selectivity as a function of the critical band-rate, i.e. along the basilar membrane.

Masked thresholds produced by narrow-band noises of different levels show an unusual but interesting and important effect: strong nonlinearity. Figure 4.5(c) shows the excitation level—critical band-rate pattern produced by 1 kHz critical-band wide maskers at five different levels. The maximal values and those produced at lower critical band-rates change corresponding to the masker level increment. The upper slope, however, flattens drastically with increasing masker level, an indication that a strong non-linearity is present. Single tones and complex tones used as maskers produce similar effects.

4.4.2 Temporal Effects

Masking effects described above are those of simultaneous masking, i.e. masker and test-tone are presented at the same time. Further, the test sound is a tone burst longer than 200 ms. If the duration T_T of the test tone-burst is decreased below 200 ms, the test tone's intensity I_T must be increased so that $I_T \cdot T_T$ remains constant. This is one temporal effect which, however, can be allowed for (if constructing the excitation critical band-rate pattern of narrow-band noise) by appropriate upward adjustment of the level in dB.

A much more important temporal effect arises from post-masking (also called forward masking): a masker burst influences the audibility of a very short test-tone burst which is presented a time t_v after the masker's end (see Figure 4.6).Similarly, pre-masking (also called backward masking) is created when the test-tone burst is presented a time Δt before the masker's onset. The two effects act asymmetrically: While post-masking can be measured up to delay times, t_v, of as much as 200 ms, pre-masking is rarely effective if the masker is delayed by more than 20 ms. Therefore, the latter is often ignored in the first approximation. Simultaneous masking is assumed to be independent of time, at least for masker and test sound burst having the same spectral characteristic — for example, when both are cut out from white noise.

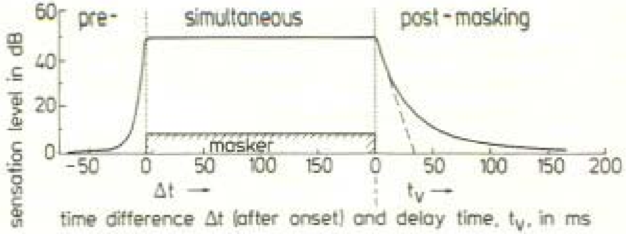

Figure 4.6 Schematic drawing of the temporal effects in masking: pre-, simultaneous and post-masking (also called backward, simultaneous and forward masking)

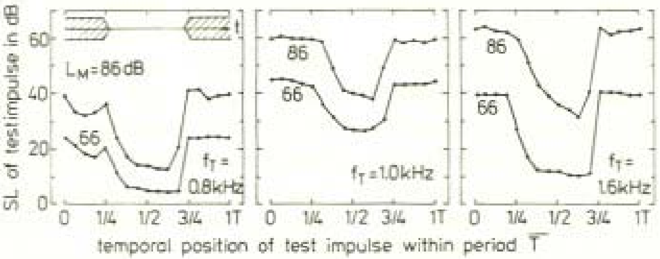

Figure 4.7 Masking-period patterns i.e. sensation level, SL, of a just audible short tone burst (frequency, f_T, is indicated in the three parts) as a function of its temporal position within the masker period, T. Masker is a 1-kHz tone rectangularly amplitude modulated with a repetition-rate of 10 Hz corresponding to T = 100 ms. Parameter is the level, L_M, of the masker

Generally, the masker shows temporal as well as spectral structure. A simple example is a 1-kHz tone rectangularly amplitude modulated with a modulation frequency of 10 Hz. In this case, pre-masking, simultaneous masking and post-masking are of interest not only at a test frequency of 1 kHz but also on the lower and upper slopes, i.e. 0.8 kHz and 1.6 kHz, respectively. The masked threshold re threshold 'in quiet', i.e. the sensation level SL, is plotted for two different masker levels L_M as a function of the time within the period T of the masker (Figure 4.7).The threshold 'in quiet' (SL = 0 dB) is never reached, i.e. excitation does not drop to zero. For test frequencies above the masker frequency, however, the excitation seems to drop more quickly and more deeply. The slope of the decay (postmasking) reaches values as large as 2 dB per ms. The slope of the rise, on the other hand, (premasking) is about three times as large, i.e. some 6 dB per ms.

For a complex sound as, for example, the spoken word 'electroacoustics', the third dimension, the time t, becomes important. Its masked threshold pattern as a function of frequency and time looks very complicated and so does the

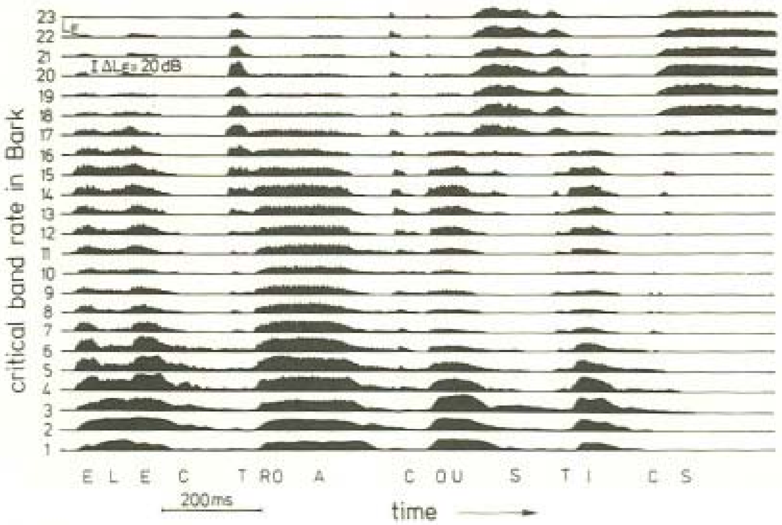

Figure 4.8 Schematic excitation level-critical band rate-time pattern of the spoken word 'electroacoustics' with about 70 dB sound pressure level. The bars indicate an excitation level difference of 20 dB and a duration of 200 ms. Parameter is the frequency expressed in critical band rate from 1 Bark to 23 Bark

schematic excitation level pattern as a function of critical band rate and time depicted in Figure 4.8. The excitation level, L_E, is plotted for the critical band-rates 1 Bark to 23 Bark as a function of time. The temporal structure within vowels is still visible, especially at larger critical band-rates (higher frequencies). The temporal pattern of the sequence of vowels and consonants together with its spread along the basilar membrane, i.e. its spectral distribution, contain the important information.

Before the transformation of the excitation patterns into the corresponding loudness patterns is discussed, some basic facts about loudness must be sketched.

4.5 FUNDAMENTAL LOUDNESS PHENOMENA

The most well-known effect regarding loudness is the relation between the SPL of a 1-kHz tone in free-field condition and its loudness sensation produced in man. This so-called loudness function is displayed in Figure 4.9(a) with the reference point 40 dB $\hat{=}$ 1 sone. The dashed straight line represents the approximation used for levels greater than 40 dB. Besides the formulae indicated, this approximation is also often expressed as: loudness grows by a factor of two if the level of the 1-kHz tone (or loudness level) rises by 10 dB.

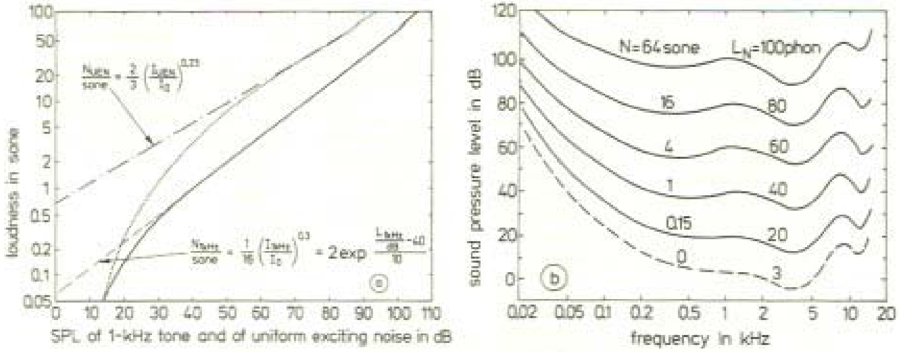

Figure 4.9(a) The loudness function, i.e. the relation between SPL of a 1–kHz tone and the loudness it produces (solid line). The loudness of uniform exciting noise is indicated as a dotted line. Approximations for larger SPL's are indicated; (b) Equal loudness contours, i.e. connection of equally loud points in the SPL-frequency plane for tones, with loudness (in sones) or loudness level (in phons) as parameter

Threshold 'in quiet' of a pure tone depends on its frequency, as does loudness. Figure 4.9(b) shows the so-called equal loudness contours. These curves connect points of equal loudness in the SPL-frequency plane of pure tones. The curves show the loudness level in phons, i.e. the SPL of the equally loud 1-kHz tone, and the corresponding loudness in sones. The equal loudness contours become flatter with increasing values of the parameter L_N, especially at low frequencies. This indicates that the frequency dependence of the threshold 'in quiet', i.e. the 3-phon or 0-sone curve, is based on the increasing body-noise at low frequencies and on the frequency dependent transmission attenuation a_0 (see Figure 4.14) at high frequencies.

Besides the two well-known facts outlined in Figure 4.9, other important results have been found. Loudness increases strongly with increasing bandwidth of noises or with increasing number of tones in the corresponding frequency range, even if the total SPL is kept constant. Figure 4.10(a) shows this effect for noise bands with the geometric centre frequency of 2 kHz and SPL of 47 dB (corresponding to 2 sones): up to a bandwidth of about 300 Hz (the critical bandwidth at 2 kHz) the loudness remains constant but increases by more than a factor of three for wider bandwidths. This effect is smaller at low and high levels, as can also be seen from the difference of the loudness of uniform exciting noise and that of the 1-kHz tone as drawn in Figure 4.9(a).

Loudness also depends on the duration of a sound. For an SPL of 57 dB, out of which the 2-kHz tone-burst of different duration is cut, loudness decreases with decreasing duration from 4 sones at 500 ms to about 1.5 sones at 5 ms. As an approximation, for durations smaller than 100 ms, this behaviour can be expressed as a decrement of 10 phons in loudness level for each tenfold reduction in duration.

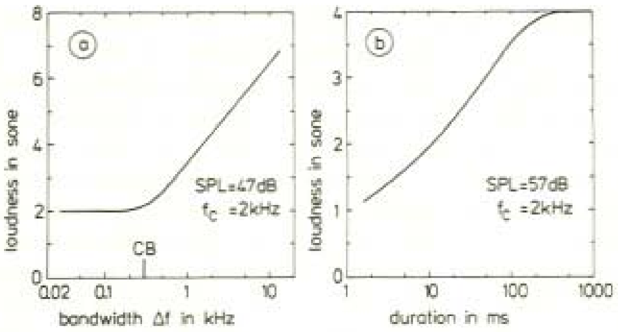

Figure 4.10 Dependence of loudness (ordinate) on the important variables, bandwidth (a) and duration (b). SPL and centre-frequency as indicated

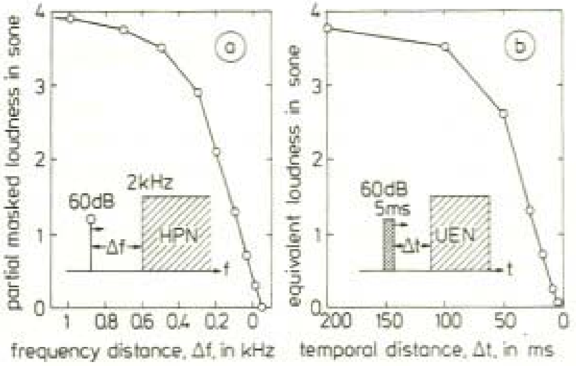

Figure 4.11(a) Spectral partial masking i.e. reduction of the loudness of a pure tone when shifted towards a high pass noise as a function of the difference between tone frequency and cut-off frequency of the noise; (b) Temporal partial masking, i.e. reduction of loudness of a tone burst when shifted temporally towards a uniform exciting noise as a function of the time difference between the end of the burst and onset of the noise

Corresponding behaviour to the two most prominent masking effects, simultaneous spectral (upper slope) masking and non-simultaneous temporal (post-)masking is found in loudness measurements. It is called spectral partial masking and temporal partial masking. Figure 4.11 demonstrates these two effects and also illustrates — see the inserts — the spectral and the temporal conditions. Figure 4.11(a) shows that the loudness of a 60-dB pure tone decreases as the tone is shifted spectrally towards the slope of a high pass noise with a cut-off frequency of 2 kHz. This effect clearly indicates that the loudness of the tone is not only created at that location along the basilar membrane which corresponds to the frequency of the tone, but that its loudness is an integral over a distribution of loudness density along the basilar membrane. From this point of view the loudness function of a uniformly exciting sound — e.g. the uniform exciting noise — may be a more fundamental relationship than that of the 1-kHz tone. The loudness function of that noise is drawn in Figure 4.9(a). For higher levels of the noise, the threshold 'in quiet' is exceeded in the whole audible frequency range and the excitation is spread uniformly. Interestingly enough, the approximation of that loudness function at high levels leads to an exponent of 0.23 instead of 0.3 as for the 1-kHz tone.

Figure 4.11(b) shows the other basically important effect, temporal partial masking: the closer a short 2-kHz tone-burst is shifted temporally towards the beginning of a uniform exciting noise-burst the more is the loudness of the tone-burst reduced. This indicates that the sensation of loudness is built up not immediately but needs time to do so.

4.6 EXCITATION PATTERN AND LOUDNESS PATTERN

The excitation pattern, i.e. excitation level L_E, as a function of the critical band-rate z, is very closely related to the masking pattern, and can be derived from it. However, it can also be constructed by using the sound pressure level existing in the critical-bands for the main or peak values. The slopes on either side of the main values are either defined by the neighbouring main values or by the slopes of the masking patterns. As seen in Figure 4.5(c), these slopes depend on level but not on frequency if plotted as a function of critical band-rate. Although excitation patterns are very informative, they can not be used directly to interpret the formation of loudness, because the level value does not represent loudness sensation and can not be integrated.

Specific loudness, i.e. kind of loudness density, is the value which is needed. From Figure 4.9(a), we can derive an exponent of the loudness function of a uniform exciting noise (no slopes of excitation) for larger levels of about 0.23. Although there are other methods for developing the relation between specific loudness and excitation, this is didactically the simplest way: A noise of 24 critical bandwidths with a total level of — for example — 64 dB SPL produces a total loudness of 21 sones. The excitation level within each of the 24 critical bands is $(64 - 10 \lg 24)$ dB ≈ 50 dB and that part of the total excitation produces a specific loudness (loudness within 1 Bark which is the total loudness divided by 24 Bark, i.e. nearly 1 sone/Bark. With the exponent of 0.23, the relationship between specific loudness and excitation is defined except for very low values, where — per definition — the specific loudness must be zero for the excitation at the threshold 'of hearing'. Therefore specific loudness N', as a function of the excitation level, L_E, deviates at low levels towards lower values. Figure 4.12 shows that relation with the sound pressure level L_{TH} at threshold

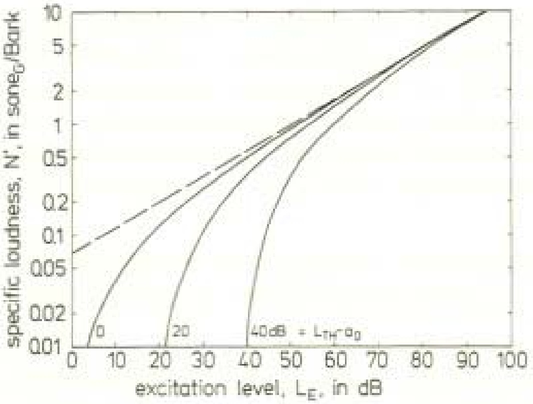

Figure 4.12 Specific loudness, N', a kind of loudness density, as a function of excitation level, L_E, with the parameter theshold level, L_{TH} (the transmission attenuation a_0 is incorporated). The dashed line is the asymptote with an exponent of 0.23

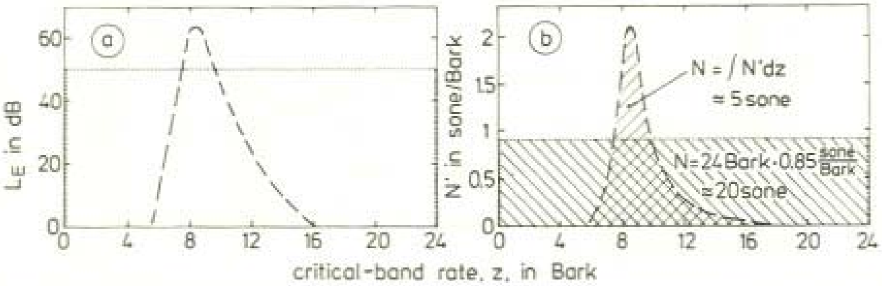

Figure 4.13 (a) Excitation-level critical band-rate patterns of uniform exciting noise (dotted) and of critical band wide noise at 1 kHz (dashed), each with 64 dB SPL; (b) Specific-loudness critical band-rate patterns of the same two noises. Total loudness is also indicated

in quiet as parameter. The transmission attenuation, a_0, is taken into account in this figure so that the figure can be simplified.

The excitation and loudness patterns are plotted in Figure 4.13(a) and Figure 4.13(b), respectively, for a 64-dB uniform exciting noise (dotted) as well as for a 64-dB critical-band wide noise centred at 1 kHz (dashed). The latter has the same loudness as a 64 dB-1 kHz tone. The transformation of sound intensity into excitation is thereby assumed to be frequency independent for didactical reasons. Threshold 'in quiet' is also assumed to be constant. As described above, the excitation level of the 64-dB uniform exciting noise is 50 dB, independent of critical band rate z. That of the 64-dB narrow-band noise, however, depends strongly on z (Figure 4.13(a)). Specific loudness N' (Figure

4.13(b)) shows a corresponding shape. The area under the curves, however, can be integrated to obtain the total loudness N, as indicated. Although both sounds have the same SPL of 64 dB, uniform exciting noise shows — calculated theoretically as well as measured psychoacoustically — about four times the loudness of critical band-wide noise. The transformation of the data of Figure 4.13(a) into those of Figure 4.13(b) clarifies why that is the case.

4.7 LOUDNESS CALCULATION PROCEDURE BASED ON PSYCHOACOUSTICAL EXCITATION

It is only a rough approximation to assume a frequency independent transmission factor from free-field sound intensity to excitation as the size of the head, the mass-loaded middle-ear ossicles, and the resonance of the outer-ear canal are neglected. These effects have to be taken into account for precise calculations using the frequency dependent transmission attenuation, a_0, which is shown in Figure 4.14 for free-field (dashed) and diffuse-field conditions (dotted).

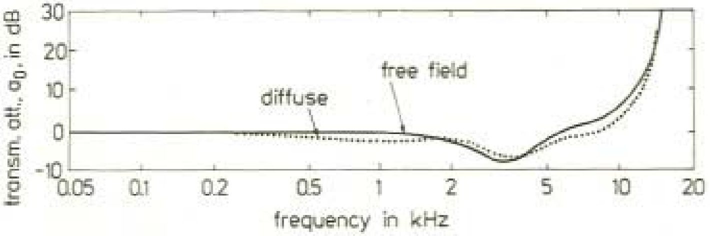

Figure 4.14 Transmission attenuation for free and diffuse fields as a function of frequency

Loudness calculation uses three psychoacoustically confirmed steps: first, sound intensity is spectrally divided into critical-band intensities. Since this separation is not ideal, then secondly, the high-frequency slope has to be taken into account. Thirdly, total loudness is formed by adding up the specific loudness along the critical-band rate. Using these rules, three methods of calculating or measuring loudness have been developed: the first uses a graphical procedure and third-octave band levels as approximation of critical-band levels to calculate the loudness of steady sounds. The second reproduces in an electronic set-up the spectral and temporal effects obtained from psychoacoustics. This way, a very precise loudness meter is created. The third uses approximations of the measured facts to simplify the apparatus into a handy, small, but still precise loudness meter.

The graphical method uses ten different graphs for five different level ranges and two kinds of sound field (free and diffuse). The procedure is standardized. Figure 4.15 illustrates the examples used above, the critical-bandwidth noise or

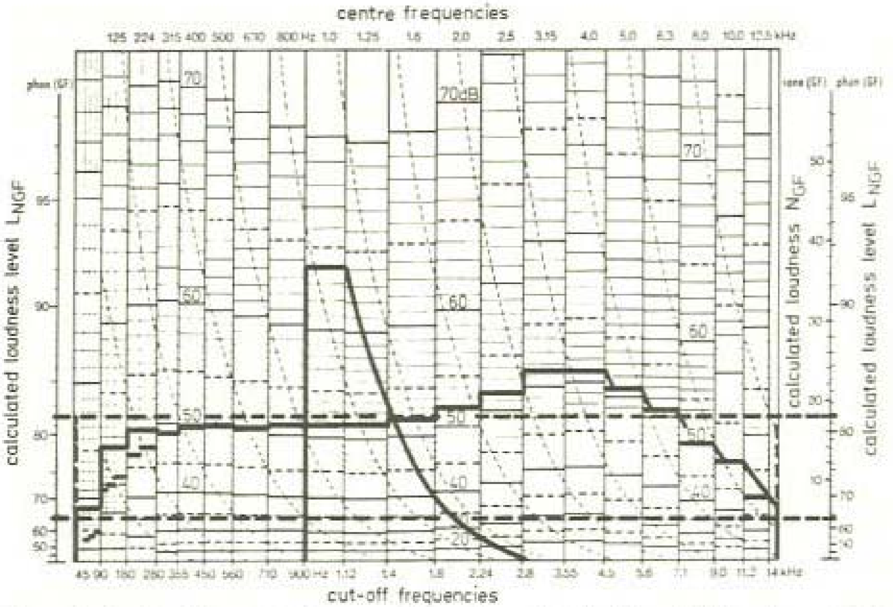

Figure 4.15 Loudness of uniform exciting noise and critical bandwidth noise at 1 kHz (both with 64 dB SPL) calculated for free-field condition using the graphical procedure according to ISO 532B

the tone at 1 kHz with 64 dB SPL and the uniform exciting noise with the same SPL. All the thin lines (solid, dashed and dotted) belong to the original graph sheets. The measured third-octave band levels are displayed as thick horizontal bars between the corresponding cut-off frequencies of the third-octave band in question using the ladders, the steps of which are marked in dB third-octave band level. (Note: third-octave bands — and so the levels — are usually larger than critical bands.) At the left-hand of each horizontal thick bar, a vertical line connects a given third-octave band level with its left-hand neighbour or the abscissa. This approximates the steep low-frequency slope of specific loudness (shown in Figure 4.13(b)) by a vertical line. At each right-hand end of a thick bar, a curve parallel to the thin dashed curves of the graph must be drawn to the abscissa or the first right-hand neighbour whose level exceeds the curve. The decaying curve approximates the flatter upper slope of Figure 4.13(b). Thus, an area is produced which is limited by the abscissa, by the left or right end of the graph and by the upper thick bars or lines (see Figure 4.15). The two areas correspond very well to the loudness of the 1-kHz tone and the uniform exciting noise. Specific loudness of the latter is not flat as in Figure 4.13 (b) because of the influence of the three frequency dependent values: threshold 'in quiet', transmission attenuation, and bandwidth ratio of the third octave band to the critical-band. In order to calculate the areas most easily, each is transformed into a rectangular area by means of a line parallel to the abscissa from the left to the right end of the graph. The height of this line is chosen accurately enough by eye so that the area under the curve and the rectangular area are equal in size (thick dashed lines in Figure 4.15). Outside the graph, scales are drawn with scales of loudness as well as loudness level. The height of the rectangle is a measure for the size of the areas and thereby a measure for the total loudness of the two sounds. The 1-kHz tone produces, according to the calculation demonstrated, a loudness $N_{GF} = 5.3$ sones (GF) corresponding to a loudness level $L_{NG} = 64$ phons (GF). The uniform exciting noise, however, produces 18 sones (GF) corresponding to 82 phons (GF) and thereby is about 3.5 times as loud as the tone in accordance with the psychoacoustical data mentioned above. The indices added to the symbols and units stand for the critical-band (Frequenzgruppen in German) and, in our case, free-field condition (as opposed to diffuse-field which reads GD).

An electronic set-up, reproducing this graphical procedure is a loudness meter which can be used not only to measure loudness of steady sound but also the loudness of temporally variable sounds as a function of time. In this case, electronic models of the psychoacoustically measured temporal effects for masking and loudness sensation have to be installed: short rise time of the specific loudness, longer time constant and delay for that channel which—after summation — forms the total loudness. As an example, the word 'electroacoustics' used in Figure 4.8 is displayed in Figure 4.16 for 22 channels of the specific loudness, the summated specific loudnesses, and finally (on top) the total loudness; all as a function of time. In many cases only the upper curve, i.e. the loudness-time function is of interest as it contains the information necessary to determine the loudness.

4.8 APPLICATIONS

Only three out of the many applications, one of the loudness calculation procedure and two of the loudness meter, will be described. Both procedures have the important advantage that partial areas correspond to parts of the loudness. Therefore, not only the total loudness can be calculated or measured but also those spectral components of the sound or the noise which are responsible for the largest part of the loudness stand out very clearly. The spectral parts which are masked by others, on the other hand, are cancelled out completely because they lie below the upper border of the area corresponding to loudness and therefore can be ignored.

Figure 4.17 explains why a motorcycle (A) with an A-weighted SPL of 84 dB(A) does not necessarily sound less loud than a motorcycle B with 87 dB(A). While type B produces the most prominent part of its loudness near 630 Hz, the other parts do not contribute much to the total loudness. For type A, however, the specific loudness is distributed almost uniformly, thus producing a large

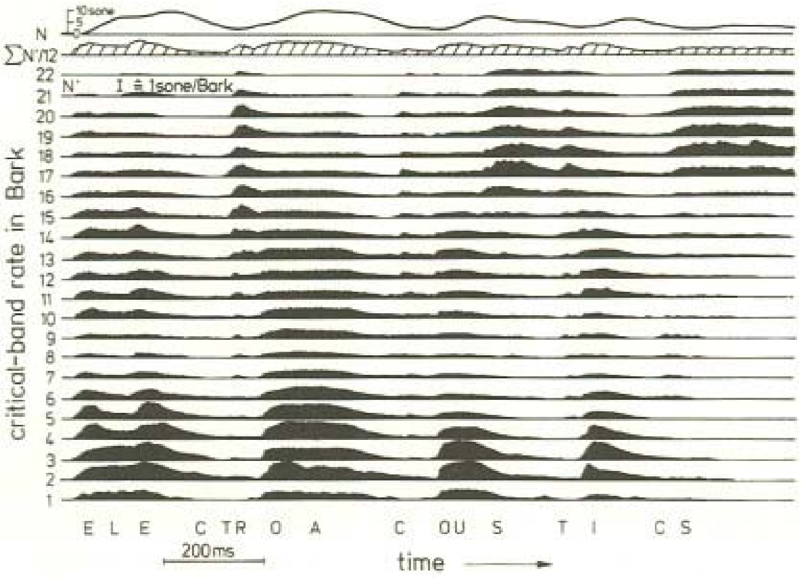

Figure 4.16 Specific-loudness critical band-rate time pattern of the spoken word 'electroacoustics' of Figure 4.8. Parameter is the critical band-rate from 1 Bark to 22 Bark. The shaded curve on the second pattern from the top shows the sum of all specific loudnesses divided by 12. The top curve displays the total loudness as a function of time

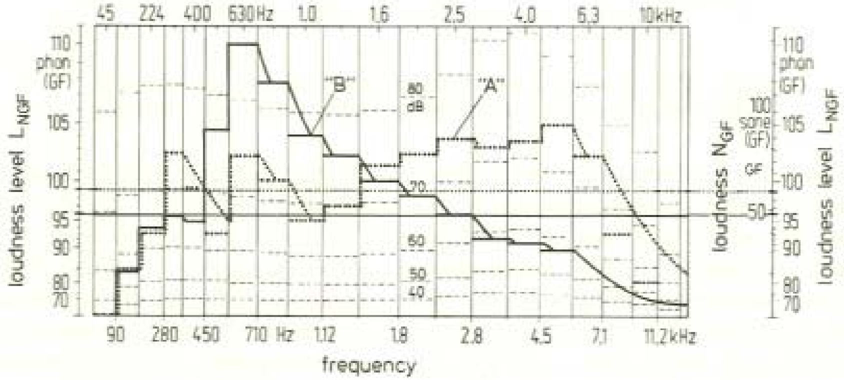

Figure 4.17 Loudness patterns of two motorcycles: Type B (solid) with an A-weighted SPL of 87 dB(A) but a loudness of only 47 sone(GF) and type A (dotted) with only 84 dB(A) but 59 sone(GF)

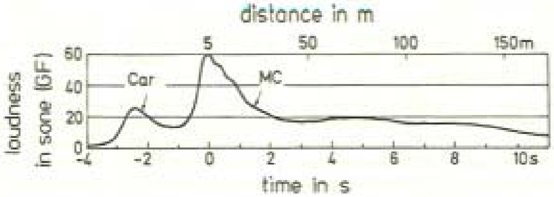

Figure 4.18 Loudness-time function registered on a road. The motorcycle (MC) of type A (see Figure 4.17) follows a car at a distance of about 40 m. The distance, *d*, between meter and motorcycle is also indicated (minimal perpendicular distance is 5 m)

area (especially at higher frequencies) and thereby a large loudness of 59 sones (GF), corresponding to a loudness level of 99 phons (GF). Type B, on the other hand, produces 47 sone(GF), corresponding to 96 phons (GF), although its A-weighted SPL of 87 dB(A) is actually 3 dB(A) greater than that of type A.

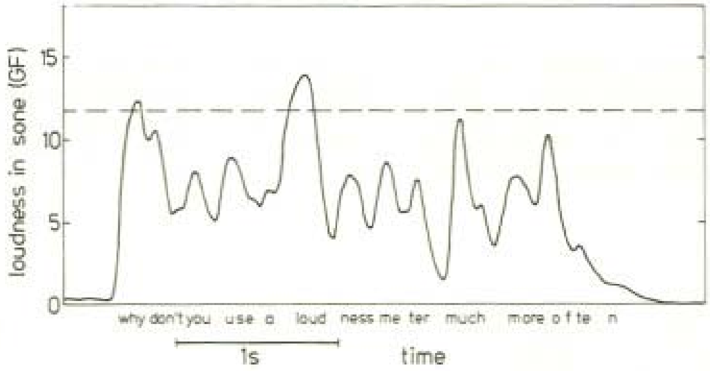

Figure 4.19 Loudness-time function of running speech and loudness of an equally loud speech-simulating steady noise (dashed)

Using the loudness meter the loudness of the type-A motorcycle following a car on the road was measured as a function of time corresponding to the distance from the meter. The loudness-time function produced by the two vehicles is plotted in Figure 4.18 and shows the loudness peak of the car two seconds in front of the loudness peak of the motorcyle, which reaches a loudness more than twice that of the car. It also shows very clearly the long 'tail' of loudness produced by the motorcyle which remains for a long time near the peak loudness of the car: the loudness of the car is very much surpassed by that of the motorcycle.

The loudness of running speech is important in acoustic communication, for example, in telephone networks and broadcasting. Figure 4.19 shows the loudness of running speech as well as the loudness of an equally loud steady noise (psychoacoustically measured) with a frequency characteristic corresponding to the long time spectral distribution of speech. The comparison indicates that the loudness of speech is created by the loudest vowels as, for example, occurs in 'loud'. Using these peaks in the loudness-time function of running speech as a measure, the loudness of speech can be easily determined.

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CHAPTER 5

Aural Reception

E. A. G. SHAW

5.1 INTRODUCTION

Noise pollution is primarily a macroscopic phenomenon: a blanket of noise spread by many motor vehicles moving through a network of city streets, or many machine tools enclosed in a cavernous workshop. And it is primarily the macroscopic characteristics of noise that capture the attention of those who seek to bring it under quantitative control. With this broad perspective, noise environments are commonly characterized in terms of comprehensive parameters such as the A-weighted average sound level and measured over representative periods of time such as the working day. This chapter is concerned with those aspects of aural reception that provide the scientific link between the noise environment defined in these broad terms and the human acoustical receiver with its unique characteristics.

5.2 THE DIRECTIONALITY OF THE HUMAN HEARING SYSTEM

A-weighting is widely used in noise measurements and is a mandatory feature of sound level meters. This particular frequency response is somewhat similar to that of the human hearing system in that it de-emphasizes low-frequency sounds and provides maximum sensitivity around 3 kHz. On the other hand, modern sound-level meters are usually equipped with microphones that are essentially omnidirectional except at the highest frequencies. In this respect, as we shall see, they are markedly different from the human hearing system. The reasons are clear: omnidirectionality simplifies the calibration of sound-level meters, improves the reproducibility of sound-level measurements and is well adapted to the quantitative characterization of noise environments.

The family of curves presented in Figure 5.1 shows the average transformation of sound-pressure level from the free field to the human eardrum as a function of frequency at twenty-four angles of incidence in the horizontal plane. To minimize overlapping, the curves are divided into three groups each

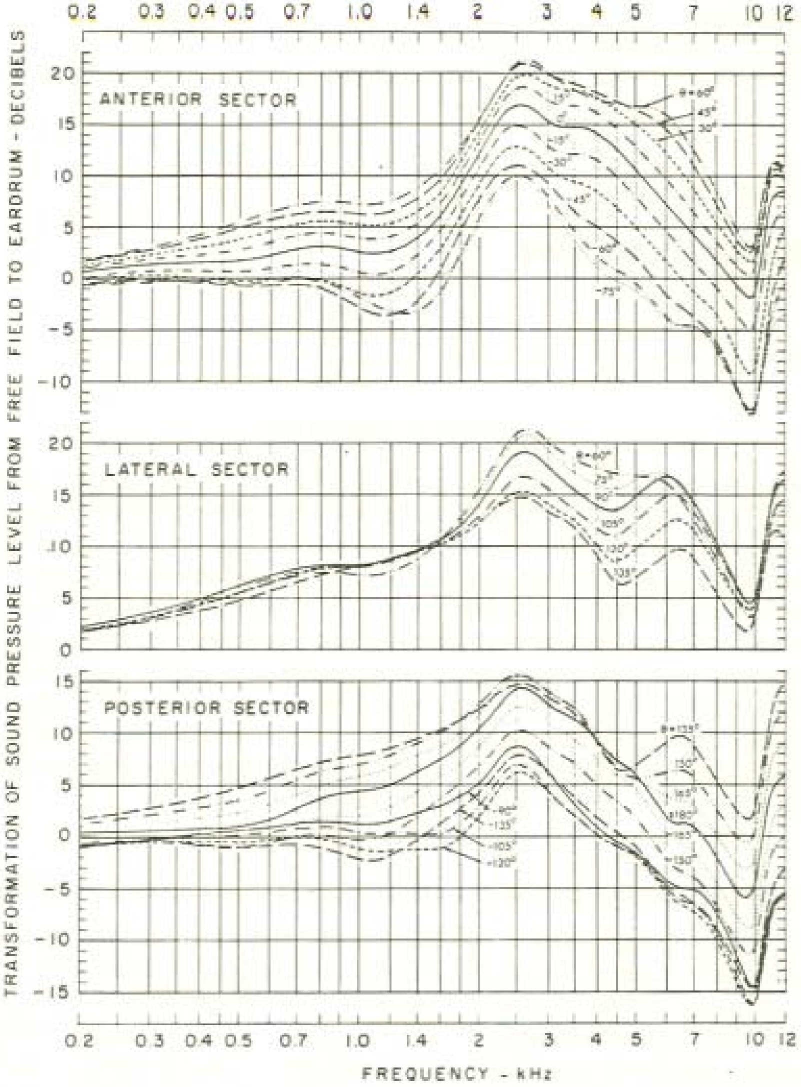

Figure 5.1 Average transformation of sound pressure level from free field to human eardrum as a function of frequency at 24 angles of incidence in the horizontal plane. Azimuth Θ = 0° indicates frontal incidence. Azimuth 90° indicates that sound source is facing left ear. After Shaw (1974c)

representing a broad sector. It should be noted that direct measurements of sound pressure at the eardrum are not easy and few such measurements have, in fact, been made. The self-consistent curves presented here were fitted to many kinds of relevant experimental data collected in twelve laboratory studies, in five countries over a forty-year period covering a total of 100 subjects (Shaw, 1974c). Such data processing eliminates much of the fine structure seen in the individual curves but preserves the common characteristics. For individual subjects, the response curves measured with one-third octave bands of noise can be expected to deviate from the average curves by less than 1 dB at frequencies below 500 Hz increasing to 5 dB or more above 5 kHz.

Most of the angular dependence seen in Figure 5.1 is due to diffraction by the head and torso but the external ear also makes a significant contribution at the higher frequencies. This is particularly evident in the lateral sector where the response is strongly dependent on the angle of incidence between 3 and 6 kHz. This is largely due to diffraction at the rear edge of the pinna.

Generally speaking, occupational noise exposure regulations specify the position at which measurements of sound level are to be made but make no mention of the nature of the sound field. (Measurements may, for example, be required at the 'head position' of the employee during normal operations.) It is, however, clear from the scientific studies which preceded the regulations (e.g. Kryter *et al.*, 1966) that it is primarily a random-incidence (diffuse) sound field which is implied. Such a sound field is, in fact, a good description of the acoustical environment in many manufacturing plants especially those which have hard walls, floors and ceilings and are therefore highly reverberant. Curve A of Figure 5.2 is pertinent to such an environment. It shows a recent estimate of the average response of the human ear at the eardrum as a function of frequency when the subject is placed in a perfectly diffuse sound field (Shaw, 1980). Curve B, which is taken from Figure 5.1, shows the average response when the sound field is highly directional and the source of sound is directly in front of the subject's head (azimuth 0°). As can be seen, the frontal-incidence response is similar to the diffuse-field response except at very high frequencies (7–10 kHz). This is fortunate since these two cases may well be sufficient to characterize the majority of sound fields encountered in industrial environments.

The situation is very different, as shown in Figure 5.1, when the sound field is highly directional and the source faces one side of the head. At azimuth 60°, for example, the response at most frequencies is increased by 4–8 dB as compared with the response at 0° azimuth whereas, on the far side of the head at azimuth −60°, the response is decreased by 3–12 dB. A calculation based on Figure 5.1 shows that the A-weighted sound level increases by 4.7 dB at the left ear and decreases by 5.8 dB at the right ear when a 'pink' noise source (equal mean-square sound pressure per octave) is moved from azimuth 0° (frontal incidence) to azimuth 60°. This variation in sensitivity with source direction has important consequences for those who are exposed to intense directional sound fields. For example, it is not unusual to find that people who use shot guns and rifles develop markedly different amounts of hearing loss in the two ears.

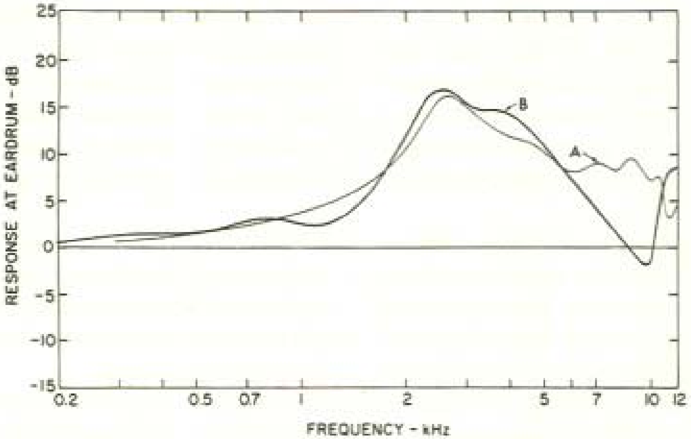

Figure 5.2 Curve A estimated average transformation of sound pressure level from diffuse (random-incidence) sound field to human eardrum as a function of frequency based on theoretical considerations and measurements with a model ear. After Shaw (1980). Curve B shows free field response with frontal incidence ($\Theta = 0°$) taken from Figure 5.1

For angles of incidence lying outside the horizontal plane, the available information on the directionality of the human hearing system is insufficient to warrant the preparation of average curve comparable to those presented in Figure 5.1. However, recent studies with sources near the ear indicate that the response between 7 and 10 kHz is substantially increased when the source is well above the horizontal plane (Shaw and Teranishi, 1968; Shaw, 1972). Figure 5.3 shows estimated average transformation functions for the symmetry plane of the head at source elevations between 0° and 60° based on these studies (Shaw, 1974a). The striking increase in sensitivity of the ear to sounds in the 7–10-kHz band, as the source is raised well above the horizontal plane, is reflected in a strong enhancement of the diffuse field response in this frequency region as shown in Figure 5.2. The explanation of this variation in sensitivity with source elevation lies in the mode structure of the human external ear. A set of shallow cavities, the cavum, the cymba and the fossa, bring the ear into transverse resonance in this region causing it to act primarily as a dipole receiver with vertical orientation and, hence, minimum sensitivity in the horizontal plane (Shaw, 1975; Shaw 1982a).

5.3 RECEPTION AND PERCEPTION

When the directionality of human hearing is discussed in the context of sound level measurement it is implicitly assumed that the two ears operate separately and that variations in the received spectrum are significant only in-so-far as

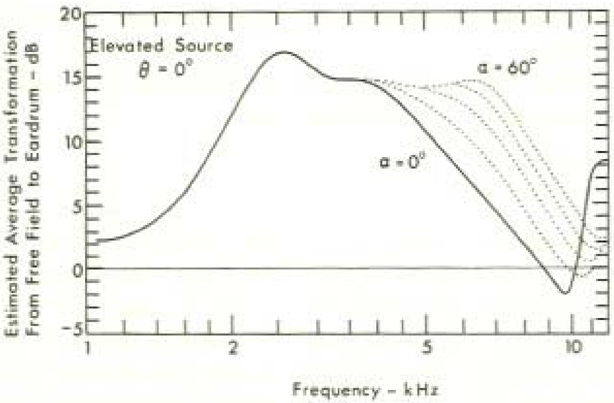

Figure 5.3 Estimated average transformation of sound pressure level from free field to eardrum as a function of frequency in symmetry plane of head at source elevations $\alpha = 0°, 15°, 30°, 45°$ and $60°$. From Shaw (1974a) with permission

they affect the A-weighted level. These assumptions, while justifiable in the assessment of hearing hazard, are inappropriate when importance is attached to the reception of acoustical signals in the presence of noise.

In general, perception is enhanced wherever the spectral and spatial attributes of signal and noise are distinguishable with respect to the receiver characteristics. There is, for example, enhancement when the listener is able to focus attention on a single voice among many in a crowded meeting room. The focusing of attention includes the identification of the chosen voice, especially through its spectral characteristics, and the perception of an acoustical space in which that voice is separated from others. Much research has been devoted to the elucidation of mechanisms relating the perception of acoustical space to the characteristics of the human receiver (e.g. Gatehouse, 1982; Blauert, 1982a, 1982b). For present purposes it will be sufficient to indicate how the interaural difference of sound-pressure level, the interaural time difference and the monoaural spectral factor come into play in typical situations.

The nature of the monoaural spectral factor is clearly indicated in Figure 5.1. Consider, in particular, a broadband sound source located in the horizontal plane and moving through the lateral sector from $\theta = 60°$ to $\theta = 135°$. It is evident that the spectral quality of sound received by the ear will change substantially as the source moves from front to rear thereby contributing to the localization of the source and the formation of a spatial image. The interaural differences of sound pressure level can also be inferred from Figure 5.1 by comparing pairs of curves such as ($\theta = 45°, \theta = -45°$). Families of difference curves are presented elsewhere (Shaw, 1974c). As can be seen, for $\theta = 45°$

this difference amounts to 5 dB at 500 Hz increasing to more than 10 dB at higher frequencies.

It can be shown that the interaural time differences approach the following asymptotic values at high and low frequencies:

$$t_{LF} = (a/c)\,(3 \sin \theta)$$
$$t_{HF} = (a/c)\,(\sin \theta + \theta)$$

where a is the radius of the head (~ 8.75 cm), c is the velocity of sound in air (~ 344 m/s) and θ is the azimuth of the source (see, for example, Kuhn 1977, 1982). At azimuth 45°, the values of t_{LF} and t_{HF} are 0.54 ms and 0.38 ms respectively. The high frequency value is based on geometrical acoustics with the assumption that the ray travelling to the right ear bends to match the contour of the head. The low-frequency value follows from diffraction theory. At intermediate frequencies (0.5 to 2 kHz) the system is dispersive; as a consequence, the interaural time difference in this transition region depends on the nature of the signal.

These factors, though much studied in psychoacoustics (e.g. Jeffress, 1972), seem to have received little attention in environmental acoustics. An exception concerns the effects of hearing protectors on signal reception. In one study it has been shown that the ability to localize sound sources is little affected by earplugs but is greatly reduced when circumaural hearing protectors are worn (Noble and Russell, 1972). Other studies have been concerned with the effect of hearing protectors on the ability to receive warning signals partially masked by noise (e.g. Wilkins and Martin, 1982). Finally, it has long been known that, in high background noise levels, subjects with normal hearing obtain slightly higher speech discrimination scores when wearing hearing protectors than when unprotected. However, a recent study shows that this is by no means true of subjects with substantial hearing loss in which case the attenuation provided by the protector can readily reduce the speech signal to inaudibility (Abel *et al.*, 1982).

5.4 THE HUMAN EAR AS A RECEIVER OF SOUND ENERGY

The performance of any acoustical antenna system as a sound collector can be expressed in terms of the parameter universally used in radiation theory: the absorption cross-section. For the ear immersed in a diffuse (random incidence) sound field, the absorption cross-section can be defined as the cross-sectional area of the transparent sphere which, when placed in the same sound field, would intercept an amount of sound power equal to that absorbed by the ear.

Figure 5.4 shows recent estimates of the performance of the human ear in terms of the sound power absorbed at the eardrum and at the oval window of the cochlea (Shaw, 1982a). As can be seen, the amount of sound power extracted from the sound field is very small indeed at low frequencies but increases by almost a factor of 1,000 as the frequency increases from 0.2 to 2.7 kHz (the principal resonance frequency of the human external ear). At this frequency, the absorption cross-section is only a factor of two below the theoretical limit $\lambda^2/2\pi$ set by radiation theory. With further increase in frequency the absorption cross-section remains quite close to the theoretical limit while decreasing in absolute value.

Below 1 kHz, the absorption cross-section at the oval window, though small, is only a little less than the cross-section at the eardrum. This means that much of the sound power extracted from the sound field is transmitted to the inner ear. Above 1 kHz, however, the transmission efficiency of the middle ear decreases progressively with increasing frequency and, at high frequencies, only a small fraction of the sound power received by the external ear reaches the inner ear.

It is tempting to link the peak at 2.7 kHz with the tendency for noise-induced hearing loss to appear first in the vicinity of 4 kHz. While the characteristics of the external ear and middle may well contribute to the evident vulnerability of the ear in this frequency band, there is evidence to suggest that the characteristics of the cochlea are of greater significance. Nevertheless, the frequency characteristics seen in Figure 5.4 clearly indicate that the ear is well adapted to the reception of noise impulses with half-cosine durations of the order of 150–200 μs. This has relevance to the measurement of impulse noise and the estimation of hearing hazard.

5.5 SOUND PRESSURE MEASUREMENTS WITHIN THE EAR

As we have noted earlier, industrial noise exposure is generally defined in terms of the A-weighted sound-pressure level of the sound field to which the employee is exposed. Where hearing protectors are worn, a suitable allowance is made for the expected sound attenuation based on published data and other criteria (Shaw, 1979). An alternative procedure which could, in principle, find wide application in industry takes advantage of recent progress in transducer technology. High-quality microphones are now available which are so small that they can easily be placed inside the external ear. This makes it possible to monitor the sound-pressure level within the ear and, hence, obtain values of noise exposure which take into account the complexity of the sound field or the use of hearing protection as well as variations in sound level and sound spectrum as a function of time.

To be useful, measurements within the ear must lead to data that can be accurately related to the limits specified in noise exposure regulations. In particular, it is essential that the placement of the microphone take full account of the wave properties of the external ear. It has been shown that the cavum of the concha is a particularly attractive location for the microphone since pressure measurements within the cavum are well correlated with the

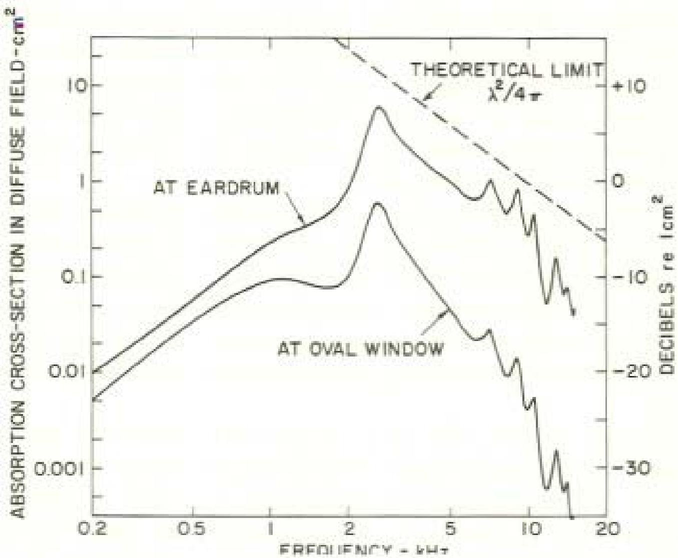

Figure 5.4 Calculated absorption cross section of human ear as a function of frequency at eardrum (upper curve) and at oval window of cochlea (lower curve) based on network representation of middle ear and on measurements with physical model of external ear. Broken line shows theoretical limit as a function of wavelength of sound λ. From Shaw (1982a)

sound-pressure levels at the eardrum and relatively free from measurement artifacts (Shaw, 1974b). The cavum is also a very convenient location for a measurement microphone (see Brammer and Piercy, 1977).

Figure 5.5 shows measured values of the transformation of sound-pressure level from the free field (frontal incidence) to the cavum of the concha for four subjects seated in an anechoic chamber (after Brammer and Piercy, 1977). As can be seen, the repeatability of the data is excellent and the total *spread* of data is little more than 2 dB up to 500 Hz and only exceeds 5 dB in 5 of the 19 ⅓ octave bands. The average of these data (graph line in Figure 5.5) can be combined with the difference between Curve B and Curve A in Figure 5.2 to provide an estimate of the average transformation of sound-pressure level from a *diffuse* sound field to the cavum. This is shown as Curve I in Figure 5.6. An independent estimate of this function can be obtained by combining Curve A of Figure 5.2 with information which can be inferred from the wave properties of the external ear (Shaw 1974c). This is shown as Curve II in Figure 5.6. The differences between these curves can be ascribed in part, at least, to real variations in the amount of sound reaching the ears from any given sound field due, for example, to variations in the absorption of sound by clothing. In

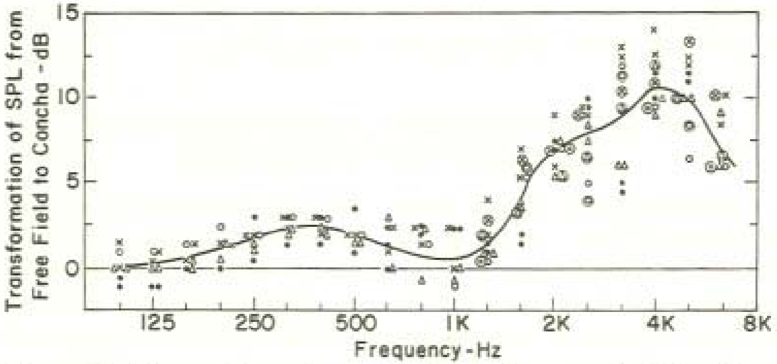

Figure 5.5 Measured transformation of sound pressure level from free field (0° azimuth, horizontal plane) to cavum of external ear as a function of frequency for four adult male subjects. After Brammer and Piercy (1977)

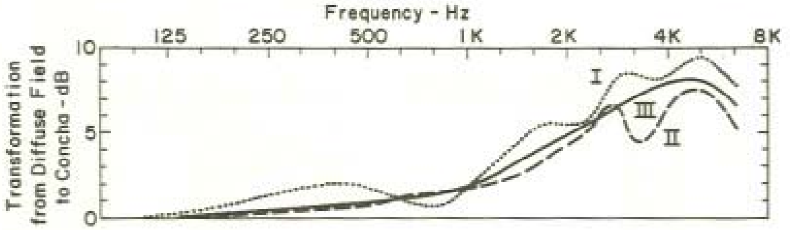

Figure 5.6 Estimates of average transformation of sound pressure level from diffuse (random-incidence) sound field to cavum of external ear as a function of frequency. Curve I: From Figures 5.2 and 5.5. Curve II: From Fig. 2 and Shaw (1974c). Curve III: Smooth curve proposed for practical use

any event, these differences are not large at most frequencies (1–2 dB below 3 kHz) and, for practical purposes, can best be handled by drawing a smooth curve such as Curve III in Figure 5.6 which can serve as the link between 'in-ear' measurements of sound-pressure level and noise exposure regulations. To implement such a measurement system it is necessary to extract A-weighted sound levels which are equivalent to those specified in the regulations. This can be done by inserting an additional weighting network, which is the inverse of Curve III, at a suitable point in the measurement system (e.g. in the microphone amplifier circuit).

The measurement of sound-pressure levels within the ear provides a means of determining noise-exposure levels which cannot be measured by standard methods. This technique is particularly suited to noise-level measurements where the ear is covered by earphones or protective clothing. It has also been successfully used to measure the noise exposures of motorcycle riders and industrial vehicle drivers (Brammer and Piercy, 1977).

5.6 SOUND PRESSURE MEASUREMENTS WITH BODY-MOUNTED MICROPHONES

It is common practice to monitor human noise exposure with instruments such as the personal noise dosemeter which use body-mounted microphones. Unfortunately, the A-weighted sound-pressure level measured with a microphone mounted on a worker's shoulder, breast pocket or helmet is not necessarily an accurate measure of the sound field to which he is exposed.

When a small microphone is placed on the surface of a rigid impervious obstacle the measured sound pressure is, in general, different from the pressure in the free-field. Figure 5.7 shows how this difference varies with the wavelength of sound λ and the angle of incidence θ for a spherical body of radius a (Shaw, 1974a). As can be seen, there are increases in sound pressure

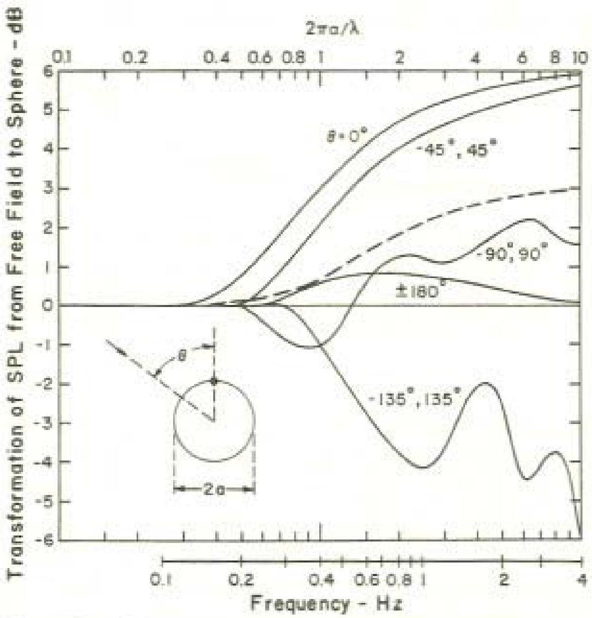

Figure 5.7 Calculated transformation of sound pressure level from free field to a point on a hard sphere of radius a as a function of $2\pi a/\lambda$ for various values of azimuth θ of incident plane waves. After Shaw (1974a). Frequency scale at bottom is for a sphere of radius 13.7 cm representing human torso. Broken line shows transformation from diffuse field to sphere based on Kuhn (1979)

level when the microphone is on the 'bright' side of the sphere ($\theta = 0, 45°$ and $-45°$) and comparatively little change in level at grazing incidence ($\theta = \pm 90°$). On the 'dark' side of the sphere (e.g. $\theta = \pm 135°$) there are decreases in level except for the 'bright spot' at the centre of the dark side ($\theta = \pm 180°$) where there is a small increase in level. There is also an increase in level, as shown by the broken line in Figure 5.7, when the sphere is placed in a random-incidence sound field. All of these effects are significant when the wavelength of sound is comparable with or exceeds the circumference of the sphere. The frequency scale at the botton of Figure 5.7 has been drawn for the value a = 14 cm, which is approximately the radius of the human torso (Shaw, 1974a) to give a rough indication of the magnitude of the diffraction effects which are to be expected with body-worn microphones.

When the obstacle is covered with sound-absorbing material, the sound-pressure levels to be expected are, in general, lower than those indicated in Figure 5.7. At high frequencies, this has been confirmed experimentally. Unfortunately, the experimental conditions have varied from study to study and the results have varied accordingly. It is however worth noting that Kuhn

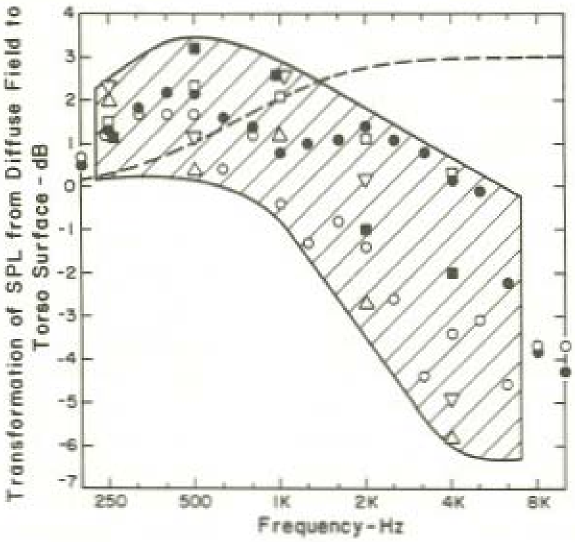

Figure 5.8 Transformation of sound pressure level from diffuse (random-incidence) sound field to torso surface as a function of frequency. Broken line shows theoretical curve for a hard sphere of radius 13.7 cm based on Kuhn (1979). Experimental points show data adapted from five experimental studies with human subjects and a mannikin clothed with shirts or jackets. Shaded area probable range of values. From Shaw (1982b)

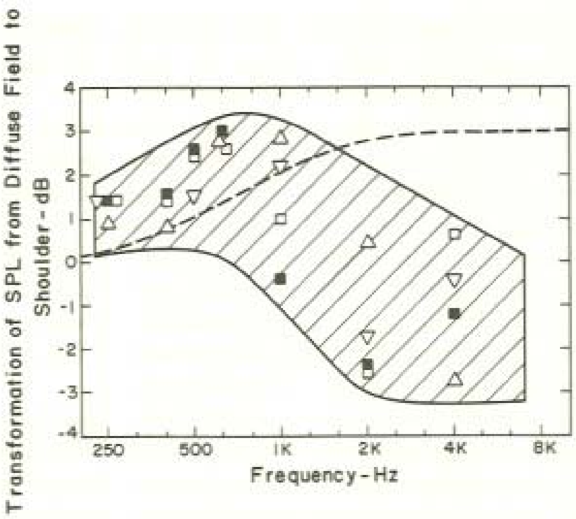

Figure 5.9 Transformation of sound pressure level from diffuse (random-incidence) sound field to shoulder as a function of frequency. Broken line shows theoretical curve for a hard sphere of radius 13.7 cm based on Kuhn (1979). Experimental points show data adapted from two experimental studies with a human subject and a mannikin clothed with shirt or jacket. Shaded area indicates probable range of values. From Shaw (1982b)

(1979) has reported results for a torso-mounted microphone on a bare plastic mannikin which are in good agreement with the broken line in Figure 5.8. The experimental data shown in Figure 5.8 are drawn from four studies using microphones mounted at the chest or breast pocket position on human subjects or dressed mannikins (Shaw 1982b). The original measurements were made with octave bands of noise, one-third octave bands or pure tones and the data are presented for a random incidence sound field. Some of the spread of data can probably be attributed to differences in the weight of clothing used and differences in the placement of the microphone. There is, however, no consistent pattern and one is forced to conclude that the shaded area in Figure 5.8 is a realistic indication of the uncertainty which is present when measurements are made with body-mounted microphones in a random-incidence sound field. As can be seen, this uncertainty ranges from 2 dB at 250 Hz to 6 dB at 5 kHz.

Two of the four authors cited in Figure 5.8 also made measurements with the microphone mounted on the shoulder. Data for this location are presented in Figure 5.9. This small pool of data indicates that, for frequencies greater than 2 kHz, measurements of sound-pressure level at the shoulder position are less subject to uncertainty than measurements made with a chest-mounted microphone. However, this advantage virtually disappears when the response to pink noise with A-weighting is considered.

In both cases it can be inferred that the use of body-mounted microphones introduces an uncertainty of approximately ±2 dB in the A-weighted sound level measurement.

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CHAPTER 6

Recent Advances in Understanding Hearing Mechanisms and Hearing Impairment

E. F. EVANS

6.1 INTRODUCTION

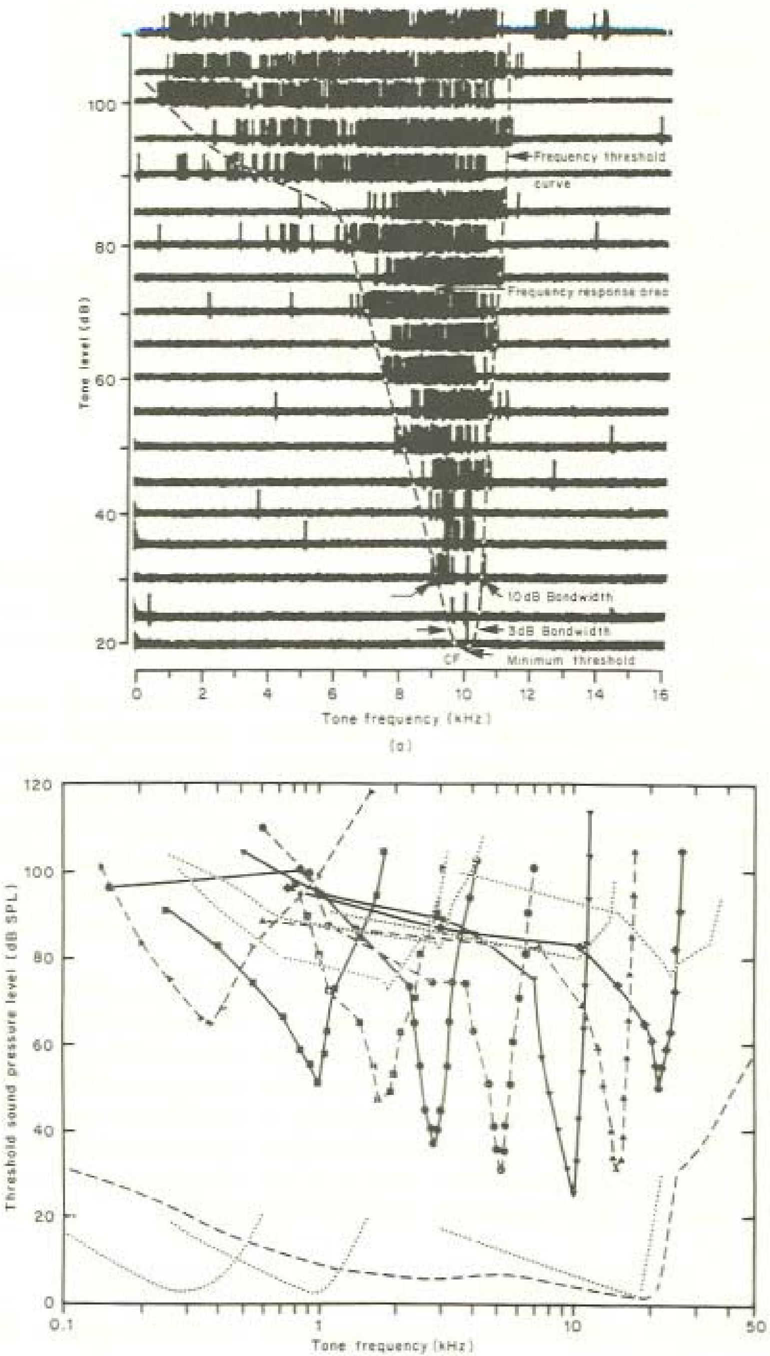
Over the past 20 years in particular, the cochlea has received an enormous amount of attention from the physiologist. The two main reasons for this attention form the focus of this brief review, and are of relevance to our understanding of sensorineural hearing loss of cochlear origin.

First, has been the demonstration that the cochlea is more than merely a particularly sensitive microphone. It carries out the substantial part of a most important function of the auditory system, namely frequency analysis: the ability of the ear to resolve or filter complex sounds, like speech, into their component frequencies. On this depends much of our ability to hear speech sounds clearly, especially in competing noise. While we do not fully understand how this remarkable filtering action of the cochlea is brought about, it requires energy and is physiologically vulnerable. Consequently, it is easily impaired in pathological conditions of the cochlea.

This leads to the second reason for the contemporary interest in the cochlea: pathological conditions of the cochlea can be readily set up in animals as animal 'models' of cochlear hearing loss. These have helped to account for a number of features of cochlear hearing loss in physiological terms, particularly recruitment and deterioration in speech intelligibility. On this basis, new tools for diagnosis and new aids for rehabilitation are beginning to emerge. Finally, very recent physiological studies of the effects of various agents on the animal cochlea appear to offer a potential animal model of tinnitus.

6.2 FREQUENCY ANALYSIS BY THE COCHLEA

In everyday use, the ear has to analyse complex sounds, like speech. These contain frequency components which have to be separated out for the speech sounds to be recognized. This process of separating one frequency component


Frequency threshold curve
Frequency response area
10 dB Bandwidth
3dB Bandwidth
CF
Minimum threshold
Tone level (dB)
100
80
60
40
20
0
2
4
6
8
10
12
14
16
Tone frequency (kHz)
Threshold sound pressure level (dB SPL)
120
100
80
60
40
20
0
0.1
1
10
50
Tone frequency (kHz)

(a)

(b)

Figure 6.1

from another simultaneously present, is called frequency analysis, frequency resolution, or frequency selectivity. This is a most important function of the ear, and yet rather neglected compared with the more well-known function of frequency discrimination. This is the ability of the ear to discriminate one frequency as being different from another presented sequentially, not simultaneously. The two functions, frequency selectivity and frequency discrimination may well be related (Evans, 1978), but for the purposes of understanding speech, the former is the most important.

It has long been known that the ear is capable of a remarkably good frequency analysis, within certain limits, but it has been an open question as to where this frequency analysis is accomplished. Recent physiological and psychophysical evidence now suggests that this most important function is already largely accomplished at the level of the cochlea. In the cochlea, the peripheral auditory system is supplied with a bank of remarkably sharply tuned filters, each filter filtering, out of a complex sound, signals within a relatively narrow bandwidth of frequency (Evans, 1975, 1978, 1981).

Frequency Threshold Curves (FTC)

The cochlea's filtering ability is best understood by reference to the properties of the afferent nerve fibres from the cochlea to the central auditory nervous system, in the cochlear or auditory nerve (Figure 6.1). Figure 6.1(a) shows the result, from a single cochlear nerve fibre, of sweeping a pure tone up and down in frequency at increasing sound levels across the cochlear fibre's frequency response area. The spike responses are the individual action potentials of that cochlear nerve fibre recorded by a microelectrode inserted into it. Outside the cochlear fibre's frequency response area, only occasional

Figure 6.1(a) Microelectrode record from single fibre in cochlear nerve of guinea-pig, in response to continuous tone swept in frequency in 5 dB steps of successively higher signal level. Alternate sweeps are in opposite direction. Spikes are monophasically positive and 0.9 mV in amplitude. Sweep rate linear: 14 kHz/sec. The outline of the frequency response area thus defined is the frequency threshold curve (FTC). The characteristic frequency (CF) is 10 kHz. See text (b) Frequency threshold curves (FTCs) of single cochlear fibres recorded from normal and abnormal cochleae, compared with analogous data for the basilar membrane. Guinea pig. Continuous and dashed lines through data points: FTCs of eight cochlear fibres from six normal cochleas. Upper dotted curves: FTCs of cochlear fibres from cochleae rendered abnormal by circulatory inadequacy (CFs at 1.9, 3 and 10 kHz). The dotted curve of highest CF (24 kHz) was obtained in an otherwise normal cochlea. Lower dotted curves: analogous curves derived from the measurements of the vibration amplitude of the guinea-pig basilar membrane, by von Bekesy (1944: curves with tip at 0.3 and 0.95 kHz), by Johnstone, Taylor and Boyle (1970: dotted curve at 18 kHz) and by Wilson and Johnstone (1972: dashed curve at 20 kHz). All threshold curves are corrected to sound pressure level (in dB SPL) at the tympanic membrane under closed bulla conditions. The basilar membrane curves are positioned arbitrarily on the ordinate scale. After Evans (1972).

action potential spike occur spontaneously. Within the frequency response area, however, the cochlear fibre responds by generating a continuous burst of spikes. This is its excitatory response, the only response given by cochlear fibres to single tones. The outline of the roughly triangular response area we call the frequency threshold or 'tuning' curve (FTC). In Figure 6.1(b), a family of such FTCs is plotted for eight cochlear nerve fibres, each originating from a different position along the cochlear partition. The curve centred at 10 kHz is, in fact, the frequency threshold curve for the fibre of Figure 6.1(a). The frequency corresponding to the tip of each FTC is called the characteristic frequency (CF) of that fibre. It is the frequency at which the fibre's response is most sensitive. The characteristic frequency of a cochlear fibre therefore obviously depends on the position along the cochlear partition from which it originates. The curves to the left of Figure 6.1(b) are of cochlear fibres taking origin from the apical, low-frequency end of the cochlea and those to the right, from the high-frequency basal end.

Filtering Action of the FTC

These cochlear fibre frequency threshold curves represent quite formidable filters. An engineer would measure their bandwidth 3 dB up from the tip (the half power bandwidth) and would find them to be one-third to one-sixth of an octave wide. The cut-off slopes, from the tip of the FTC to the 'skirts', are very steep, exceeding several hundred dB per octave, particularly on the high frequency side and for cochlear fibres with CFs above about 2 kHz. A characteristic of these cochlear fibres is that the steep low-frequency cut-off becomes suddenly less steep, to form a 'low-frequency tail' at about 70 to 90 dB SPL. For cochlear fibres with CFs below 2 kHz, their FTCs are more symmetrical, and the cut-off slopes become progressively less steep, the lower the CF.

Any auditory stimulus having energy that falls within the FTC of a cochlear fibre will, in principle, evoke an excitatory response from it. Furthermore, for cochlear nerve fibres with CFs up to about 3 to 4 kHz, the patterning in time of their discharges will be dominated by the frequencies at the tip of the FTC. This means that, for complex signals like speech, each individual cochlear nerve fibre will have its response governed both in terms of the number of discharges per second (the mean discharge rate) and the temporal patterning of the discharges (for low CF cochlear fibres) by the frequency components falling within their frequency response area. These generalizations, however, only apply strictly at lower intensities. At higher intensities, certain non-linearities make themselves felt, particularly saturation of the spike discharge rate about 40 dB on average above threshold, and lateral suppression, described in detail elsewhere (Evans, 1975; Rose *et al.*, 1974; Sachs and Kiang, 1968; Young and Sachs, 1979).

These filtering characteristics of the cochlear nerve fibres are important for our understanding of how the ear analyses complex sounds, because the neural filter bandwidths are more than adequate to account for the psychoacoustic frequency selectivity of the ear (Evans and Wilson, 1973; Pickles, 1975). (There are a number of difficulties in attempts to reconcile filter bandwidths derived from all the different psychoacoustic, animal behavioural and physiological techniques of measurement, but taken together they suggest that a value of about 10% for bandwidth — about one-sixth octave — affords a reasonable description of the filtering ability of the cochlea.)

To a first approximation, therefore, the ears' psychoacoustic frequency selectivity is already determined at the level of the cochlea. The cochlea, therefore, is no mere microphone, but is instrumental in carrying out much of the most important function of frequency analysis. Without this we would not be able to hear speech clearly.

Active Filtering in the Cochlea Partition

One question which has dominated a great deal of cochlear physiology in the last 20 years, is how this extremely sharp tuning is produced by the cochlea. Until very recently, measurements of the tuning of the basilar membrane had shown it to be much too broadly tuned to account for the sharp cochlear fibre tuning properties (Von Bekesy, 1944; Johnstone *et al.*, 1970; Rhode, 1971; Wilson and Johnstone, 1975; Sellick *et al.*, 1982). Thus, in Figure 6.1(b), the lower curves represent measurements of basilar membrane vibration in the guinea pig plotted so as to be analogous with the cochlear fibre FTCs. The basilar membrane curves appear to be those of low-pass filters. These, and other findings, suggested that in the cochlea, we might have a two stage filtering process: a first filter, that of the basilar membrane, followed by an hypothetical 'second filter' responsible for the sharp band-pass tuning properties of the cochlear fibres (Evans, 1972; Evans and Wilson, 1973). Some very recent measurements of basilar membrane motion, however, suggest that the previous results may well describe what might be called the passive vibration characteristics of the basilar membrane. Under conditions where the measurement technique does not disturb the very delicate organ of Corti, much more sharply tuned responses have been obtained (Khanna and Leonard, 1982; Spoendlin, 1972). These, and other results to be referred to later, suggest that the basilar membrane and organ of Corti may work together to form an active filter complex.

Physiological Deterioration of Cochlear Filtering Mechanism

An important discovery of the last 15 years relevant to this question, is that the cochlear filtering mechanism is physiologically vulnerable. This means that alterations in the physiological condition of the cochlea can cause the normally sharp filtering properties to deteriorate. A variety of effects can cause reversible alteration in the cochlea's filtering (Figure 6.2). Thus, a short

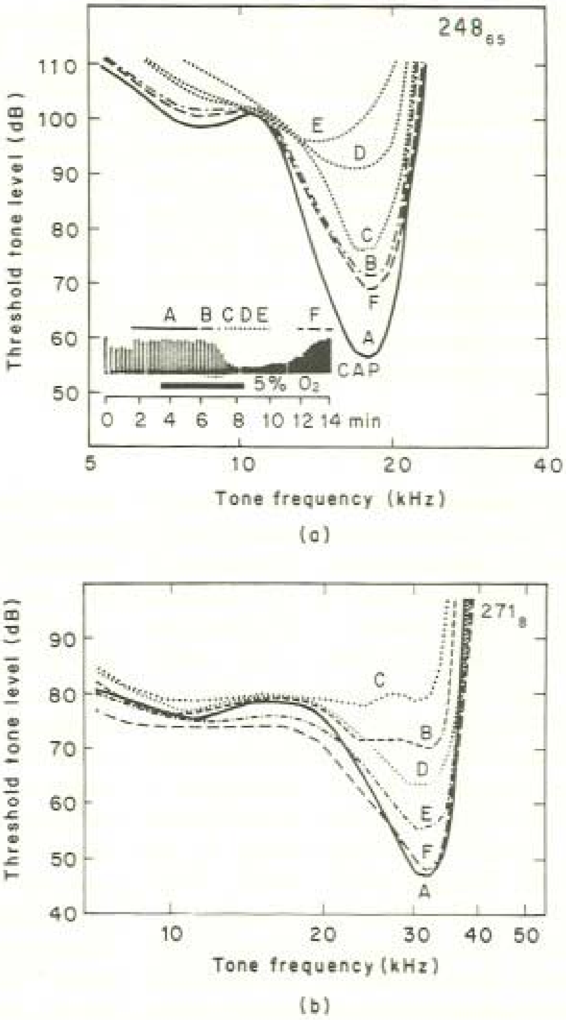


Figure 6.2(a) Reversible effects of hypoxia on the tuning of a single cochlear fibre in the cat. Inset shows time course of gross cochlear action potential (CAP) amplitude in response to click stimuli of constant amplitude (approx. 40 dB above threshold) presented every 10 sec. The thick bar indicates the duration of reduction of inspired oxygen to 5%. The bars over the CAP record indicate the times during which the FTCs illustrated in the main figure were determined. Curve A: control obtained before cochlear hypoxia developed (see text). Curves B to E: during development of cochlear hypoxia. Curve F: during recovery from hypoxia. Note loss and partial recovery of low threshold, sharply tuned segment of FTC. After Evans (1974) (b) Reversible effects of furosemide, a potent ototoxic diuretic, on FTC of cat cochlear fibre. Arrows: injection of 20 mg furosemide into the subclavian artery of the same side as the cochlea. Curve A: control FTC. Curves B, C: during action of furosemide on cochlea. Note loss of low threshold segment of FTC. Curves D, E, F: recovery. After Evans and Klinke (1974)

period of hypoxia (Evans, 1974; Evans, 1974; Robertson and Manley, 1974) (Figure 6.2(a)) or an intra-arterial injection of furosemide (Evans and Klinke, 1974) (Figure 6.2(b)) will cause, within the space of a few minutes, the cochlear fibre FTC to lose its low threshold, sharply tuned tip, becoming high threshold, and broadly tuned (upper dotted curves in Figures 6.2(a) and (b). If the physiological insult is short-lived, virtually complete recovery of the tuning can occur (Figure 6.2, Curve F). Similar, but irreversible, effects have been shown to occur as a result of over-exposure of the ear to sounds (Liberman and Kiang, 1978) and to antibiotics of the streptomycin family, such as kanamycin (Kiang *et al.*, 1970; Evans and Harrison, 1976; Harrison and Evans, 1979). In these cases, it is often the outer hair cells which are preferentially destroyed, and the changes in the FTCs noted in Figure 6.2 occur for those fibres originating in the cochlear regions where the outer hair cells are missing. This is mapped out in Figure 6.3(c) for the same guinea pig cochlea from which the cochlear nerve FTCs were measured in Figure 6.3(b). While the inner hair cells appear to be intact (by light microscopical examination at least), the outer hair cells are missing for the basal half-turn (0–5 mm). The corresponding frequencies are about 10 to 15 kHz, and here the FTCs are high threshold and blunt. (The significance of Figure 6.3(a) will be referred to later.) Findings such as these suggested that the normal sharp tuning of cochlear nerve fibres, most of which originate in the inner hair cells (Spoendlin, 1972), might be dependent upon the integrity of the outer hair cells. This apparently paradoxical situation has led to suggestions that some form of interaction occurs between the inner and outer hair cells either at the mechanical cellular electrical or even neural level (Evans, 1976; Zwislocki and Sokolich 1974). The latter possibility has been unequivocally excluded by the very recent microelectrode recordings from individual inner hair cells in the guinea-pig cochlea, by Russell and Sellick (1978) (Figure 6.4). Recording from the basal turn of the guinea-pig cochlea, Russell and Sellick showed that inner hair cells produce an asymmetrical receptor potential reflecting the stimulus waveform (Figure 6.4(a)). At high frequencies, the receptor potential is not able to 'follow' the stimulus waveform, and a d.c. potential remains. This receptor potential is as sharply tuned (Figure 6.4(b)) as the cochlear nerve fibre FTCs. Whatever the cochlear filtering mechanisms are, they must precede the generation of receptor potentials in the inner hair cells.

Cochlear Acoustic Emission

Another very recent and exciting finding relevant to this question of cochlear filtering, is the demonstration that ears not only receive sounds, but under certain conditions can emit sounds (Kemp, 1978; Wilson, 1980). This acoustic emission can take two forms: an evoked emission where a brief click or tone-burst can evoke a brief emission (the so-called cochlear 'echo' (Figure 6.5)), and a continuous spontaneous emission untriggered by an external

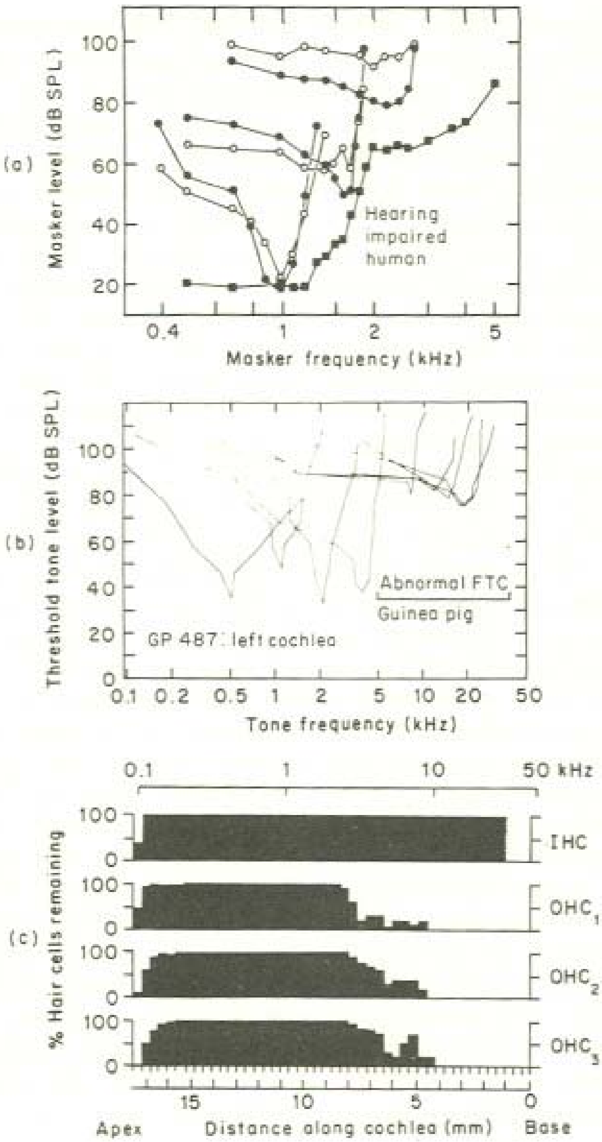


Figure 6.3 Similarities between human 'psychophysical tuning curves' (a) in a patient with high frequency hearing loss, and physiological 'tuning curves' (b) in a guinea pig ear damaged by kanamycin. The shaded areas (c), indicate the proportion of inner and outer hair cells remaining in the cochlea at the time of the physiological recording. All of the outer hair cells (OHC) are missing from the first 4–5 mm of the cochlea, the high frequency end. The cochlear nerve tuning curves (middle section) have lost their sharp tuning in the region corresponding to the loss of outer hair cells. The 'psychoacoustic tuning curves' (a) are obtained by a tone on tone masking technique (see text). (After Evans & Harrison (1976) and Wightman *et al.*, (1972).)

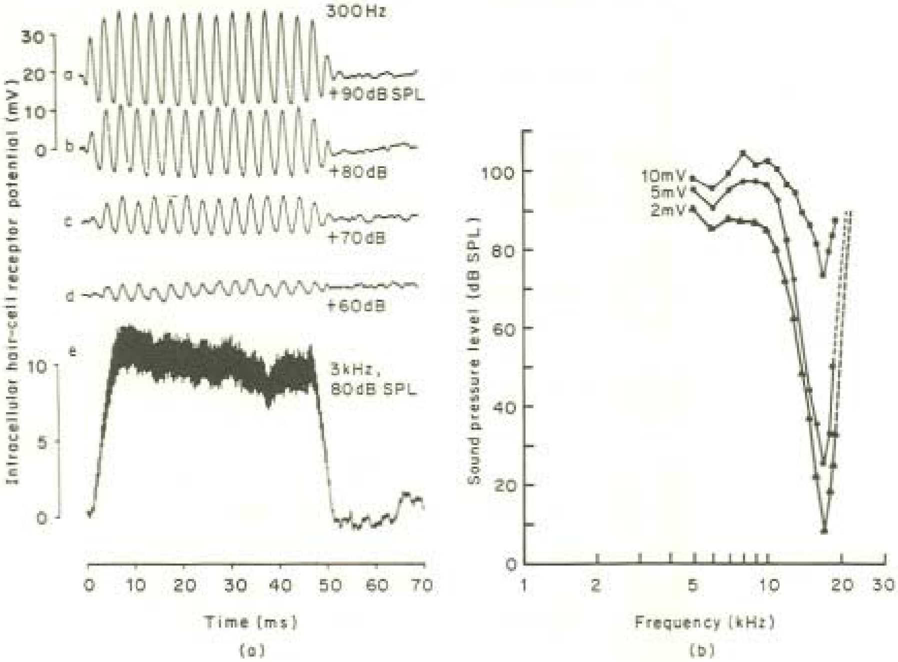


Figure 6.4 Intracellular potentials from mammalian inner hair cells. (a) Intracellular potential waveforms recorded by a microelectrode in an inner hair cell in the basal (high frequency turn) of guinea pig: (a–d) to a tone burst of low frequency (300 Hz) and at different sound-pressure levels. The waveform of the stimulus can be seen in the response (with distortion at high levels). (e) response to 3 kHz tone. Note small a.c. response superimposed upon a substantial (c. 12 mV) depolarising potential. (Courtesy of Dr. I. J. Russell, *J. Physiology*, in Press.) (b) Variation in stimulus level required to keep d.c. receptor potential constant across frequency for three voltages (isovoltage frequency tuning curves). After Russell and Sellick (1978)

stimulus. Much recent work suggests that this strange phenomenon may originate within the organ of Corti by mechanisms not understood. Very recently, the organ of Corti has been shown to contain contractile proteins, particularly actin (Flock, 1980). This leads to the highly speculative suggestion that the organ of Corti may be able to respond mechanically to incoming sounds. Since the cochlear emission phenomenon is physiologically vulnerable and has a number of other features related to the sharp tuning of cochlear nerve fibres, it has been suggested that the phenomenon may be bound up with the cochlear frequency selective mechanism (Kemp and Chum, 1980). This would mean that the cochlear 'micromechanics', i.e. the mechanical properties of the basilar membrane-organ of Corti complex are not passive but active in the sense of requiring energy for normal sharp tuning function, and possibly

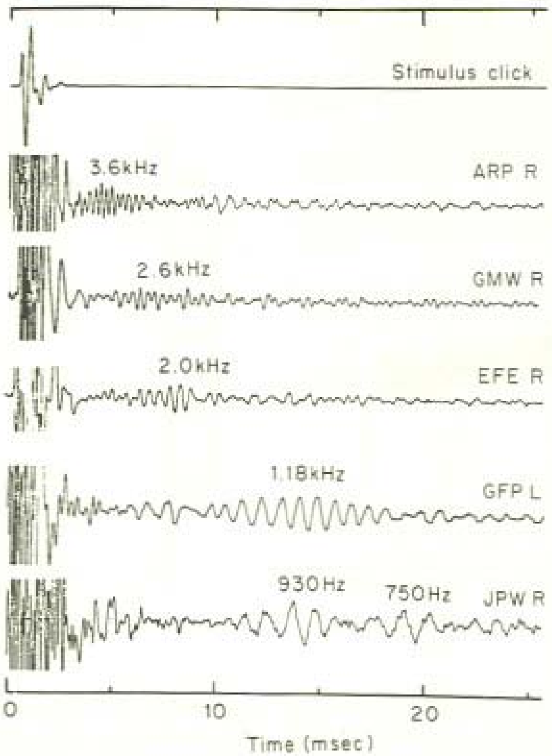


Figure 6.5 Evoked 'cochlear emissions'. Averaged responses to clicks recorded by a sensitive microphone in ear canal of five human subjects. The first 3 ms shows averager overloaded by stimulus (upper). Subjects were chosen to show a wide range of response frequencies and the correpsonding change of latency. From Wilson (1980)

involving the active generation of vibration. It is conceivable that such a mechanism could achieve a high degree of sensitivity and tuning by means of 'positive feedback' whereby a mechanical response is generated by the organ of Corti in phase with the incoming signal. This must remain in the realms of speculation, however, until further information on these phenomena become available. However, taking all the recent data together, they do suggest that the cochlea cannot now be considered to have passive mechanics, but that the activity of the hair cells (the hypothetical 'second filter') must be an integral part of the cochlear 'micromechanics' and be the source of energy input to the filtering process. There is even accumulating evidence that the active mechanical properties of the cochlea can be controlled by stimulation of the efferent nerve supply to the cochlea (Mountain, 1980). Thus it is possible that the mechanical stiffness properties of the hairs or hair cells could be controlled by efferent 'tone'. Again, the situation here is paradoxical: the great majority of cochlear efferents in mammals end upon the outer hair cells, whereas the majority of afferent nerve fibres originate from the inner hair cells (Spoendlin, 1972). Presumably, the micromechanics of the cochlea must depend upon the physical integrity and mechanical properties of the cellular elements within the organ of Corti, particularly the outer hair cells.

6.3 COCHLEAR HEARING LOSS

It will be clear from the above, that the cochlear filtering mechanisms are extremely vulnerable to physiological insult. Overexposure to noise (Liberman and Kiang, 1978), reduction in the oxygen supply to the cochlea (Evans, 1974; Robertson and Manley, 1974), exposure to the loop diuretics (e.g. furosemide (Evans and Klinke, 1974)), salicylates (Evans and Borerwe, 1982), and to the aminoglycosides (e.g. kanamycin (Kiang *et al.*, 1970; Evans and Harrison, 1976; Harrison and Evans, 1979)) all produce deterioration in the filtering characteristics, which if prolonged, become permanent (upper curves in Figure 6.1(b)). Similar effects are obtained as a result of surgical interference with the cochlea (upper curves in Figure 6.1(b)), haemorrhage, etc. In other words, all modifications in cochlear function so far studied have one common end result: deterioration in the tuning properties of the cochlear nerve fibres.

This means that in human cochlear pathology we should expect an identical deterioration in the frequency selectivity of the cochlea to occur. Obviously, we cannot study this directly, hence there has been a considerable interest in the last 10 years in the study of 'animal models' of hearing loss, and in extrapolations from these animal models to clinical findings. The animal models suggest that for the types of cochlear pathology mentioned above, the chief physiological change is a deterioration in frequency selectivity.

If the frequency selectivity function of the auditory system is already largely determined at the cochlear nerve level, then we should expect, under conditions of cochlear pathology, to observe deterioration in this ability. This has been recently demonstrated to occur by a variety of techniques (Leshowitz and Lindstrom, 1977; Pick, *et al.*, 1977; Wightman *et al.*, 1977; Zwicker and Schorn, 1977). Of the psychoacoustic techniques, the most readily understood result (although possibly the most difficult technique to apply) is that of the 'psychoacoustic tuning curve' technique (Figure 6.3(a)). These psychoacoustic tuning curves are obtained by plotting out the frequencies and intensities at which a second tone will mask a tone of constant frequency and intensity. The shapes of the psychoacoustic tuning curves resemble those of cochlear fibre FTCs in normal ears, and this is one of the evidences for the statement that the ear's psychoacoustic frequency selectivity is already largely determined at the cochlear nerve level. Under conditions of cochlear pathology, however (Figure 6.3(a)), the psychoacoustic tuning curves lose their low threshold, sharply tuned tip and become as blunt as the physiological tuning curves obtained in the animal models of cochlear hearing loss (Figure 6.3(b)). Other psychoacoustic methods are more easily applied in the clinic, and involve, for example, the masking of a test tone by noise stimuli having alternating peaks and valleys in the spectrum, i.e.: comb-filtered noise (Pick *et al.*, 1977). From these measurements, values for the filtering bandwidths for the ear for those frequencies can be obtained. Generally speaking, the greater the hearing loss, the greater the deterioration in frequency selectivity, in other words, the wider the tuning bandwidth. This is in agreement with the findings of the animal models of cochlear pathology. It is clear, however, that there is a large variation from point to point, representing individual ear differences. Deterioration in frequency selectivity can therefore be used as a sensitive test of damage to the cochlear function at least in certain individuals (Pick and Evans, 1980), and is a direct measure of the expected loss in auditory function. A number of laboratories are therefore investigating the value of more selected and more specialised tests such as these, for the diagnosis and assessment of patients with cochlear hearing loss.

Another approach is to use the auditory evoked potentials. Using electrocochleography, and simple masking techniques (Harrison *et al.*, 1981), it is possible to obtain so called 'gross cochlear action potential tuning curves', which resemble approximately the tuning curves of individual cochlear nerve fibres. Under conditions of cochlear pathology in both animals and human patients, these gross cochlear action potential tuning curves show the same kind of deterioration in shape as shown in Figure 6.3.

These findings from animal models of cochlear pathology are relevant to our understanding of the changes in auditory processing of diagnostic importance, namely, recruitment of loudness and the intelligibility of speech, dealt with in detail elsewhere (Evans, 1975; Evans, 1975; 1978).

6.4 TINNITUS

In the last two or three years, efforts have been directed at setting-up valid animal models of human tinnitus. A major problem in this is that at present it is not possible to devise a behavioural index that an animal is experiencing tinnitus. Two ways round this problem have been explored (Evans *et al.*, 1981).

The first is to use sufficient doses of salicylate until blood levels are obtained that would be associated with tinnitus in man (Mongan *et al.*, 1973). This has been done in a number of anaesthetized cats (Evans and Borerwe, 1982; Evans *et al.*, 1981). Under salicylates, the mean spontaneous discharge rate shifted upwards. This is in the opposite direction to that normally encountered in animal studies of the effects of ototoxic agents. This may well, therefore, be a physiological correlate of salicylate-induced tinnitus, at least. The only other report in the literature of an increase in spontaneous discharge rate following cochlear pathology is that observed in a minority of cats examined about one

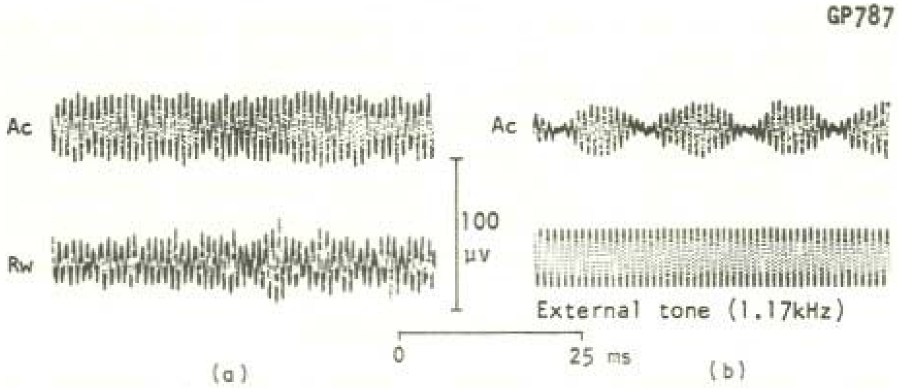


Figure 6.6 Effects of various manipulations on the spontaneous emission signal simultaneously recorded from a guinea pig acoustically in the ear canal (Ac) and electrically from the round window (Rw) of the cochlea. a, spontaneous emission signals (1.16 kHz; 21 dB SPL; 7 μV r.m.s.). b, beats produced in the acoustic emission signal by the addition of a second tone (1.17 kHz, 22 dB SPL). From Evans *et al.*, (1981)

month following noise over-stimulation (Liberman and Kiang, 1978). This again, may be the correlate of tinnitus in cases of noise over-stimulation.

Accompanying the increase in spontaneous discharge rate in salicylate poisoning are alterations in the temporal discharge patterns of cochlear fibres (Evans and Borerwe, 1982; Evans *et al.*, 1981). Whether these are relevant to the perception of tinnitus is unknown.

A second animal model of human tinnitus that has recently been studied is that of a continuous, tonal emission in a guinea pig (Evans *et al.*, 1981) (see Figure 6.6). This emission had a number of characteristics in common with that recorded in human subjects (Wilson, 1980): it could be recorded as an acoustic signal in the ear canal; its amplitude and frequency were affected by changes in the stiffness of the middle-ear system; it could be synchronized by tones of neighbouring frequency and suppressed by tones of higher frequency. The levels of the continuous emission and of the synchronizing and suppressing tones were analogous to those recorded in man. In the animal model, however, it was possible to demonstrate that the emission could be recorded as an electrical signal from the round window (Evans *et al.*, 1981). It was also possible to demonstrate that the tonal emission was not likely to be generated by the middle ear: it was unaffected by muscle paralysing agents and by section of the tendon of the stapedius muscle. Furthermore, it could be substantially attenuated in the ear canal by changes in the stiffness of the middle-ear system without significant change in the amplitude of the round window recorded signal. Its latency (4 ms) was also too short for the middle-ear muscles to be involved. The sensitivity of the emission to both acoustic trauma and hypoxia indicated that it was as physiologically vulnerable as the tuning of cochlear nerve fibres. All the evidence therefore suggests that the origin of this spontaneous emission is some sort of metabolically labile mechanical disturbance within the cochlea itself of the kind discussed above in connection with the 'cochlear echo' phenomenon. From measurements on human subjects, this form of tinnitus, associated with a recordable signal in the ear canal, is likely to be restricted to the category of so-called 'physiological tinnitus' (Wilson and Sutton, 1981). How far it is representative of the types of tinnitus encountered in the clinic is currently under study.

ACKNOWLEDGEMENT

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PART II

EFFECTS OF NOISE ON MAN

Noise Pollution
Edited by A. Lara Sáenz and R. W. B. Stephens

CHAPTER 7

*Auditory After-effects of Noise**

W. DIXON WARD

7.1 INTRODUCTION

The most obvious effects of intense or prolonged noise were known at least 350 years ago to Francis Lord Bacon (1627), who wrote that 'A very great sound, near hand, hath strucken many deaf'. Furthermore, he had himself experienced a temporary partial loss of hearing coupled with a tinnitus: '... myself, standing near one that lured [whistled loudly to call back a falcon] loud and shrill, had suddenly an offence, as if somewhat had broken or been dislocated in my ear; and immediately after a loud ringing (not an ordinary singing or hissing, but far louder and differing) so as I feared some deafness. But after some half quarter of an hour it vanished'.

Thus, even in Bacon's time the temporary and permanent manifestations of acoustic trauma — effects produced by a single, very intense exposure — were well known. On the other hand, a slow but progressive loss of hearing associated with extended exposures to less intense noises was apparently not as clearly recognized, as suggested by this observation of Bacon's: 'It is an old tradition, that those who dwell near the cataracts of Nilus are strucken deaf, but we find no such effect in cannoniers, nor millers, nor those that dwell upon bridges.' Perhaps cannons and mills were quieter in Bacon's day than they became later. With the Industrial Revolution, at any rate, noise sources became ever louder, so that by 1830 (Fosbroke, 1830), in a review of what was then known about deafness, could refer to damage to hearing 'caused by continued noise, as blacksmith's deafness' as though it were already an established syndrome. However, despite the length of time that noise-induced hearing damage has been recognized, the precise relation between the parameters of the acoustic exposure (intensity, duration, spectral characteristics, and temporal pattern) and the resultant loss of sensory capability is still highly controversial.

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7.2 IMPAIRMENT AND HANDICAP

It is generally accepted that the most serious consequence of noise exposure is indeed partial deafness, particularly insofar as such a loss of hearing produces a social handicap. Unfortunately, there is no widespread agreement on how this social handicap is to be defined and measured. Until the middle of this century, a hearing loss was regarded as handicapping, and therefore compensable as being the result of an occupational hazard, only if it was disabling, in that it led to a loss of earning power of the individual, a condition whose existence could be relatively easily and unambiguously determined. Since then, however, with the gradual acceptance of the principle that a worker is entitled to compensation for any material impairment suffered as a result of employment, handicap has come to be any condition that interferes with everyday living.

Representative of this viewpoint is the definititon of handicap adopted by the American Academy of Otolaryngology: 'an impairment sufficient to affect a person's efficiency in the activities of daily living' (Anon., 1979). Since 'activities of daily living' include so much, yet vary so widely from person to person, recent practice has been to attempt to measure auditory handicap in terms of a reduction in the individual's ability to understand ordinary speech, a simplification that ignores, among other things, the social significance of the perception of warning signals, sounds of nature, and music.

However, even this oversimplification fails to solve the problem, because there is no accepted definition of 'ordinary speech'. Speech consists of messages of various degrees of complexity and redundancy, spoken by talkers differing in age, sex, ethnic background, education and dialect, at a large range of sound levels, in quiet and in the presence of a near-infinite variety of interfering noises. Any test that claims to measure an individual's ability to understand ordinary speech would have to include enough test items to provide a representative range of all these parameters — providing that agreement could be reached on what 'representative' means. No such direct test has yet been developed.

At the present time, therefore, hearing ability is still assessed in terms of the ability to hear pure tones, particularly those at frequencies most important to the understanding of speech, viz., 500 to 4,000 Hz. *Impairment* of hearing is measured by the individual's Hearing Threshold Levels (the number of decibels by which the sound intensity must be increased to be heard, relative to 0 dB Hearing Level, which is the sound level that can be heard by an ear that presumably has never been affected by any deleterious agent) at these frequencies. *Handicap* is then defined in terms of the number of decibels by which the Hearing Threshold Levels (HTLs) exceed the 'low fence', a fixed although somewhat imprecisely-determined empirical line that, in theory, separates individuals who have 'no' difficulty in understanding conversation from those who have 'some' difficulty, by self-report. Just how well this line of demarcation based on pure-tone thresholds actually divides individuals in terms of speech understanding is a question still being hotly debated; the low fences actually used in different countries and states vary widely. Noble (1979) has recently reviewed the problem of handicap and its measurement in some detail. But because the audiogram is the easiest and best-standardized test of ability to hear that can be administered to large numbers of people, it will doubtless continue to be used to assess the auditory 'after-effects' of noise exposure, no matter what method of relating pure-tone thresholds to handicap is employed.

7.3 HEARING DAMAGE

7.3.1 Tinnitus

Inability to hear weak sounds is not, of course, the only manifestation of damage from noise. Its opposite, in a sense, is also a frequent result: the hearing of sounds that do not exist. Tinnitus, the ringing in the ears mentioned by Bacon, is a common accompaniment of noise-induced hearing loss. However, although intractable tinnitus is often distressing to the individual concerned, its measurement is difficult. Furthermore, only seldom does noise cause a permanent tinnitus without also causing hearing loss. So although the person with tinnitus should probably be considered more impaired than someone with the same audiogram but without tinnitus, the question of how *much* more impairment a particular tinnitus represents has not yet been solved.*

7.3.2 Paracusis

In addition, some sounds may be heard, but heard incorrectly. Musical paracusis is said to exist when the pitch of tones near a region of impaired sensitivity due to noise is shifted; i.e., a tone is heard, but one having an inappropriate pitch. Unfortunately, direct measurement of paracusis is possible only in highly musical persons, so the phenomenon has received little attention. If the paracusis is greater in one ear of a given individual than in the other, then *binaural diplacusis* will be found: a particular tone will give rise to different pitches in the two ears, and the magnitude of this difference can be inferred by having the listener adjust the frequency of a tone in one ear to match the pitch of a fixed tone in the other. Again, however, noticeable degrees of paracusis or diplacusis that are attributable to noise exposure only occur in conjunction with a considerable loss of sensitivity, so the importance of paracusis *per se* in determining social handicap is still unknown.

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* Chapter 6 by Evans, E. F. (in this volume).

7.3.3 Speech Misperception

Noise-induced hearing loss, it will be shown later, is frequency-specific, almost always involving high frequencies, especially around 4 kHz, much more than low frequencies. The noise-impaired auditory system therefore acts, broadly speaking, like a filter, so that the spectrally complex sounds of speech, particularly consonants may be heard, but heard incorrectly. For example, in a study designed to find differences in the associated auditory characteristics of high-frequency losses presumably caused by steady noise *vis-a-vis* similar losses caused by gunfire, individuals with a high-frequency loss that began at 2,000 Hz consistently heard an initial 't' as a 'p'; e.g., when given the word 'tick', with no opportunity to see the lips of the speaker, they almost always responded 'pick' when forced to choose between 'tick' and 'pick' (Ward *et al.*, 1961). In recent years, these misperceptions of speech sounds have received increasingly greater attention, and eventually some standardized consonant-confusion test may be adopted as a part of a battery of speech tests designed to assess the ability to 'understand ordinary speech'.

7.3.4 Physiological Measures of Hearing Damage

All of the preceding indicators of damage to hearing are associated with a measurable loss of threshold sensitivity. However, damage to the auditory mechanism may occur without affecting the threshold. Evidence from animal studies, for example (Henderson *et al.*, 1974), implies that several hundred of the hair cells that have been presumed to be important in the process of hearing may be destroyed before a change in threshold is measurable. This clearly casts doubt on the adequacy of threshold sensitivity as the only behavioural indicator of damage. To date, however, efforts to find a psychophysical indicator that is more sensitive to physiological damage have been unsuccessful, although many have been proposed, such as the ability to (1) identify small changes in intensity or frequency of a signal (difference limens), (2) discriminate signals from interfering sounds (masking), or (3) detect longer signals more easily than shorter ones (temporal integration). The problem is that the existence of diffuse hair-cell destruction can be validated only in experimental animals, while reliable estimates of difference limens, masking, and temporal integration can easily be obtained only in man. Until such time as some method for determining hair-cell loss in the intact organism is developed, therefore, the auditory threshold remains the most dependable indicator of the physiological normalcy of the auditory system, just as it is the most easily measured indicator of its normal functioning.

7.4 THRESHOLD SHIFTS, TEMPORARY AND PERMANENT

If the auditory threshold is measured before and after a noise exposure, giving values of HTL_0 and HTL_t, respectively, then the difference HTL_t-HTL_0 is by definition the threshold shift (T), which may be temporary (TTS) or permanent (PTS). The term *noise-induced* may legitimately be attached if it can be established that no other reason for the difference exists. Thus a TTS associated with, for example, an eight-hour exposure to noise in an iron-smelting plant can reasonably be termed a noise-induced TTS (NITTS) provided that: (1) the same audiometer was used for both the pre- and post-exposure tests, and its physical characteristics did not change; (2) the testing technique, recording technique, and ambient noise level in the test-room were adequate and invariant; (3) the subject's criterion for deciding when he heard a tone was same (i.e., there was no 'learning'); (4) body noises in the subject's head were not different (e.g., he did not have a pounding heart because of exertion just prior to either test); and (5) the heat and fumes from the molten metal did not influence the threshold directly. While the first two requirements can be met fairly easily, that the others were fulfilled can be verified only by the use of appropriate controls. In this case, such a control group would be a group of workers exposed to all the same conditions except for noise. Complete elimination of the noise being impossible, the best solution would be to require the use of well-fitted ear protectors by half of the workers on one day of testing, by the other half on another, in order that each worker could serve as his own control.

Laboratory tests of TTS are usually conducted with conditions so well regulated that a formal control experiment is usually not necessary except for assessing 'learning effect' when initially naive test subjects are used. Because of the ease of performing such research, there is a considerable body of knowledge concerning the effects of spectrum, level, duration, and temporal pattern of exposure on NITTS in man: the pre-exposure Hearing Threshold Level HTL_0, the noise exposure NE, and the post-exposure HTL_t can all be accurately measured, and the influence of extraneous factors on the threshold can be minimized (Ward, 1970).

For NIPTS, however, this is not the case, because NIPTS in humans cannot be produced in the laboratory, but must be inferred from field observations. In most attempts to measure NIPTS, the only measurement which can often be confident is the post-exposure threshold HTL_t, and even this will be true only when: (1) it has been measured correctly, i.e., using calibrated apparatus and standard procedures; (2) there has been no recent exposure to a TTS-producing noise; and (3) adequate steps have been taken to ensure that malingering will be detected, particularly when the results of the measurement are likely to be used to determine the amount of compensation to be awarded the worker for hearing loss.

Even when HTL_t has been accurately determined, PTS cannot be calculated unless HTL_0 is also known, and until recently this was seldom the case. Hearing was measured only *after* something had happened to it, not before. Next, in order to determine how much of the PTS is a NIPTS, we must somehow correct it for *presbyacusis*, the gradual deterioration of sensitivity with age, and for *nosoacusis*, the effect, over the time concerned, of all damaging influences other than aging or noise: industrial chemicals like benzene, carbon disulphide, carbon monoxide, or aniline dyes (Lehnhardt, 1965); ototoxic drugs such as kanamycin and streptomycin; illnesses, especially chronic middle-ear infections; hereditary progressive hearing loss; and traumata such as blows to the head.

The final problem to be encountered is that in order to be of any practical use, the NIPTS must be related to the noise exposure NE, and characterization of NE poses formidable problems. People are exposed to noises of various levels, spectra, durations, and temporal patterns in the work situation, and then are also exposed to similarly diverse noises on the way to and from work, at home, and while engaging in hobbies. The term *sociacusis* is applied to hearing loss attributable to these noises of everyday life — i.e. those outside the work environment. The mere recording of the noises entering a single ear over a period of years would be nearly impossible (indeed, it has so far never been attempted), and even after that were done, one would still be faced with the problem of reducing all that information to a manageable number of significant parameters.

7.4.1 PTS from Steady Noise Exposures

As a result of this complexity, about all that is known about the relation between noise exposure and NIPTS in man concerns the effect of reasonably constant industrial noise environments on large numbers of workers who presumably started with normal hearing. Certain industries have used the same machines for many years, and in some of these industries the workers remain at the same job for a lifetime. It is therefore possible to select two groups of workers, one of which worked in this noise environment for a known number of years, while the other worked in 'quiet' conditions. If the ages of the groups are matched, then presbyacusis will have affected each group to the same degree. If, in addition, a questionnaire reveals that certain nosoacusic agents in the aggregate history of the groups are about equal, then it may be postulated that any difference in HTLs between the groups is due to their total noise exposure, and is in fact NIPTS. Finally, if it can be assumed or demonstrated that both groups are also equally exposed to noise outside the work situation, and so presumably have the same sociacusis, then the difference in HTLs can legitimately be called the *industrial* NIPTS (INIPTS), provided of course that one accepts the proposition that all of these influences are simply additive — i.e., that an individual's HTL, is equal to the numerical sum of the changes of HTL, in decibels, that would have been caused by presbyacusis alone, the changes ascribable to nosoacusis alone, those attributable to sociacusis alone, and those due to the industrial noise alone. There is no evidence, either theoretical or empirical, to support the notion of simple additivity; it has been accepted for so long, however, that its replacement by some other principle will require overwhelming evidence.

Passchier-Vermeer (1968) summarised in a single document the results of the cross-sectional (retrospective) hearing surveys that came close to meeting the stipulations listed above: steady and relatively invariant noise environments to which a significant number of workers had been exposed eight hour/day for many years. It must be pointed out, however, that even these few surveys did not use exactly the same rules for exclusion of individuals from analysis (other than a history of working at more than one noisy job), e.g., middle-ear problems or demonstrated conductive hearing loss, family history of hearing loss, military service, noisy hobbies, etc. So it is seldom really clear of what section these groups of workers were a representative sample. Furthermore, in some of these surveys adequate provisions were not made to ensure exclusion of TTS from the data (by measuring thresholds only before beginning work, or by requiring the use of ear-protectors until the audiogram was made). In others, there is no clear evidence that the testing environment was quiet enough so that if a worker happened to have better than 'normal' hearing, it could be measured. Finally, the control groups used by the authors of the surveys were often either inadequate or, in some cases, non-existent. In such cases, Passchier-Vermeer employed a set of 'average presbyacusis' curves developed by Spoor (1967) in a comparable synthesis of retrospective surveys of non-industrial, noise-exposed persons, in order to correct the data for aging plus some sociacusis and some nosoacusis. These average presbyacusis curves for males are shown in Figure 7.1, for females in Figure 7.2. Thus, for example, if a male worker of age 50 has a HTL at 6,000 Hz 20 dB higher than non-exposed males 25 years of age, his inferred industrial-noise-induced hearing loss would be zero. It must be emphasized that these curves represent neither the *sole* effect of age, completely untainted by sociacusis or nosoacusis, nor the *combined* effects of age, disease and non-industrial noises, but something between the two, probably closer to the latter. Robinson and Sutton (1979) have recently developed some equations that fit the Spoor curves fairly closely; however, it must be remembered, if these equations are actually adopted in an ISO document, that their use as a correction factor for industrial data will always leave the industrial-noise-induced loss still confounded with some degree of sociacusis and nosoacusis. It is unfortunate that there still exists no survey, performed under meticulously-controlled conditions, of the hearing of a random sample of the population of a particular country from which the *only* reason for exclusion was a 'yes' answer to the following question: 'Have you ever worked more than a few days in a noise so loud that you had to raise your voice in order to be heard?' Only with such a survey can the true combined effect of presbyacusis, nosoacusis and sociacusis be determined, and a realistic determination of industrial NIPTS be made.

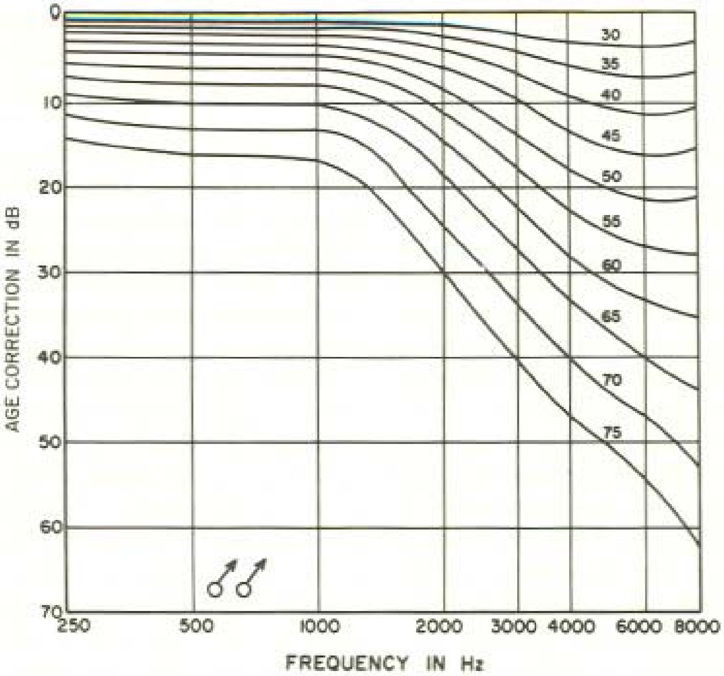

Figure 7.1 Age-correction curves for males, after Spoor (1967). The ordinate indicates the difference between the Hearing Threshold Level of a person of a given age (parameter) and that of an average 25-year-old, as a function of frequency (abscissa). These correction values incorporate not only the effects of the aging process *per se*, but also assume a moderate amount of sociacusis and nosoacusis

Despite all the deficiencies of the survey data, Passchier-Vermeer's analysis showed surprisingly consistent results. When the inferred INIPTS of the aggregate data, as determined by applying Spoor's correction for 'presbyacusis', were related to the overall A-weighted level of the noise, the results showed a clear linear relation. It must be mentioned, however, that a similar result was found when the exposure was expressed in terms of NR ratings, and Kraak (1979) has recently shown that these same data will fit his hypothesis that NIPTS is proportional to the integral of the sound pressure over time. Apparently many functions are consistent with this survey data, and determining the ultimate relation between exposure and resultant INIPTS is still to be accomplished.

However, the relation between A-weighted level and NIPTS, with duration of exposure held constant, is sufficiently simple that it lends itself well to the setting of exposure limits for industrial workers. In Figure 7.3, the ordinate shows the inferred INIPTS at 4 kHz, the frequency most severely affected by

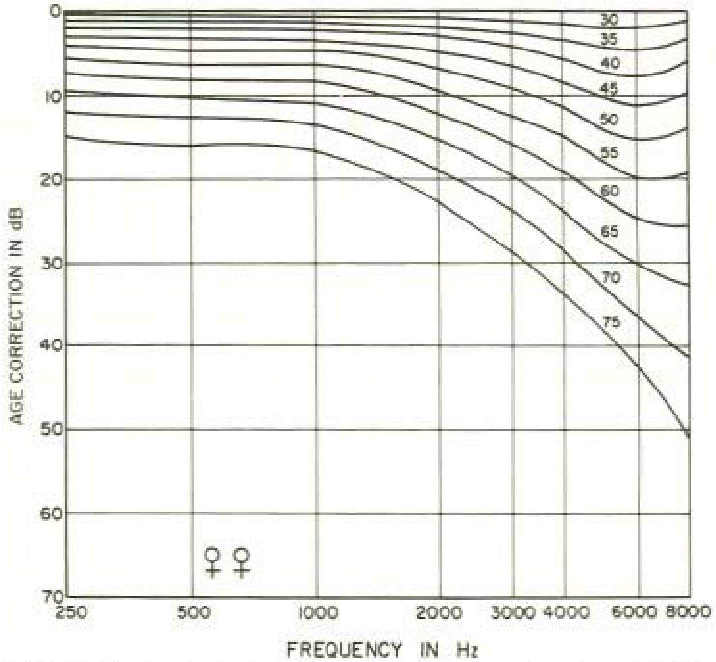

Figure 7.2 Age-correction curves for females, after Spoor (1967)

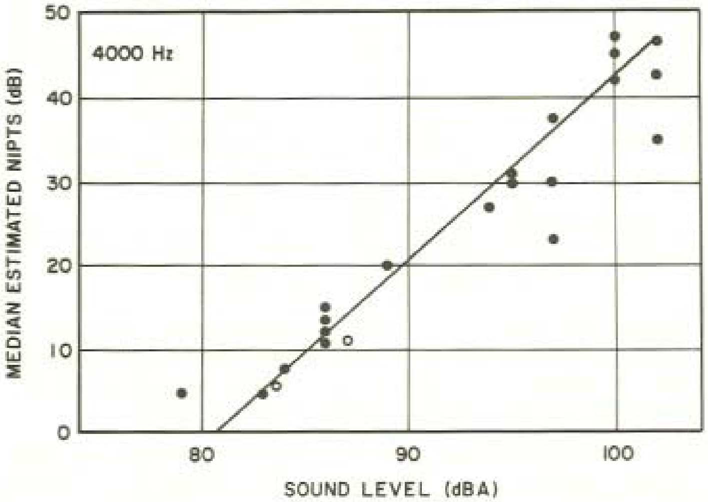

Figure 7.3 Estimated industrial-noise-induced permanent threshold shift at 4 kHz produced by 10 years or more of exposure to noise at the indicated A-weighted level. Solid points indicate values calculated from the literature by Passchier-Vermeer (1968), and open points represent recent studies by Robinson *et al.* (1973) and Yerg *et al.* (1978)

noise, after 10 years of exposure to a steady industrial noise environment whose A-weighted level is given on the abscissa. It can be seen that a reasonable fit to the data is given by a straight line passing through 0 dB at 80 dBA and 20 dB at 90 dBA. The point at 78 dBA can safely be ignored, as it represents only 14 ears of seven workers (Kylin, 1960).

The accuracy of this summarization is indicated by the two open circles, which represent the results of two subsequent large-scale studies of workers employed in levels of 80 to 90 dBA. Robinson *et al.* (1973) found that textile workers who had an 83-dBA environment showed a loss about 5 dB greater than a control group who worked in 70 dBA or below, and a recently concluded study involving several industries found a loss of 11 dB in workers whose daily A-weighted exposure levels were about 87 dBA (Yerg *et al.*, 1978).

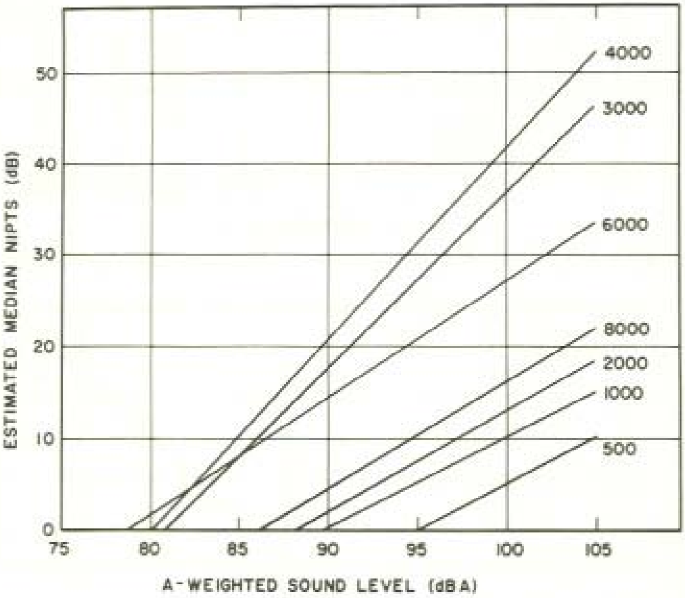

Figure 7.4 Estimated industrial-noise-induced permanent threshold shifts at various frequencies produced by 10 years or more of exposure to noise at the indicated A-weighted level. From data summarized by Passchier-Vermeer (1968)

The set of curves relating the growth of median INIPTS at all of the normal audiometric frequencies to the A-weighted level (eight hours per day steady noise, interrupted only by normal rest and lunch breaks, five days per week for 10 years or more) is shown in Figure 7.4. As a first approximation, it appears that: (1) 80 dBA is the level that can be regarded as being innocuous; (2) 85 dBA will result in a loss of about 10 dB at the most noise-sensitive audiometric frequencies of 3, 4, and 6 kHz (10 dB is the smallest loss in the individual case that could be regarded as meaningful); (3) 90 dBA will generate a loss of 20 dB at these frequencies, although the traditional speech frequencies (500, 1,000, and 2,000 Hz) are still largely unaffected; only above 90 dBA does the noise adversely affect these lower frequencies; and (4) noises of 100 dBA, which are still common, will produce severe losses at high frequencies, and also moderate losses at the low frequencies — losses that, when added to the effects of presbyacusis, nosoacusis, and sociacusis, will produce a hearing handicap in a large proportion of those workers so exposed.

At present, 90 dBA has been adopted as the eight-hour exposure limit in most countries, although 85 dBA is advocated by those who feel that a 20-dB loss at high frequencies is too great to be tolerable. Those holding this view point out that the figure of 20 dB is only an average one, one that does not take individual differences into account. When the average INIPTS is 20 dB, a good many workers will have lose 30 dB, and a few even 40 dB (and, of course, some will have lose none at all). In order to protect the most sensitive individuals, it is contended, the exposure limit should be set at a lower value than merely what is necessary to protect the average worker. As the distributions of inferred NIPTSs were estimated by Passchier-Vermeer, her statistics can be used to predict what fraction of the exposed population will suffer any given amount of INIPTS, but at that point the issue ceases being a scientific one and becomes a political question, as the exposure limit adopted must depend on what INIPTS is deemed 'acceptable'. Millions of dollars have been squandered in arguments over what is acceptable.

7.4.2 PTS from Intermittent Noise

Figure 7.4, regrettably, represents just about everything that is known about the relation between noise exposure and NIPTS in humans. Furthermore, it is unlikely that any further direct evidence will be gathered on the topic, except for exposures below eight hours at 90 dBA, because noise exposures considered at all hazardous are being eliminated rapidly from our industrial environment. We are left, then, with only the relation between habitual exposure to a steady noise for eight hours/day, five days/week, fifty weeks/year and the hearing loss that develops. Unfortunately, few noise exposures, industrial or otherwise, are for eight hours at a constant level. The problem of assessing the permanent effect of noise exposures that are intermittent, time-varying, impulsive, or merely shorter than eight hours can be solved only by extrapolating from temporary effects to permanent effects, by extrapolating from PTS in experimental animals to PTS in man, or by refusing to wait for development of enough evidence to make a decision and simply postulating that some arbitrary but simple rule must be used. Animal work is underway in several laboratories that will eventually provide at least partial answers to the problem of intermittence, but in the meantime the most reliable evidence comes from studies of TTS.

7.4.3 TTS from Steady Noise in Man

As indicated earlier, TTS can be generated and measured under controlled conditions, so much is known about this phenomenon. Most work has been applied to the study of shifts persisting more than 2 min, as these are considered to indicate a true 'auditory fatigue'. As early as 1930 (Peyser, 1930) suggested that these longer-lasting effects, observed in industrial workers, might be classified as either 'physiological' or 'pathological', depending on whether or not full recovery from one day's exposure occurred before the next day's began. Pathological fatigue was, he proposed, the precursor of NIPTS. If this idea were correct, perhaps a reasonable 'critical value' of recovery time would be 16 h or about 1,000 min. TTSs recovering by this time would be considered physiological and therefore normal, while only those requiring longer times would be termed pathological. In general, the range of 'normal' would include values of TTS_2 (the TTS two min after cessation of exposure) up to 25 or 30 dB, at least when normal ears and steady uninterrupted daily exposures are involved.

This 'ordinary' TTS has been studied intensively in the laboratory because of the assumption that its dependence on the frequency, duration, and intensity of the exposure might reflect fairly accurately the dependence of NIPTS on these same parameters (Temkin, 1933). Although this assumption is currently being challenged, the evidence is still far from conclusive one way or the other, and thus some of the more established characteristics of TTS are worth recounting.

Both the growth of TTS_2 and its recovery are exponential processes; for all practical purposes, in a constant noise level an asymptote of TTS_2 is reached in eight to twelve hours. The magnitude of the TTS_2 grows approximately linearly with SPL once the SPL has exceeded some base value below which only short-duration effects (those running their course in two minutes or less) are produced. This basic SPL, termed 'effective quiet', appears, to be about 70 to 75 dB for octave bands of noise. That is to say, a 75-dB-SPL octave-band noise will not produce much TTS_2 no matter how long it is on; a 105-dB-SPL noise will generate about twice as much TTS_2 as one at 90 dB if duration of exposure is the same; and a 100-dB-SPL noise will produce a value of TTS_2 midway between those following 90 and 110 dB SPL. The actual rate of growth with level, of course, will depend on the duration and frequency characteristics of the fatiguing noise; high frequencies induce a more rapid rate of growth than low frequencies, even though effective quiet is relatively independent of frequency.

The foregoing principles are illustrated in Figure 7.5, which summarizes some experiments in which ten normal-hearing young adults were exposed for eight hours to various octave-band noises. The dashed line at the bottom shows the

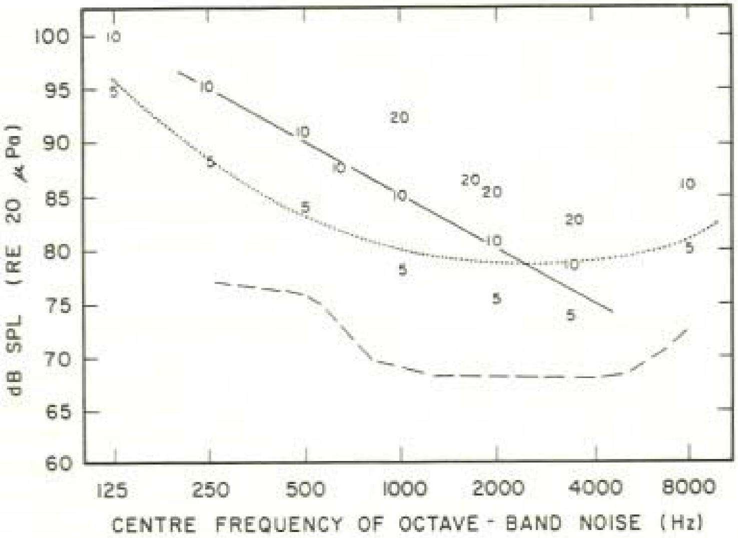

Figure 7.5 Octave-band sound pressure levels that will produce a 'particular' temporary threshold shift. The dashed line represents 'effective quiet'—i.e., that level that will just produce no TTS, nor retard recovery from TTS, in 95% of those exposed. Numerals denote the values of TTS$_2$ produced in the average listener by a continuous 8-hour exposure at the indicated frequency and SPL. The solid line, having a slope of −5 dB per octave, indicates 'magenta noise' that will produce approximately equal TTS$_2$ at all frequencies up to 4,000 Hz. The dotted line shows the locus of all SPLs having equal A-weighted levels, in this particular case an A-weighted octave-band level of 80 dBA. After Ward *et al.* (1976)

values of SPL that produced no effect — that is, no TTS$_2$ — in any ear, even the most sensitive. The numerals indicate the average TTS$_2$ (i.e., 5, 10, or 20 dB) generated by the eight-hour exposure at the indicated frequency and level. It appears that to produce an equal TTS$_2$, a given frequency needs to be only about 5 dB less intense than the octave below it: the most hazardous noises are those in the 3,000-Hz range (the resonant frequency of the outer-ear canal).

Temporary threshold shifts are asymmetrically distributed relative to the exposure frequency. The maximum TTS$_2$ is found at a frequency half an octave above the frequency of the fatiguer in the case of a pure tone, or half an octave above the upper cut-off frequency of a fatiguer that is a band of noise.

It should be clear that this fact, in combination with Figure 7.5, implies that a broadband noise, one having significant energy through the entire spectrum, will tend to produce a maximum TTS at 4 or 6 kHz. In such a noise the greatest energy reaching the cochlea will be in the 3-kHz region, and this will therefore produce the most TTS half an octave to an octave higher.

At this point it is possible to see one of the reasons for adoption of

A-weighting for assessment of all steady noises. The dotted curve in Figure 7.5 portrays the relative weighting assigned to different frequencies by the A-weighting network of the sound level meter; that is, all points on that curve have equal weight in contributing to the overall output of the meter. Even though A-weighting was originally based on judgements of equal loudness of very weak sounds, it happened that it came the closest of the existing standard weighting networks to predicting equal TTS-producing capacity of different frequencies at high levels, a fortuitous but useful occurrence.

7.4.4 TTS from Intermittent Noise, and the Total-Energy Theory

Prediction of the TTS produced by time-varying and intermittent noise exposures is somewhat complicated, because of partial recovery during the quieter periods. However, for relatively rapid interruptions or fluctuations (periods of five minutes or less), the TTS_2 is proportional to the mean number of decibels by which the instantaneous sound level exceeds 'effective quiet' during the entire exposure. Thus, for example, if 'effective quiet' for that particular noise is 70 dB SPL, the same TTS_2 will be produced by eight-hour exposures to an 85-dB steady noise, or a 100-dB noise that is on half the time and off half the time (by 'off' is meant any level below 70 dB), or a noise that changes at regular intervals from 75 to 85 to 95 dB and back to 75 dB, or a noise that fluctuates irregularly but for which the average number of decibels by which 70 dB is exceeded is 15 dB.

The temporary threshold shifts produced by patterns of longer exposures and rest-periods can be calculated by means of empirical equations describing alternate growth and recovery. In either case, however, the TTS_2 is considerably less than the TTS_2 that would have been produced by a steady noise over the same time but whose level was such as to keep the total energy constant. For example, in the case of the noise that is on half the time at 100 dB and off the other half, the total energy of the exposure is the same as a 97-dB noise that is on all the time, yet it produces only the same TTS as an 85-dB noise, which is a significant difference. Thus TTS is not a function of the total energy or even the total A-weighted energy of the exposure; how the energy is distributed in time makes a considerable difference in the magnitude of the TTS produced.

7.4.5 TTS from Impulse Noise

The same is true for TTS from impulse noise, such as gunfire. Although 30 impulses of simulated gunfire at 150 dB SPL peak level may produce a TTS_2 of 20 dB in a particular ear, 300 impulses of the same pulse shape but at 140 dB SPL (i.e., the same total energy) will usually produce no TTS_2 whatever in this individual (McRobert and Ward, 1973). Here it appears that there is a critical level (which, however, is a function of pulse duration) below which no effect is produced but above which the TTS increases with level. Unlike the growth of TTS_2 with time for steady or interrupted noise, the TTS_2 from impulses appears to be proportional to the number of impulses, as if each impulse produced the same amount of TTS in dB. However, the whole problem of impulse noise is vexed with confusion arising from the unavailability of an apparatus that can produce pulses whose rise-time, duration, and peak level can be independently varied over a large range; experiments from different laboratories can seldom be compared because they differ in more than one parameter.

If exposure is so long or intense that more than 40 dB of TTS_2 is produced, or if even somewhat lower values of TTS_2 have been developed by prolonged intermittent exposure to higher intensities (105 dB and above), recovery neither proceeds in the exponential manner described above nor is complete by the end of 16 hours of rest. Instead, this 'delayed recovery' proceeds in nearly a linear manner – that is, diminishing by a constant number of dB each day. Full recovery may require several days or, in unusually severe instances, weeks. Peyser's (1930) suspicion seems reasonable in this case – namely, that the hazard of incurring PTS will be increased if the auditory system is once again exposed to noise before full recovery has occurred. If this is true, then TTS_2 is probably not an appropriate index of noxiousness. Instead, hazard might better be based on the amount of TTS remaining after 16 hours of recovery.

7.4.6 The CHABA TTS-based exposure limits

Exposure limits based on TTS data were developed in the USA by the Committee on Hearing and Bioacoustics (CHABA) of the National Academy of Sciences (Kryter *et al.*, 1966), by making the assumption that a TTS_2 at the end of the work day will be completely reversible, and hence not hazardous *per se*, provided that it did not exceed 10 dB at 1,000 Hz and below, 15 dB at 2,000 Hz, or 20 dB at 3,000 Hz and above. Using the knowledge about the growth of TTS cited earlier, exposures that just produced those values of TTS_2 were calculated and presented in a very complicated set of charts that specified tolerable durations and levels for continuous exposures or those with various degrees of intermittence.

The CHABA contours for single continuous exposures are shown in Figure 7.6. It can be seen that the contours for two- to eight-hour exposures are enough like the inverse of the A-weighting network (Figure 7.5) that A-weighting has subsequently been widely supported as the best means of reducing spectral information to a single number, even though for shorter exposures, the low frequencies are less hazardous (at least if TTS is an adequate measure of hazard) to an even greater degree than an A-weighted measurement would imply. A series of equal-TTS contours for exposure to intermittent noise was also developed, a different set of contours for each specific octave band.

These CHABA contours proved to be too complicated to gain general acceptance. In addition to the difficulty of interpretation of some dozen charts, doubts were raised as to the adequacy of TTS_2 as a predictor of NIPTS; a given TTS_2 may take longer than 16 hours to recovery (i.e., delayed recovery occurs) if it is caused by short bursts of high-intensity high-frequency noise, and hence must be regarded as more dangerous than the same TTS_2 caused by a continuous exposure at a lower level.

The problem of delayed recovery can be solved by taking into account not only the TTS, but also its duration. Kraak *et al.* (1977) have presented extensive evidence that the integral of TTS over time from onset of exposure to the end of recovery will be a more valid measure of hazard than mere TTS_2. With accumulation of more empirical evidence on the recovery from specific patterns and levels of exposure, a set of contours similar to the CHABA contours, but based on equal integrated TTS, could be established. However, this has not yet been done, probably because the contours would still be as difficult to use as those they will replace.

7.4.7 Simplifying Assumptions: Regulations by Decree

If the complexity of the relation between intermittence of exposure and TTS is so great that it is not judged to be usable in prediction of NIPTS, then another solution is to make simplifying assumptions. Because of the resemblance of the equal-TTS curves of Figure 7.6 to the A-weighting network, almost all bureaucratic agencies concerned with establishment of exposure limits have, in the interests of simplicity, simply decreed that A-weighting shall be used, thus 'solving' the complex problem of differential effects of different frequencies at various levels. Then another arbitrary decision is made: how much NIPTS, as indicated by the data of Figure 7.4, is tolerable, and therefore what eight-hour exposure level is to be the limit. A further simplification can be effected by pretending that it makes no difference whether the daily noise exposure comes in one continuous segment or in bursts, so that effectiveness of a noise can be assessed simply by adding up periods of noise. The final thrust at the Gordian Knot is then administered by postulating some simple relation between level and duration for equal effect, so that an increase in level of some fixed number of decibels must be balanced by a decrease in permitted duration of exposure.

A wide range of exposure regulations, with different standard exposures and trading relations, can be found throughout the world. Even in a single country, several different exposure limits may apply. In the USA, for example, the official (OSHA) standard is a 90-dBA limit for eight hours, a trading relation of 5 dB per halving time, and a prohibition against levels over 115 dBA as measured with an ordinary sound level meter or against peak levels of 140 dB.

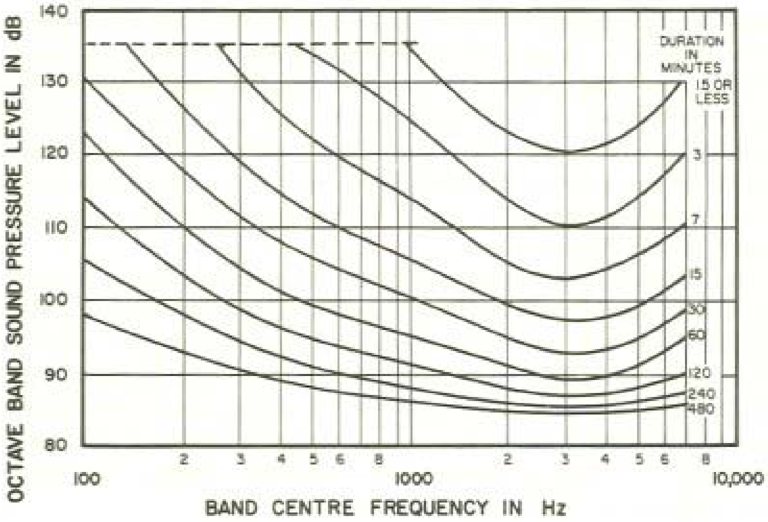

Figure 7.6 CHABA damage-risk contours for single continuous noise exposures. These contours indicate those combinations of octave-band SPL (ordinate), frequency (abscissa) and duration (parameter) that will just produce a temporary threshold shift, measured 2 min after exposure, of no more than 10 dB at 1,000 Hz or below, 15 dB at 2,000 Hz, or 20 dB at 3,000 Hz or above, in the average normal listener. Adapted from Kryter *et al.* (1966)

However, another government agency (NIOSH) is promoting a change of the eight-hour limit to 85 dBA, a suggestion adopted by the US Army, and the Environmental Protection Agency seeks to reduce it to 80 dBA, maintaining that 75 dBA is really necessary to protect everyone against the slightest NIPTS. EPA also believes that the trading relation should be 3 dB per halving of duration, in accordance with a proposed ISO standard. This amounts to simply integrating the sound intensity (after A-weighting) over time, thus calculating total energy. Because of the controversy between the proponents of the 3-dB and 5-dB rules, the US Air Force has adopted a 4-dB rule, beginning at 84 dBA for eight hours (Ward, 1977). It must not be thought that the list of possibilities is yet exhausted: Kraak contends that the best predictor of damage based on measurement of the exposure itself rather than on integration of the TTS it produces, is the integral of the instantaneous *pressure* over time, which leads to a 6-dB trading relation.

All of these simple standards are of course to some extent incorrect; non linear functions cannot be changed to linear ones by executive fiat, although in the case of the total-energy rule (3 dB per halving), that fact is regrettable, because the total A-weighted energy of an individual's exposure can be readily and reliably measured. Indeed, it is because of its simplicity that the total-energy principle has been adopted by ISO, not because there was any good evidence in its favour. Some proponents of the principle go so far as to postulate not only the pattern of exposure during the day is irrelevant, but even that the distribution over the lifetime of the individual can be disregarded in predicting the NIPTS. In such systems, the concept of the 'safe exposure' is non-existent: every erg of acoustic energy that enters the cochlea makes an equal contribution to hearing loss, and the apparent recovery of threshold sensitivity is only illusory.

The simplicity of the total-energy theory is so attractive that there is a real danger that it may be accepted in its most extreme form as just expressed; its supporters point out, correctly, that it errs only by being too conservative. However, the costs of overprotection can be astronomical, especially when, as in the USA, use of hearing protectors is officially regarded as permissible only as a last resort, when it is not 'feasible' to reduce the noise at the source. The urgent need for valid evidence from controlled animal experimentation relative to the effect of intermittence is obvious.

7.4.8 Animal Research on the Total-Energy Theory

Animal experimentation on the effects of long exposures at moderate levels is not very exciting, so data are only slowly beginning to accumulate. It is already clear, however, that the total-energy principle is not correct, just as one would predict from the behaviour of other biological systems. For example, a 220-min exposure of chinchillas to a particular noise produced markedly less PTS and cochlear destruction when the exposure came in the form of 22 10-min exposures administered twice a week rather than a single uninterrupted exposure (Ward and Turner, 1980). However, one such datum is not sufficient to establish any sort of simple rule by which the true hazard of any particular pattern can be predicted. It may turn out, of course, that the total-energy principle can be used as the basis for predicting the effect of single uninterrupted exposures, regardless of length; indeed, the animal experimentation just cited showed that the same NIPTS and cochlear damage as that caused by 220 min at 112 dB SPL was produced by 2,200 min at 102 dB, by 22,000 min at 92 dB, and by 220,000 min (150 24-hour days) at 82 dB. But in order to be useful in predicting the effect of repeated exposures, the effective total energy must be adjusted by applying some sort of correction factor. It can only be hoped that such a system of correction factors, when finally determined, will be sufficiently simple that it will be accepted and used.

7.4.9 Critical Intensity

The same chinchilla study also showed that at some 'critical level' the amount of damage increases precipitously (Ward *et al.*, 1981). When the intensity level was 120 dB for a 22-min exposure (which therefore contained somewhat *less* energy than the 112-dB 220-min exposure), the cochlear damage increased from about 10% hair-cell destruction to 70%, and the NIPTS from about 20 dB to more than 50 dB. This change illustrates what has long been termed the 'critical intensity', an intensity somewhat lower than the critical intensity for impulses mentioned earlier. Although the underlying physiological explanation of the phenomenon is not clear, it is generally presumed that it represents the point at which damage changes from being primarily metabolic to primarily structural — from a problem in depletion of energy stores or a build-up of toxic products to one of mechanical damage to the organ of Corti, damage that may permit the intermixing of perilymph with endolymph, a situation that appears to be toxic to hair cells. This critical level is not completely independent of duration, however, as incorrectly assumed by the earlier theorists in this area. Considerable work remains to be done in defining critical levels for particular doses for both continuous and impulse noises in a variety of animals if there is to be any hope of generalizing the results to man.

4.10 Summary

At present then, the curves of Figure 7.4 indicate the only reasonably certain relation between noise exposure and resultant hearing loss, a relation that is specific to eight-hour exposures to continuous noises having average spectral characteristics. If the exposure is intermittent instead of steady, less NIPTS will be produced, although it is not yet clear how much less hazardous a particular pattern of intermittence will be. On the other hand, if the energy of the noise were all concentrated in the 3-kHz region, considerably more NIPTS would be generated. Eventually the results of animal experimentation may permit development of more accurate predictors of damage; in the meantime it must be remembered that any schemes that use a simple relation between exposure and loss, such as the total-energy or total-pressure theories, cannot be correct.

7.5 INDIVIDUAL SUSCEPTIBILITY

The foregoing discussion has dealt with averages. However, average results seldom occur in individuals, and the present situation is no exception. Even in a population of workers of the same age, whose work exposure histories are known and nearly identical, the HTLS, and so the inferred NIPTSs, will vary over a wide range. No matter how innocent the noise exposure history, there will always be some individuals with severe losses; conversely, even among a group of boilermakers, someone will have completely normal hearing even though he has never used ear protection. Some of these differences, of course, can be ascribed to differences in nosoacusis and sociacusis, and to errors in estimating exposure. However, no one doubts that individual differenes in susceptibility to hearing loss also play a large role.

7.5.1 TTS Predictor

Unfortunately, susceptibility is still little more than a *post-hoc* hypothetical construct. Although one can have faith that such characteristics as the size of various elements of the ear, the mass of the ossicles, the stiffness of the cochlear partition, and the density of cochlear blood vessel contribute to susceptibility, few such indices can be measured in the intact organism. Some 50 years ago, Temkin (1933) reasoned that the same factors that determine susceptibility to PTS should determine susceptibility to TTS. For the next 40 years a 'TTS-test' was sought that would predict 'susceptibility to PTS'. It was finally realized that this was a hopeless quest because the ear most susceptible to TTS from high-frequency noise was not necessarily the most susceptible to low-frequency noise, and neither of these bore a significant relation to susceptibility to TTS from impulse noise. Accordingly, the search for a test of 'overall' susceptibility has largely been abandoned; it has become clear that the only likely candidate for a successful susceptibility test based on TTS is one that involves an exposure to a noise having the same spectrum as the noise to which the individual will be primarily exposed at work. Such tests are being given in some industries; Kraak *et al.*, for example, cite a thesis of Richartz in which the integral over time of TTS (during both growth and recovery) produced by the first day of work in an actual industrial environment was used as the TTS index, successfully predicting PTSs produced by two years of work. Temkin may eventually be proven correct after all.

7.5.2 Drugs and Chemicals

Obviously there are certain conditions under which susceptibility — even in the global, general, sense — can be affected. Noise exposures that cause no damage in the normal experimental animal may have a pronounced effect when the animal is being administered ototoxic drugs (e.g., kanamycin, neomycin) at dosages that are, by themselves, subtoxic. It also seems likely that the ear's resistance to PTS could be reduced by certain mineral and vitamin deficiencies, or by illnesses that affect the blood-flow to the cochlea or produce a biochemical imbalance in the auditory system. However, the evidence relating to this topic is either anecdotal or so inferential that little confidence can be placed in its validity.

The same is true of medications administered in hopes of decreasing susceptibility or hastening the process of recovery from exposure. Although the literature abounds with articles extolling the virtues of vitamin A, nicotinic acid, procaine, nylidrin, adenosine triphosphate, brain cortex gangliosides, carbogen (95% oxygen, 5% carbon dioxide), and dextran, to name a few, in the treatment of acoustic trauma, there is still no convincing evidence that a placebo would not produce just as much effect as any of the substances cited (Ward, 1980). The most recent example of negative results can be seen in a report by Eibach and Berger (1980) involving more than half a dozen of these substances.

7.5.3 Miscellaneous Factors Affecting Susceptibility

Women usually have average Hearing Levels that are slightly better than those of men working in the same noise environment, as Figures 7.1 and 7.2 imply. Although this could mean that women have 'tougher' ears than men, alternative explanations are equally tenable — i.e., that women are exposed to less sociacusic influence, or that they have a higher absentee rate (hence, less exposure), or that they are freer to quit a job that involves noise so loud that it bothers them. Only if these possibilities are eventually excluded by proper controls should we conclude that only women should be hired for noisy jobs.

The same line of argument applies to reports of differences between workers with brown eyes and those with blue, and between black and white workers. Although melanin in the cochlea may have something to do with susceptibility, equally likely alternative explanations exist.

There is also little evidence that very young or very old ears, or those already damaged by noise, are especially susceptible. Similarly, no convincing experimental support exists for the notion that the auditory systems of those who work in noise gradually become 'toughened' and so less susceptible. On the other hand, it has been clearly demonstrated that middle-ear problems, such as chronic otitis media, generally reduce the transmission of energy to the cochlea and so reduce 'susceptibility' in the same way as earplugs.

7.6 SUMMARY

No index of noise exposure has been devised that can succinctly characterize the relative noxiousness of different noise exposures. Although, on the average, the threshold limiting value (TLV) for measurable damage from steady industrial noise is about 85 dBA for an ordinary eight-hour exposure, the relative hazard associated with briefer or interrupted exposures cannot yet be determined. Even the eight-hour TLV is questionable because of the impossibility of eliminating sociacusic and nosoacusic influences from the data on hearing loss in industry. Prospects are dim for identifying individuals, in advance of employment in noisy industries, who are unusually susceptible to permanent hearing loss by means of any index based on temporary threshold shifts.

A vast amount of data has been published on NIPTS, but most of it is scientifically useless. Furthermore, although an extensive fund of information exists on the temporary effects of noise, the relation between temporary and permanent effects is still unknown. Finally, since no satisfactory method of characterizing noise exposures has been devised, we are in the uncomfortable position of having an undefined independent variable, a non-dependable dependent variable, and many potent irrelevant variables.

It appears that the only viable solution is to continue intensive studies of the development of NIPTS in animals whose environments can be subjected to the necessary strict control, and hope that the results can legitimately be generalized to man by appropriate corrections for differences of species. Only then can a realistic criterion for control of exposure to noise be developed —one that is stricter than the present standard, which permits the development of significant hearing losses in the more susceptible individuals, and yet not as strict as limits advocated by anti-pollution activists who fail to realize that 'noise pollution' differs from air and water pollution in that, although our stomachs were not designed to digest mercury compounds nor our lungs to absorb sulfur dioxide, the normal function of our ears is to process sounds.

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CHAPTER 8

Non-auditory Effects of Noise: Physiological and Psychological Effects

GERD JANSEN AND ECKHARD GROS

8.1 INTRODUCTION

Physiologically adverse noise effects (e.g. alterations in the peripheral blood circulation) still pose the question whether noise causes extra-aural diseases besides noise-induced hearing loss. This question can not be answered in the affirmative until now. However, noise was found a health hazard in combination with other stressors.

Regarding the psychologically adverse noise effects, it is to be said that the stressor noise mainly affects performance and detracts from people's individual and social wellbeing. *Direct* noise effects are disturbances in auditive and non-auditive performance, communication, information-processing, rest and relaxation. *Indirect* noise effects are impairment of people's wellbeing: windows have to be closed, people reduce their speech communication or refrain from it, they change their dwellings or dwelling areas. Various social-scientific investigations harmonize in a high degree in their result regarding the quantity of environmental noise pollution and ensuing main psychic effects (comprised by the term 'annoyance').

The presented noise effects are to be seen as mean reference values fluctuating in dependence on the individual's characteristics. Application of moderator variables can considerably improve the accuracy of predictability of noise effects.

Acoustical-defined guidelines and limit values are intended to protect the average population. Allowances have to be made therefore, for critical groups who need special protection due to their enhanced sensitivity to noise.

8.2 PHYSIOLOGICAL EFFECTS OF NOISE (Gerd Jansen)

Besides the affections to the inner ear, some other vegetative and physiological effects of noise are known (Welch and Welch, 1970; Jansen, 1972). The question is: Can these physiological effects already occur below the level at which noise-induced hearing loss is to be expected? This question is definitely to be answered in the affirmative. At sound levels of 50 and 60 dB(A) vegetative responses can already be observed. First reactions become manifested by monitoring electroencephalographic (EEG) responses even at 35–40 dB(A) (evoked potentials).

Do these reactions already signify illness? This question has concerned us for a long time. Before going into the details it can be stated: Hitherto no noise-induced trauma — in addition to hearing loss — has been found and there is no indication that a 'noise-disease' exists (cf. WHO, 1980).

But how is the dilatation of the pupils to explain what is shown in Figure 8.1? Strictly speaking, this is a 'reaction' only. Every organism has to stand some stress day after day and reacts to the stressors. Even to get out of bed is stress! From the responses can be learned that certain physiological processes take place. In response to a sound stimulus the pupils dilate. Other investigations have shown that the activity of the salivary as well as the perspiratory glands becomes affected. Also the peripheral circulation, the gastric-intestinal movements, liquor pressure and many other functions have been proved affectable by noise (summarized by Jansen, 1980). But in all these cases we can only speak of 'reactions' and not of 'diseases'. Of course, there is another question: Bearing in mind the range of sound levels which cause hearing loss — would not, nevertheless, the physiological effects of noise signify illness if there were not already a noise-induced hearing loss? For, hearing loss protects the organism in a certain degree from the transmission of sound energy, thus preventing it from obvious physiological responses.

At present, it can already be stated that noise below the threshold value of 90 or 85 dB(A) cannot be proved to be a health hazard. Yet it would serve our purpose to have an objective criterion which could be used as a reference measuring value. Thus, we could find out whether there is any quantity to recommend for the determination of an approximate value. If there were levels of risk below the threshold value which is given to protect people from noise-induced hearing loss we would not have to investigate this problem any more, as an unacceptable level or a limit of unreasonableness would have been established long ago. But that is not the case.

Another noise-related effect is the affection of the peripheral circulation. Figure 8.2 illustrates the effects of an artificial sound. At rest circulation is normal. Application of broad-band noise results in a reduction of blood supply which is to understand as vasoconstriction. The physiological response to noise ends simultaneously with noise exposure. The degree of circulation disturbances depends on the different noise sources, for example, straightening machine for small iron parts, pressing of a pneumatic hammer, noise of turbines and broad-band noise. In all these cases the responses are rather

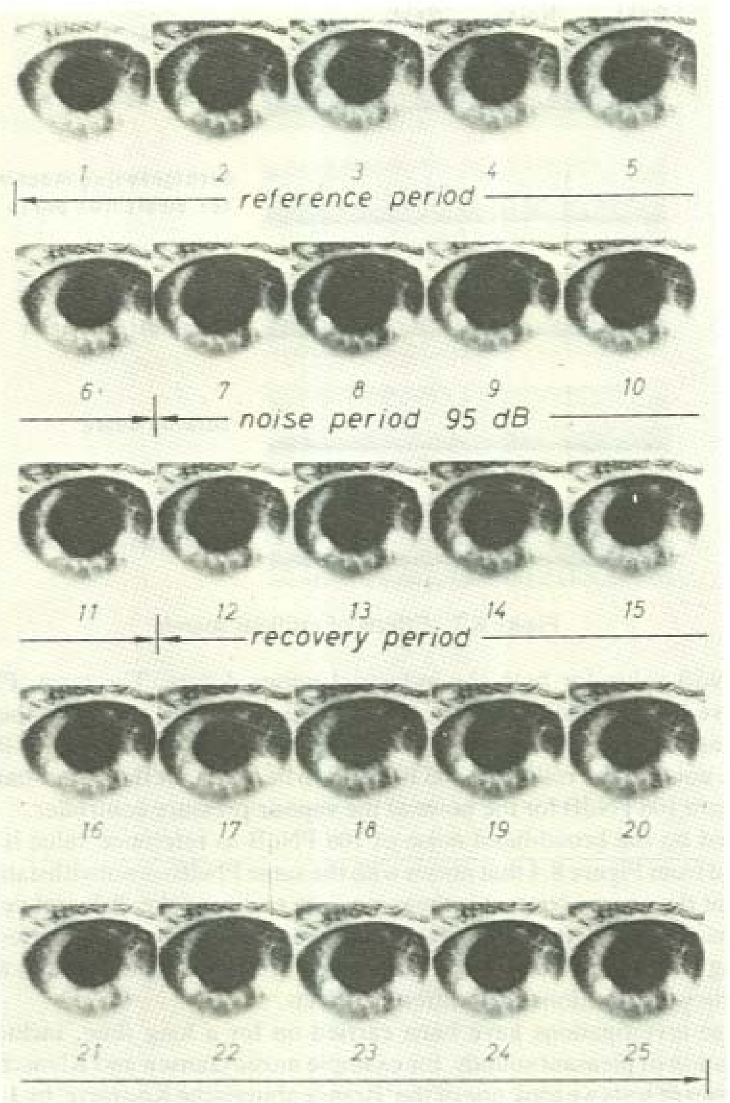


Figure 8.1 Original photograph of pupil

similar. By that the question arises, are all the mentioned different noise sources of the same effectiveness or is there still a differentiation possible?

In the beginning of our studies on noise we tested already the effects of three noises in comparison namely, broad-band noise, and those emanating from a rolling mill train and a vapour-pressure controller of a turbine-driven ship. These noises, demonstrated in Figure 8.3, are of the same energetic content but

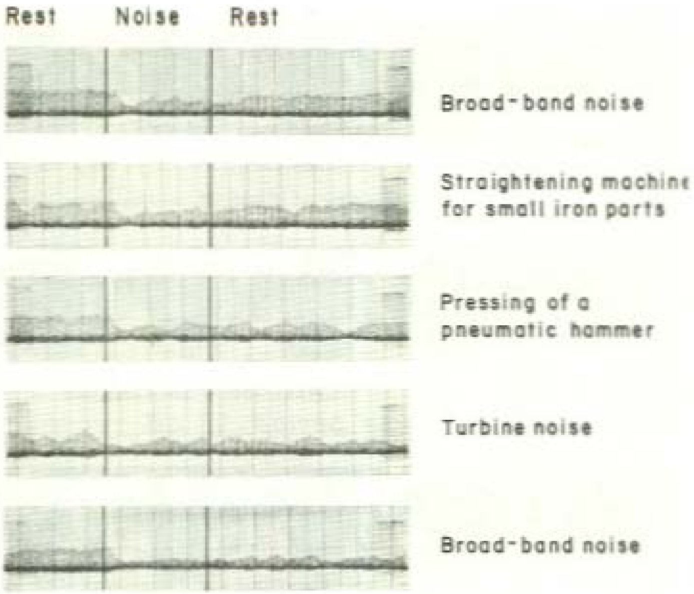


Figure 8.2 Effects of artificial sounds

the PNdB-value for both the industrial noises differs. The term 'PNdB' = Perceived Noise Decibel was proposed by Kryter (1970) to denote the level at which annoyance arises from the perceived noiseness. If we assume 100 PNdB for the noise of the rolls then 108 PNdB is to be taken for the broad-band noise and again 108 PNdB for the noise of the vapour-pressure controller.

Based on the broad-band noise of 108 PNdB as reference value it is to be learned from Figure 8.4 that noises with the same PNdB — notwithstanding the fact that the energy content is the same — in reality evoke different vegetative responses. Hence, it can be stated that what we know about noise-induced hearing loss is also true for the physiology of noise effects namely, different frequency distributions elicit different effects.

These investigations have been carried on for a long time, including the application of pleasant sounds, for example music (Jansen and Klensch, 1964). In a series of tests we took one of the 'Brandenburgische Konzerte' by J. S. Bach and at the same time made our measurements (Figure 8.5). Here it is also illustrated that sound levels of about 90 dB(A), independently whether they emanate from music or broad-band, have the same general effect on the cardiac output (supplied blood volume per heartbeat), pulse frequency, minute volume and blood pressure; but there are, nevertheless, some differences. The effect of music is, as a rule, not so considerable. The blood pressure, for example, shows a slight increase under the influence of broad-band noise but such an increase is scarcely recognizable if music is the stimulating sound.

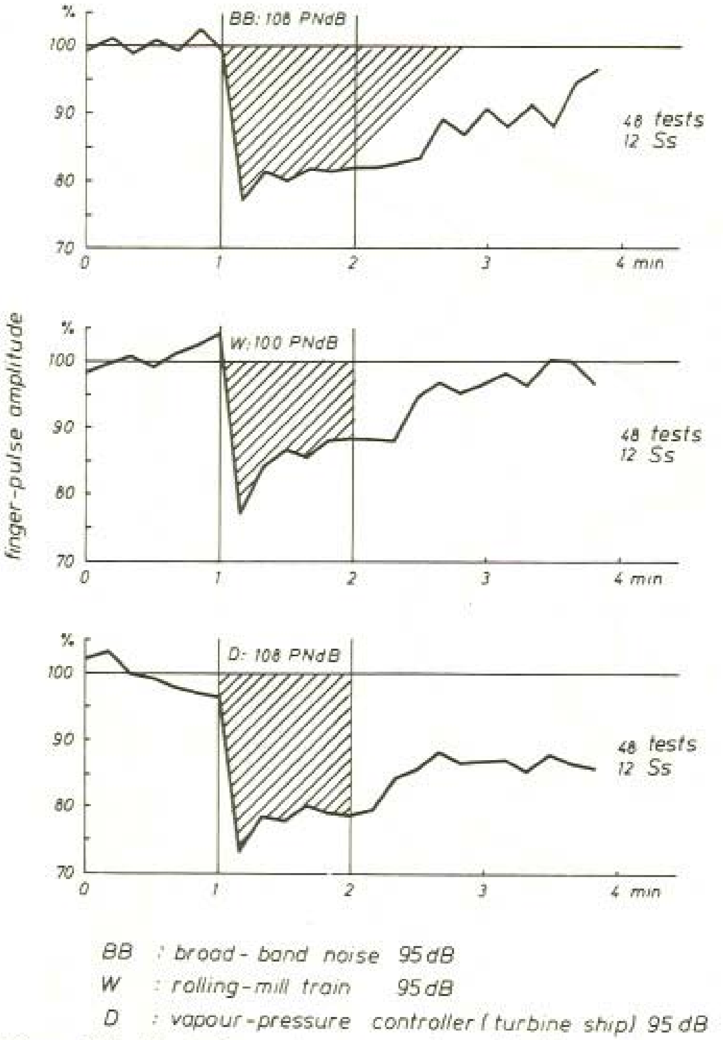


Figure 8.3 Vegetative responses to noises with different frequency spectrum

We examined not only the effects of music but also those of everyday noise, traffic and aircraft noise as well as noise with Doppler-character (change from high to deep sounds and vice versa, simultaneously becoming louder or lower). We applied, also, the so-called 'wobble-noise' and it became again evident that the responses differed, but were partly dependent on the psychological constitution of the subjects. Figure 8.6 shows at the right a column 'information bearing, 95 dB'. In that case the applied sounds were of industrial origin or gave a feeling of annoyance. In consequence of psychological tests the subjects had

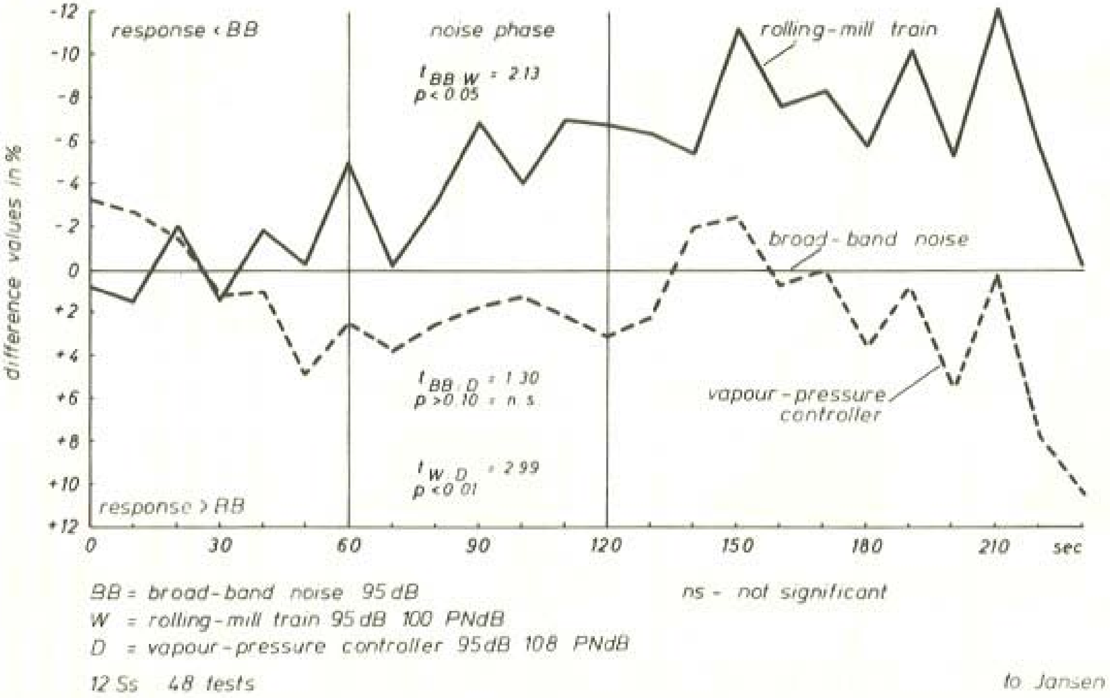


Figure 8.4 Differences between the values of the PNdB test series

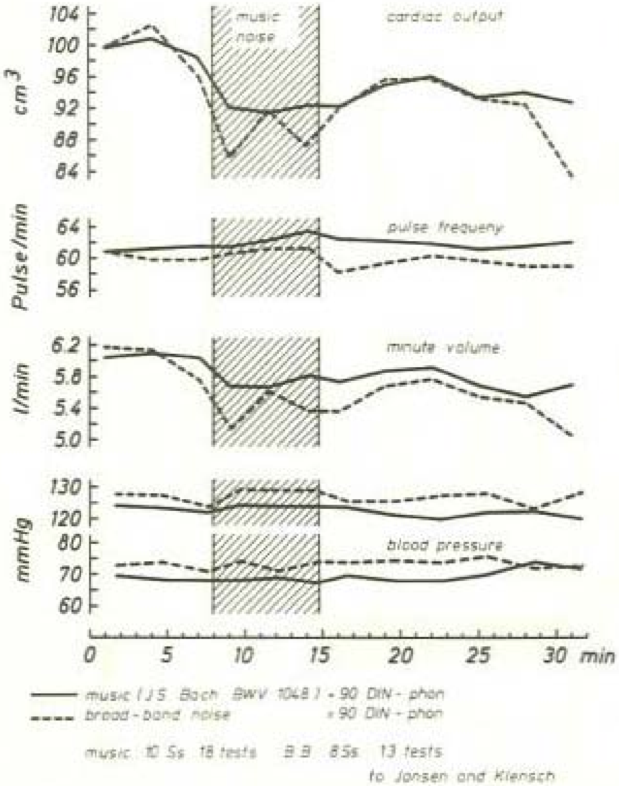
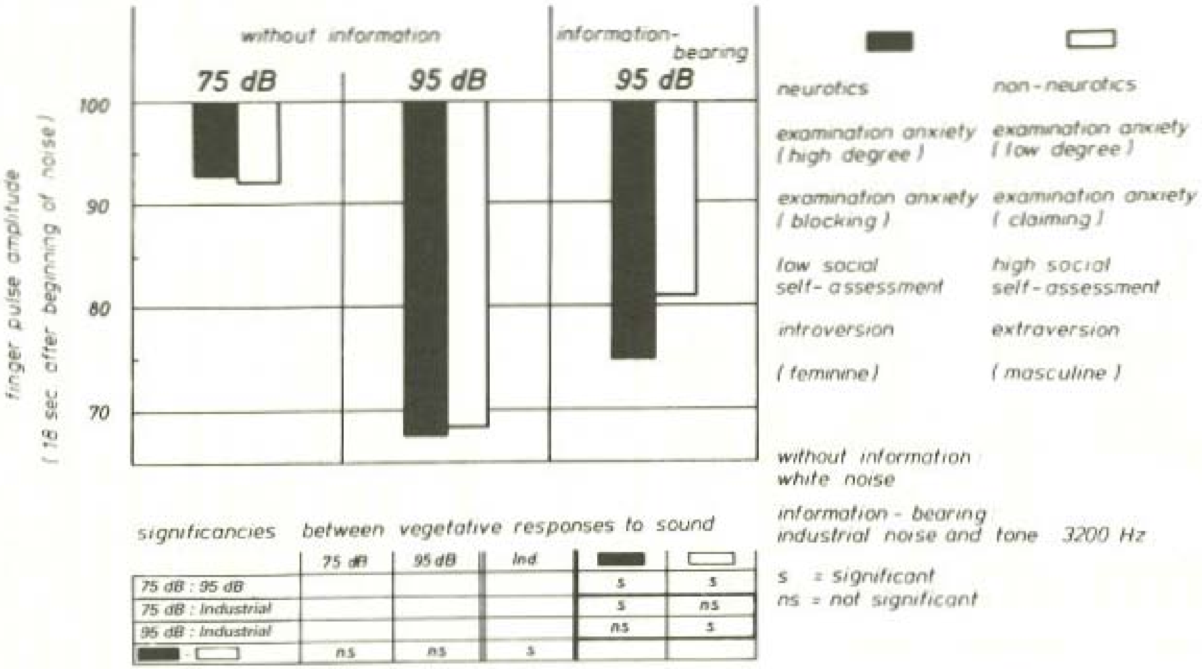


Figure 8.5 Peripheral blood circulation at music and noise

been divided in two groups namely a so-called 'labile' and a 'stable' group (neurotics and non-neurotics). Both types of human beings are always easy to find in populations. There are people really unaware of noise (e.g. seamen who sleep in their cabins being exposed to 90 dB(A)) whereas others wake-up at the slightest sound (for example, when a lorry passes in the distance). Such people are extremely sensitive and — as is to be seen in Figure 8.6 — they are the 'labile' group who, in fact, shows the stronger physiological responses to information-bearing noises.

This cannot only be proved by the finger-pulse amplitude but also by some other vegetative responses. The responses are similar if music is offered as the sound stimulus. Here again the 'labiles' respond intensely whereas the 'stables' are, one could say, not at all responsive. The subjects exposed to music and noise (shown in Figure 8.5) are categorized in the 'stable' group. This evidence shows that the frequency distribution nevertheless plays a role.

What we have observed is that some subjects who have been exposed to broad-band noise as well as industrial noise daily for weeks and years always



significancies between vegetative responses to sound

	75 dB	95 dB	Ind	■	□
75 dB : 95 dB				s	s
75 dB : Industrial				s	ns
95 dB : Industrial				ns	s
■ - □	ns	ns	s		

Figure 8.6 Personality traits and vegetative responses to noises without information and with information-bearing ones

showed the same reactions. The same music or information-bearing noises induced in the beginning different responses in stable and labile persons. But these differences disappeared in the course of time. Those, who showed in the beginning strong reactions to information-bearing noises have reacted less intensely after a certain time. Afterwards, both groups were similar in their responses. This behaviour emphasizes that the more the habituation to a certain noise the less the information taken from it, and the physiological responses become balanced for both groups (compare Figure 8.6, the respective pairs of columns). However this is only true for intensities above the level of noise-induced hearing loss.

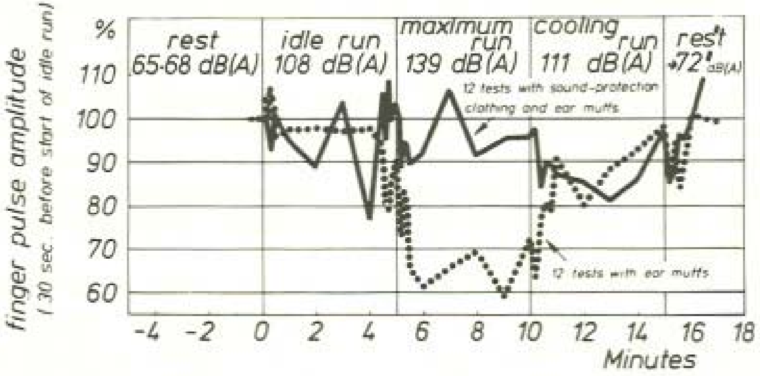


Figure 8.7 Finger pulse amplitude in jet-engine test-drive using noise protection

More distinct effects manifest themselves if the noise-induced hearing loss level is widely exceeded. Figure 8.7 relates to mechanics who had been engaged in maintaining jet-engines when test-drives took place. The typical working situation is depicted, after rest (65–68 dB(A)), the turbines are set in motion, the 'idle-run' results in a noise of 108 dB(A), this ascends to 139 dB(A) in the 'maximum-run', then lowers to 111 dB(A) in the 'cooling-run' and returns again to the rest situation. This procedure has to be carried out by the test-mechanics three to four times daily all the year round.

The mechanics were furnished with ear-muffs as well as with sound-protective clothing, but they were not willing to wear the clothing. The sickness rate of the test-group was about 50%, resulting from diseases of the gastric-intestinal system (from gastritis to ulcers) as well as headaches associated with migraine. From this we can conclude that the physiological reactions to noises below the critical levels – i.e. 50, 60, 70 and 80 dB(A) – gradually develop to illness-causing responses at the moment when the level of 100 dB(A) is not only exceeded but reaches such extreme values as are reported here. It has to be mentioned that 50% of the mechanics who had been subjected to extremely high levels did not show any alteration in their physical condition.

The dotted line in Figure 8.7 demonstrates the peripheral circulation of the subjects when earmuffs with an effective attenuation of 30 to 35 dB(A) were used. This means, when the attenuation effect of the earmuffs of about 30–35 dB(A) has been deducted from 139 dB(A), 105 dB(A) still remain. If sound-protective clothing is worn, the noise effects, shown by the normal line in Figure 8.7, could be nearly eliminated.

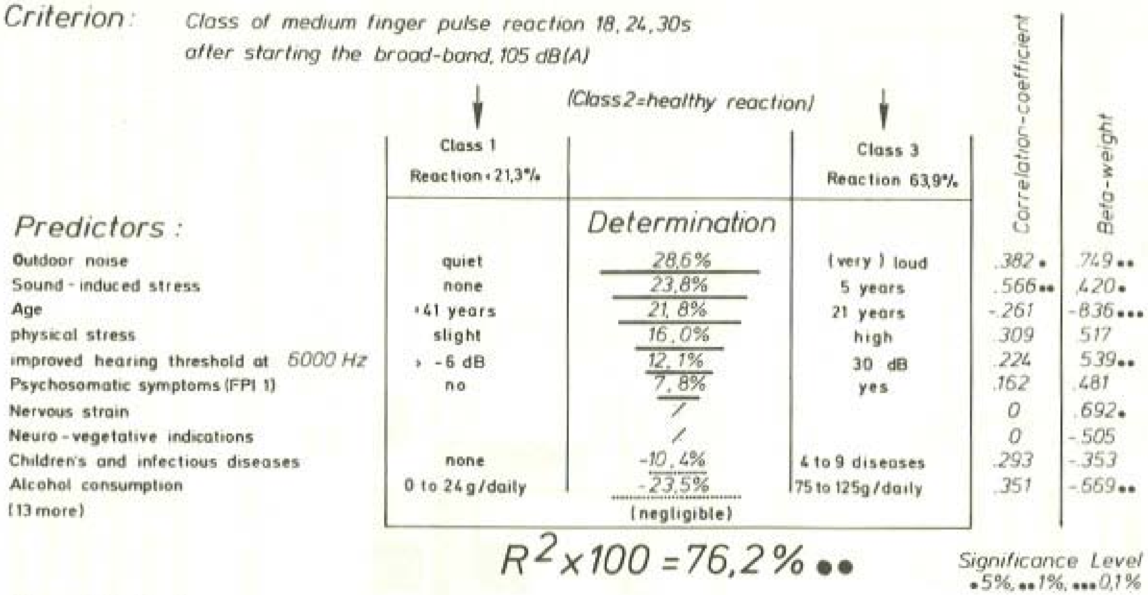
We have carried out additional investigations which provided evidence that the internal organs can be affected directly by noise (cf. Döring *et al.*, 1980). Using an underwater loudspeaker to direct sound waves of 90, ascending to 150 dB(A), to isolated pieces of intestines it was found that no gastric-intestinal movements took place at the upper level. Returning to the example of the test-mechanics, assuming 105 dB(A) to be conducted by the ears but at the same time also directly absorbed by the organism (the mechanics do their job only dressed with loose shirts in summer which means that their whole organism is exposed to the noise). It is suggested that this might contribute to the aforesaid incidence of sickness. Consequently it can be stated that a risk to health only begins at very high noise levels, independent of the kind of noise. The noise effect is definitely of a physiological nature and depends exclusively on the noise level.

It may be added that we have tried to find out whether the predictors, shown in Figure 8.8, were really the factors which had caused the diseases in a group of sick people. The most important predictors were: outdoor noise level (people are exposed to high-noise levels in their recreation time), high-noise levels originating from jet engines at the workplace, age, physical stress, hearing threshold, psychosomatic symptoms and so on.

Three-fourths of all the health impairments could be attributed to the above mentioned predictors.

What matters now is whether, in cases where noise is a health hazard, other factors can also be held responsible for these physical impairments. The conclusion is justified: besides noise-induced hearing loss noise can never be the only cause of physical impairment! In connection with our test group it is undoubtedly correct to say that noise was the main factor in their physical impairment, since noise influences in their private life and noise-induced stress at their workplace had been the most considerable predictors out of the whole range of environmental stressors.

But in normal cases there exist other exogenous factors besides noise, namely vibration and dust, climate, toxic agents, etc. (Figure 8.9), which affect human beings and elicit reactions, additionally or in combination, moderated by individual constitution, disposition and motivation. There are also a number of other psychological factors which have played their part in the case of the jet-engine mechanics who felt the stress due to noise to be the main cause for their physical impairments namely, psychosomatic symptoms and stress in their private life.



Criterion: Class of medium finger pulse reaction 18, 24, 30s after starting the broad-band, 105 dB(A)

(Class 2=healthy reaction)

Predictors:	Class 1 Reaction <21,3%	Determination	Class 3 Reaction 63,9%	Correlation-coefficient	Beta-weight
Outdoor noise	quiet	28,6%	(very) loud	.382 •	.749 ••
Sound-induced stress	none	23,8%	5 years	.566 ••	.420 •
Age	<41 years	21,8%	21 years	-.261	-.836 •••
physical stress	slight	16,0%	high	.309	.517
improved hearing threshold at 6000 Hz	> -6 dB	12,1%	30 dB	.224	.539 ••
Psychosomatic symptoms (FPI 1)	no	7,8%	yes	.162	.481
Nervous strain		/		0	.692 •
Neuro-vegetative indications		/		0	-.505
Children's and infectious diseases	none	-10,4%	4 to 9 diseases	.293	-.353
Alcohol consumption	0 to 24 g/daily	-23,5%	75 to 125g/daily	.351	-.569 ••
(13 more)		(negligible)			

$R^2 \times 100 = 76,2\%$ ••

Significance Level
• 5%, •• 1%, ••• 0,1%

Figure 8.8 Evaluated reaction of the finger pulse amplitude to sound as well as variables of stress and the general physical constitution

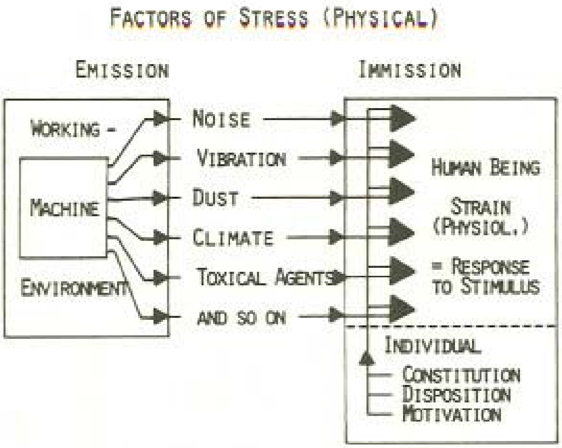


Figure 8.9 Stress due to environmental factors

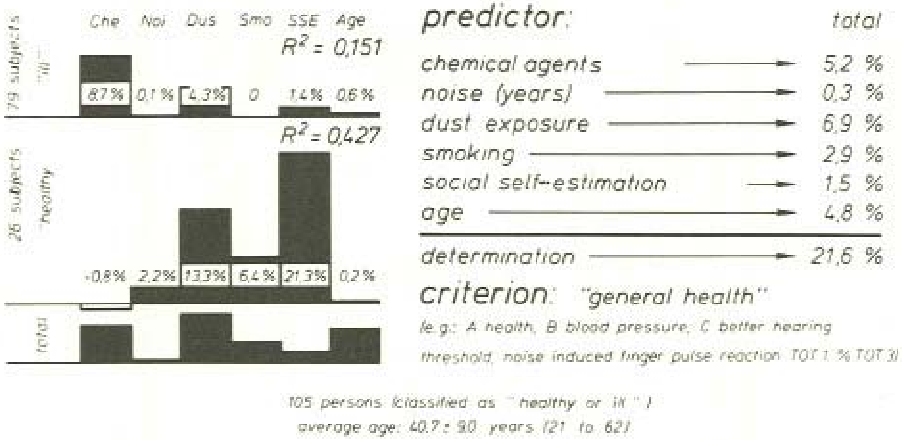


Figure 8.10 Different exposure factors and 'general health'

Figure 8.10 illustrates experimental-analytical and epidemiological investigations (Jansen *et al.*, 1981). A group of industrial workers was examined with regard to the toxical agents they have been exposed to, the years of their noise exposure, airborne dust at their workplaces; but, also, with regard to other factors of risk, namely smoking habits, social self-estimation and age. As Figure 8.10 shows, only 20% of the physical impairments in these workers (who had been exposed to an average noise-level at work of 90–115 dB(A)) were due to the afore-mentioned predictors. Airborne dust was most detrimental to their health and the noise exposure was of much less consequence.

From that it can be inferred that the question about noise effects and the valence of the different noise sources cannot be answered clearly and precisely. The individual noise sources can have a certain effect relevant to health or no effect to health at all. But we have to consider the large number of further predictors in human beings and their surroundings. Psychological and sociological factors have to be taken into account. This leads to the problem of the psychological effects of noise.

8.3 PSYCHOLOGICAL EFFECTS OF NOISE (Eckhard Gros)

Information theory uses the following three terms to describe the information-exchange process:

Emission — Transmission — Immission

A similar pattern is used by Psychology to explain human behaviour and sensations:

S(stimulus) — O(organism) — R(reaction)

To understand the psychological effects of noise the following three main factors have to be considered as a whole:

S(noise stress) — O(organism) — R(noise effects)

The factor 'organism' covers a complex system namely, processing of information, habits and attitudes as well as important personal and/or situational characteristics. Figure 8.11 shows the combined action of stress and strain with special regard to the so-called moderator variables. A moderator variable is operationally defined as a quantity of influence, at first unknown, between stress and strain. It can decisively determine the intensity of the reaction to strain without being directly connected with the occurrence of stress (cf. DFG, 1974). In the following, the psychological effects of noise are considered and the influence of moderator variables is taken into account.

8.3.1 Interference with Human Performance and Behaviour

Performance alteration due to noise is the most controversial topic in the field of research on noise effects (cf. Broadbent, 1979; Burns, 1973; Gulian, 1973; Kryter, 1970; Miller, 1974; Poulton, 1979). The relevant scientific literature renders both, reports which prove that performance increases under the influence of noise and such which maintain just the contrary. Others, however, could not find any effect on performance at all (summarized by Loeb, 1980).

The two extremes on a two-point scale could be presented in a simple manner by discussing the positions of two eminent noise researchers. Kryter (1970) is of the opinion that noise has a rather positive effect on performance

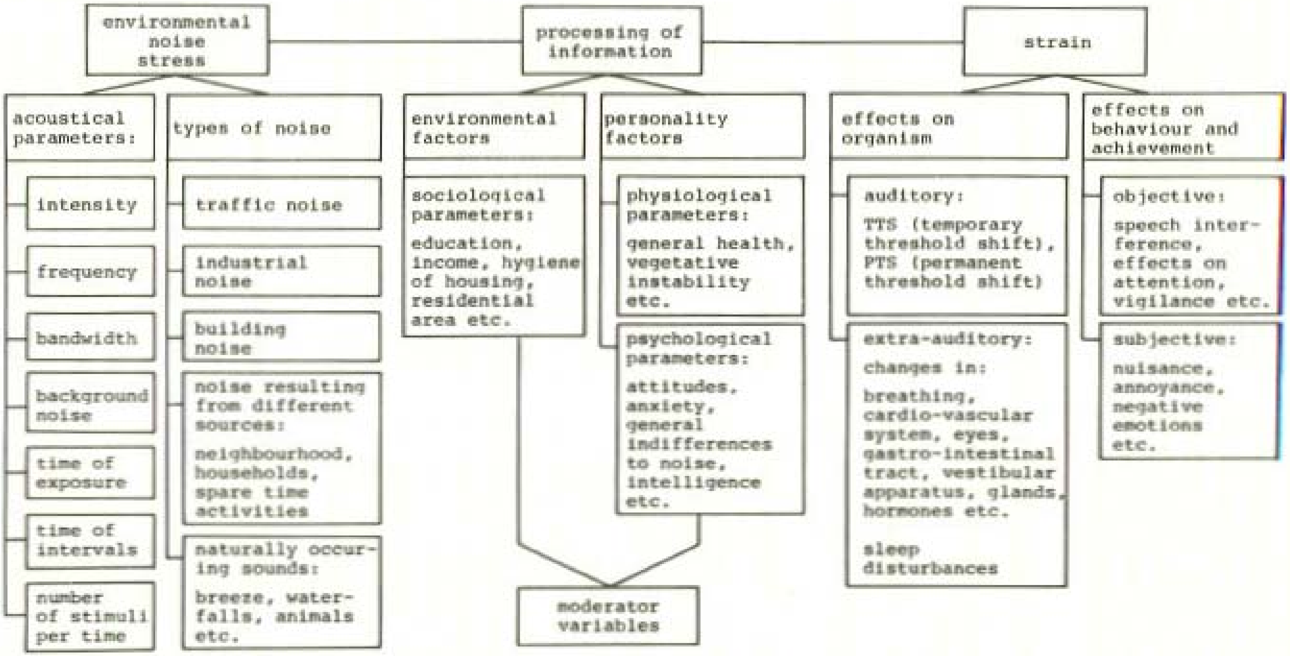


Figure 8.11 The relationship between stress and strain with special regard to moderator variables

whereas Broadbent (1971) thinks that performance is affected quite negatively by noise. A possible explanation of this problem seems to be the different use of the term 'performance': The most varied forms of reaction (e.g. control activity, opportunity to choose, rapidity of reaction, learning achievement, memory training) are all defined as 'performance' or 'achievement'.

A possible criterion for splitting up the comprehensive term 'performance' is, for example, to separate from it the part of intellectual activities. In the determination of sound-level threshold values, that ensure an undisturbed performance, the specific kind of activity should be taken in consideration, as was emphasized for example by Schönpflug and Schulz (1979):

- —Sound levels higher than 90 dB(A) will, as a rule, lead to a drop in performance and a decrease in wellbeing *at activities of any kind*. Below this level, however, the reasonableness will largely depend on the kind of work to be done. Even very low noise levels (below 55 dB(A)) can produce disturbances
- —Threshold values are to be set on particularly low in case that the task to perform
  - —makes high demands on worker's intellect (e.g. planning activities),
  - —makes high demands on worker's functions of memory,
  - —if the worker lacks practise.

The kind of work to be done under the influence of noise was also taken into consideration when a guideline was established in the Federal Republic of Germany: 'Assessment of Noise in the Working Area with Regard to Specific Operations (VDI-Guideline No. 2058, Part 3, 1981)'.

There are three sound-level classes depending on specific activities: the highest permitted noise levels at the work-place, including the disturbing outdoor noise that pours in, are (see VDI 2058, Part 3, 1981):

- —55 dB(A) if the intellectual part of work predominates (e.g. if activities demand intense concentration, creative thinking, or if decisions of consequences are to be made),
- —70 dB(A) if uncomplicated or partly mechanized office work is to be done (or similar activities),
- —85 dB(A) at all other activities.

Jansen & Klosterkötter (1980) contributed — in cooperation with some other renowned scientists of different faculties — to the clarification of the varied explanations of noise and its effects. They found the most frequently explanations in case of alterations in performance to be the following:

1. Distraction and/or reduction in attention.
2. Prolonged reaction time, simultaneously resulting in a slow-down of physical and mental processes.

3. Changes in aspiration level.
4. Increase in readiness of risk-taking behaviour (in connection with speeding up of mental processes).
5. Increase in the general activity of the organism (psychophysiological activation) connected with a decrease in discrimination ability and increase in interference.

Summing up, the authors stated that, generally, all the physical and mental performances can be affected by noise with regard to their quantity (e.g. volume, speed) as well as their quality (e.g. grade, frequency of errors). Impairment of performance will be the more likely, the more complex, difficult and timeconsuming the activity necessary is to achieve the result.

Figure 8.12 shows a rough pattern based on the sound level. In the individual case, there can result shifts from specific characteristics of personality and situation. A coincidence of some of these characteristics can lead to effects that exceed the sum of the single effects.

Sound level in dB(A) measured during test		Effects observed
–70	↓ Shifts due to supervening specific characteristics of personality and situation ↑	Substantial and lasting decrease in performance infrequent
70–85		Increased probability of decrease in performance with high need for achievement; compensation possible
85–100		Increased probability of substantial decrease in performance; compensation more difficult
Higher than 100		Substantial and lasting decrease in performance to be expected

Figure 8.12 Sound levels and effects on performance

With regard to the pattern shown in Figure 8.12, Jansen and Klosterkötter (1980) especially drew the attention to the fact, that allowances have to be made for both, the differences between the individuals (inter-individual differences) and the varying responses in one and the same person depending on the time (intra-individual variability).

According to Jansen and Klosterkötter (1980), the individual differences are to be attributed to the following factors:

- —individual excitableness and sensitivity,
- —individual proneness to being disturbed, distracted, as well as lability,

- —individual performance capability (as determinant of the task-inherent difficulty),
- —individual attitude towards the noise and the noise source,
- —degree of achievement motivation.

The compensation of noise effects, also mentioned (see Figure 8.12) (by increasing motivation, for example) can in itself produce adverse effects (psychic costs).

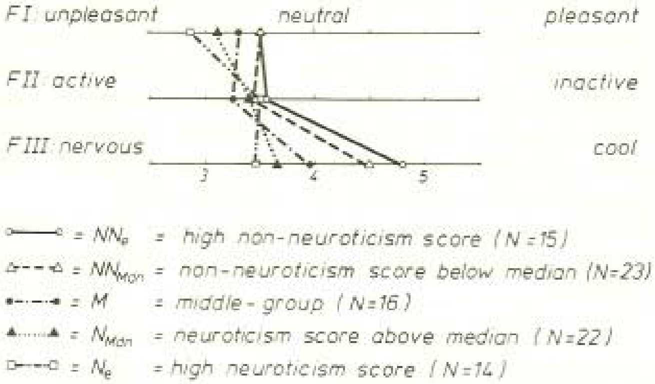


Figure 8.13 Noise-ratings, judged by various subgroups

Besides the influence quantities, with regard to sound level and kind of activity, individual's characteristics play an important part. Jansen and Hoffmann (1965, 1973) studied, for example, the subjective mood as well as changes of handwriting-pressure under different noise situations in dependence on the personality factor neuroticism. The noise situations contained: white noise 75 and 95 dB, octave-band noise 95 dB (mid-frequency 3,200 Hz), third-octave-band noise 95 dB (mid-frequency 3,200 Hz), and pure tone 95 dB (3,200 Hz). Judging noise situations by means of adjective scales it was proved that increasing loudness caused increasing annoyance. The concept of annoyance consisted of three dimensions; emotional factor (pleasant–unpleasant), activity (active–inactive), and tension (nervous–cool). The negative judging of noise was intensified by the personality factor neuroticism (see Figure 8.13). Handwriting-pressure tests showed a noise-induced drop in handwriting pressure. The effects of narrow-band noise exceeded those of broad-band noise. Thus neuroticism was found to be a factor that increases noise-induced effects.

Basow (1974) was able to prove the effects of white noise on the performance of attention as a function of the tendency to become anxious. Discipio (1971) likewise found the psychomotoric performance depended on white noise as well as on personality variables. Guski (1975) investigated in an empirical study the approach of Glass and Singer (1972) according to which a person's reaction to noise depends in a higher degree on his cognitive evaluation of the noise event than on the noise itself or one of his own personality characteristics. Based on his studies, Guski (1975) concluded that the observed drop in performance under noise exposure is mainly due to the subject's evaluation of the noise situation and therefore the alteration in performance is only to be seen as a secondary, by cognition elicited sound effect. In a field-experiment dealing with noise, sleep and performance, similar results were found by Gros (1985). Methodical aspects of researching noise and performance effects are discussed by Grös and Mehnert (1986).

Summing up it may be said, the present stage of knowledge regarding the psychological effects of noise on human performance can best be described by the theoretical concept of the 'moderator variables'. It is assumed that noise elicits cognitive and emotional evaluation processes which are modifiable by characteristics of the situation as well as of the individual.

Figure 8.14 (based on DFG, 1974) demonstrates the possible different effects of noise on performance by means of the moderator variable 'sensitivity to noise'.

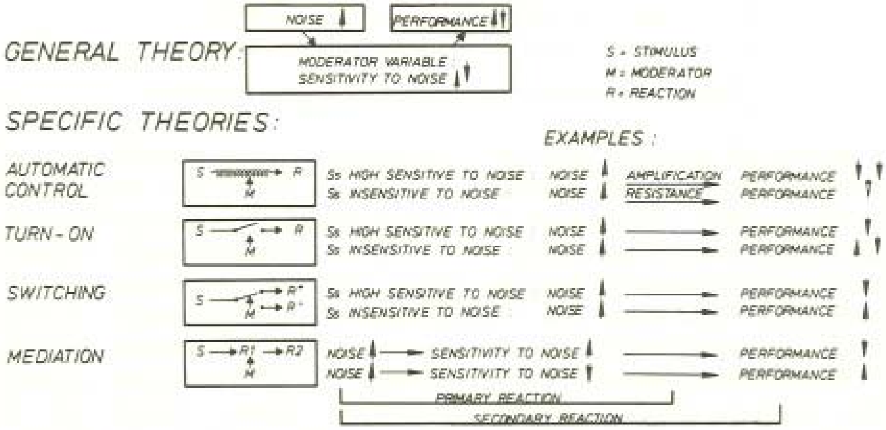


Figure 8.14 Examples for different effects of a moderator variable

8.3.2 Psychological Well-Being and Annoyance

Sound events that elicit annoyance detract from people's wellbeing (UBA, 1978). Noise has, because of its acoustical characteristics (e.g. intensity, bandwidth or impulse content), *directly* adverse effects on man, startle response or defensive blocking, for example. Other direct effects can be due to the information-bearing characteristics of the noise source (e.g. moped, lorry). But annoyance mainly results from people's knowledge not to be able to escape that as unnecessary felt noise.

The *indirect* adverse effects of noise can be impairment of people's psychic wellbeing due to disturbances during recreation and relaxation. Annoyance results also from being compelled to close the windows or to raise one's voice in order to reduce or to drown the noise coming from outdoors (cf. Rohrmann, 1976, 1977, 1978; Rohrmann *et al.*, 1978, 1980; Finke *et al.*, 1980). From this lasting alteration in behaviour — e.g. increased drug consumption — can ensue (Meier and Müller, 1975). Further noise-induced alterations in behaviour are, turning up of radio or television, reducing speech communication or refraining from it, changing one's dwelling or moving to another area.

The extent of continual annoyance due to sound emission is only reflected in people's reaction. It was ascertained that the connection between the degree of annoyance and the physical sound pressure, above all in the mid-intensities (45 to 70 dB(A)), is not especially close. The acoustically characteristic values of noise represent in this connection only *one* determinant of the annoyance reaction besides the sociological, physiological and psychological characteristics of the aggrieved individuals. Thus, the concept of the moderator variables can also be applied to the effects of annoyance due to noise.

The DFG study on aircraft noise (DFG, 1974) comprises an empirical examination of the moderator concept. The accuracy of prediction regarding noise effects could be doubled by inclusion of moderator variables.

World-wide demoscopical surveys have been carried out in order to ascertain the extent of annoyance elicited by environmental noise (Bradley, 1980; Brown and Law, 1978; DFG, 1974; Fidell, 1977, 1978; Finke *et al.*, 1980; Rohrmann *et al.*, 1978; Suzuki, 1978). According to this as well as to other studies, about 80% of the Western German population, for example, feel disturbed — depending on the noise source. Looking in this connection at traffic noise, the most annoyance-causing effects are ascribed to lorry noise, followed by aircraft noise, industrial and construction noise, as well as noise originating from the neighbourhood (UBA, 1978).

The most commonly used social-scientific measuring instruments are interviews, questionnaires and psychological tests which are executed in connection with an identification of respective acoustical data. Common to all social-scientific procedures is the collection of substantially very different aspects of annoyance-effects which are finally reflected in global values which have to be obtained by statistical procedures (Guski *et al.*, 1978). It is to be taken into account that global values only represent average annoyance effects. Therefore, they are suitable at most for the interpretation of average reactions in general. Figure 8.15 gives an example (cf. Shaw, 1975).

Social-scientific inquiries within communities that are exposed to noise will fail to register the direct noise effects but rather establish the indirect and long-term ones. Nevertheless, these investigations are — under simultaneous measurement of the noise level in the respective area — of great importance for the research on noise effects. The connection between the degree of acoustical

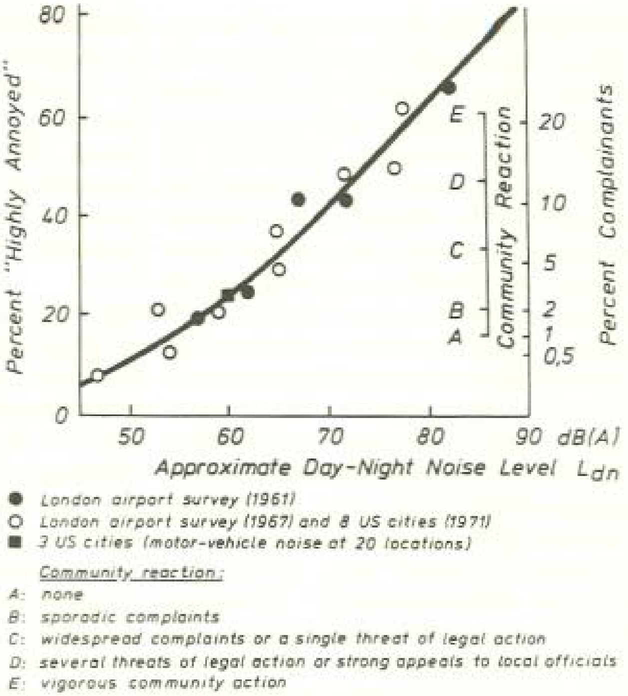


Figure 8.15 Community reaction to average noise levels

environmental pollution and the social-scientific registerable noise effects is, as a rule, more markedly reflected in such surveys than in other studies on noise effects. The inquiry results of independent research teams harmonize to a high degree (e.g. Relster, 1975; Tracor, 1970; Vallet *et al.*, 1978).

8.4 NOISE AND CRITICAL GROUPS (Eckhard Gros and Gerd Jansen)

Measures of noise abatement are, in general, based on acoustical threshold or limit-values, identified as protective to the average person within the community. But there exist critical groups within the population who have a right of being protected against noise by specific measures. Although no model of a generally acceptable classification of the critical groups has been available until now, it can be stated that the elderly, children, sick people (especially those living in acute conditions as, for example, hypertonics or reconvalescents), pregnant women, as well as the lower social clases need particular attention (Jansen and Gros, 1976; Gros and Jansen, 1978; Rehm and Gros, 1980; McLean and Tarnopolsky, 1977; WHO, 1980).

Using physiological criteria, those critical groups may be defined as people who are in more vulnerable condition, permanently or temporarily. The aim of a study carried out by Rehm and Gros (1980) was to show whether the physiological reaction of ill people to noise was different from the reaction of healthy people. They found that in comparison to healthy subjects, patients suffering from cerebro-vascular disease showed a reaction to noise which could be judged as abnormal. It seems to be most important that the capacity of increasing the peripheral blood flow after having had a vaso-constriction due to noise is very much reduced (Rehm and Gros, 1980). This appears to suggest that a normal adequate physiological response to sound stimuli is not warranted in these sick people — a condition which could thus make them more susceptible to the detrimental effects of noise.

If, for example, a *medically defined* health-protective threshold value were taken as a basis, all those would have to be protected who are especially sensitive to noise; since they are already at risk at noise levels that are far below the *acoustically defined* threshold values, covered by administrative regulations (see Figure 8.16, based on Rohrmann, 1977).

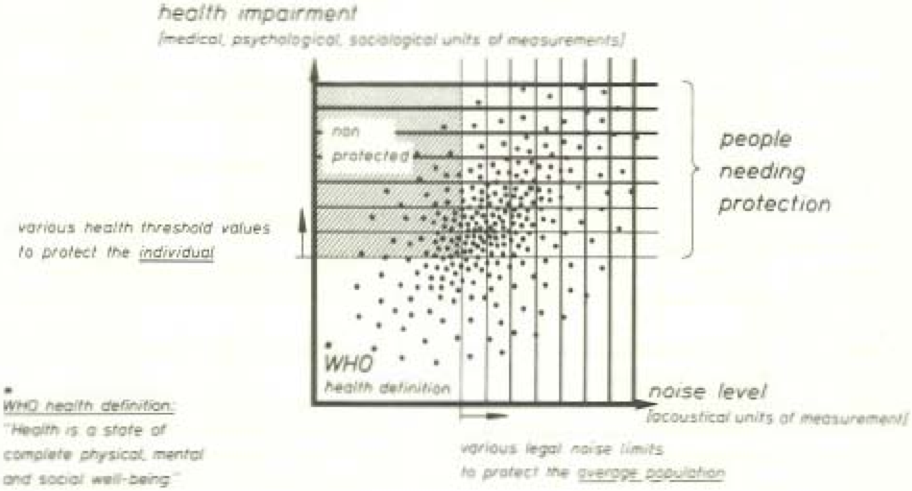


Figure 8.16 The localization of people needing protection based on acoustical and social-scientific values

It should be borne in mind, additionally, that the mentioned groups not only suffer particularly from noise pollution but can scarcely participate in the advantages of e.g. modern transportation techniques, one of the main originators of environmental noise.

Another noise-related effect can be seen in a shift in the social-structure of especially noise-exposed areas (cf. Herridge and Low-Beer, 1973). First, the population fluctuates, then a change in its structure takes place since only those people stay who are not in a position to move to quiet living areas due to financial or other reasons (e.g. the elderly, foreigners, socially underprivileged). Then, gradually, the quality of the infra-structure deteriorates, recreation grounds, medical, cultural and material care centres become reduced.

Hence, it follows, shall those population groups, who are particularly sensitive to environmental noise, be subsumed under the protection of acoustically defined threshold values either noise protection has to be made more individual or the noise level must be so low that it ensures adequate protection as far-reaching as possible.

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CHAPTER 9

Noise Interference with Oral Communications

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9.1 COMMUNICATION BY SPEECH

Speech is the most important means of communication for human beings. Its functioning is linked with a bilateral human capability, that of the ability to form and to understand speech. Basic conditions of this are the intention to communicate, the system of signals used are according to a common agreement, the emitting and receiving organs being in perfect condition and there is the ability to comprehend. The chain of speech communication is a complicated system where brain, nerves, speech organs and hearing are all participating (Figure 9.1). Feedback serving for the checking of transmission, namely, the fact that the speaker also hears his own voice, is not a basic condition but improves the speed and safety of communication.

Communication by sounds is known also in the world of animals, but this differs from human speech, because with animals each information is given by a separate signal. (Thus, of course, it is inept for information on thoughts). Human speech is a system of signals built up on 35–40 elements, where the meaning relies on various forms of connections between the elements. The possibility is given, not only to form a new speech sound compound for any meaning, but also for the construction of a grammatical system in order to develop a literary language semantically perfectly aligned.

Speech is perfectly understandable — under appropriate acoustic circumstances — for healthy people mutually knowing the system of acoustical signals agreed upon, i.e. the language. By acoustical circumstances are meant that the distance between speaker and hearer and the environmental background noise are suitable for the speech loudness. 'Intelligibility' depends on these factors and it may even be lost. Therefore, the notion of intelligibility has a great importance in the evaluation of speech communication. With noise present, both the speaker and the hearer are faced with a difficult task: the former is disturbed by noise in thinking and the formation of speech, whilst the latter in

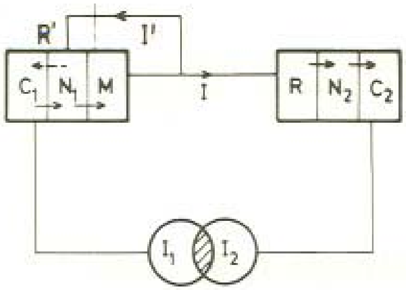

Figure 9.1 Diagram of the communication chain: I = information, $C_{1,2}$ = cerebral function, $N_{1,2}$ = nervous connections, M = motoric emission, R = reception, I', R' = feedback information for the emitter, $I_{1,2}$ = information store of both emitter and receiver

hearing the series of signals and the cerebral evaluation of the information content. It is, first of all, the phenomenon of 'masking' that makes communication difficult. (Zwicker, Chapter 4, this volume).

Brain-work is, as a matter of fact, the decoding of the acoustical material heard, and it will become more and more difficult according to what share and what part of the information is made unintelligible. Therefore, the harmful effect of speech-noise interference consists not only in the fact that the information is not understood, but also that the establishment of communication requires great efforts both on the side of emission, e.g. by shouting and on that of reception, i.e. combinative thinking.

That is why Robinson (1970) ranks speech interference among primary human effects of noise. In the case of speech interference, our brain deals not directly with the determination of some property of noise, but with the decoding of information material distorted indirectly by the masking effect of noise. It is also true that speech interference is not a secondary effect of such character as that of impaired hearing, nerval or organic diseases. This chain of thought necessitates the insertion of a third kind of noise effect between the two extreme types, the sensational judgement of the quantitative data of noise and the development of harmful effects of noise. To this inter-state, could be ranked also the sleep-disturbing effect of noise, whose further consequences are tiredness, reduced mental alertness, nervousness, etc. It is characteristic of these categories (speech interference, sleep interference) that they exist only when noise is present and with its elimination the phenomenon also disappears. This is not the case with impaired hearing, nerval taint or organic diseases which remain after the removal of noise. These are the real secondary noise effects.*

Sound-forming is usually of a not-too-differentiated quality, but it has variable components. Such is first of all the frequency band used. Within one species the emitted band of sound and the sensibility range of the receiver organ are naturally in harmony. But the sound will not necessarily be perceived by members of another species. It is very interesting that among mammalia examined until now, man is perhaps the most sensitive in the range of low-frequency sounds, while fully insensitive to those of a very high pitch. The frequency of the highest sound heard by man is 16–18 kHz, while the ears of a chimpanzee are sensitive up to 22 kHz, those of a dog go up to 38 kHz, of a washbear up to 50 kHz, of a cat up to 75 kHz and those of a bat up to 120 kHz. Non-mammals are usually insensitive to high-pitched sounds. This is surprising because previously we had though that crickets as well as birds were sensitive to very high-pitched sounds. In reality, the upper limit of the hearing of birds is around 8–12 kHz according to experiments of Tembrock and colleagues (Tembrock, 1959).

Variation is possible first of all in pitch and time but it seems much less probable that the quality of sound would have an information-carrying role. However, for man even this factor results in unlimited combination possibilities, i.e. the multiplication of meaning content.

9.2 MECHANISM OF SPEECH FORMATION

9.2.1 Vibration of Vocal Chords

The primary source of the formation of speech sounds if the glottis (Figure 9.2). The closed vocal chords are made to vibrate by the flow of air flowing out of lungs. The fundamental tones generated in this way are transformed into speech sounds by various resonator cavities, finally the sound will be radiated into the environmental airspace through the oral aperture and/or nostrils.

Beneath the vocal chords one single large cavity — the chest — is to be found. This cavity includes the energy source of the sound formation system —

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* For acoustical communication, several examples may be found also in the world of animals. The primary reason for this is the suitability of biological sound for communication purposes. This type of sound may be easily and rapidly formed, it contains a relatively wide variation of information possibilities and has also adequate propagation qualities even in the presence of natural obstacles (bush, wood, forest). An important characteristic is that acoustic signals may be 'coded', that is animals belonging to other species do not know what information is contained in the given signal. Animal sound has therefore the features to be a carrier of a most important chain of communication. In the course of investigations it turns out that most animals have a relatively abundant acoustical vocabulary. At least a dozen animals are known that are able to issue 18–25 various phonetic signals, e.g. finch, dolphin, roaring monkey, etc.

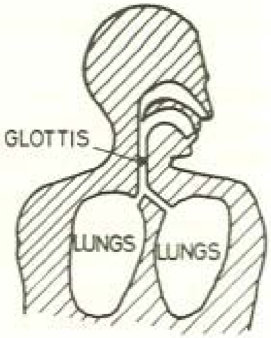

Figure 9.2 Schematic view of speech organs

the lungs. Since there are several soft and thus largely damping substances in the cavity, it is first of all the trachea that has the role of a resonator. Since this resonator has a rather low self-resonance, it does not influence the sound quality of speech sounds but may characterize individual timbre. In case of a normal speech sound the pressure of air flowing out of lungs corresponds to that of a water column of about 4 cm. When shouting very loudly and with high pitch it may even reach the pressure of a 20-cm-high water column. The energy of the streaming air changes partly into sound energy, but the efficiency of transformation is very low, only of the order of 0.1%.

Vocal chords block up the way of air like an elastic-tightened membrane and form the sound source of speech and of the singing voice. It comprises a pair of folds whose longitudinal tension, setting and gap-size may be changed depending on our will. Muscles are partly imbedded into the vocal chords and partly motivate the cartilages placed around them. Vocal chords adhere to the cartilages and thus the exact setting and control is made by means of these. Cricoid is the basic cartilage of the larynx. Above it is the thyroid cartilage and which can tighten the front wall of the larynx on the inner part of which are situated the beginnings of the vocal chords. Arytenoid cartilages are placed on the backside of the cricoid and carry the ends of the vocal chords which they activate. The cartilage covering the larynx has a protective role and has nothing to do with sound formation. In Figures 9.3(a) and 9.3(b), the cross section of larynx and the rough layout of vocal chords are presented. The movement of vocal chords may be best explained on the cross section, but experimentally it may be examined precisely in the two other major directions. Pseudo-vocal chords to be seen in the figure do not participate in sound formation under normal conditions, but in pathological cases and with operative help they may take over — imperfectly — the voice-forming role of vocal chords.

The length of vocal chords is 20–25 mm. Their movement takes place in such a way that the air-flow pouring out of lungs knocks against the obstacle raised by closed glottis. If surplus pressure exceeds the compressing strength of vocal chords the flow of air breaks through the closure. In this way the surplus pressure will immediately diminish and resulting from their elasticity vocal

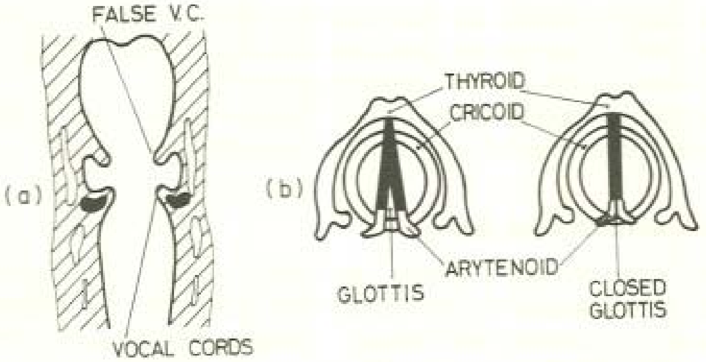

Figure 9.3 (a) Vertical cross-section of larynx; (b) horizontal sections in the height of the glottis in the open and closed states

chords are closed again. Air flowing out is continuously replaced from lungs, therefore after a certain time it will reach the surplus pressure required for a break through again, and the movement goes on. The elasticity data of vocal chords and the flow data of the air current are naturally in harmony. The relationship between flow velocity and pressure in the contraction is such that at the narrowest part of larynx (glottis) the air pressure will be least. This physical relationship partly governs the closure of the vocal chords.

Vocal chords do not form a system opening and closing in plane, but move away and upward, then with an elliptical movement they collide further down and, when closing the edges are pressed together or may even be placed one above the other. Closure does not take place at once along the glottis, either, but the glottis is gradually closed from the front to the back and thus the entire movement has a character of snake-like movement in space that may be observed by means of a stroboscope. After closing, vocal chords strive for the repetition of the process even by themselves — because of their elasticity — and therefore, they start again towards the opening upwards. The well-timed increase of pressure of air coming from lungs assists this movement (van den Berg, 1958).

Speech sounds are basically generated through the movement of vocal chords, but more detailed data of the process require examination. Such are the form of vibration, the relationship between the duration of opening and closing of the chords as well as the harmonic content of sound thus obtained. The time-pattern of the glottis opening is a function of typical triangular form where the initial stage is a steeply increasing opening. The duration of opening and closing state may be examined either by the stroboscope method or by the waveform in time of the sound obtained. According to data obtained from oscillograms the opening quotient amounts to 0.2 at the normal pitch of speech sound and may increase up to a value of 0.7 with a two-octave increase of pitch. As against this, according to the stroboscopic method the opening quotient hardly depends on the frequency and its value is around 0.7 (Timcke, 1956). Experiments show that the absolute value of the opening time is constant: 2–2.5 ms (Joos, 1948; Tarnoczy, 1951).

It is difficult to make a conclusion here, because of the problem of defining exactly what we mean by an acoustically-open state.

9.2.2 Differentiated Phonation

The sound generated by the glottis — the voice — is one of the raw materials of speech. Its oscillogram has the characteristic saw-tooth form similar to that of mechanical or electrical self-induced vibrations. The harmonic content of the voice decreases by about 12 dB/octave. This raw material is transformed into speech sounds with a characteristic timbre by the resonance effect of cavities above the glottis.

However, there are also several other methods of forming speech sounds. In the cavities above the glottis, closures and narrowings may be established and thus various kinds of noise may be created. Narrow gaps may be formed between lips, lips and teeth, tongue and teeth as well as between tongue and various parts of the palate. Voiceless fricatives (f, s, ʃ, etc.) are formed in this way. If also the voice is excited, the corresponding voiced-pairs (v, z, ʒ) will be heard. With the sudden bursting of corresponding closure stops p, t, k, b, d, g, are obtained in a voiced-form. The rapid consecutive application of the closure- and gap-forming methods will result in new sounds, they are the so-called affricates, e.g. ts, tʃ. Also the timbre of noise sounds is influenced by the cavities above the glottis, but the real resonance effect is exercised first of all in the formation of vowels and semi-vowels (m, n, l, r, etc.).

Fullest information is known about the physical structure of vowels. Vowel-forming cavities transform the voiced sounds in their harmonic content as a result of their resonances (Figure 9.4). The regions of resonance amplification shown in the figure are called 'formants'. Helmholtz suggested a filter type of theory to explain the generation of vowels but this is replaced by a more modern 'tube theory' (Fant, 1960). Figure 9.2 shows a tube with varying cross-section leading from the glottis to the opening of the mouth, its length being about 17 cm. If the vowel-forming tube is considered as a system of one-quarter of a wavelength long, its fundamental tone will be around 500 Hz, that may, of course, be modified by the geometry of the tube (tongue, opening of the mouth). Indeed, the first formants are to be found between 200–1,000 Hz, and further resonances (formants 2, 3, etc.) may be found around 1,500 Hz, 2,500 Hz, etc. also with very wide modification possibilities.

The first two formants show the acoustical character of vowels rather well. The final acoustical form of speech sounds develops after radiating through the apertures of resonator cavities. The radiation resistance of the oral cavity

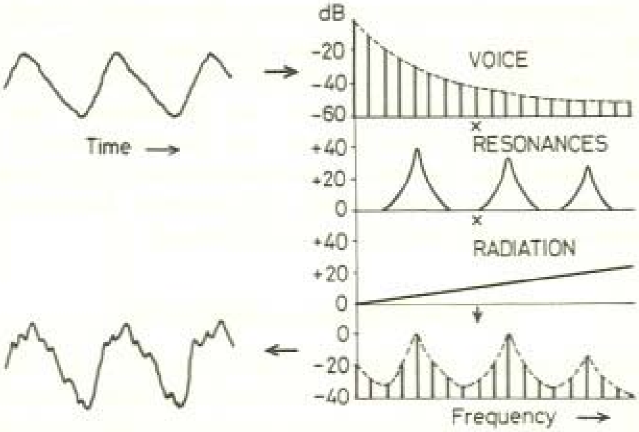

Figure 9.4 Evolution of vowel sounds. Upper left: cord tone, right: Fourier-spectrum of cord tone and modifying effects caused by transfer functions, *below right*: final spectrum, *left*: final oscillogram

raises the upper range of the spectrum by 6 dB/octave. Thus the hearing character of the upper formants will be stronger.

Therefore, the development of the acoustical character of vowels is a complicated process. Figure 9.4 gives an outline of the individual phases of the process. According to the system theory, resonance curves modify the original series of harmonics. The effect of radiation resistance already mentioned is superposed on this to give the final acoustical form. However, this may only be measured on the axis of the radiation. Laterally the radiation diagram is frequency dependent because of interferences and the shadowing effect of the head, respectively. The usual frequency spectrum of speech sounds is distorted laterally and at the back, thus making intelligibility more difficult.

Much less is known about the physical character of consonants but the formation of so-called semi-vowels is identical with that of vowels. In acoustical quality also elements of noise character may be observed and the formants of surrounding vowels also strongly influence the formation of the consonant character in time. The character of the consonant in continuous noise develops over a wide frequency band, but it may be quite well recognized and identified from analysis patterns. The most complicated mechanical recognition task is caused by stops. With them attempts are made to achieve some result by the 'locus' notion for the time being. Locus is a frequency place to which second — eventually third — formants of surrounding vowels are directed when transforming the cavities (Delattre, 1955).

With an appropriate formation of cavities a theoretically infinite number of vowel kinds may be created, but within one language usually only 5–15 vowel qualities are really used. Even if not exactly, but a nearly similar consideration holds also for consonants. From an information and theoretical viewpoint it is very important that out of the continuously changeable possibilities in very large numbers of discrete elements. This phenomenon is, of course, connected also distinguishing tone qualities. Most languages build up their vocabulary usually from 35–45 speech sounds.

9.3 SPEECH AS INFORMATION

The information content of a phonetic signal is around 5–5.5 bits. Since the speed rate is about 10–12 signals per second, the information capacity of speech is 50–60 bit/sec. The information content of a short sentence reaches 500 bit units. If our brain worked like a computer both the sending and the receiving intellect ought to make at least $2^{500} = 10^{150}$ decisions during this time for coding and decoding of the information, respectively. This data indicates how much faster the brain performs its evaluating work and how much more effeciently, than computers.

The question will be made even more complicated if we try to determine the information content of speech sounds analysed from the physical side by artifical recognition. A physical analysis of speech sound will not result in the determination of a single quality, but the analysis is extended to the pitch of sound, duration, intonation and resonance data of 3–4 formants, etc. The quality of sound should be determined on the basis of these permanently changed 8–10 data.

The solution of the problem has not been possible with our contemporary technical possibilities. However, by means of synthetization and transformation into acoustical signals of the same information data a well-understandable artificial speech may be generated. This fact points to the special activity of the brain in decoding speech information. Because of the overlapping of formant places dependent on pronunciation, decisions made on the basis of formants are not always ambiguous. Additionally, the individual timbre, the connection of the sound in question with other sounds and the emotional content of the text give a lot of extra information to the acoustical signal. Physical analysis is not able to distinguish between elements of the recorded information 'parcel'. It is an elementary observation, for example, that the loudness of speech may alter the formant structures more than would be characterized by the difference between two vowels. Physical analysis is not able to separate from the 'main information' the disturbing 'additional information' which sometimes necessarily seems more significant in characterizing the real quality, and thus, a simple analysis is not suitable for the mechanical recognition of quality. This 'parcel' character of the physical data of speech sounds is one of the important basic principles of research (Tarnoczy, 1965).

It results from the foregoing that the brain is likely to take considerably more data into consideration than is physically available when making a decision concerning quality. Besides, the brain makes not only a short-time analysis within a given sound, but permanently considers also relations with the preceding and the following sounds. What is more, it even compares the material perceived with its own lingual and intellectual vocabulary and corrects afterwards the eventually wrongly identified signal qualities. Thus, the work of the brain is enlarged further.

An interesting technical idea is that the automatic recognition and identification of quantized signals may be technically solvable. However, arising through the failure of the automatic recognition of speech sounds as signals, with the present technical level that is not possible for continuous signals. Speech itself is not a succession of information signals, but their total confluence out of which our signal recognition systems are unable to select discrete qualities. First of all, two things have yet to be solved: one is the segmentation of individual signals, while the other is their identification with elements of the quantized quality system. However, identification is not completely possible because of the suppressing effect of additional information, even if the possibility of correlation analysis is included in the solution.

Therefore, physical data of human communication have developed according to the abilities of man. The speed of formation and of understanding is about the same, and this determines the capacity of elementary information material and the information capacity of speech sound. It is obvious that the most open system types (Morse signals) could not correspond to human needs because of the time-duration of their decoding, while the closest ones (picture-writing) because of their absurdly large memory store. Therefore, speech elements had to develop by number and quality for psycho-physiological reasons.

The carrier of the information material of speech communication is always some series of physical signals. But, this is subject to the interference of environmental physical and biophysical phenomena in the course of their spreading, transformation, perception and even understanding. Only quantitative data of the information material transmitted may be measured, but not an evaluation of its contents. Yet, a relatively small phonetical change may involve a considerable deviation of its contents. Therefore, the stability of signals is a decisive problem of communication.

The informative effect of signals is not unambiguously influenced by various distortions. For example, the resonances of the oral cavity are, practically, distortions in the development of speech sounds, or in the dynamical compression of hearing in understanding. All this promotes the adequate development and reception of signals carrying information. As against this, interference by noise is always effective in the direction of the reduction of information content.

The signal-to-noise ratio (difference between signal and noise levels) is one of the most fundamental parameters in the efficiency of communication. In the understanding of speech sounds the judgement of so-called distinctive features (difference thresholds) has an important part and this judgement is made difficult by the masking effect of noise. It is a general rule of nature that the intelligibility of a series of signals masked by noise may be regained by increasing the redundancy of the carrier signals. Redundance may, for example, be increased by the multiplication of distinctive features of the individual elements, by the numerical increase of the series of signals or by the repetition of signal processes (phonetical or verbal redundance).

The next redundance possibility is in the length of the sound-signal series designating meanings and grammatical categories. The entire vocabulary of a language could be made up of sound relations of two, three and four elements. All combinations (e.g. four identical consonants one after the other) are, however, usually not made use of by languages in order to ensure intelligibility, i.e. information. Instead of this, longer words are formed. Longer signal series are less sensitive to noise, because the loss of one or another information element may be easily corrected in the brain and in this way the time for information is increased. Shortness in the length of signal increases the amount of information per unit time, but also increases the sensitivity to noise. Speech has developed in such a way that these two viewpoints are in the balance.

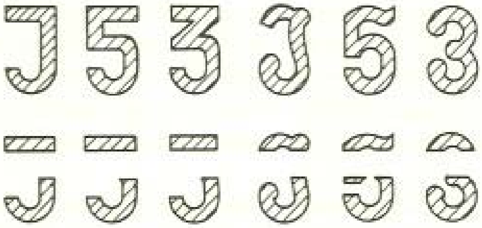

Figure 9.5 Example shows the conserving effect of redundancy. The distortion in the second row cannot eliminate the meaning of the redundant form

In Figure 9.5 the informational effect of two signal series are presented without and with noise interference, respectively. Interference has hardly any harmful effect on the information content of redundant series, while a perfectly informative signal series (containing no insignificant auxiliary signals) will become fully indecipherable (Tarnoczy, 1965).

With a large basic noise content, therefore, redundance should be increased in speech communication. For example, space language vocabularies do not allow the 'yes–no' version, but instead, the use of 'affirmative–negative' is obligatory (Webster, 1965).

9.4 ACOUSTICAL DATA OF SPEECH AND INTELLIGIBILITY

Resulting from the particular feature of speech sounds, acoustical performance and spectrum are permanently changing in the course of speech. In order to be able to determine acoustical data for the speech itself certain statistical considerations have to be made. It may be stated concerning a longer speech whether it was too still, or of normal intensity or too loud. The similar procedure may be followed also in the course of measurements. The average sound pressure level of normal speech is about 72–76 dB at a distance of 30 cm from the speaker. Measuring data under various circumstances may be found in Table 9.1. The table contains the average of the Hungarian speech of 18 men, measurements were made by the so-called speech-choir method (Tarnoczy, 1970, 1971).

Table 9.1 Average sound pressure level (dB) of man's speech at 30 cm distance from head

Speech	Front	Side	Behind
Murmured	63	—	—
Still	67	62	57
Normal	74	70	64
Loud	81	76	72
Shouted	86	—	—

Beside the average sound levels, the form of the average spectrum of speech has also to be known. In Figure 9.6 an average of eight European languages was indicated for man's and woman's voice. Data are plotted in spectrum level (energy level falling to 1 Hz theoretical bandwidth) and with a fluctuation possibility of ±3 dB are valid for the English, German, Swedish, Russian, Italian, Hungarian (Tarnoczy, 1971) as well as Spanish (Banuls-Terol, 1965) and French (Tarnoczy, 1975) languages. In Figure 9.6 the zero level is the average (long-time) sound pressure level of speech.

From Figure 9.6 speech levels falling to octave bands of 250–4,000 Hz medium frequencies may easily be converted. These data are needed if we wish to calculate the intelligibility of speech in advance for noises of various spectral compositions.

Speech sounds are of various intensity and structure, therefore noise does not equally mask them, but the more intensive the noise the more it will mask. According to traditional definition, intelligibility is the numerical quotient of

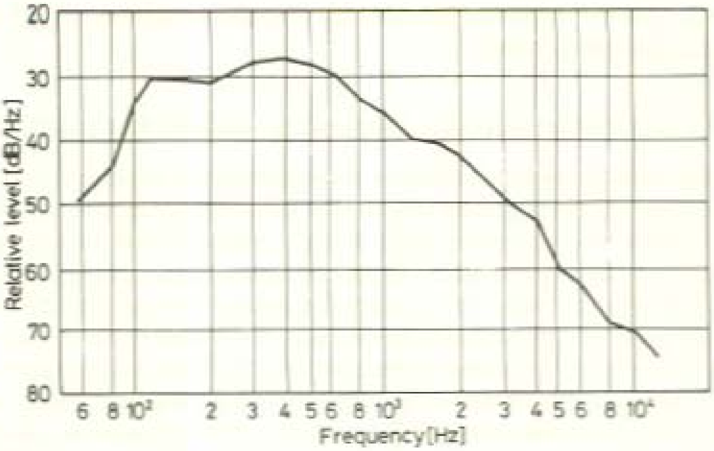

Figure 9.6 Average speech spectrum of European languages. All data fall within ±3 dB band of the curve plotted

the understood elements over all the speech elements (sound, syllable, word) communicated. However, intelligibility percentages determined on the basis of fluent speech are quite different from the values referred to individual syllables or separate (meaningful or meaningless) words (Fletcher, 1954). Namely, in the identification of meaningful texts very great deviations may be stated depending on the practice, individual abilities and intelligence as well as on the text. For example, with a 50% syllable intelligibility, speech intelligibility may reach 90%. Therefore, almost exclusively syllable intelligibility is used for investigations.

For direct measuring several procedures are known. Their common feature is that they they to find an answer to the intelligibility of mainly monosyllabic and disyllabic words with identical, or similar, voice structure as the language investigated. It is not absolutely necessary that the individual words have meaning. But, if so, then mistakable words are selected where, for example, changing one phoneme (speech sound occurring in the language in question) cause changes also in the meaning. For example, boon–coon–loon–moon–noon–soon.

The intelligibility percentage determined may be used for indicating the suitability for work of the acoustical surrounding. However, because of the clumsiness of subjective measuring some computation methods have developed also in the course of time.

One of them is the estimation method using the total noise level. Following from the data of Table 9.1 the masking effect of noise may be somewhat compensated by an increase of sound intensity. An important consideration is the relationship between spectra of speech and interfering noise. For example, 'white noise' (the energy density of spectrum is constant as a function of

Table 9.2 Percentage intelligibility stability of stops for the English and Hungarian languages

Sound	English	Hungarian
p	50.5	46.5
t	76.5	87.5
k	50	78.5
b	75	75
d	73	68
g	59	66.5

frequency) masks stops according to Table 9.2. The basic assumption of the data of the table is that the sound pressure level of speech and noise should be identical, i.e. the signal to noise ratio is 0 dB. In such cases the intelligibility of the individual sounds is called intelligibility stability (Miller and Nicely, 1955)

Under similar circumstances the intelligibility of vowels may reach even 98%. Therefore the exact knowledge of specral relations is needed. Fletcher (1954) gave possibilities for other solutions by introducing the term of 'articulation index'. The essence of articulation index lies in that the intelligibility, referring to the entire frequency range, is made up of partial intelligibilities achieved in the individual frequency bands. On the basis of this the action of speech interference level (SIL) (Beranek, 1960) and its modified forms were introduced.

Table 9.3 Admissible PSIL-values in dB mean values as a function of speech distance and sound intensity

Distance (m)	Normal	Raised voice	Loud	Shouted
0.3	68	74	80	86
0.6	62	68	74	80
0.9	58	64	70	76
1.2	56	62	68	74
1.5	54	60	66	72
1.8	52	58	64	70
3.6	46	52	58	64

The preferred speech interference level (PSIL) is the simple arithmetical mean value of the noise level to be measured in octave bands with 500, 1,000 and 2,000 Hz medium frequencies, respectively. As a function of this Table 9.3, according to Webster's personal communication (Burns, 1973), gives the admissible distance and sound intensity to be used for intelligibility in speech communication. The data are 3 dB higher than Beranek's figures for lack of influence by lip-reading.

The computations presented did not take spectral deviations of speech and interfering noise into consideration. The spectrum of speech may be assumed as given according to Figure 9.6. Of course, the spectral forms of speech with intensities deviating from the normal one are also known (Tarnoczy, 1971). The spectrum of the given noise should be compared to them. But, this is not enough to forecast intelligibility, since also partial intelligibility percentanges falling in the individual octave bands have to be known. Reference data are presented in Table 9.4 where partial values falling to the individual octave bands may be found for English (Fletcher, 1954), Russian (Jofe, 1954) and Hungarian (Tarnoczy, 1974) languages. The first two are the results from conversion, while the third is from direct measurement.

Table 9.4 Partial intelligibility percentages (X) measured in octave bands, without background noise

Band middle (Hz):	125	250	500	1k	2k	4k	8k
English	3	15	29	28	17	8	–
Russian	1	6	23	32	26	10	2
Hungarian	2	13	18	22	22	20	3
Mean values:	2	11	23	27	22	13	2

It follows from the table that the octave band with 4,000 Hz medium frequency largely contributes to the intelligibility. Therefore, level values of noise components should be determined in five octave bands. Furthermore, according to an idea of D. E. Broadbent (see Burns, 1973) we may agree that if some component of noise level is at least 30 dB below the speech level, then it has no effect on intelligibility, while if it is at least 20 dB above it, then understanding will be made quite impossible. Transitional cases are handled proportionally. Level data of the individual bands are weighted by partial percentages of intelligibility, and the partial results are then added. Thus the final intelligibility percentage will be obtained in the given noise.

In Figure 9.7 beside octave-band data of the average energy spectrum of speech of normal intensity, octave levels of an imagined noise source were also plotted. If the computation mentioned is made according to the summation of

$$\frac{(S-N)_{250}+20}{50}X_{250}+\frac{(S-N)_{500}+20}{50}X_{500}+\ldots$$

then an intelligibility of 51.4% will be obtained for the English language and that of 54.7% for the Hungarian one. For the verification of the computation use data of Table 9.4 and Figure 9.7.

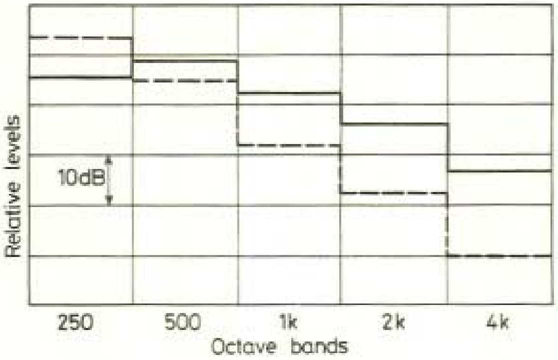

Figure 9.7 Diagram for computation of interfering effect of a given noise with speech, i.e. of intelligibility of syllables in a given language. Straight lines: speech spectrum, dashed lines: noise spectrum. See details in the text

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Noise Pollution
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CHAPTER 10

Noise Pollution during the Night — A Possible Risk Factor for Health

BARBARA GRIEFAHN

10.1 INTRODUCTION

Within the circadian rhythm the sleeping–waking rhythm is most prominent. Sleep itself is characterized by cyclic changes. After the onset of sleep the depth of sleep normally increases and decreases four to five times during a night. This can be measured with the electroencephalogram (EEG), where, expressed simply, the waves gradually become larger and less frequent with increasing sleep depth.

With regard to several particular patterns (K-complexes, sleep spindles, vertex sharp waves) this continuum is divided into five sleep stages, that is to say into the stages 0 to 4. Stage 0 (or W) indicates the awake state and stage 4 the stage of deepest sleep. When sleep stage 1 is regained after deeper stages, it is usually — and in contrast to stage 1, immediately after sleep onset — accompanied by Rapid Eye Movements which are recorded with the electrooculogram (EOG). This is called stage REM, or dream sleep.

A sleep cycle is defined from sleep onset or the end of stage REM up to the end of the first, or respectively the following REM stage. The average duration of a sleep cycle is about 90–100 minutes and is repeated three to four times a night; the maximum sleep depth as well as the time within deeper stages gradually decreases, but the time spent in stage REM increases.

Though our knowledge about sleep is still very poor, it is supposed that the undisturbed cyclic development is necessary for optimum repose and that delta-sleep (stages 3 and 4 combined) is crucial for physical and stage REM for psychic relaxation.

10.1.1 Sleep Disturbances

Complaints about sleep disturbances are widespread and an increasing problem in the practice of a physician. Based on the cause of the sleep disorders they may be divided into 2 main types:

— those based on illness. These are diseases accompanied by pains or many internal diseases and mostly consist of psychiatric disorders.

— the second type arises from environmental stimuli, among which noise pollution assumes considerable importance.

As a consequence of the difference in type different strategies have to be applied for their control. Sleep disorders based on illness need causal medical treatment; the occurrence of the second type must be prevented by appropriate methods, as for instance by damping the source of noise, by fitting sound insulation etc. Counter-measures are particularly essential under the aspect that — according to a hypothesis commonly accepted — chronic sleep disturbances are supposed to lead to illness (see Figure 10.1).

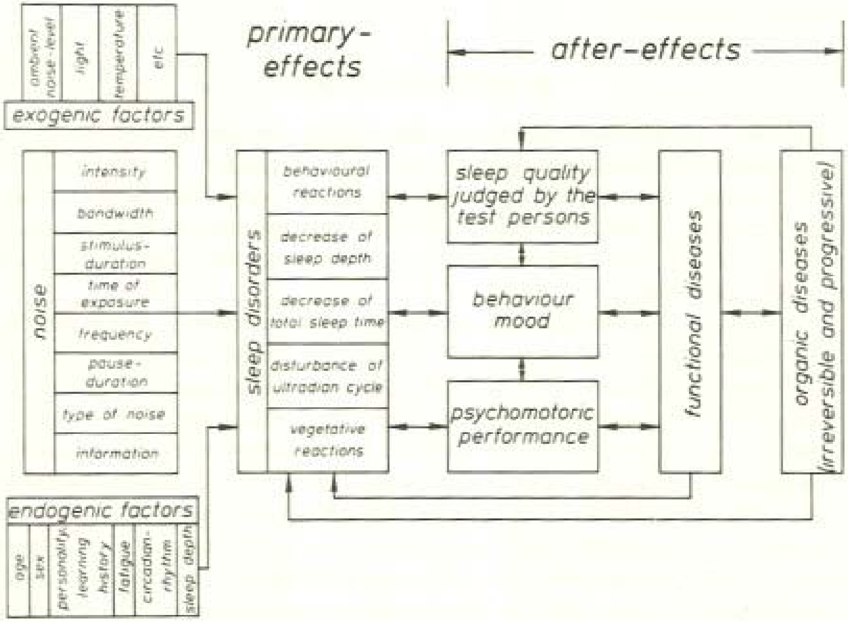


Figure 10.1 Disturbance of sleep and its effects

This leads to the question of the upper limits of noise pollution. From the medical point of view, it is desirable to protect every individual against high-intensity noise. But there are always some people who are disturbed by almost every sound. Breaking off all acoustical stimuli implies the suppression of nightly activities, e.g. industrial work, including the printing of newspapers, nightly transportation, including the transportation of fresh food ....

From these examples it becomes evident that there are competitive interests not only between the producer and the exposed individual but even for the individual alone.

The decisions where to set limits are a task for politicians, not for scientists, but the decisions should be based on scientific research. They would be relatively simple, if a general limit could be found above which noise cannot be tolerated any longer. These decisions become difficult in the case of a linear dose–response relation because the interests of a certain percentage of people cannot be considered.

The finding of upper limits or dose–response relations is extremely time-consuming. One experiment can only be completed within 24 hours, so from an economic time viewpoint it is desirable to record not one but several parameters. Subsequent evaluation, however, also needs much time. As a convenience, investigations dealing with this problem have been carried out either with very few subjects or with only one to three nights devoted to each subject. Although a relatively large number of studies have already been published, it is only a few of them which are directly comparable and can be used for a summarizing calculation. Most of the results are supported from other reports but in some cases they conflict. Hence, at the present time conclusions can be drawn only with reservation.

For a better comprehension, the citation of single results has been avoided. A selection of papers dealing with the problem in question (irrespective of whether they support or reject the general trend) are cited at the end of each paragraph.

10.1.2 Effects of Noise on Sleep

The effects of noise on sleep are commonly divided into:

— 'primary effects' to be recorded immediately after stimulus' onset and all over the night.
— 'after-effects' to be observed the following day or later.

Sleep disturbances do not necessarily imply awakening. Transient changes of the EEG such as evoked potentials lasting for about 1.5 seconds may be the only effect, but also we find shifts to shallower stages and, in the extreme, to the 'awake state'. Body movements and vegetative reactions can also be registered.

The extent of noise-induced responses is dependent on exogenic and endogenic moderator variables. These are the determinants of noise itself and also the characteristics of the particular individual, personal attributes and different stages of activity.

10.2 PRIMARY EFFECTS

10.2.1 Electroencephalogram (EEG)/Electrooculogram (EOG)

According to the general assumption that EEG and EOG data are objective measures for sleep quality, the effects of noise on these parameters are most intensively studied. This is especially true for the immediate reactions. Furthermore most of the papers present the data of whole night's sleep recordings.

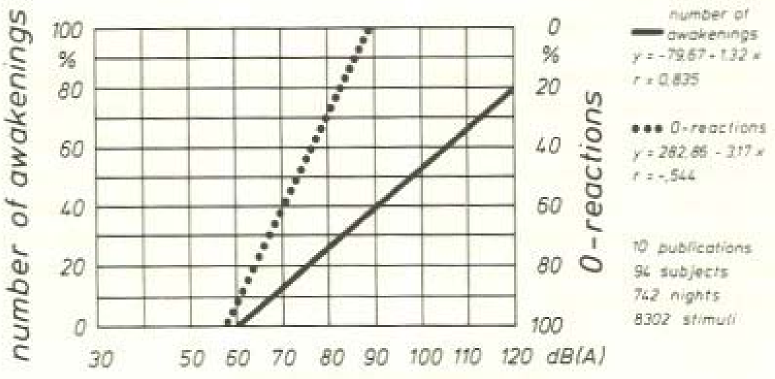
A. Immediate Reactions

This type of reaction occurs within 30 seconds after the onset of the stimulus. So it is obviously evoked by noise and frequently described. In this respect its extent depends on exogenic and endogenic influences.

Exogenic Variables

Intensity. A dose–response-relation has been found between the maximum noise level and the probability of sleep disturbances. The function presented in Figure 10.2 results from a summarizing calculation, but, whenever human reactions are considered, linear functions are realistic just within limits. In case of noise-induced sleep disturbances there are always some people who react to stimuli well below the 60 dB(A) threshold. The ascent of the curve then increases with intensity up to a certain point where the responses are directly related to intensity. For the upper part of this function the inverse effect is true. Some people will never be disturbed and the curve will never attain 100%.

Thus it is better to refer to the 68 dB(A) value rather than to the 'threshold' at 60 dB(A). A maximum level of 68 dB(A) indoors will cause a diminution of sleep-depth (one stage at least) in one-third of the population. Again one-third of these (i.e. 10% of the whole population) will be awakened.



0-reactions = reactions less than a change of one sleep stage
stimuli: 40 - 120 dB(A)
(corrected to the 5th test night except the results of MUZET 1973)

Figure 10.2 Relation of number of awakenings and of 0-reactions to noise level

No further 0-reactions (reactions less than a change of one sleep-stage) are expected at a minimum level of 88 dB(A). This level only leads to smaller sleep-stages or to awakenings.

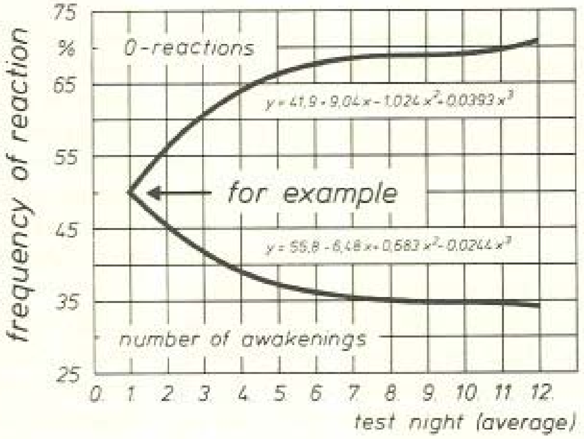
Type of noise and content of information. One important factor is presumably the type of noise. After having gathered the available data from nine publications a correlation was found between the number of awakenings and the bandwidth of noise. But nevertheless the underlying predominant factor in sleep disturbance is probably the content of information which is not only a function of the frequency spectrum but firstly dependent on learning history.

A well-known example for this is a mother's sleep which will be interrupted even by the weakest cries of her baby. On the other hand, high-intensity road-traffic noise does not lead to similar reactions.

The significance of the learning history (or conditioning) has been indicated in experiments where 56 different names were presented during the night. Though the subjects were undoubtedly asleep, more evoked potenials, more decreases of galvanic skin resistance and more signalled arousals were recorded when the particular name of a subject was presented. This is because the human brain is able to distinguish between unimportant and significant stimuli even during sleep. Playing back the tape in the reverse direction, the frequency spectrum and intensity are the same. But now responses to the name of an individual are similar to those of the other names.

Responses to new stimuli are also at lower thresholds because they are classified as potentially dangerous. If this is not true the subject then will learn to neglect them in the future. Thus — depending on the significance of a given stimulus — it is possible either to increase or to decrease the threshold for responses. For the latter effect the significance increases. In case of an increasing threshold the stimulus gradually becomes less important. This can be studied in people living near railroads and highways or in the surroundings of airports and factories. After a certain number of nights with more or less remarkable sleep disturbances the inhabitants cease to report sleep disturbances.

After having summarized the data of eight laboratory experiments the habituation effect was calculated and is demonstrated in Figure 10.3. This graph gives evidence that the number of awakening reactions decreases whereas the number of 0-reactions increases up to the sixth night at least. The terminations of both curves suggest the possibility of a second decrease or increase. Though this second effect needs to be demonstrated in further investigations, a second part of habituation seems to be realistic in view of the common experience that people feel remarkably less disturbed after having slept in noisy environments for a long time. On the other hand — as we know from field studies — the process of habituation seems to be limited. Slight sleep disturbances can be recorded even after years of exposure.



theoretical habituation to acoustical stimuli
during sleep;
number of awakenings in the first test night: e.g. 50 %

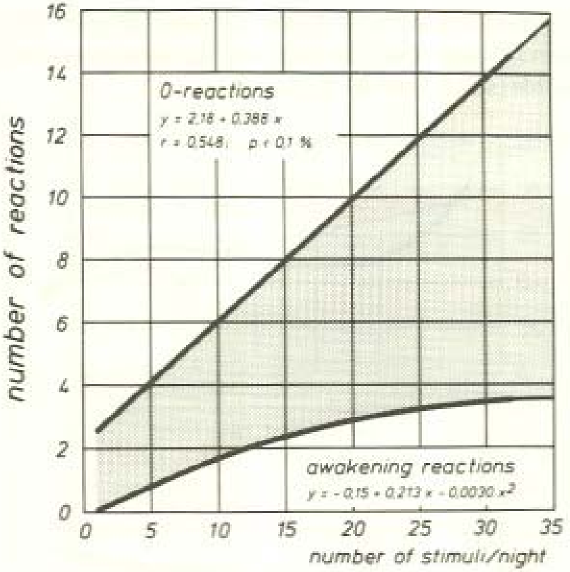
0-reactions = reactions less than a change in sleep stage
calculated from: 8 publications with 72 subjects in 802 nights
after 8138 noise stimuli
aircraft noise, pink noise, truck noise (40-86 dB(A))

Figure 10.3 Theoretical habituation to acoustical stimuli during sleep, e.g. number of awakenings in the first test-night is 50%

The conclusion to be drawn from this chapter is that while experiments carried out for only one or three nights per subject, as well as experiments in which unusual stimuli are applied, are important for learning something about the mechanisms of sleep, they cannot be the basis for far-reaching decisions.

Duration and number of stimuli. Although some authors report correlations between the probability of being awakened and the duration of a stimulus, these findings seem to be merely effects of conditioning. In these investigations the stimuli were presented with a successive increase in intensity until the subjects were awakened and then switched off the noise.

Contrary to this, the probability of any reaction is clearly related to the number of stimuli per night. Figure 10.4 shows an increasing number of awakening reactions when more stimuli are presented. This increase, however, becomes gradually smaller and is 0 at 35 stimuli per night. Afterwards, a decrease seems to take place. Though not yet proven this decrease seems to be realistic as it is suggested by habitants in streets with



0-reactions = reactions less than a change of one sleep stage
10 publications with 421 subjects within 1025 nights after 9096 stimuli
stimuli: sonic booms, pink noise, different aircraft noises (58 - 87 dB(A))
(corrected to the 6th test night, except the results of MUZET 1973)

Figure 10.4 Relation of number of reactions to number of stimuli/night

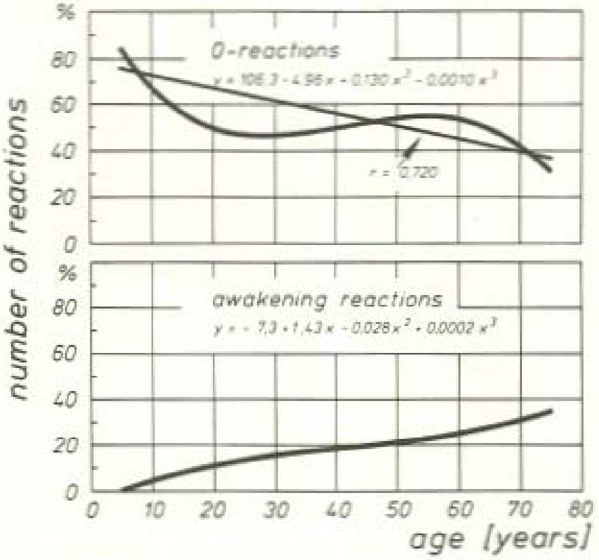
high traffic load. The probability of shifts to lower stages (including awakenings), however, gradually increases with the number of stimuli.

Additional factors. Under natural conditions the organism is influenced by a varying combination of different stimuli leading to a permanent oscillation of cortical activity. The extent of the response evoked by a defined stimulus varies according to the law of initial value.

Ambient noise level, ambient temperature and greater intensity of light are among the environmental stimuli causing a variation of noise-induced reactions.

Endogenic factors

Age. The influence of age seems to be the most prominent. Whereas children of about 10 years react with awakenings at a rate of 5%, the probability is 30% for aged people of about 70 years; This means a difference of 25% for the same maximum level. The age dependent difference grows remarkably in comparison to the probability of reactions of less than a change of sleep stage. Where 10-year-old children do not show any reaction in 72% of all cases the proportion of non-reactions is 40% for the aged people. This difference is especially important regarding the fact that the elderly regularly have worse hearing-thresholds (see Figure 10.5).



0-reaction = reactions less than a change of one sleep stage
from 3 publications, 26 subjects, 368 nights, 4428 stimuli
(58-86 dB(A), sonic booms and aircraft noises)

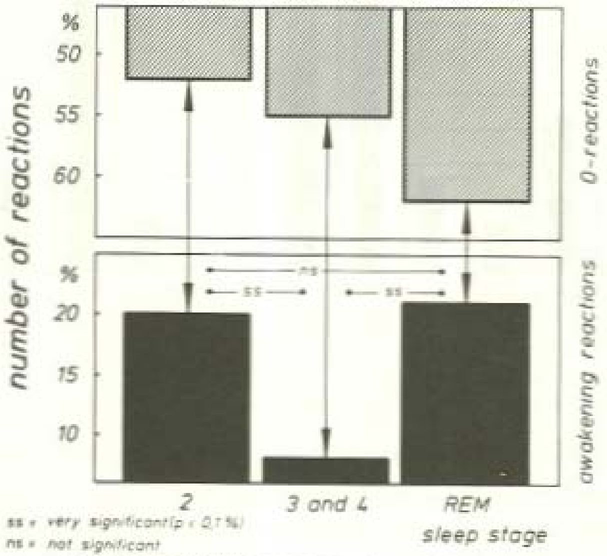
Figure 10.5 Variation of percentage of reactions with age of individual

Sex. With respect to sex contradictory results are reported. Whereas American authors pointed out a higher sensitivity to noise for female subjects, French researchers report a greater number of reactions for male subjects, though in both studies aircraft noise was presented during sleep. Field studies carried out recently reveal that women react more intensively and more often than men.

Biorhythmic changes of activity. Additional causes altering the extent of reactions are related to biorhythmic changes of activity. Although sleep during the day is poorer than during the night, there are more disturbances under noisy conditions.

Examining the time of night several authors observed an increase of noise-induced sleep disturbances during the second half of the night. This may partly be explained by the fact that the subjects are then mainly within low stages of sleep and partly because they are relatively recovered in comparison to the first half of night. But these results came from studies where noise exposure normally began after sleep onset. In those studies, however, where stimulation began before the subjects were asleep (this is, of course, true for field studies) more extensive reactions were found during the first half of night. During the second half the organism then tries to compensate them.

Cyclic changes of the EEG and EOG pattern are related to a varying sensitivity to environmental stimuli. This dependency is very consistent so that depth of sleep is even defined by the intensity of stimuli necessary to cause awakening. Figure 10.6 demonstrates a relatively high amount of awakening-reactions during sleep-stage 2 concomitant with a small number of 0-reactions whereas the same stimuli cause relative few awakenings and more 0-reactions during Delta-sleep. An exception is stage REM sometimes requiring higher intensities than stages of Delta-sleep and on the other hand requiring less intensive stimuli than sleep-stage 2. The reverse was pointed out for reactions less than a change of sleep-stage.



ss = very significant (p < 0.1 %)
ns = not significant

0-reactions = reactions less than a change of one sleep stage
calculated from: 6 publications with 54 subjects within
46 nights after 2910 + 1485 + 1334 stimuli (68 - 120 dB(A);
impulse noise, sonic booms and aircraft noises)

Figure 10.6 Variation of percentage of awakenings and of 0-reactions with the particular sleep-stage

LITERATURE LIST I

Berry *et al.* (1970), Collins *et al.* (1973), Dobbs (1972), Griefahn (1977, 1980), Griefahn *et al.* (1974, 1975, 1976), Jansen (1970), Jurriens (1980, 1981), Kramer *et al.* (1971), Le Vere *et al.* (1973), Ludlow *et al.* (1972), Lukas *et al.*

(1968, 1969, 1971, 1972, 1973, 1975), Metz *et al.* (1976), Muzet (1980), Muzet *et al.* (1971, 1973), Osada *et al.* (1972, 1974), Oswald *et al.* (1960), Rylander *et al.* (1972), Schieber *et al.* (1968), Scott (1972), Steinicke (1957), Thiessen (1969, 1973, 1980), Tizard (1966), Vernet (1979), Vallet *et al.* (1980), Wilkinson (1980, 1981), Wilson *et al.* (1966).

B. Whole Night's Sleep

Regarding the results just reported it is an obvious conclusion that the immediate reactions — particularly the awakening reactions — cummulate during the night and — in connection with a frequently observed delayed sleep onset — result in a considerable loss of sleep. But Figure 10.7 gives evidence that neither the total sleep-time (from sleep onset to final awakening) nor the real sleep-time (total sleep-time — intermittent wakefulness), is substantially altered. However, the analysis of the amount of the different sleep stages shows that their distribution is (although very slightly) significantly affected in noisy nights; whereas intermittent wakefulness increases and Delta-sleep decreases; the lower sleep-stage 2 and stage REM remain at the same level.

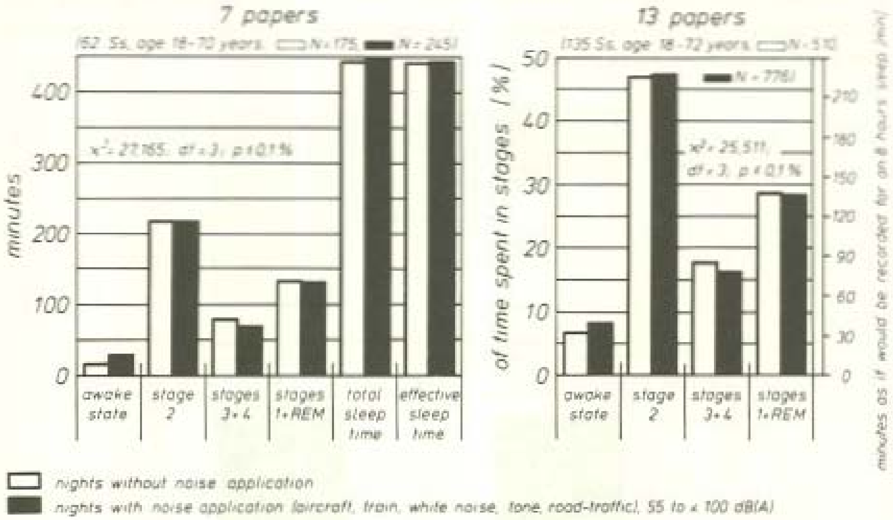


Figure 10.7 Analysis of sleep stages and effect of noise

These results obtained by summarizing calculation are very consistent. They are mostly reported in the individual papers although — due to the relative small number of observations — they often are not significant. Less consistent are the effects on REM sleep. Several researchers report about a remarkable reduction of time spent in stage REM in connection with a significant REM rebound within subsequent quiet nights. Some authors only found REM reductions, others only REM rebounds. Some papers report an increase in the REM amount.

But even when the amount of the different stages is not changed, effects of noise may be observed when the temporal organization of sleep is analysed. The temporal distribution of stage X relative to the centre of the night is called the barycentre. The barycentre of stage-awake tends to shift towards the beginning, the barycentre of stages 3 and 4 combined towards the end of the night.

This latter finding provides evidence that the organism tries to compensate sleep disturbances already during the same night. Moreover habituation takes place during the experiments. But, as we learned from field studies, this habituation is incomplete. Small alterations are still recorded of habitants living in noisy environment for several years.

By an increasing number of stimuli whole night's sleep seems to be less affected. More extensive alterations are expected with higher ambient temperature.

The influence of endogenic factors is less clear than for the immediate reactions. Age-related differences were reported only occasionally and they were small. More pronounced differences were found due to sex. The sleep of female subjects seems to be more disturbed. Personality factors are not less important. Subjects with higher values for anxiety, dependency or introversion have stronger reactions.

LITERATURE LIST II

Collins *et al.* (1973), Ehrenstein *et al.* (1974, 1980), Globus *et al.* (1973), Griefahn (1977, 1980, 1985), Griefahn *et al.* (1974, 1976, 1980a), Herbert *et al.* (1973), Knauth *et al.* (1972), Kramer *et al.* (1971), Lukas *et al.* (1968, 1969, 1971, 1972, 1973, 1975), Metz *et al.* (1976), Muzet (1980), Muzet *et al.* (1973, 1974), Olivier-Martin Schreider (1973), Otto (1970), Rylander *et al.* (1972), Scott (1972), Thiessen (1973), Jurriens (1980a, 1980b), Vallet (1981, Vernet (1979), Wilkinson (1981).

10.2.2 Body Movements and Vegetative Reactions

The typical reaction to noise starts with a K-complex followed by an increase of cortical activity of more or less duration, by an increase of heart rate and finally by body movements.

Though body movements are easy to record and though they are regarded as sensible indicators of noise-induced sleep disturbances they are investigated relatively seldom. Therefore our knowledge of this parameter is very poor.

Vegetative reactions were studied more intensively. They occur immediately after the onset of the stimulus and they are already found during daytime but at remarkably higher thresholds (at least 10 dB(A)). Most frequently investigated is the ECG as an indicator or heart-rate which increases during noise. Heart rate increases and consecutively decreases when stimuli with short rise-times are applied. Galvanic skin resistance (GSR) and fingerpulse amplitudes used as an indicator of peripheral blood flow also decrease. PATs (phases of transient activity consisting of EEG and EOG changes combined with changes of the EKG and eventually with body movements) evoked by single noise peaks are mainly discussed in French papers.

GSR, FPA, and PATs are parameters showing spontaneous alterations even during non-disturbed nights. The whole number of these changes was normally not increased during noisy nights. But, the use of the pseudostimulus technique for evaluation makes evident that they are now evoked by the single noise events.

The extent of the vegetative reactions is positively correlated with the peak levels of the acoustic stimuli. Variations of ambient temperature of at least 8 °C cause a reduced response of fingerpulse amplitudes to the same stimuli. This variable turned out to be dependent also on age: children and aged adults have larger constrictions than younger adults. The extent of the vasoconstrictions is smaller in slow-wave-sleep than in REM and stage 2, and decreases with a higher prestimulus heart rate. Pulse rate positively related to the noise peak level increases less during Delta sleep than during the other stages and is greater for younger subjects.

The main finding for all the vegetative reactions is the lack of any habituation. Even during a fortnight noise-induced reactions on heart-rate and on peripheral blood-flow did not reveal any diminution.

LITERATURE LIST III

Baust *et al.* (1971), Collins *et al.* (1973), Griefahn (1975a, 1975b), Hofman *et al.* (1980), Jurriens (1981), Keefe *et al.* (1971), Kramer *et al.* (1971), Metz *et al.* (1976), Muzet (1980), Muzet *et al.* (1971, 1973, 1974, 1980), Oswald *et al.* (1960), Schieber *et al.* (1971), Townsend *et al.* (1973), Vallet (1981), Wilkinson (1981)

10.3 AFTER-EFFECTS

After effects or carry-over effects are, for instance, subjective variations like the feeling of having had a poor sleep, an alteration of mood and perhaps of perfomance. These alterations can probably be detected during the day following a night of disturbed sleep. As even the relationship to sleep itself often remains unsolved it is, furthermore, difficult to refer those effects to noise. Late after effects, supposed to occur after years of permanent noise exposure have not yet been proven.

Subjective sleep quality as judged every morning by the subjects is relatively easy to record and therefore utilized in many studies.

In general, sleep quality is assessed to be worse during noisy nights and correlated to the equivalent noise level during bedtime. Sleep is reported to be less deep, shorter, the number of awakenings remembered increased; sleep latency is estimated to be longer, the process of falling asleep difficult, and the subjects feel more tired in the morning.

Subjective sleep quality will especially be affected if stimulation already starts when the subjects are awake (as it is in field studies)

Sleep disturbances are also supposed to decrease individual performance. Apart from one study, in which a small increase of reaction time was found, a clear decrease of performance has regularly been connected with a considerable loss of sleep, much more than it is recorded for noisy environments.

The reason for these results may be that noise-induced sleep disturbances are really unimportant (for several nights) or that sleep disturbances can be compensated for a limited time. Another assumption is that the performance tests utilized are not sensitive enough to detect small differences or that the number of experiments fail to reveal significant differences.

The most recent study in which performance tests were applied is a joint European project. It was carried out as a field study where in the overall more than 1,000 nights of 63 subjects were recorded. A clear decrease of performance — probably related to noise — was found (increase of reaction time in the unprepared Simple Reaction Time Test or an increase of errors during the Four-Choice Test).

LITERATURE LIST IV

Griefahn (1985), Griefahn *et al.* (1980a, 1980b), Griffiths *et al.* (1968), Herbert *et al* (1973), Jurriens (1980, 1981), Kramer *et al.* (1971), Langdon *et al.* (1977), Le Vere *et al.* (1972), Ludlow *et al.* (1972), Lukas *et al.* (1971, 1972, 1975), Metz *et al.* (1976), Muzet (1980), Olivier-Martin, Schneider (1973), Rylander *et al.* (1972), Townsend *et al.* (1973), Vallet (1981), Vallet *et al.* (1980), Wilkinson (1980, 1981).

10.4 CONCLUSION

Overlooking the data presented (in this paper) one could come to the conclusion that the knowledge of noise-induced sleep disturbances is almost complete. However, the data available only make some problems a little bit more comprehensible than they were before, but we are still far from any solution.

For example, noise has different primary effects on sleep. These so-called sleep disturbances are alterations in the EEG and EOG, behavioural reactions like body movements and awakening as well as vegetative reactions. They are affected likewise. However, when correlating the individual data, large discrepancies are evident. Most of the researchers working in this field have experience with subjects reporting severe sleep disturbances, where the objective data (EEG and EOG) indicate sufficient quantity and quality of sleep. The reverse effect is as well known.

The global data reveal that both parameters tend to habituate during test series but the individual data are not necessarily correlated. Thus, in view of the hypothesis that chronic sleep disturbances finally lead to manifest diseases the significance of these parameters is doubtful. Consequently, more and more scientists begin to record variables which are not submitted to habituation. Those parameters are the vegetative reactions, as for instance heart-rate and pulse amplitudes. But we have to stress the point that we still do not know the parameters really indicating or even predicting the detrimental effects on health.

Based on a critical interpretation of the literature a detailed research hypothesis was specified which enables working to continue in a carefully directed manner (see Figure 10.1).

Taking into account the very long time necessary for this field of research, scientists are requested to use methods of recording and evaluation which are comparable to those of other teams. If this course were not adopted then the collection of data would merely point to problems but not solve them.

Such a co-operation was practised in a recent study. This study was initiated by the CEC and was carried out by four different teams in the Federal Republic of Germany, in France, in the Netherlands, and in the United Kingdom. The aim of the study was to investigate the effects of long-term exposure to road traffic noise. Physiological sleep data (EEG and EOG), subjective sleep quality, and subsequent performance were considered. Sleep recordings were completed in 70 subjects sleeping in their homes situated along streets with high traffic load. During test series sleep was recorded under both noisy and quiet conditions. During the experimental phase the noise level was either increased or lowered by wearing earplugs, fitting double glazing, closing or opening the windows or moving to another bedroom in the rear of the house. EEG and EOG as well as noise levels were continuously registered throughout the nights. Additional variables such as EKG, signalled awakening, body movements, or respiration were optional. In total more than 1,000 nights were recorded. The data summarized so far clearly indicate that the three different parameters of sleep quality are affected by noise. These are the time spent in intermittent wakefulness, the subjective sleep quality and subsequent performance. In continuation to the CEC-study, an experimental study was carried out in the laboratory where a critical load for high-density road traffic noise was determined. This is an equivalent noise level of L_1 = 10 dB(A) indoors. This limit seems to be valid.

Such a co-operation should be maintained and of course widened. This will be extremely important when the presumed connection between nightly occurring noises and health are investigated. This proof cannot be shown in the laboratory. It has to be carried out as an epidemiological study. According to the large number of permanently varying influences hundreds of subjects have to be investigated.

Though some aspects of noise-induced sleep disturbances are sufficiently clear, most of the problems have to be solved in the future but as soon as possible. There is no doubts that sleep disturbances are stressful to the individual. Stress, however, is regarded as a most important risk factor, especially for the pathogenesis of the cardiovascular diseases, and it may be possible to lower this risk by introducing sound attenuation.

LITERATURE LIST V

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CHAPTER 11

Hearing Conservation

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11.1 INTRODUCTION

If the statistics are closely examined, we find that there are at least 25 million people in the United States who have a hearing impairment which produces a significant communication problem. Since sensorineural hearing loss is by far the greatest part of this problem and treatment at the present time leaves much to be desired, it is quite obvious that we must look to prevention. Prevention is not only important in industry, but also in schools and other walks of life which bear no relation to industry.

If we define hearing conservation in the broadest sense we must not confine our efforts to the preservation of normal hearing but also include the preservation and conservation of residual hearing. There is no question that industrial noise produces more hearing loss in more people than all other causes combined. The tragedy of this statement is that nearly all of industrial hearing loss can be prevented with proper hearing conservation procedures. Is it any wonder that preventing hearing loss due to excessive noise exposure has become a major concern in the United States as well as in most of the rest of the world?

Recognition of the need for hearing conservation in industry should be obvious from the statistics quoted above. However, the recognition of this need seems to be based on something beside the number of individuals who have sustained hearing loss from industrial exposure. We have been quite concerned about this problem since the late 1930s but nothing was done about it until about ten years later. The initiating factor was the award of compensation for occupationally-induced hearing loss. From that point on, the interest has grown until at the present time there are rules and laws which have been written and re-written which will enforce the introduction of hearing conservation measures in industry throughout the United States and in many other countries of the world.

The medical profession recognized the need for doing something about noise exposure as far back as 1800. It was not until the end of World War II that other professionals took notice and the medical profession interested enough to attempt to do something about it. At the present time, there are many separate disciplines and organizations involved in establishing the need for hearing conservation in industry; these include industrial hygienists, audiologists, safety personnel, State and Federal agencies, research scientists, nurses and even audiometric technicians. This need has initiated training programmes for those concerned with hearing conservation and the number of personnel who are employed in hearing conservation programmes increases daily.

11.2 COMPONENTS OF A HEARING CONSERVATION PROGRAMME

11.2.1 Noise Measurement

Obviously, the measurement of the offending factor is essential before one can determine the need for a hearing conservation programme. Let us consider the types of noise measurement and why they are essential. First of all, noise measurement is usually done for two reasons: (a) to determine whether or not there is need of a hearing conservation programme and (b) to obtain enough information to apply noise-control. Two simple measures will suffice when one is determining the need for hearing conservation. One is the noise level in dB(A), and the other is the time of exposure. However, where noise-level control procedures are concerned it is essential to obtain much more information. But the purpose of this chapter is not to describe noise-control measurements nor methods of noise control.

All standards concerned with hearing conservation are given in dB(A) because dB(A) measures the sound level in relation to the human ear frequency response. It is well known that frequencies below 500 Hz have little or no effect on the hearing of exposed individuals unless these levels are extremely high (above 130 dB). Having measured the noise level at the appropriate location to determine whether the level exceeds the stated criteria (presently 90 dB(A) in U.S.A.), we must then determine the amount of exposure in time. If the noise level reaches the limit but the exposure time is less than eight hours, there is no need for a hearing conservation programme. On the other hand, if the exposure continues for more than eight hours, the accepted level in dB(A) is reduced accordingly. Most standards agree that dB(A) sound level measurements should be made with the sound level meter set at a slow-meter reading time. Most dB(A) measurements should be made at the level of the exposed individual's ears and at the location where he usually works. Furthermore, care should be taken to determine the effect of the surrounding surfaces and directionality of the sound source. If care is taken to direct the microphone appropriately at the usual source of the noise, and the effect of enclosures and various types of surface material are included then such a measurement should be reasonably valid.

One of the real problems with noise measurements in situations such as these is that the level is not always constant and, therefore, various measurements should be made at various times of the day over a period of a month or so to determine an average level for that particular location. (Ordinarily this is not done and, therefore, when one attempts to correlate hearing loss with noise level in these locations, the correlations are found to be faulty, the noise level varies from time to time and no allowance has been made for this variation.) In the author's opinion, it is desirable to make a number of measurements in any particular location on different days at different times of the day, then average these levels to derive a valid representation of the general exposure.

More recently, instruments called dosimeters have been developed which are coming into general use. Most of these instruments are based on the limit level for an eight-hour continuous exposure. The dosimeter accumulates the total dosage over an eight-hour period and registers it as a percentage of the reference L_{eq}. The problem with most dosimeters is that they make no allowance for intermittency unless the time level trade-off is corrected for appropriately. More recently, some dosimeters do not summate the readings over all but give a direct reading of on and off times which gives a more accurate picture of the exposure characteristics.

I feel quite strongly that if levels exceed criteria by any amount for periods that exceed one to two hours for that day, then hearing conservation measures should be initiated, even though the risk of hearing loss is much less if the exposure is less than eight hours.

It is essential that employees be protected at all times when they are in a general area that exceeds the stated criterion. This is particularly true where there is a large area containing numerous noise-making devices. Some of these devices may not be hazardous, but within a few feet another worker may be located where the level and exposure time is hazardous; he will be required to wear ear protection while the man next to him is not. I would rather overprotect by the use of noise control and/or ear protection than try to explain why some individuals, but not others, are wearing ear protection.

11.2.2 Hearing Measurement

According to all present standards, it is necessary only to do air conduction threshold pure-tone audiometry at 500, 1,000, 2,000, 3,000, 4,000 and 6,000 Hz. There are a number of important factors which influence the validity and the reliability of such tests, and one is the environment in which the tests are made. Obtaining a proper environment is sometimes difficult and certain steps should be considered prior to establishing a location that is suitable for doing pure-tone threshold audiometry. Unfortunately, ambient levels in most locations are usually too high for satisfactory testing of learning. It is necessary, therefore, to provide some sort of booth which will meet the specifications.

This is usually accomplished by installation of a pre-fabricated booth, which in the author's opinion, is the most satisfactory solution. A simple procedure is to make octave-band level measurements in the location where it is planned to do the hearing tests and then determine what sort of enclosure is required to reduce the levels to those necessary. The amount of attenuation provided by the commercially available booths can be determined quite simply by reading the specifications provided by the manufacturers. If the attenuation provided by the booths as a function of octave bands does not provide satisfactory ambient levels, then one of two alternatives is left. Firstly, one should consider choosing another location in which to place the enclosure, or secondly, to purchase an enclosure which provides enough attenuation to bring the levels down to those considered satisfactory.

There are two general methods of making hearing tests in industry at the present time; one is with a simple pure-tone audiometer which should provide for threshold audiometry at the usual frequencies, but if not, at least at 500, 1,000, 2,000, 3,000, 4,000 and 6,000 Hz. In the author's opinion, it is quite essential that the audiometer used for industrial testing should have the provision for either a steady tone or a pulse tone. There are times when the pulse tone is of great assistance in determining the threshold in industrial cases, particularly where tinnitus may be present. The other method of testing is the use of the Békesy type audiometer, which is more recently called the self-recording audiometer. This audiometer provides for air conduction thresholds at the essential frequencies and sometimes in addition at 8,000 Hz. In these audiometers a steady tone or a pulse tone is already available. Which of these two methods is used depends to a great extent on the needs of the particular company. Where the number of individuals to be tested are few, such as less than 100, manual audiometry is quite suitable. On the other hand, if more than 100 individuals are to be tested, the self-recording audiometer is usually better since it allows more than one audiometer to be operated by the same individual. Further, it does not tie the operator to the testing until it is completed. The self-recording audiometer allows for a self-administered test under reasonable supervision. The person being tested should not be started and left alone until the test is completed; it is essential that the testing be scrutinized several times before completion to be certain the individual is proceeding properly.

Before valid and reliable audiograms can be obtained through self-recording audiometry, it is essential that certain criteria be adopted and followed. The pen excursion, as it proceeds from low to high level and vice versa, should not exceed 15 dB from peak to valley. If this value is exceeded, there are not enough threshold crossings for each frequency to determine the true threshold for that frequency.

More recently, computerized audiometers have been developed and are available to industry at the present time. I believe these computerized instruments will eventually replace all other types of equipment, at least for industrial use.These audiometers provide completely automatic testing. The test procedure is computerized to the extent that false positives and false negatives are reduced to a minimum. Further, they can be programmed to analyse the data on-line and make decisions regarding the individual being tested immediately. They also provide hard-copy records immediately, thus avoiding the possibility of false records due to repeated transposition of the data.

'In-house' programmes and the appropriate equipment which provide the enclosure for testing and have provisions for the needs of the individual plant are, in the author's opinion, necessary to complement outside services. 'In-house' programmes can be used for doing pre-employment tests and any interim re-checks. 'Outside' services that provide hearing testing and computer analysis are extremely valuable as an adjunct service to 'in-house' programmes. These companies use 'mobile vans' equipped to test 4, 6 or 8 subjects at a time. Their best use is for the annual tests. These services can do large numbers of tests under controlled conditions in a relatively short time and provide extensive computer data analyses.

Such service, if properly organized, also can provide quality control of the 'in-house' hearing conservation programme.

The most important part of the hearing measurement programme is determining what action should be taken on the basis of the test results. If no action is taken, then hearing tests are a waste of time. The mere gathering of tests and filing them away is useless as far as hearing conservation is concerned. Outside services, if properly organized, should provide computer analyses for both group and individual actions.

A. What Hearing Tests are Necessary for an Industrial Conservation Programme?

There are two principal types of tests that are essential; one is the pre-employment audiogram, which ideally should be made at the time of hiring; and if not, at least within 30 to 60 days of the time of hiring. The other is the re-check test, usually done annually.

I feel it is also wise to do a pre-placement audiogram; for example, if an individual is hired but does not work in a noisy situation initially, but is then transferred into a noisy area, an audiogram should be done at that time. In some areas a terminal audiogram also is recommended, that is, if the individual quits working at a particular plant an audiogram is done to determine the status of the hearing at the time of leaving his employment. Generally, however, it is agreed that pre-employment audiograms and re-check audiograms done annually are the recommended tests.

Another important test is referred to as the 'repeat-test'. When a re-check test is completed and a shift of threshold is found, another audiogram is made within 30 days to check the validity of the re-check test. Whether the 'repeat-test' is necessary depends on the referral criteria that are used. Examples of referral criteria:

a. When there is a shift of 20 dB or more at any frequency from the previous hearing test.
b. When there is a shift of 10 dB or more average of 500, 1,000 and 2,000 Hz (AHL), or a shift of 20 dB or more average of 3,000, 4,000 and 6,000 Hz from the previous audiogram.

If the 'repeat-test' confirms the 're-check test', certain actions are necessary. Usually, these are the following:

a. Ask the employee about his ear protection habits.
b. Re-instruct the employee about ear protection.
c. Counsel the employee about hearing conservation.

If the shifting threshold continues at the next re-check test, serious consideration should be given to removing the employee from the noise source since he appears to be losing hearing in spite of ear protection.

B. Record Keeping:

Record keeping for an industrial conservation programme is one of the programme's most important aspects. Because these records may become part of a medical–legal procedure at a time in the future, it is essential that they be kept accurate and legible. I have seen many industrial records used in cases of litigation where it is almost impossible to tell what the recorded history says because of poor legibility or poor methods of recording, particularly with reference to the results of audiometry. In general clinical audiometry records are grids with curves using red ink for the right ear and blue or black ink for the left ear. The symbols are circles for the right ear and an X for the left ear. Unless these symbols are carefully placed on the audiometric grid, it is almost impossible to decide what value they were intended to be. Furthermore, when the usual clinical records are used, it is very difficult to compare one audiogram with another because there is no sequential information except on separate cards, making scrutiny very difficult. However, if the records are kept in columns and rows preceded by dates and the threshold value is recorded in squares, it becomes a very simple matter to decide what that value is as well as compare sequential or serial audiograms. In addition, this method makes it possible to record numerous audiograms on one page, thereby making filing of the information much less difficult.

If self-recording audiometry is used, tracings should be translated into numbers and recorded on a master sheet. However, since the self-recording test-card is the original, it should be kept in case it is necessary for medical–legal reasons.

This brings up the real purpose of hearing tests and their relation to hearing conservation. I know many hearing conservation programmes that include hearing tests that are filed away without evaluation and analysis. It should be noted that making audiograms without evaluation and subsequent appropriate action is a worthless activity. The hearing test is merely a monitoring system to determine what action is essential. If no action is taken, testing is a waste of time.

C. Personnel

It is essential that the ultimate responsibility for a hearing conservation programme be delegated to a physician. I do not mean that the physician should carry out the actual details of the programme, but that he should be responsible for policy and decisions concerning the disposition of the individuals involved. In the case of a large corporation where many plants are involved, someone on a corporate level should be responsible for the day-to-day activities of the hearing conservation programme. This individual should, in co-operation with management and the medical director or medical consultant, determine what the corporate programme should be. This person should also be responsible for the preparation of a manual to be used by all individual plants as a corporate programme meeting all the requirements of appropriate regulations. Ideally, this person should be someone who is trained in the audiological profession, e.g. an audiologist, provided of course the programme is large enough to warrant the continuous activity of such an individual. Some corporations have delegated this responsibility to the industrial hygienist and/or the corporate safety supervisor. However, due to the fact that the industrial hygienist and/or the corporate safety supervisor have many other duties to perform, they would not be able to give adequate time to the hearing conservation programme to make it a success. Therefore, I believe it would be wise on the part of the large corporation to employ an audiologist or an appropriate consulting firm to work with the industrial hygienist or the corporate safety supervisor. This person can supervise the programmes in each plant, and analyse the data for corporate purposes with respect to disposition of individuals who are under the surveillance of the hearing conservation programme.

Individuals at the plant level where the actual programme is conducted can be used even though they may be less qualified. They may be nurses, nurses' aids or clerk-secretary personnel provided they are properly trained and supervised by someone who is responsible for the hearing conservation programme. However, the responsibility for the conduct of the whole programme should be placed in the hands of whoever is appropriate to accept this level of responsibility.

11.3 IMPLEMENTATION OF THE PROGRAMME

11.3.1 Education

Before any hearing conservation programme can be a success the personnel involved, both employer and employee, should be educated to its needs, purposes and results. Perhaps the personnel who most need this education are management and union representatives. If these two groups do not agree and do not participate in motivating the persons involved, it will be far from successful. In my opinion such education should consist of appropriate films, discussions with union stewards and group supervisors, as well as discussions with the workers. It is essential that all individuals be convinced that noise does produce a hearing loss and that it can be prevented with active cooperation between employer and employee.

Education on hearing conservation is very important, even more so than many other kinds of safety education. The consequences of noise exposure are not as obvious as those from accidents. The results of a piece of metal entering an eye are immediately obvious; whereas, the results of noise exposure are not obvious until it is too late. Therefore, education becomes exceedingly important and convincing the individual of what can happen to his ears if they are not protected is essential. Hearing loss is a gradual process and the individual may accumulate considerable hearing loss without realizing it.

Obviously, education is one means of promotion but other methods should also be used such as visually designating areas where noise hazards exist. Posters and signs can be appropriately placed to indicate the hazardous areas.

Hearing conservation needs continual reminders. Such reminders can appear in company communications of any kind. It is also essential that if posters are used, they be rotated from time to time, to arouse more attention in different areas of the plant. In addition when an individual comes to the area for a hearing test the tester should make it his/her business to talk to the worker, asking how he/she is doing with his/her ear protection, etc. If a change does appear between successive audiograms, the employee should be warned of this and his/her ear protection habits should be reviewed.

Hearing conservation discussions should be an important item at all safety meetings. As stated above, since the need for hearing conservation is not overt it is very important to have continual reminders for the employee and supervisory personnel.

11.3.2 Voluntary Programme

At the present time, most hearing conservation programmes are voluntary. In my opinion voluntary programmes are acceptable only in the early stages. They do give individuals the opportunity to try ear protectors, or to work under the conditions that have been created by noise control procedures. However, it has been the author's experience that a voluntary programme is not successful over a long period. After a period of perhaps 1 to 6 months or less, a **mandatory programme** should be initiated. There are many industries with mandatory programmes that are highly successful. The large number of individuals who will finally abide by the hearing conservation rules without protest is surprising. There will always be some individuals who will be recalcitrant, but this usually is a very small number. A mandatory programme can be successful and is the only eventually successful method.

Hearing conservation programmes are now incumbent on all of industry since the regulators in many areas have ruled that a worker's hearing must be protected. If this is not accomplished, the employer, not the employee, is considered to be at fault. Although the regulators have stated that management shall initiate hearing conservation programmes, there has been no instruction on how this shall be enforced. Most employers with mandatory programmes have resorted to the following: if a worker appears without protection, he/she is given one day off without pay; if he/she appears a second time without protection the worker is given three days off without pay, and if this occurs a third time, the person is dismissed from employment. Further, when an individual is hired and it is known that he will be employed in a noisy area, ear protection is made a condition of employment and the agreement with the employee is such that if the employee refuses to wear the ear protection, dismissal can result without further action.

In the early stages of hearing conservation, such programmes were invoked and when such action was taken considerable reaction on the part of the employees or their union resulted. This is not nearly as common now, since both union and management realize that protection of hearing is essential. Even though hearing conservation programmes may be costly to industry in terms of dollars, it is now realized that the cost of hearing loss is much greater not only in the cost of dollars in the compensation courts, but also in preventable human suffering.

11.4 METHODS OF HEARING CONSERVATION

In general, there are two classes of hearing conservation measures: one is noise control of the environment at the source, and the other is hearing protection at the ear. Although I believe that noise control, whether this consists of barriers between the noise source and the ear, such as enclosures, walls or ear protectors is necessary, the method of choice is to control the noise at the source and thereby get rid of the hazard. During the past five to ten years experience has accumulated, showing that there are many effective ways of controlling noise at the source. Perhaps the two major deterrents in this area are technical feasibility and economic considerations. It should be quite obvious that some noises can be reduced technically, but the cost would be exorbitant making it not feasible from an economic standpoint. In fact, attempts at noise control at the source have been so costly as to force some companies out of business.

I am the first to agree that noise control at the source should be accomplished; however, I do not believe it should be mandatory unless it meets the provisions of being technically and economically feasible. I have found through years of experience that noise control away from the source can be just as effective as noise control at the source. The real problem involved is that even though certain reduction of noise can frequently be accomplished by engineering methods, the reduction is not enough to comply with regulations, or to be considered non-hazardous as far as hearing is concerned, and in this case, the employer is left with having to initiate procedures of noise control at the ear.

The method of noise control at the ear has been criticized because it is felt that these measures are not nearly as effective as noise control at the source; that is, ear protectors are not as effective as erecting barriers between the noise source and the ear, such as enclosures, barrier walls and reflecting walls. I find this difficult to agree with because it takes just as much supervision to get the employee to use the enclosures effectively as it does to see that he uses ear protection as he should, and my experience has shown that a well-supervised ear-protection programme can be just as effective as barriers and enclosures.

In summary, any engineering noise-control procedures that do not reduce the noise to a non-hazardous level will have to be supplemented by an ear protection programme, whether by barriers or ear-protectors and, therefore, superivison will be the key to the success of the programme. On the other hand, one could ask why engineering noise control procedures should be carried out at all, unless there is a guarantee that they will be reduced to a non-hazardous level. I do not agree with this attitidue. I feel that if reasonable amounts of noise reduction can be accomplished, that is to say a minimum of 5 dB(A), it should be done because this will then make it much easier to bring the levels at the ear into non-hazardous levels.

11.4.1 Ear Protectors

I am frequently asked the question, 'What is the best ear protector?' My usual answer is, 'The one that is worn'. This answer points out that the critical feature of any ear protector is comfort or 'wearability'. Attenuation is of no value if the device is not worn. As a matter of fact, most ear protectors provide about the same amount of attenuation. They may differ somewhat as a function of frequency and muffs usually give somewhat more protection than plugs (Table 11.1). Various methods of rating ear protectors have been devised, but none has

Table 11.1 Attenuation for the eight different ear protectors tested* (in dB re 1951 ASA audiometer reference zero)

	Frequency (c/s)								
Type	125	250	500	1000	2000	3000	4000	6000	8000
Ear plugs									
A	–	21.9	25.0	25.9	33.4	38.0	41.2	33.0	37.5
B	15	15.9	16.2	21.3	28.8	33.7	33.7	32.9	39.1
C	8	16	16	19	23	29	27	34	40
Ear muffs									
A	8	23	30	32	33	40	39	39	28
B	19	30	38	38	42	44	45	40	35
C	7	13	23	31	34	34	42	40	35
Cotton	5	6	8	9	13	15	13	14	16

* Data derived from tests performed according to the American Standards Association method for the measurement of real-ear attenuation of ear protectors at threshold.

proved very satisfactory to date. Most companies provide a limited choice depending on the user's preference and the amount of attenuation necessary to meet non-hazardous noise levels at the eardrum.

There are three general classes of ear protectors presently available: earplugs, canal caps and muffs. Each has its own advantages and disadvantages, and no single class will meet all demands. Only experience will assist in providing the best ear protector for any particular situation.

It is advisable not to accept the advertised laboratory attenuation figures for field use. It is preferable to subtract one standard deviation from the stated numbers to obtain the degree of protection that will be afforded under field conditions (Figure 11.1).

11.5 SUMMARY

Hearing conservation programmes, where appropriate in industry, are a must at the present time. Even though one may not wish to adopt an altruistic attitude towards the conservation of hearing one must, like it or not, initiate a hearing conservation programme to meet the regulations in many areas. Since industrial noise exposure produces more hearing loss in more people than all other causes of hearing loss combined, it is incumbent on all noise makers to do something about protecting human hearing.

The tragedy is that nearly all industrial hearing loss can be prevented with proper hearing conservation measures. The cost of hearing conservation is far

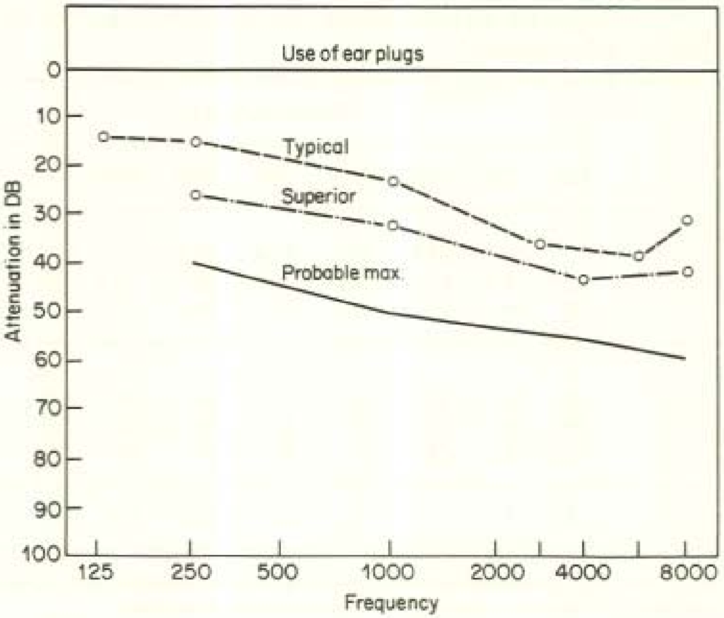

Figure 11.1

less than the cost of hearing loss in terms of human suffering, and dollars in the compenstion courts. Proper education of both managements and labour can result in successful hearing conservation programmes. The method of choice is reduction of the noise at the source, but in many cases this is not feasible either technically or economically, therefore protection at the ear must be used. Management must make well-supported attempts to carry out noise control, and if this cannot be done the decision must be supported by the opinion of experts on noise control at the source. Experience has shown that with proper superivison, ear protection programmes can prevent a large hearing loss in the majority of individuals exposed.

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PART III

SOURCES OF NOISE AND CONTROL

Noise Pollution
Edited by A. Lara Sáenz and R. W. B. Stephens

CHAPTER 12

Road Traffic Noise: Generation, Propagation and Control

C. Lamure

12.1 ROAD VEHICLES AS SOURCES OF NOISE

12.1.1 Sources of noise on the vehicles

The noise radiating from a motor vehicle can come from a number of different sources whose contribution to the total noise can depend on the speed of the vehicle. (see Figure 12.1). Table 12.1 shows the average, or rather the range of values, for the contribution to the total noise of the vehicle for each of these sources for both cars and heavy lorries. The amount of noise coming from each source depends very much on the type of vehicle involved and on the condition of the silencers. The noise due to the contact between the tyres and the road surface becomes dominant at high speeds. There are considerable variations in the relative contributions of noise coming from the engines and the exhaust systems in the case of two-wheeled vehicles.

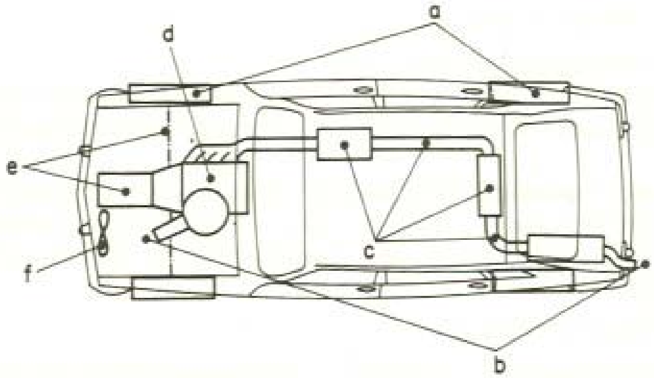


Figure 12.1 Sources of noise on a motor vehicle

Table 12.1 Percentage contributions from the different basic sources to the total amount of noise radiated by a well maintained road vehicle (IRT-CERNE, 1979)

	Light vehicles		Heavy vehicles	
Source of noise	Town	Open road	Town	Open road
Air intake inlet, exhaust outlet	15 to 35	20 to 70	15 to 60	40 to 80
Exhaust pipe assembly	15 to 30			
Engine block	20 to 30		30 to 80	
Gear box and transmission	5 to 30			
Cooling fan	–		10 to 50	
Tyre-road surface contact	5 to 10	30 to 80	5	20 to 60

A. *Engine noise*

The explosions inside the cylinders and the impact of the pistons against the cylinder walls excite the block and the various engine accessories, including in particular the different cases and housings. The latter include the sump case and the rocker arm cover, which often account for a significant proportion of the total noise coming from the engine.

The amount of noise radiated by the engine depends on its speed and the load to which it is being submitted, the latter determining the torque that is being produced.

The load does not have much effect in the case of a **diesel engine**, except for delayed indirect injection which can lead to a 5 dB reduction in the noise level when the engine is lightly loaded. For frequencies above about 500 Hz, the noise level L in dB(A) at a given frequency increases in proportion to 30 log N, i.e.

$$L_A = 30 \log N + \text{constant}$$

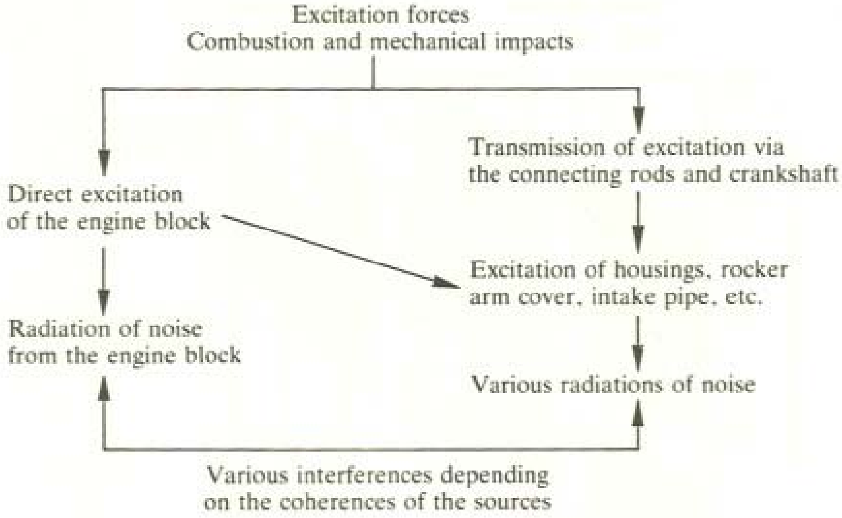
where N is the engine speed in r.p.m.

On examining the frequency spectrum for the noise it will be seen that the acoustic pressure level falls at a rate of 30 dB per decade for frequencies above 2000 Hz.

In the case of **spark ignition engines** the effect of load can account for as much as 5 to 6 dB(A) in the level of noise and it is found that the acoustic pressure level increases very rapidly with engine speed in accordance with the relationship:

$$L = 50 \log N + \text{constant}$$

The acoustic pressure level in the case of these engines falls at the rate of 50 dB per decade above a frequency of 2000 Hz.



Radiation of noise from the engine

The noise level does not increase so rapidly with the engine capacity C and we can say that in principle the total noise level in dB(A) varies as follows:

Diesel engines: $L_A = 30 \log N + 17.5 \log C$

Supercharged diesel engines: $L_A = 40 \log N + 17.5 \log C$

Spark ignition engines: $L_A = 50 \log N + 17.5 \log C$

These equations show that for the same power output a large capacity engine, which will be running at a lower speed, will be quieter than a faster running engine. The following graph (Figure 12.2) shows how the noise level for different types of engine varies with engine speed and rating.

B. Noise coming from the transmission and silencers

We do not have a very good understanding of the noise coming from the gear box and the transmission and it is considered that the mechanical excitation here can be partially due to the engine. It is known moreover that on certain cars the noise coming from the complete transmission system can be dominant. The most simple sound-proofing measure than can be applied in connection with this noise is the provision of a screen beneath the complete transmission system, which can usually take the form of a simple extension of the screen fitted beneath the engine.

The reduction of noise as a result of the provision of silencers associated with

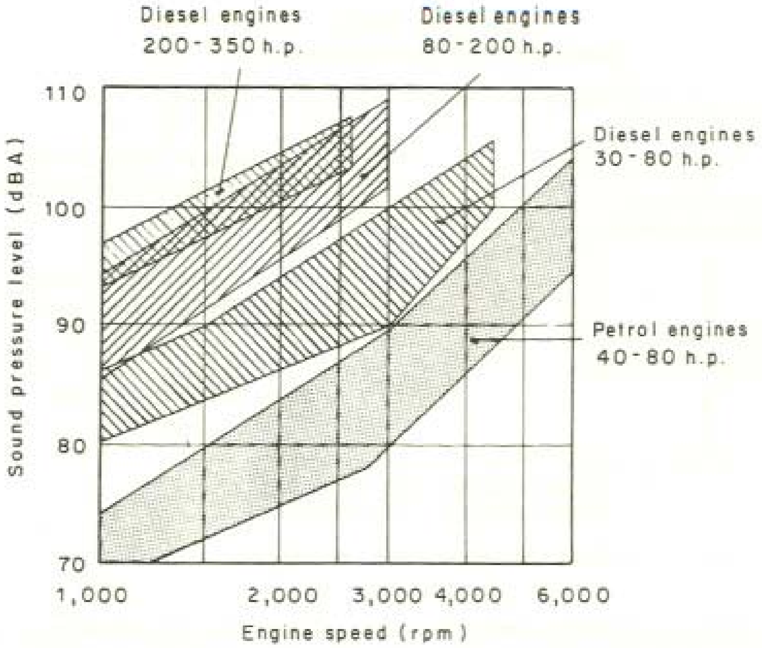


Figure 12.2 Noise level as a function of steady engine speed for different types of engine (Priede, 1971)

the air intake and engine exhaust systems gives rise above all to problems in connection with the life and size of these accessories. The size of the silencers is a problem in that their effectivness at low frequencies is a function of their volume.

C. *Noise due to the tyre-road surface contact*

The rolling noise is due to a number of different effects as is shown in Table 12.2. So far as the generation of noise is concerned we can classify the surface texture of the road surface in terms of the power spectral density of the longitudinal profile for wavelengths ranging from 2 to 200 mm (Sandberg and Descornet, 1980). If we define the mean square of the surface irregularities over a range of wavelengths centred on λ as T_λ, then the 'texture factor' can be expressed as:

$$L_\lambda = 10 \log_{10} \frac{T_\lambda}{10^{-12}}$$

where L_λ is expressed in dB with reference to a level of 10^{-12} m^2.

Surfaces having a high 'texture level' give rise in particular to radial excitation of the tyre and type I phenomena predominate. Surfaces having a low 'texture level' on the other hand give rise in particular to type II and type III disturbances.

Table 12.2 Noise due to tyre–road contact

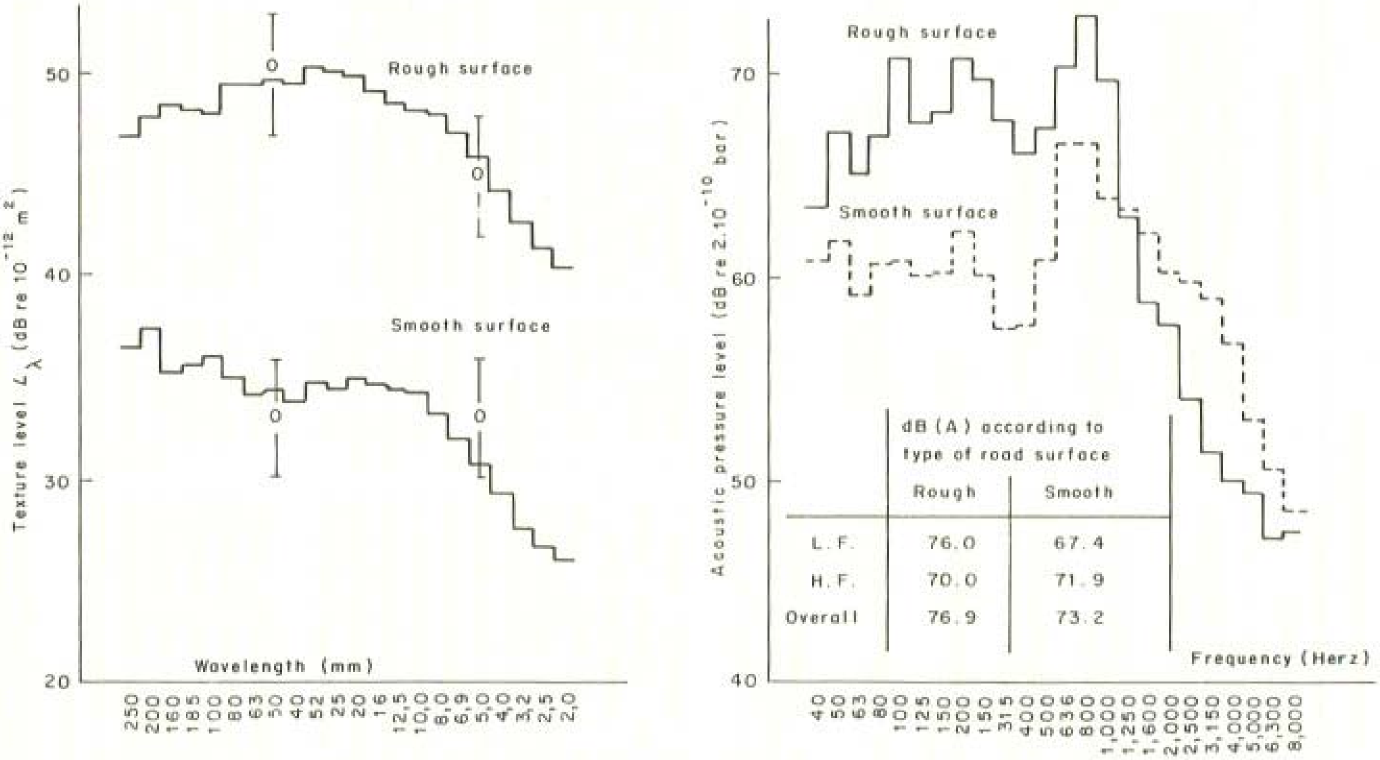
	Phenomenon	Road surface parameter
I	Vertical excitation and radiation of noise from the tyre casing	Longitudinal profile (macrotexture) Mechanical impedance at the point of contact (elastic properties of the road)
II	Tangential excitation as a result of stick and slip action	Physico-chemical properties and longitudinal profile
III	Suction and expulsion of air (air pumping and air pocket resonance)	Geometry and porosity
IV	Aerodynamic action and air turbulence	None
V	Radiation of noise from the road itself	Elastic properties of the different layers making up the road structure
VI	Radiation of noise from the vehicle body or the load being carried	Profile (surface evenness)

Figure 12.3 shows the texture level and the noise frequency spectra for two different road surfaces, namely a rough surface made up of a double bituminous coating and giving rise to a high level of noise at the lower frequencies, and a surface consisting of a non-macadam blinded and closed asphaltic concrete giving rise to noise where frequencies above 1000 Hz predominate. The vehicle speed involved here amounted to 80 km/hour.

The importance of the impedance of the road surface is also not very well understood. All that is known is that road surfaces having a high mechanical impedance (hydraulic concrete or an old bituminous surface) tend to give rise to a greater degree of noise than road surfaces of moderate impedance such as recently layed bituminous surfaces, although the difference in noise level is not very great, amounting in fact to only a few decibels.

Experimental results. The results of some early work suggested that there was some relation between the skid resistance of a road surface and the generation of noise. However, as a result of work carried out since 1979 it is now known that this relation is only true on being considered for each particular type of road surface. Thus there is no basic relation between the average depth of the road surface texture, as determined on carrying out a sand test, and the generation of noise.*

* This test is a matter of packing a small area of the road surface with sand and smoothing off the surplus so as to determine the average depth of the surface texture.



	dB (A) according to type of road surface	
	Rough	Smooth
L.F.	76.0	67.4
H.F.	70.0	71.9
Overall	76.9	73.2

(a)

(b)

Figure 12.3

On making use of laser beams it is now possible to determine the power spectral densities of road surface profiles with a high degree of accuracy and at low cost.

Rolling noise increases very rapidly with vehicle speed V because the overall acoustic power that is generated increases in proportion to the third to fourth power of V. Thus we have:

$$L_{RA} = 30 \text{ to } 40 \log V + \text{constant} \qquad \text{(see Figure 12.4)}$$

Thus the noise level increases by more than 6 dB(A) when the speed is multiplied by a factor of 1.5. Figure 12.4 shows how the noise varies with speed for different types of tyre fitted to cars and heavy lorries. The noise level for the same road surface can differ by nearly 8 dB in the case of cars and by more than 12 dB in the case of heavy lorries.

Finally it should be noted that there are indications that it will be possible in future to provide new and quieter road surfaces for highway sections where high road surfacing costs would be acceptable in comparison with the cost of reducing noise by other means.

12.1.2 Noise from the Vehicle as a Whole

A. Noise as a Function of Engine and Road Speeds

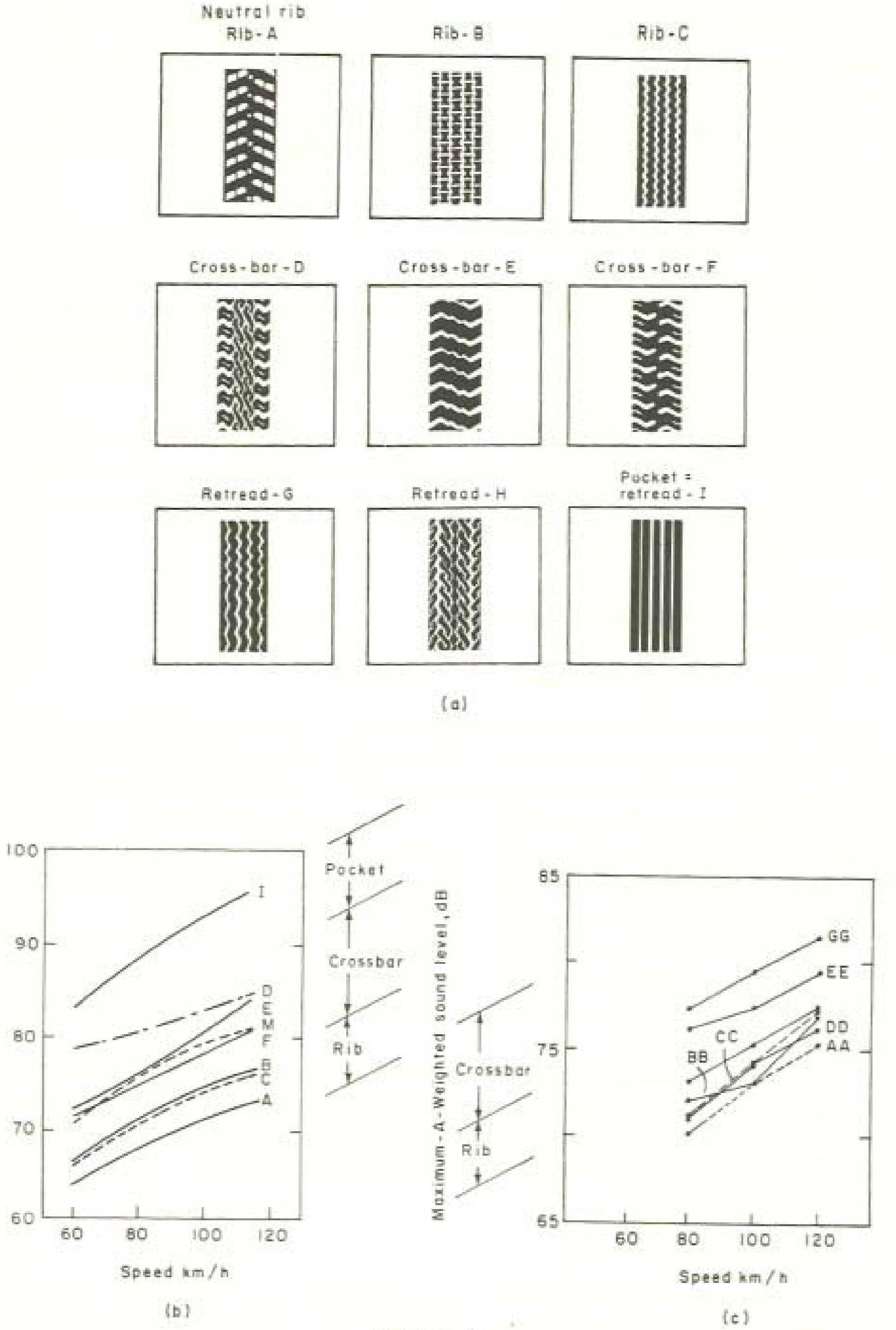
The above considerations have shown how the total noise emitted by a vehicle is the sum of the noise coming from different sources where the contribution from each source depends on the engine speed N except for the rolling noise which depends on the road speed V. The relation between V and N is determined by the gear ratio that is in operation and in the case of a four-speed gearbox, the variation of the noise level with road speed for different gear ratios tends to be as shown by the graph of the following Figure 12.5.

The overall effect of acceleration, also shown on this graph, is not very great except when starting from rest and when re-engaging first and second gear. When running in fourth gear, the noise is mainly due to the tyre-road surface contact.

In the case of heavy lorries, the gearbox allows any one of a number of different gear ratios to be selected so as to ensure that the engine operates over the range resulting in minimum fuel consumption. The level of noise in this case is not very dependent on the gear ratio that is being employed.

B. Noise Frequency Spectra

There is a very rapid attenuation of the noise from cars, heavy lorries and two-wheeled vehicles for frequencies above 2,000 Herz and rolling noise becomes significant over the octave from 1,000 to 2,000 Herz. The acoustic



(a)

(b)

(c)

Figure 12.4

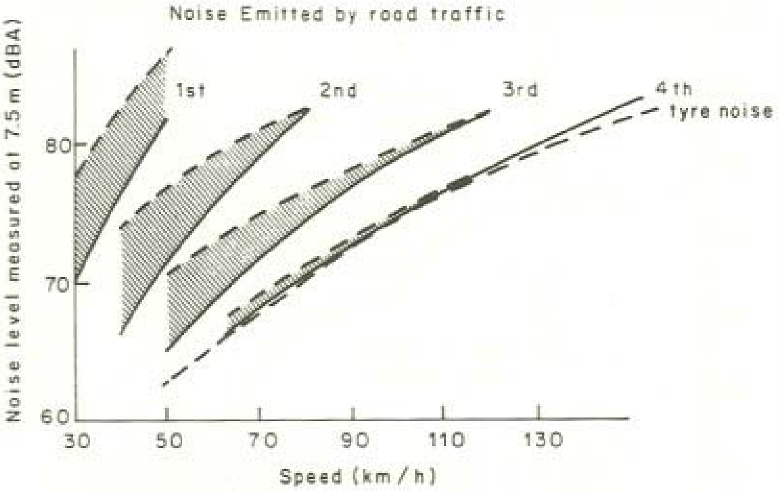


Figure 12.5 Noise from a Renault R16 car for different speeds and accelerations when running in first, second, third and fourth gear

pressure for heavy lorry engines rises to a very high level at the lower frequencies. The graph of Figure 12.6 shows the frequency spectra for isolated vehicles and the standard frequency spectrum that is taken into account when studying the sound proofing of building facades. The A-weighted spectrum shows that in the case of a zone located at a distance of 50 metres from the road, the perceived traffic noise is mainly confined to the three octaves ranging from 250 to 2,000 Herz.

12.1.3 Acoustic Power and Pressure and Evaluation of L_{eq} for an Isolated Vehicle

A. Acoustic Power and Pressure

For a point source of noise in free space radiating in all directions and

---

Figure 12.4 Tyre-road contact noise in dB(A) at a distance of 7.5 m for different types of tyres on a concrete surface (National Bureau of Standards, 1970)(Leasure & Bender, 1975)

(a) Different types of truck tyre tread design (U.S.)

(b) Maximum A-weighted sound level (in decibels *re* 20 μPa) is measured at 50 ft, versus speed for a loaded single-chassis vehicle running on a concrete surface. Various types of new tyres were mounted in dual pairs on the drive axle. Letter designations for each curve correspond to the tyre types

(c) Maximum A-weighted sound level (in decibels *re* 20 μPa), as measured at 50 ft, versus speed for a full-size passenger automobile running on a concrete surface. Various types of new tyres were mounted on the rear axle. Letter designations for each curve correspond to the tyre types

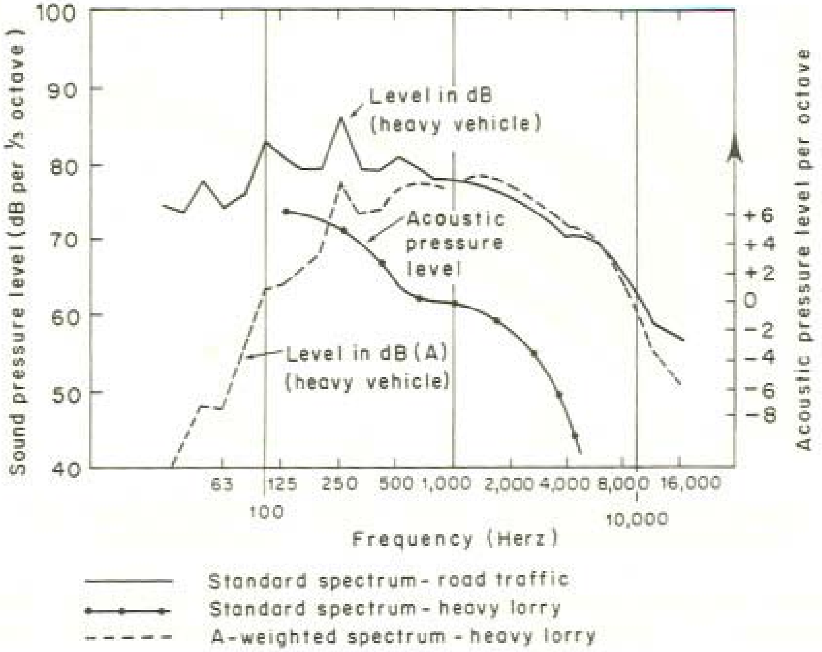


Figure 12.6

neglecting any air absorption, we have:

$$L_p = L_w - 10 \log 4 \pi r^2$$

where

L_p is the acoustic pressure level at a distance of r from the source of noise

L_w is the acoustic power level of the source of noise

If we consider a source of noise that is close to the sound-reflecting surface of the ground and assume that this source radiates in all directions in the upper hemisphere we have:

$$L_p = L_w - 10 \log 2 \pi r^2$$

Let L_p be the maximum acoustic pressure level recorded during the passage of a road vehicle. In practice, it should be noted that we measure the acoustic power in dB(A) at the standard distance of 7.5 metres from the vehicle. If L_w is the acoustic power level of the vehicle we have:

$$L_{p\,7.5} = L_w - 10 \log 2\pi (7.5)^2$$

$$L_{p\,7.5} = L_w - 25.5$$

If L_0 is the acoustic pressure level at a distance d_0, we have:

$$L_p = L_0 + 20 \log \frac{d_0}{d}$$

Whereas in referring to an acoustic pressure level for a source of noise we need to specify the distance from the source of noise at which this pressure is measured, this is not the case for the acoustic power. It should be noted here that at large distances from the vehicle of more than 100 metres, and where there is a ground effect, the above equations are no longer valid.

Table 12.3 Typical acoustic power and pressure levels

Vehicle	Acoustic power (watts)	L_w	L_p at 7.5 metres
Heavy lorry*	0.3	115	90
Car	0.03	105	80
Sound-proofed car	0.01	100	75
Normal speech	10^{-5}	70	45

* Maximum size allowed by the regulations.

B. *Statistical Distribution of Vehicle Acoustic Power*

In calculating the noise levels in the vicinity of road traffic it is useful to be able to refer to an established statistical distribution and hence an average value for the acoustic power for each type of road vehicle. The distribution curves given by the following Figure 12.7 show that there can be differences of up to 25 dB(A) approximately between the levels of noise emitted by isolated vehicles for similar speeds.

In practice, it can be used as a simple relationship between the mean acoustic power level and the speed for cars and heavy trucks:

$$L_w = a + b \log v \qquad [v \text{ km/h}]$$

For traffic moving at a steady speed on level roads:

$$\text{Car with} \begin{cases} v < 40 \text{ km/h} & a = 80 \quad b = 10 \\ v > 40 \text{ km/h} & a = 47 \quad b = 30 \end{cases}$$

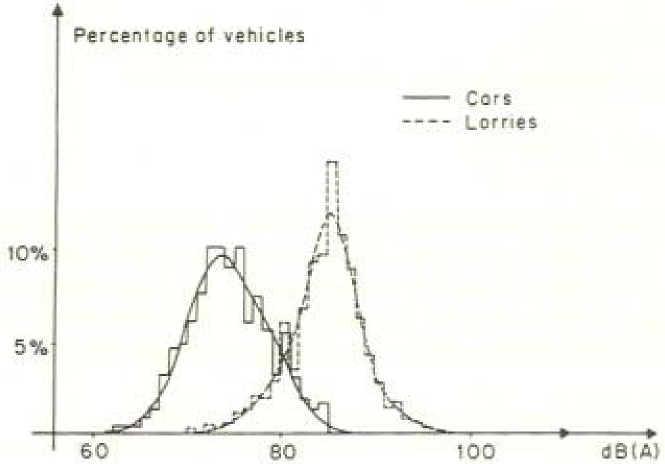


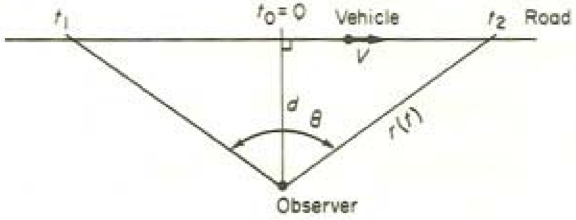
Figure 12.7 Distribution of noise levels for light and heavy vehicles in terms of L_{max} recorded at a distance of 7.5 metres from the vehicle as it passes by the microphone (for 621 cars and 566 trucks at steady speeds comprised between 60 and 80 km/h (Favre, B, 1977, IRT-CERNE)

Heavy trucks: with $v < 50$ km/h	$a = 110$	$b = 00$
$50 < v < 70$ km/h	$a = 93$	$b = 10$
$v > 70$ km/h	$a = 58$	$b = 29$

C. Evaluation of L_{eq} in the Case of a Straight Section of Road

The value of L_{eq} at the side of the road over a period of time T due to the passing of an isolated vehicle depends on the maximum noise level L_{max}, on the speed of the vehicle and — particularly in the case of heavy lorries — on the directional characteristics of the noise radiating from each of the different sources of noise on the vehicle.

We assume here that the vehicle can be regarded as a uniformly radiating point source of noise of constant acoustic power and that the vehicle is moving at a constant speed along a straight line.



The value of L_{eq} for the period of time t_1 to t_2 is then given by:

$$L_{eq} = 10 \log \int_{t_1}^{t_2} \frac{p^2(t)}{p_0^2} \, dt$$

where:

$p(t)$ = the instantaneous acoustic pressure
p_0 = the reference acoustic pressure

We also have:

$$p^2(t) = \frac{W \rho_0 c}{2\pi r(t)}$$

where

W = the acoustic power of the vehicle
ρ_0 = the air density
$r(T)$ = the distance of the vehicle from an observer at the point 0 at time t

We can accordingly write for the arithmetic mean of p^2 over the period of time t_1 to t_2:

$$|p^2|_{t_1}^{t_2} = \frac{1}{t_2 - t_1} \frac{W \rho_0 c}{2\pi} \int_{t_1}^{t_2} \frac{dt}{r^2(t)}$$

where:

$$r^2(t) = d^2 + V^2 t^2$$

Whence, given that θ is the angle subtended at the point 0 by that part of the vehicle trajectory covered during the period of time t_1 to t_2, we have:

$$\int_{t_1}^{t_2} \frac{dt}{r^2(t)} = \frac{\theta}{Vd}$$

so that:

$$|p^2|_{t_1}^{t_2} = \frac{1}{t_2 - t_1} \frac{W \rho_0 c}{2\pi} \frac{\theta}{Vd}$$

whence, for the period of time t_1 to t_2, we have:

$$L_{eq} = L_W - 10 \log (t_2 - t_1) - 10 \log dV + 10 \log \frac{\theta}{2\pi}$$

If we consider the maximum pressure level recorded at a distance d_0 from the source of noise, we have for the same period of time:

$$L_{eq} = L_{p_0} + 10 \log \frac{\theta\, d_0}{(t_2 - t_1)V} + 10 \log \frac{d_0}{d}$$

where distances are measured in metres and time in seconds.

Thus, given the maximum sound-pressure level recorded at a point 0 due to a passing vehicle, or knowing the acoustic power level, we can evaluate L_{eq}. It will be noted that:

- L_{eq} increases with 10 log θ, where θ is the angle subtended by the section of the road from the point of view of the observer.
- L_{eq} decreases with 10 log d_0/d, where d is the distance from the vehicle to the road (absorption being neglected). If we double the distance from the vehicle to the road, the value of L_{eq} is reduced by 3 dB.

For a source generating the same level of noise whatever the speed (L_w = constant), the acoustic energy received will decrease in proportion to the inverse of the speed V. This is consistent with the fact that the faster it passes by the less will the observer be exposed to the effects of the moving source of noise. However the acoustic power level L_w (or the maximum sound pressure level $L_{p\,max}$) itself varies with the speed. For a variation of 30 log v in this level, as can arise in the case of cars and heavy lorries running at speeds in excess of 60 km/h), (see Section 12.13B) it will be found that L_{eq} varies as a function of the speed V as 20 log V.

Assuming no variation in the value of L_w, which is an acceptable approximation for heavy vehicles at low speeds (Section 12.13B), it will be found that L_{eq} varies as:

10 log V

12.2 NOISE DUE TO ROAD TRAFFIC

12.2.1 Statistical Distribution of Traffic Noise Levels

The noise due to the traffic along a road is continuously fluctuating with time and it is not easy to quantify such noise. One technique is to consider the statistical distribution of the noise levels observed during a given period of time. The dispersion of the noise levels decreases very much with the flow of traffic and the distance of the observer from the road. The graphs of Figure 12.8 show some cumulative distributions of noise levels — histogrammes are seldom considered here.

12.2.2 Evaluation of L_{eq} Due to the Passing of a Series of Vehicles — Steady Traffic

A. Evaluation in the Case of Identical Vehicles

Let the mean square acoustic pressure during the period of time t_1 to t_2, due to

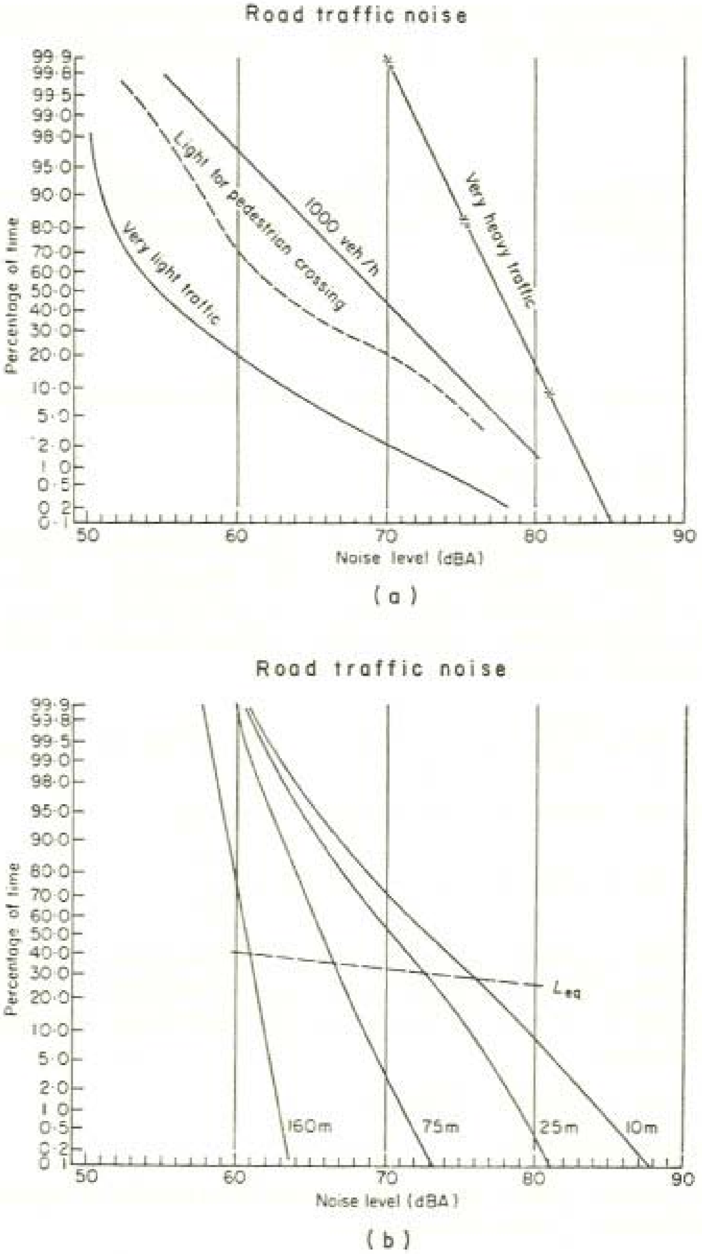


Figure 12.8 Noise level distribution at the roadside for: (a) Four types of traffic; (b) Different distances from the road (Alexandre *et al.*, 1975)

the traffic made up of a series of identical vehicles running through a road section subtending an angle θ, as seen by the observer be given by:

$$|p^2|_{t_1}^{t_2}$$

If we assume that for the series of vehicles on the road section, the mean square acoustic pressure for a vehicle i, during the same period of time t_1 to t_2, can be represented by:

$$|p_i^2|_{t_1}^{t_2}$$

then we can write, given that the different noise sources are not coherent:

$$|p^2|_{t_1}^{t_2} = \sum_i |p_i^2|_{t_1}^{t_2} = n|p_i^2|_{t_1}^{t_2}$$

where n is the number of vehicles that will have passed through the road section during the period of time t_1 to t_2, this number being given by $Q(t_2 - t_1)$, Q being the flow of vehicles, and where the period of time t_1 to t_2 is large in comparison with the time taken for a vehicle to pass through the road section.

For a vehicle i we have:

$$L_{eq} = 10 \log \frac{|p_i^2|_{t_1}^{t_2}}{p_i^2} = L_w - 10 \log (t_2 - t_1) - 10 \log Vd + 10 \log \frac{\theta}{2\pi}$$

so that for the complete series of vehicles we can write:

$$L_{eq} = L_w + 10 \log Q - 10 \log Vd + 10 \log \frac{\theta}{2\pi}$$

If the traffic is steady, L_{eq} is no longer dependant on the duration of measurement so that this latter does not need to be specified.

If the angle $\theta = \pi$ and if Q is expressed in vehicles/hour, V in km/h and d in metres we have:

$$L_{eq} = L_w + 10 \log Q - 10 \log Vd - 33$$

It should be noted that:

- If L_{eq_i} is the L_{eq} due to the passing of an isolated vehicle having an acoustic power level L_w, then we have:

  $$L_{eq} = L_{eqi} + 10 \log Q$$

- If the value of L_w is independent of the speed (urban traffic) then L_{eq} decreases as the speed increases according to $-10 \log V$.

— When the rolling noise is dominant, and allowing for the way in which the values of L vary as a function of the speeds of the vehicles (see Section 12.1.1C), it will be found that for a given flow of traffic, L_{eq} increases with speed according to 20 log V.

B. Evaluation in the Case of Equi-spaced Vehicles of Different Acoustic Power Levels

If the vehicles do not have the same acoustic power levels then calculations similar to those carried out for the previous case show that:

$$L_{eq} = \bar{L}_w + 10 \log Q - 10 \log Vd + 10 \log \frac{\theta}{2\pi}$$

where:

$$\bar{L}_w = 10 \log \frac{(1/n) \sum_i w_i}{wo}$$

$\bar{L}_w$ being the averageof the acoustic power levels of the different vehicles. wo being the reference of the acoustic power.

In the case where the reference is made to the acoustic pressure level L_0 of the vehicles at a given distance d_0 then L_{eq} can be evaluated on assuming a normal distribution for the acoustic pressure levels for the different vehicles.

Let the probability density be:

$$P(L_0) = \frac{1}{\sigma\sqrt{2\pi}} \, e^{-[(L_0-\bar{L})/2\sigma^2]}$$

where $\bar{L}$ is the mathematical expectation for the value of L_0 estimated in terms of the arithmetic mean of the L_0 values for the different vehicles.
It can be shown that (Barry and Reagan, 1978):

$$L_{eq} = L_0 + 0.115\sigma^2 + 10 \log Q - 10 \log Vd + 10 \log \frac{\theta}{2\pi} + 10 \log 4\pi \, d_0^2$$

where:

L_0 = the arithmetic mean of the acoustic pressure levels due to the individual vehicles at a distance of d_0 in metres
σ = is the standard deviation of these levels
V = the speed of the series of vehicles in metres per second
Q = the flow of traffic in vehicles per second

The assumption of a normal distribution for the acoustic power levels of

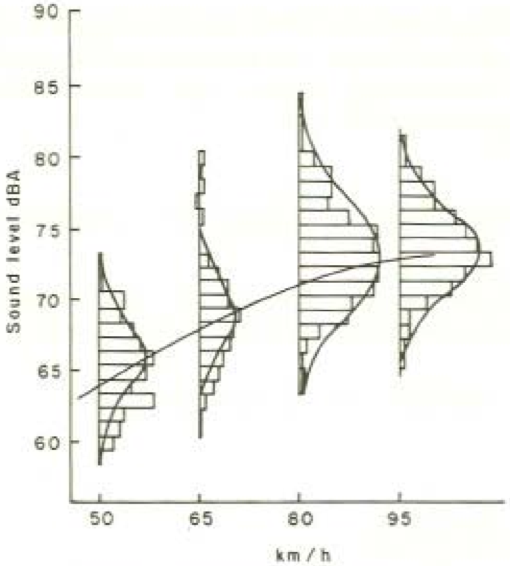


Figure 12.9 Distribution of Noise emission levels for different types of cars as a function of speed

vehicles of the same type is acceptable providing that they are all travelling at the same speed (Figure 12.9).

If the traffic is made up of different types of vehicle we can make use of the following type of equation:

$$L_{\text{eq.total}} = 10 \log \left(10^{L_{\text{eq}c}/10} + 10^{L_{\text{eq}l}/10} + 10^{L_{\text{eq}b}/10}\right)$$

where $L_{\text{eq}c}$, $L_{\text{eq}l}$ and $L_{\text{eq}b}$ are the levels applying to cars, heavy lorries and buses respectively.

12.2.3 Evaluation of L_{eq} in the Vicinity of a Highway

It is evident from what was said in par. 12, 21 and 22 that the acoustic energy emitted by road traffic is a function of:

- —The flow of vehicles.
- —The speed of the vehicles in terms of an average value and the dispersion.
- —The percentage of heavy lorries making up the traffic.
- —The gradient r in terms of the change of height for a given displacement along the length of the road.

Clearly, the most rapidly moving vehicles will have a predominant effect but speed limits and the increasing number of vehicles on the roads lead to a restriction in the range of speeds that can arise. In practice, we simply note the speed that is exceeded by 15% of the vehicles.

A wide range of heavy vehicles are employed but given the automatic traffic counting systems that are in operation, we limit our attention to vehicles having a Gross Vehicle Weight in excess of 3.5 tonnes. We can also make use of an acoustic equivalent factor E in terms of the number of cars which, under given traffic conditions, emit the same acoustic power as a heavy lorry:

Table 12.4

	Acoustic equivalent factor E for different gradients				
Type of road	$r \leqslant 2\%$	$r = 3\%$	$r = 4\%$	$r = 5\%$	$r \geqslant 6\%$
Motorway	4	5	5	6	6
Urban highway	7	9	10	11	12
Urban road (boulevard, etc.)	10	13	16	18	20

It should be noted that the contribution of heavy vehicles to the noise is very variable. It depends on the speed of the traffic and it is relatively small when the traffic is running regularly and at high speed since the cars will then be travelling at sensibly higher speeds than the heavy vehicles and emitting comparable levels of noise.

The direct effect of the heavy vehicles can be evaluated in terms of the increase K_{hv} in the value of L_{eq} for the traffic noise compared to the value that would apply if the traffic has been made up simply of cars for the same total flow of traffic. Thus the graph of Figure 12.10 shows what correction needs to be made to the value of L_{eq} due to traffic made up of light vehicles only in order to take account of a given percentage of heavy vehicles for different types of road. An indirect effect of the presence of heavy vehicles can be to result in a slowing down of the traffic such that, in practice, an increase in the percentage of heavy vehicles making up the traffic can result in only a small increase in the noise level in the vicinity of a highway.

Evaluation of $L_{eq\ A}$ in the vicinity of a highway. At the points in a free field, where the only sound received is that coming directly from the traffic, we can calculate the value of L_{eq} at a distance d from the road on giving L_w its value as a function of vehicle speed, as indicated by Section 12.1.2*A*. Thus for vehicle speeds in excess of 60 km/hour we have:

$$L_{eq\ A} = 10 \log Q + 20 \log V - 10 \log d + 10 \log \frac{\theta}{\pi} + 14$$

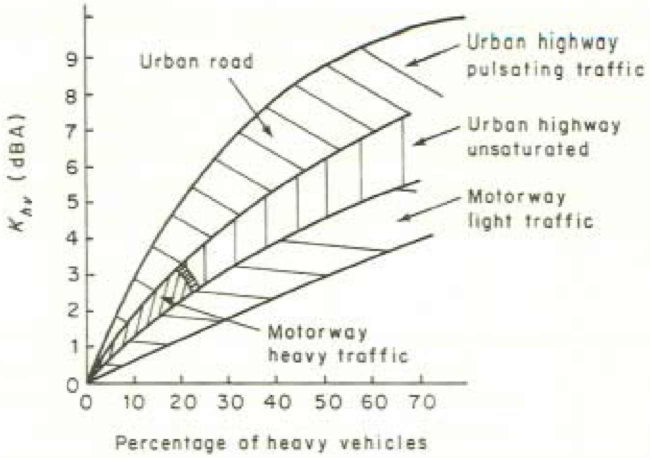


Figure 12.10 Effect of the presence of heavy vehicles on the value of L_{eq}. Correction to be made in comparison with the value due to traffic made up entirely of light vehicles

On taking account of the width of the road, the acoustic equivalent factor E for the heavy vehicles and any corrections for the effects of a gradient and the type of road surface we arrive at the complete equation:

$$L_{eq\ A} = 10 \log (Q_{lv} + EQ_{hv}) + 20 \log V - 10 \log \left(d + \frac{w}{3}\right) + 10 \log \frac{\theta}{180} + K_r + K_c + 14$$

where:

Q_{hv} = The flow of heavy vehicles per hour
Q_{lv} = The flow of light vehicles per hour
E = The acoustic equivalent factor given in the previous section
V = The speed of the traffic in km/hour
d = The distance to the edge of the road in metres
w = The width of the road in metres
θ = The angle subtended by the observed section of road in degrees
K_r = A correction factor to take account of any gradient
K_c = A correction factor to take account of the type of road surface

12.3 NOISE PROPAGATION AND GROUND EFFECT

12.3.1 Propagation of Noise in the Case of an Open Site

The distance to the outer edge of the road is generally considered to range from 5 to 300 metres so that in practice the most important effect with regard to the propagation of the noise, apart from that due to the geometrical divergence, is that due to the presence of the ground, given that the atmosphere is assumed to be generally stable and of uniform composition.

The effect depends very much on the nature of the ground and the equations employed to predict the value of L_{eq} in the vicinity of main roads tend to be based on a relationship for the decrease in noise level with distance lying somewhere between that due to the geometrical divergence and involving the term $1/r$ and an inverse square law involving the term $1/r^2$. A common practice is to assume an attenuation of 4 dB for each doubling of the distance from the source of the noise, i.e. a relationship involving the term $1/r^{1.3}$, and the equation:

$$L_{eq\,d} = L_{eq\,d_i} - 13 \log \frac{d}{d_i}$$

where d and d_i are two distances from which the respective noise levels are to be compared.

In the case of the L_n noise indices, the rate of decrease with distance becomes more marked in going from L_{99} to L_1, as shown by the graph of Figure 12.11:

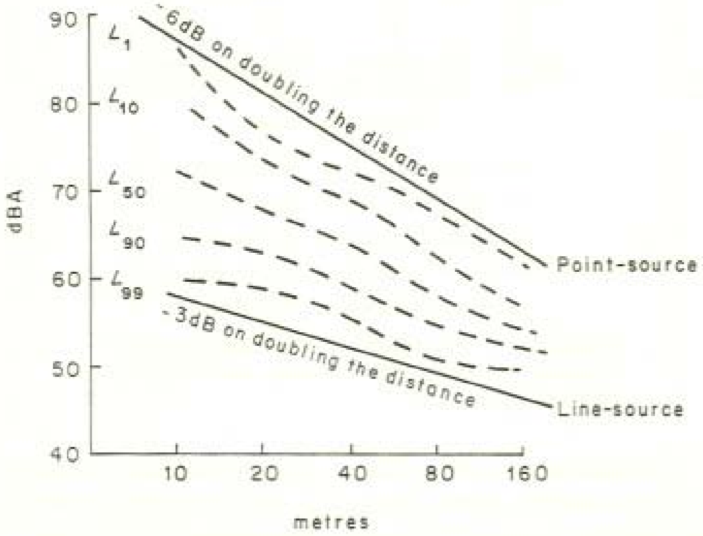


Figure 12.11 Attenuation of the L_1, L_{10}, L_{50} and L_{99} indices with distance (traffic of 2,200 vehicles per hour)

Thus the peak levels are attenuated more rapidly and the fluctuations in the acoustic pressure levels reduced as the distance from the source of noise is increased. There is little change in the frequency spectrum of the noise except for a greater attenuation in the 1,000 to 2,000 Herz range due to air absorption and the ground effect (see Figure 12.12).

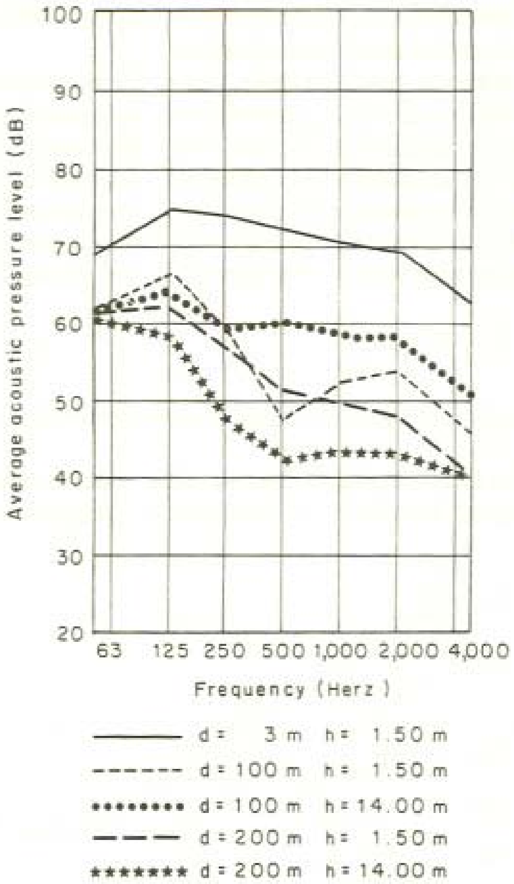


Figure 12.12 Variations in the frequency spectrum of the noise with distance and height of receiver (grass land)

Finally, it should be noted that the degree of attenuation depends on the height above ground of the point of reception, the difference here being greater to the extent that the ground effect is more pronounced (see Figure 12.13).

12.3.2 Effects of the Transverse Profile of a Site on the Propagation of Traffic Noise

For roads going through a cutting or those that are very much enclosed, it is possible to evaluate the diffraction effects on employing the procedure referred to in a following section of this paper concerned with noise screens. Unfortunately, as in the case of the provision of noise screens, it is difficult to

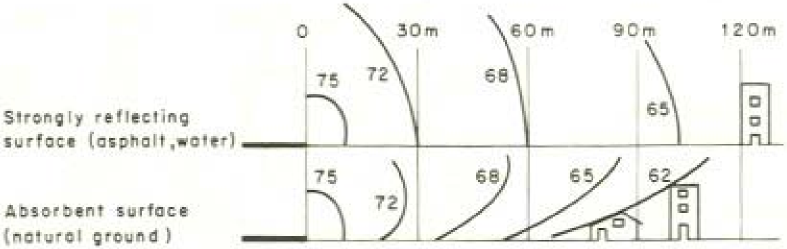


Figure 12.13 Isophones for different ground surfaces, at various distances from the road

allow for the effects due to the varying degree of absorption of the side slopes in carrying out the calculations. See classical works on diffraction by barriers (Maekana, 1965; Jonasson, 1972; Kurze, 1971).

The evaluation of possible solutions must, of course, take account not only of the effectiveness of the noise screens but also of the costs of any occupation of land and of carrying out civil engineering work. When the layout of the site allows, it is sufficient to enclose the road in a shallow cutting bounded by a bank to the side such that there is no net displacement of soil. The Figure 12.14 shows the shape of the isophones for different transverse profiles. In the case of enclosed roads, the absorbent materials that are provided operate in accordance with the same principles that apply in the case of the provision of noise screens. The provision of embankments cancel out any ground effects but as a compensation it will be found that screens of a given height are more effective.

12.3.3 Noise Levels in the Case of a Street with High Buildings on Each Side

The reflection of sound from the front faces of buildings to each side of a street modifies the acoustic field, at least in the vicinity of these faces, giving rise for a sufficiently high h/d ratio to a reverberation enclosure (see Figure 12.15). The acoustic field can be considered to include an infinite number of image sources located above ground level.

Assuming that the equivalent absorbing surface for the street is essentially the overhead opening then the noise level for the reverberating enclosure, where L_w is the acoustic power level of the sources, is given by:

$$L_p = L_w - \log d + \text{constant}$$

Whereas in practice the h/d ratio may not be very great (less than 1), experimental results show that for $h/d > 0.2$:

- —The value of L_p at the front face of a building varies as a function of $-10 \log d$.
- —The value of L_p decreases only very slightly as the height of the receiving

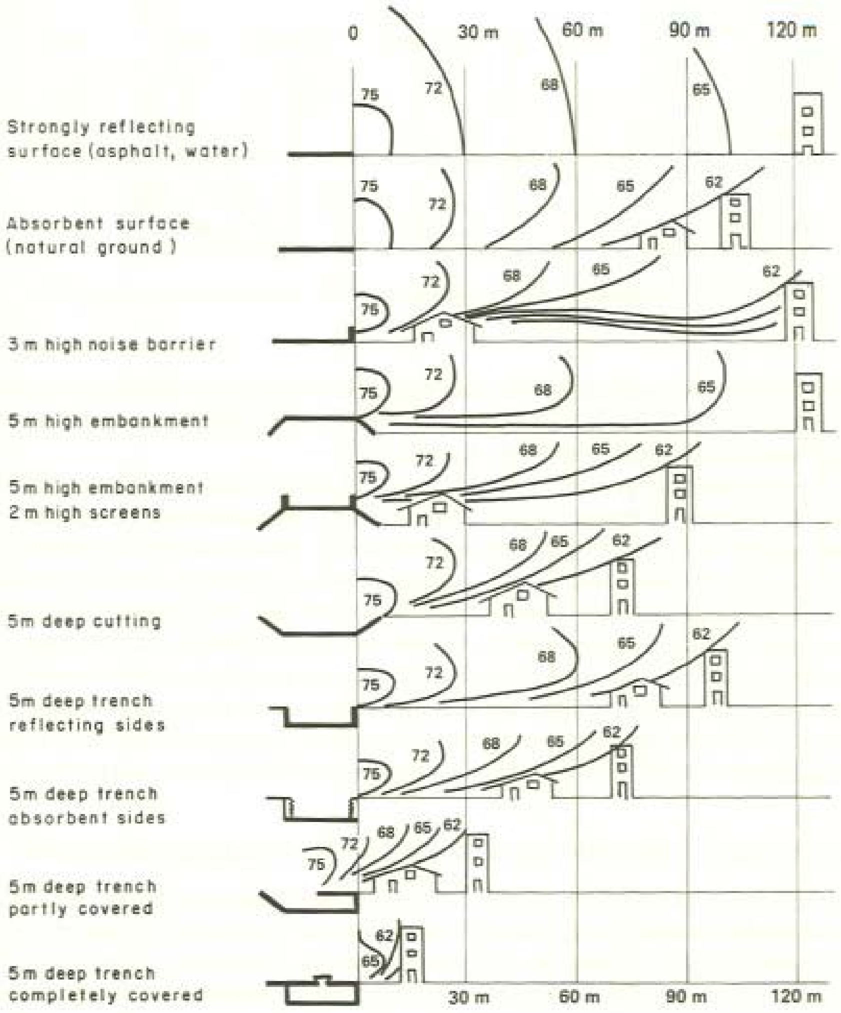


Figure 12.14 Effect of different transverse profiles and means of protection from noise. Equal noise level curves or isophons. The isophon values shown are for the L_{eq} in dB(A) for a traffic of 2,000 vehicles per hour. Position of a house and/or a three-storey building for an L_{eq} of 62 dB(A) at the facades

point on the front face of a building above ground is increased (reduced importance of direct radiation).

12.4 METHODS FOR PREDICTING NOISE LEVELS

12.4.1 The Different Methods that can be Employed

In general, the different methods that can be employed to determine the L_{eq} levels for road traffic noise are as follows:

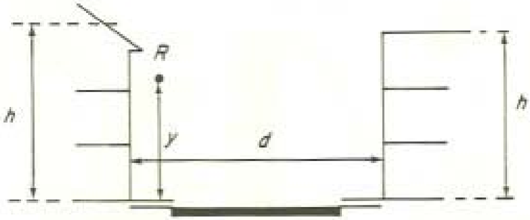


Figure 12.15

d = width between facades
h = effective height of buildings
y = height of reception point above road surface
All distances in metres

- —Use of the equations considered above.
- —Manual methods based on the use of equations and graphs.
- —Office calculator procedures.
- —Use of computer programs.
- —Use of reduced scale models operating in air or water.

The equations considered in the previous sections of this paper cannot be used when the composition of the traffic and/or the arrangement of the buildings and the topography of the site are too complicated. Simple programs, compatible with the capacities of office calculators can be employed in studying quite complicated cases, particularly when it is a matter of determining the effectiveness of noise screens but such programs cannot normally be employed in dealing with more than two dimensions in the plane perpendicular to the road. When multiple reflections are involved it is necessary to make use either of computer programs or of reduced scale models. The computer programs can include subroutines that define the composition of the traffic that is involved.

12.4.2 Use of Computer Programs in Predicting Noise Levels

Computer programs for use in the evaluation of noise levels are now available in a number of countries, the structure of these programs being very varied (Barry and Reagan, 1978; Göteborg OCDE, 1979; Lamure, 1981). The level of the noise at a point in the vicinity of a road depends on:

- —The characteristics of the traffic and the road which determine the average acoustic power levels of the emitted noise.
- —The characteristics of the site which influence the way in which the noise is propagated.

The parameters that are considered are:

- —The flow of traffic in vehicles per hour.
- —The composition of the traffic (proportion of heavy vehicles).

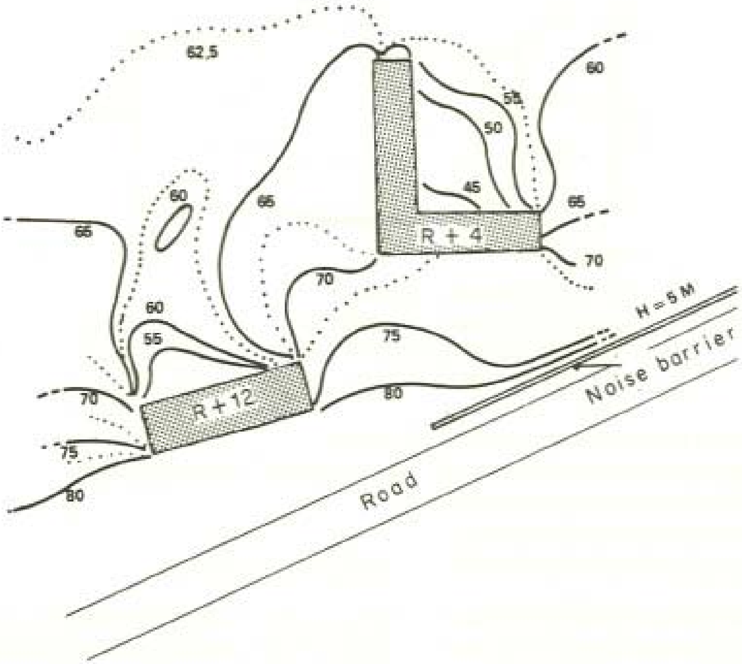


Figure 12.16 Noise contour map produced as a result of making use of a computer program (IRT-CERNE program)

- —The average speed of the traffic.
- —The degree to which the traffic is flowing smoothly where applicable.
- —The type of road surface and the gradient involved.

The acoustic power for each section of road is determined on following the same procedure that was employed in deriving the equations considered in the previous sections of this paper.

Thus, in making use of a computer programme it is possible to plot the isophones for a built-up site.

12.4.3 Use of Reduced Scale Models in Predicting Noise Levels

Reference can be made to a number of different laws of similarity in making use of reduced scale models. For example, we can simulate the acoustic conditions in air on transposing the noise frequencies that are involved. Thus the ratio between the length of the sound waves and the dimensions of the site (λ/α) can be retained on reducing these dimensions by a factor e and on multiplying the frequencies by e.

The most common practice is to employ a scale reduction factor of about 1/100. A greater reduction than this would involve working at very high frequencies such that, given the absorption of the sound waves in air, the simulation would break down. In any case, a scale reduction of about 1/100 calls for the model to be operated in a room where the humidity of the air is kept to a very low level in order to avoid any excessive absorption of acoustic energy which needs to be radiated at very high frequencies (of about 20,000 to 200,000 Herz) in order to ensure the simulation.

12.4.4 Comparison of the Different Methods of Predicting Noise Levels

The noise conditions can be evaluated on making use of one of the predicting methods mentioned above and also, in some cases, on carrying out a series of measurements. These latter have the advantage of yielding accurate results but only where the source of noise considered is both stable and dominant. Traffic characteristics, of course, change with time and the measurements must accordingly take account of variations in the rate of flow and the speed of traffic and the percentage of heavy vehicles involved. It should also be noted that the measurements can be affected by the weather conditions and that they need to be carried out by experienced personnel. The main advantage of carrying out measurements is that it is possible to determine the results of effects which are not amenable to calculation and that are concerned to some extent with ground effects or diffraction of the sound waves around obstacles of complicated shape. There is also the fact that the results of measurements can have a better psychological impact.

In fact, in carrying out their project studies, engineers and town planners generally make use of the methods serving to predict noise levels and measurements are carried out simply with a view to evaluating the initial conditions.

The selection of the appropriate method can be a difficult matter and depends on the objectives involved. Table 12.5 shows the potential of the different methods with respect to different criteria while referring to what are termed manual calculating methods of varying degrees of complexity, such methods being described in different publications such as the FHWA Highway traffic noise prediction model, (Barry and Reagan, 1978), the Guide du Bruit des Transports Terrestres (Ministère des Transports, Paris, 1980). In all cases, the use of simple methods, in the first instance, with a view to outlining the problem or identifying critical points, is recommended.

12.5 METHODS FOR REDUCING NOISE LEVELS IN THE VICINITY OF A MAIN ROAD

12.5.1 The Different Methods that can be Employed.

The following can be considered with a view to reducing the impact of noise in the vicinity of main roads:

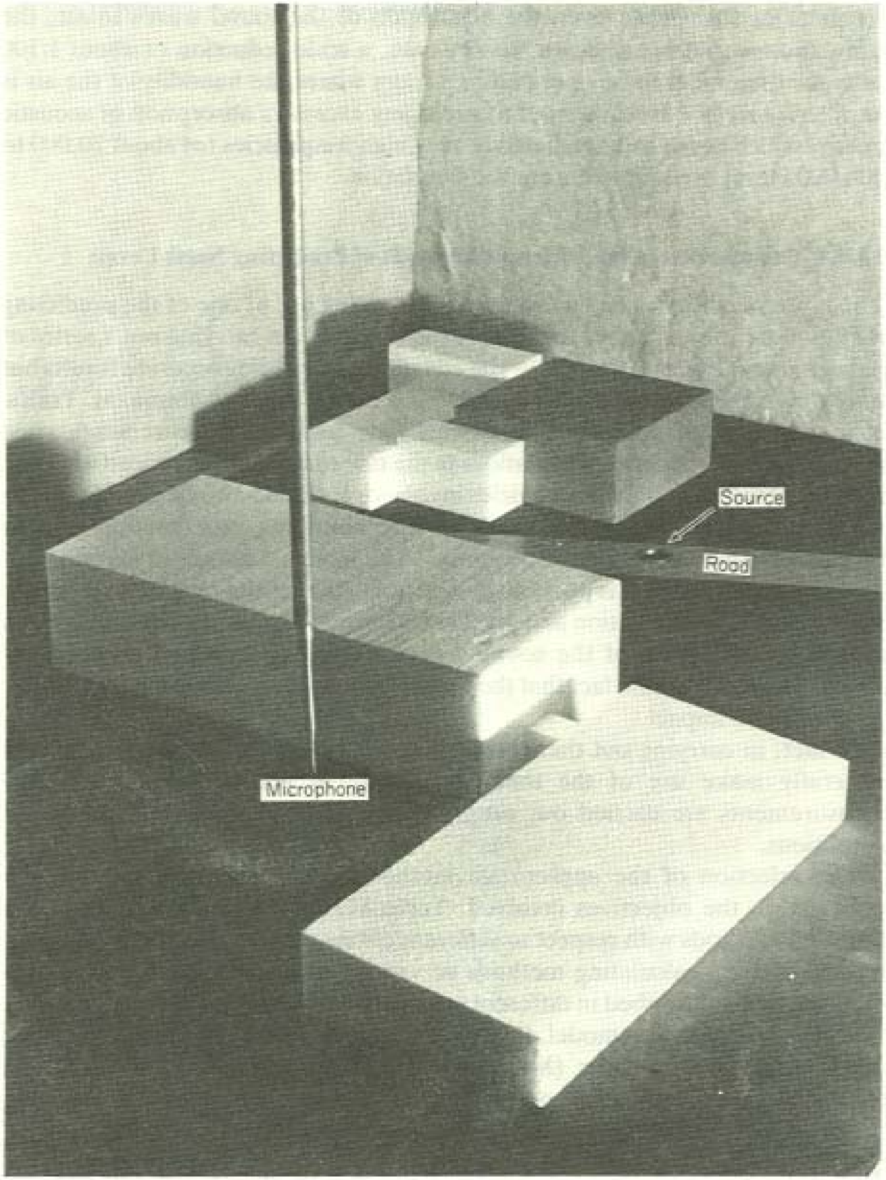


Figure 12.17 Study of a site at the CSTB modelling Centre, Grenoble

- Sound proofing of the vehicles.
- Reduction of the rolling noise at the point of contact between the tyre and the road surface.

Table 12.5 Comparison of the different methods that can be employed in estimating noise levels

	The different methods available to predict noise levels				
Criteria	Measurement	Use of equations and graphs	Calculation	Use of computer programs	Use of models
Accuracy in normal use (dBA)	± 1.5	± 3		± 2	± 2
Form of results	For a particular point in time	Outline results	For a particular point. Optimization possible	All forms. Optimizations	Complete but no optimization
Approximate cost ($)	200 to 1,000 per point			2 to 2,000 per case	20,000 per case
Time taken	2 days	1 day	1 day	2 weeks	2 months
Flexibility:					
Study of variants					
Re-adjustment to take account of results of any measurements			Fairly good	Good	Fairly good
Ease with which results can be distributed	Average	Good	Good	Average	Mediocre
Educational value	Good	Good	Mediocre	Poor	Very good

- —Action with respect to the road traffic itself and in particular the vehicle speeds.
- —Action in connection with the design of the roads insofar as the longitudinal and transverse profiles are concerned.
- —Provision of noise screens.
- —Sound proofing of existing buildings.
- —Town planning and issue of building permits.

Clearly, the method that needs to be employed depends on the particular case which can involve any one of the following situations:

(i) Road and buildings already in existence.
(ii) Road to be constructed through an existing built-up area.
(iii) Buildings to be constructed in the vicinity of a road.
(iv) Both road and buildings to be constructed.

More and more possibilities for reducing the noise levels become available in going from situation (i) to (iv). Before any buildings have been constructed the main solutions that need to be considered are those associated with town planning and the issue of building permits. However, even in situations (iii) and (iv), it is worth considering the provision of appropriate longitudinal and transverse profiles for the road or the installation of noise screens in order to avoid any unnecessary restrictions with the regard to town planning or the availability of building land.

Not many countries resort to legislation in imposing technical constraints on road construction companies or requiring them to consider the question of compensation but it is common practice to issue recommendations. In addition to this, engineers and town planners are under increasing pressure to take account of the reactions of people living in the vicinity of existing roads or of roads that are to be constructed.

12.5.2 Reduction of Noise Levels on Limiting Traffic Speeds

It should be noted (Section 12.1.3*c*) that for speeds greater than 60 km/h and in the case of light vehicles (steady speeds):

L_w and $L_{\max}$ vary with $30 \log V$
L_{eq} varies with $20 \log V$

In the case of heavy vehicles, variation of the same order can be observed for speeds greater than 70 km/h. At medium speeds (50 to 70 km/h), L_w and $L_{\max}$ vary with $10 \log V$ and L_{eq} remains practically constant. It should be noted however, that V is an average speed that accordingly needs to be distinguished, from the maximum speed. A reduction in traffic speed can therefore result in a smaller reduction in noise level than that predicted by the previously mentioned equations.

A. Case of Traffic not Containing any Heavy Vehicles (low, unsteady speeds).

For speeds lower than 60 km/h, L_{eq} may decrease as speed increases. The dispersion of vehicle speeds can lead to an L_{eq} value that is 1 to 2 dB(A) greater than the value that would be obtained on assuming that all vehicles are running at the average speed for the traffic. However, it should be noted that as soon as a speed limit is in operation, the law for the distribution of the speeds of the individual vehicles is modified and we no longer know what is the relation between the maximum speed V_{max} and the average speed for all vehicles V.

It should be noted that for speeds less than 60 km/h, an increase in average speed can lead to a reduction in atmospheric pollution and the consumption of fuel (see Figure 12.18). We need to make a distinction here between the operation of vehicles in low speed urban areas, where the speeds remain below 60 km/h, and the circulation of traffic on main roads.

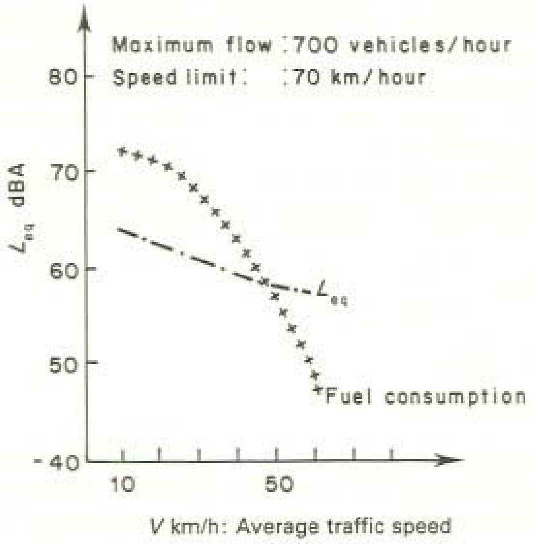


Figure 12.18

B. Case of Traffic Including a Proportion of Heavy Vehicles

Heavy vehicles normally circulate at lower speeds than do light vehicles and their acoustic power is not very dependent on their speed. The presence of such vehicles accordingly limits the effectiveness of any reduction in traffic speed. In fact, it is necessary to reduce the speed of the traffic by an appreciable amount in order to obtain a reduction in noise levels of only a few decibels as is indicated by the following table:

Table 12.6

Speed limit (km/h)		Reduction of noise according to the percentage of heavy vehicles making up the traffic (dBA)			
Light vehicles	Heavy vehicles	0%	10%	30%	100%
90	80	3 to 4	2	1	0
90	60	3 to 4	3 to 4	3 to 4	2 to 3
60	60	7 to 9	7	5	2 to 3

12.5.3 Reduction of Noise Levels on Limiting the Circulation of Traffic

This limitation, which normally applies during certain times of the day or week, is usually applied to the circulation of heavy vehicles. The degree to which such a restriction can be effective in reducing the L_{eq} value in the vicinity of highways can be determined on making use of the equation given in Section 12.2.3, where L_{eq} is expressed as a function of the percentage of heavy vehicles making up the traffic.

If we let H_0 be the original, and H' the final percentage of heavy vehicles making up the traffic, the reduction in the value of L_{eq} will amount to:

$$L_{eq} = 10 \log \frac{1 + H_0(E - 1)}{1 + H'(E - 1)}$$

If $H' = 0$ and $E = 10$ we have:

$$L_{eq} = 10 \log (1 + 9 H_0)$$

Thus the value of L_{eq} will be reduced by at least 3 dB(A) when $H_0 \geqslant 10\%$.

For average traffic speeds of more than 100 km/h, the coefficient E, giving the number of light vehicles equivalent to one heavy one, will fall since the speed of the former will be very much greater than that of the latter. The value of E can be obtained from the Table 12.4 given in Section 12.2.3.

12.5.4 Provision of Noise Screens

A. Definitions

A noise screen is a structure designed to reduce the acoustic pressure levels in sensitive zones that are exposed to noise from a particular source. In some favourable cases structures that are designed for other purposes, such as buildings, can also serve as noise screens.

The effectiveness of a noise screen for a *given site and reception point* is defined as the difference between the acoustic pressure levels in the absence and following the provision of that screen. In the case of the screening of traffic noise, the atmosphere is assumed to be undisturbed and of uniform composition. The difference between the L_{eq} values for a given type of traffic is normally expressed in the form:

$$\Delta L_{eq} = L_{eq.\,ns} - L_{eq.\,s}$$

where $L_{eq.\,ns}$ is the value of L_{eq} in dB(A) for the given type of traffic in the absence of a screen and $L_{eq\,s}$ the value of the same parameter after the screen has been installed.

In some cases, for example when we are mainly interested in the peak noise as in the case of rail traffic, we can consider the effectiveness of the noise screen with respect to other noise parameters such as L_1 or the L_{NP}.

In the case of traffic with which we are normally concerned, and which can be regarded as originating from a number of identical and regularly distributed sources of noise, the effectiveness of the noise screens does not depend either on the speed or the rate of flow of the vehicles but only on the proportion of heavy vehicles making up the traffic, given that these latter, in comparison with cars, consist of sources of noise that are at a higher level above ground level and that radiate a greater degree of noise at the lower frequencies.

The way in which the screen needs to operate depends to a large extent on the layout of the site where it is installed. At the very least it must block any direct, propagation of traffic noise from the road concerned. In the case of a reflecting ground surface the screen should also block any reflected propagation of noise. Other reflections, for example, off the faces of buildings or other surfaces (of bridges, supporting structures, etc.), can reduce the effectiveness of noise screens.

B. Types of Screen

The different types of noise screen most frequently employed are as follows:

- Earth mounds.
- Panels (made of wood or metal).
- Walls.
- Combination screens involving, for example, an earth mound and a wall or the facing of an embankment.
- Noise absorbing screens.

Apart from their acoustic qualities and in particular a minimum mass per unit surface area, the noise screens must have a number of other qualities. Thus they must be able to withstand the effects of wind, be of durable constuction, be made from non-inflammable materials and have an acceptable appearance.

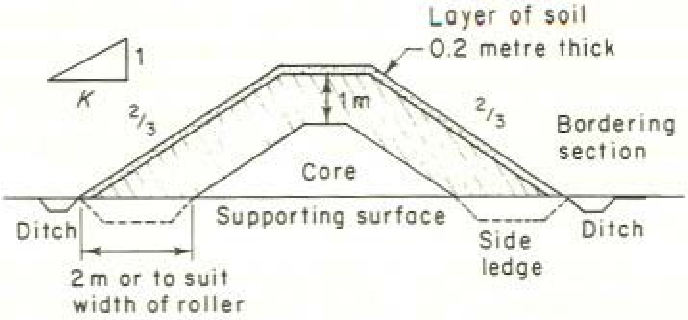


Figure 12.19 Earth mound

Safety requirements also lead to the need to locate the screens at a certain minimum distance from crash barriers, this distance depending on the degree to which such barriers are likely to be deformed in the event of an impact (a clearance distance of 1.5 metres is generally required). An exception to this clearance requirement arises in the case of structures that serve as both noise screens and crash barriers.

Absorbent screens are costly and seldom employed. They can be useful, however, in the case of sites where there can be reflections that destroy the effectiveness of a more normal type of screen or that result in the sound waves being propagated towards a sensitive zone (see Figure 12.20). The more normal solution to this problem however is found on inclining the existing noise screen from the vertical — an angle of inclination of 5 to 10° is usually sufficient.

The material employed in the noise absorbing screens needs to have a Sabine coefficient of absorption of about 0.6 over a frequency range of 250 to 2,000 Herz. The absorption must not be affected by the weather conditions or by solar radiation and there should be no risk of the material making up the screen becoming blocked with dust. The absorbent part of the screen can consist of a porous fibre, such as glass wool, etc., protected with glass wool fabric or a

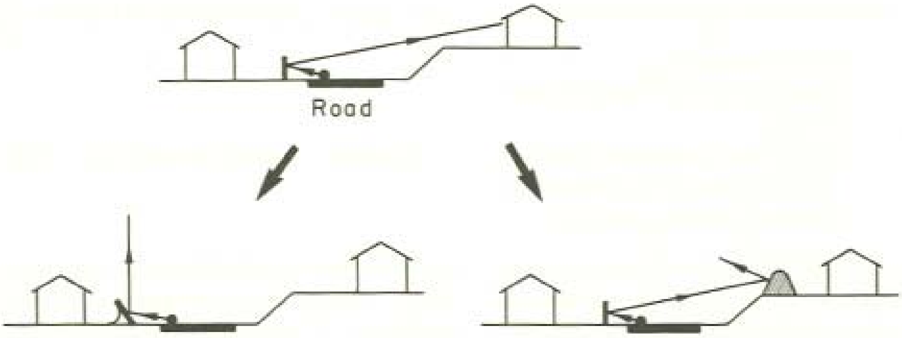


Figure 12.20

perforated plastic sheet (PVC) covered with another sheet of plastic material to keep out dust. This form of construction results in the provision of absorbent screens on open sites at a cost which can amount to as much as twice the cost involved in providing reflecting type screens.

Absorbent screens are more commonly provided in the case of locations where there is some protection from the weather such as tunnels, covered roads and underground railways systems, given that the screens themselves benefit from this protection and that reflecting type screens cannot be used in such locations.

12.5.5 Evaluation of the Effectiveness of Noise Screens

In the case of the evaluation of the effectiveness of the commonly employed type of screen made up of cylindrical elements having axes running parallel to the road, we can make a distinction between three different arrangements:

- A thin screen located on an open site and overlooking a flat reflecting ground surface.
- A thin screen located on an open site and overlooking a flat ground surface of given impedance.
- A thick screen or one of complex shape located on an open site.

The theoretical works for the calculation of the sound reduction by thin screens has been made by several authors (Mackenzie, 1965; Jonasson, 1932; Kurze, 1971). So now we can evaluate the effectiveness of reflecting screens consisting of parallepipeds with vertical edges on making use of computer programs providing that the topography of the site and the shape of any associated constructions are of a simple nature.

In evaluating the effectiveness of screens of complex shape or that are installed on built-up sites or on sites of irregular topography it will be necessary to make use of reduced scale models.

If the ground surface cannot be considered as a reflecting plane then it will be necessary, in principle, to take account of a ground effect in any calculations made to determine the effectiveness of the screens. In unfavourable cases, the partial destruction of the ground effect due to the presence of the screen can result in an appreciable reduction in the effectiveness of the latter.

Reference should be made to the Chapter 14 (this volume) by M. Maeckawa in connection with the calculations that need to be made in determining the effectiveness of the screens.

12.6 REDUCTION OF NOISE LEVELS ON APPLYING TRAFFIC-CONTROL MEASURES IN BUILT-UP AREAS

12.6.1 Reduction of Noise Levels on Applying Conventional Traffic Control Measures

One approach in trying to reduce noise levels can be a matter of considering a more appropriate use of the road system.

The application of modern traffic or transport plans that allow heavy vehicles to follow routes that have been the subject of a careful study generally produced satisfactory results. However, the application can also lead to an increase in the level and degree of dispersion of noise. For example, the general introduction of one-way traffic, leading to higher vehicle speeds and the use of streets that did not previously carry much traffic, will not invariably lead to a lessening of the impact of noise.

Thus the Table 12.7 gives the values of different noise indices before and after the introduction of one-way traffic along three fairly heavily trafficked streets in the city of Lyon. It can be seen that the noise levels were increased in each case. On the other hand, there can be some relief in the case of certain traffic corridors through sensitive areas.

Table 12.7

	Index values					
	Street No. 1		Street No. 2		Street No. 3	
Index	Before	After	Before	After	Before	After
L_{eq}	73.6	81.2	74.2	79.5	69.3	76.2
σ	4.2	4.5	3.4	4.0	5.5	4.7
L_{NP} (or L_1)	84.1	92..2	82.6	89.5	83.3	88.2

An improved circulation of traffic leads, in the long run, to an increase in trip lengths, given that the average of such lengths is approximately proportional to $V^{1.5}$, where V is the average speed of the vehicles. The application of a policy favouring the circulation of traffic therefore leads to a double disadvantage since as well as the increase in noise levels an additional number of people are subjected to the nuisance. For the main roads it is found that the product of the number of people and the acoustic energy to which they are exposed in fact increases in proportion to V^4.

Other more effective traffic control measures that can be employed to reduce noise levels are as follows:

—Control of the circulation of heavy and two-wheeled vehicles.
—Application of speed limits and of restrictions concerning the circulation of traffic.
—Elimination of traffic intersections providing that this is not likely to lead to excessive increases in vehicle speeds.
—Changes in the operation of the public transport systems.

In considering the application of any of these measures it is important to pay attention to the possibility that local improvements could give rise to degradations elsewhere.

12.6.2 Reduction of Noise Levels on Limiting the Circulation of Heavy Vehicles

It should again be noted that:

1. Depending on the nature of the traffic involved, the passage of a vehicle of more than 3.5 tonnes GVW can give rise to a disturbance equivalent to that resulting from the passage of up to 40 cars (see Section 12.2.3).
2. The maximum level of noise radiated by vehicles of more than 3.5 tonnes GVW is not very dependent on their speed when this latter is less than 80 km/hour.
3. The value of L_{eq} due to the passage of a heavy vehicle is greater in cases where the vehicle is running at a low speed. Thus inclines and locations where vehicles start off on their trips can be sources of particularly undesirable effects.
4. Sound barriers are not so effective in the case of heavy vehicles since the higher chassis will mean that the barrier is effectively lower in height while the longer wavelength of the predominant low-frequency noise of the vehicle will mean that the barrier does not act as an effective obstacle.
5. The proportion of heavy vehicle traffic carried by the major roads tends to be greater in the evening, i.e. between 20.00 and 01.00 hours, and early in the morning.

The different actions that can be taken with a view to reducing the disturbance due to the noise of heavy vehicles are as follows:

(a) Divert the heavy vehicle traffic on to roads where few people are likely to be affected or at least on to roads where there are only a few traffic intersections. This will not lead to an increase in fuel consumption providing that it is possible to reduce the number of times that vehicles are obliged to halt without an excessive increase in the distance that needs to be covered (it should not be necessary to cover more than twice the original distance). It should be noted, however, that the diversions often result in the vehicles passing through peripheral districts of a town where they can be generally discontinuous developments of public and private housing where people are very sensitive to noise.

(b) In the case of large towns, prohibit the circulation of heavy vehicles other than on a defined network of roads except where necessary for access. The difficulties here are:

—The objections of people living along the roads making up the defined network. Public consultation is necessary here and this can lead to projects being abandoned in that their application would lead to a worsening of the situation for some people.

- —The cost of applying the measures in connection with the loss of time and increased fuel consumption for the transport companies and the provision of road signs and signals and policing in the case of the local authorities.

Severe restrictions with regard to the routes that they are obliged to follow can lead to the transport companies acquiring smaller vehicles that they can use on all roads such that there will only be an improvement in the overall situation if these vehicles are quieter than the heavy vehicles that they will have replaced. In fact, under present conditions and for the transport of the same tonnage of goods smaller vehicles give rise to the same degree of disturbance as the heavy vehicles. Given these difficulties it would appear that we need to select road networks where it would be a simple matter to ensure that one of the following two restrictions were respected:

- —Obligatory use of certain roads by the heaviest vehicles (e.g. more than 16 tonnes).
- —Banning of all heavy vehicles (e.g. more than 3.5 tonnes) on certain roads.

It is clear that if vehicles could be classified according to a known and displayed noise level, as is the case for their tonnage, it would be possible to take more effective action.

(c) Prohibit the circulation of heavy vehicles during the evening and early in the morning on main roads going through densely populated areas. This restriction is sometimes imposed over the weekend which can be an advantage given that Saturday evenings and Sunday mornings are periods of time, among others, when people most want to be free of any disturbance.

During the week, unfortunately, the ban on circulation tends to be applied during the day which leads to movements of the heavy vehicles during periods of time when people are more sensitive to noise.

(d) Pay attention to a proper provision and location of vehicle terminals, goods depots and parking areas. The undesirable effects due to the circulation of heavy vehicles can be reduced when vehicle terminals and goods depots are located not in the centre of a town but close to ring roads. It should be noted here that the most common disturbance due to the presence of industrial establishments is that associated with the consequent circulation of heavy vehicles.

The provision of parking areas for heavy vehicles ensures that the vehicles are not parked or manoeuvred at night in residential areas.

12.6.3 Reduction of Noise Levels at Intersections

The way in which we quantify noise at traffic intersections, where vehicles are obliged to halt, is limited at the present time to a consideration of the peak noise levels, which depend to a large extent on the effects of starting the vehicles, and on the L_{eq} values which can be quite large as a result of the slowing down of lorries. The length of the zone of influence of an intersection increases with the cruising speed of the vehicles over the range of 0 to 60 km/h. It should be noted that at higher cruising speeds (80 to 100 km/h) the noise due to the halting of vehicles is not so troublesome, at least so far as the zone upstream of the intersection is concerned.

In the case of one-way streets, the presence of traffic lights gives rise to an L_{eq} value downstream which is greater than that upstream from the intersection. The difference between the downstream and upstream values can amount to as much as 10 dB(A) where the traffic does not include many heavy vehicles and providing that the streets are not too narrow with high buildings to each side. Thus people living upstream are in a favourable position in this situation and this factor can sometimes influence the decision that is taken with regard to the direction to be followed by the one-way traffic (e.g. such that vehicles will be accelerating and not brought to a halt on a bridge — unfortunately there is also the problem of atmospheric pollution that needs to be taken into account here).

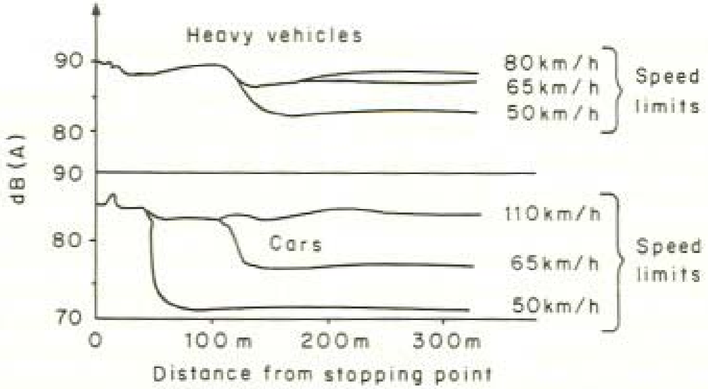


Figure 12.21 Effect of applying different speed limits on the level of noise due to vehicles accelerating away from a halt, (from Raff and Perry 1973)

The following graph shows how the halting of vehicles can lead in particular to an increase in the value of L_{max}, especially in the case of cars. A controlled, green wave, operation of the traffic lights can be an advantage here to the extent that it results in a reduction in the number of times that vehicles are obliged to stop as well as controlling their speed. There can also be an increase in the noise and fuel consumption of the vehicles when there is a gradient at the intersection.

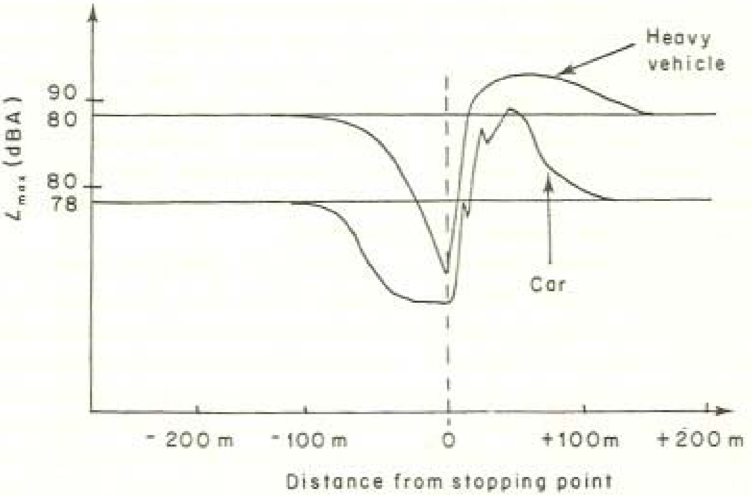


Figure 12.22 Graph illustrating the advantage of eliminating an intersection with regard to the noise from heavy lorries compared with that due to cars

12.6.4 Reduction of Noise Levels on Partitioning Town Centres

The partitioning of limited areas has been followed by application of the technique on the scale of a complete town, e.g. at Gothenburg in Sweden and Groningen in Holland. Thus in August 1970, the centre of Gothenburg was divided into five zones on the basis that the boundaries between zones could only be crossed by pedestrians and by public transport or emergency vehicles. Through traffic and traffic between zones was diverted on to a peripherial route (see Figure 12.23). Traffic on the unblocked streets in the centre of the town was reduced by 70% as a result of this measure while the total vehicle-kilometres, including that due to the through traffic, had increased by no more than 7%. There was also a significant reduction in the number of road accidents per year.

The partitioning technique was applied more recently in the case of Groningen in Holland (a town of 160,000 inhabitants). Thus the technique came into operation on the 18 September 1977, the town having been divided into four zones and through traffic diverted onto a peripheral road. Prior to the

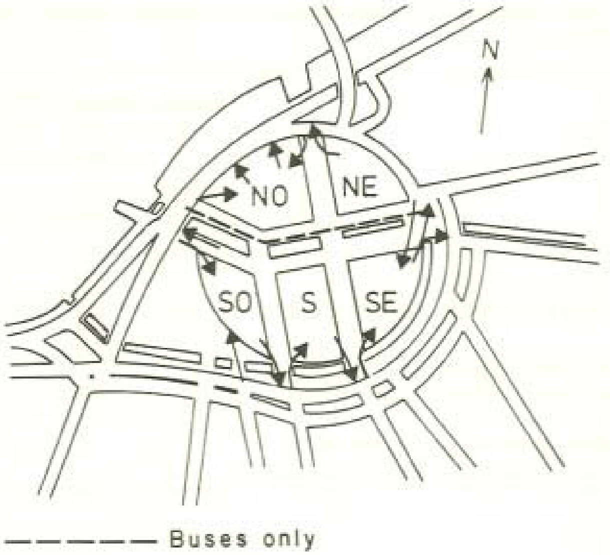


Figure 12.23 Gothenburg (downtown): traffic re-organization principle (1971) (Göteborg OCDE, 1979)

introduction of this measure some 40% of the vehicle-kilometres arising in the centre of the town was due to vehicles for which the town centre was not the destination (Göteborg OCDE, 1979).

12.6.5 Reduction of Noise Levels as a result of Coordinated Actions

The local authority for a town is in a better position than the central government when it comes to co-ordinating a number of actions aimed at reducing the noise due to road traffic, particularly when it is a matter of combining the protection of buildings from noise and the organization of the road traffic. Following the drawing up of a map giving details of the noise levels in the city of Oslo in 1975, the Norwegian government issued a white paper stressing the importance of active traffic control measures rather than passive action such as the provision of noise screens and the sound proofing of building facades. In carrying out a cost effectiveness study a comparison was made between a purely defensive strategy based on the protection from noise and a mixed strategy where the need to provide protection was alleviated by the application of traffic control measures concerned in particular with the circulation of heavy vehicles.

Table 12.8 shows the advantage of applying a mixed strategy—additional advantages are increased safety and reduced atmospheric pollution. It should be noted that in the case of the mixed strategy the cost of applying the traffic

Table 12.8 Cost of alternative strategies aimed at reducing the noise inside buildings to an acceptable level

Strategy	Cost according to different targets for the noise level inside buildings (millions of kroner)		
	35 dB(A)	40 dB(A)	45 dB(A)
Strategy A			
Sound proofing and provision of noise barriers	21.1	14.3	5.3
Strategy B			
Combination of sound proofing, provision of noise barriers and application of traffic control measures	17.3	10.1	4.8
Saving resulting from the application of the combination strategy B rather than strategy A	3.8	4.2	0.5

control measures amounts to only 5% of the capital cost involved in providing protection from the noise.

The municipal authority for Oslo allocated a sum of 0.9 million kroner for the sound proofing of the facades of buildings bordering the roads. The municipal authority decided which buildings should be treated and the individual owners had the option of calling for a higher standard of sound proofing that had been allowed for by the authority on the understanding that the owners would make up the difference in cost. It is considered in Oslo, contrary to the widely accepted view, that sound proofing does not necessarily lead to significant reductions in the consumption of energy for the heating of buildings.

Central government authorities dispose of large sums of money but are not in a position to organize the traffic in individual towns and we might ask if this is why such authorities tend to favour policies based on the sound proofing and protection of buildings from noise rather than the softer options based on a control of the traffic. Given the advantages that can result from a good organization of the traffic, it is to be hoped that municipal authorities will take a stronger line here. The example of New Zealand provides us with an indication of the possibilities. Thus the 1962 Transport Act gave the local authorities the power to restrict the circulation of heavy vehicles with a view to protecting the environment so that transport companies were no longer in a position to demand compensation as a result of any increase in trip lengths, etc. Given this legislation, the town of Auckland was able to improve the conditions in the Parkhill residential area (10 km^2) located between the docks and the industrial zones. This was done in agreement with the transport companies and the measure proved to be very effective on the basis of a very appropriate deviation of the traffic.

12.7 NOISE REGULATIONS CONCERNING THE SOUND-PROOFING OF VEHICLES

12.7.1 Noise Regulations—EEC Requirements

The radiation of noise from road vehicles is the subject of regulations in accordance with national requirements. Generally the maximum acceptable noise levels are specified with respect to precisely defined conditions in the ISO (DP 7188) standard. Thus the noise is measured, as shown by Figure 12.24, on making use of a microphone located at a height of 1.2 metres above ground level and at a distance of 7.5 metres from the centre line followed by the passing vehicle. The vehicle is operated in second and third gear depending on whether it is fitted with a gearbox having four or more ratios and at a speed resulting in maximum power output from the engine. The vehicle must be accelerated at the maximum rate over a distance of 10 metres ahead of the point where it will be immediately opposite the microphone plus 10 metres beyond this same point. The significant noise level is considered to be the maximum level recorded during the passage of the vehicle past the microphone. It should be noted that there are some arguments about the requirements of this standard to the effect that they do

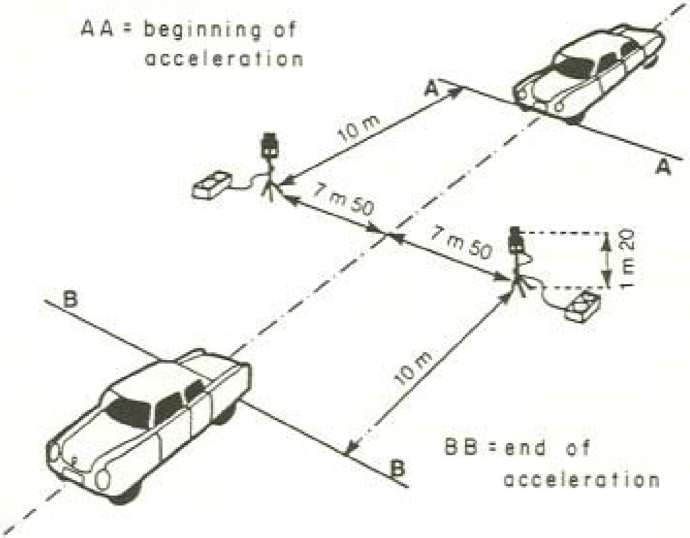


Figure 12.24 Measurements of the noise due to a car

not correspond to the type of operation most frequently encountered in practice, (Institute of Transport Economics. Norway 1979).

Table 12.9 gives the noise level limits according the EEC regulations for the different types of vehicles.

Table 12.9 Maximum acceptable noise levels for the new vehicles in the EEC

	Maximum acceptable noise levels (dBA)	
Type of vehicle	According to order dated 13 April 1972 (amended)	According to orders for 1980–1988 (order dated 16 Sept 1977)
Private cars	82	80
Vehicles other than private cars and having a GVW of not more than 3.5 tonnes	84	81
Public passenger transport vehicles having a GVW of more than 3.5 tonnes and not belonging to any of the categories listed below		
—Buses	89	82
—Coaches	89	84
Public passenger transport vehicles fitted with engines having an output power equal to or more than 200 h.p.		
—Buses	91	85
—Coaches	91	87
Commercial vehicles having a GVW of more than 12 tonnes and fitted with engines having an output power equal to or more than 200 h.p.	91	88
Commercial vehicles having a GVW of more than 3.5 tonnes and not belonging to the above mentioned category	89	86
Two-wheeled vehicles		
—Mopeds (in France)	72	
—Light motorcycles	80	
—Motorcycles	84	
Vehicles having more than two wheels		
—Motorcycles	73	
—Powered tricycles and quadricycles	81	

12.7.2 Sound-Proofing of the Vehicles

The noise emitted by the vehicles can be reduced on taking action at three different levels defined in terms of the period of time likely to be taken in achieving practical results:

A. Level 1—Short Term

This is a matter of reducing the noise emitted by existing designs of vehicle by a more or less complete enclosure of the engine and transmission, on making more effective use of the volume of silencers or on increasing this volume, by fitting different tyres, etc. In the case of vehicles that are already in use, these modifications are only being applied to buses.

B. Level 2—Medium Term

This level of action is concerned with new designs of vehicle but without involving any fundamental changes in the manufacture of the more important parts of the vehicle: use of quiet and low-speed engines, modification to the drive axle gear ratios, modifications to engine accessories such as rocker-arm covers, sump cases, etc.

C. Level 3—Long Term

This is a matter of considering a complete redesign of the vehicle subsystems and components and in particular of the engine, the engine accessories and the complete cooling system.

Reductions in the emission of noise, under the conditions called for by the ISO standard, as a result of action at Levels 1, 2 and 3, could amount very approximately to 3, 6 and 10 dB(A) respectively. Action at the first two levels has already been followed by commercial production but action at the third level has only proceeded so far as the development of prototypes of heavy vehicles that are not likely to be available as production vehicles before 1990.

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CHAPTER 13

Aircraft Noise Generation and Control: Noise Around Airports

JOHN O. POWERS

13.1 INTRODUCTION

13.1.1 Early Recognition of the Aircraft Noise Problem

In the early days of the development of the air transportation system, the sound of the aircraft was considered a sound of progress and was recognized as an indication of affluence by the nation favoured with an air transportation system. This view was shared by the individuals who were fortunate enough to fly on the nation's airlines. As time progressed, and particularly with the introduction of the turbojet aircraft in the late 1950's, the noise generated by aircraft was no longer viewed with pleasure. The early turbojet aircraft, which received its propulsive force from the momentum exchange resulting from the high-velocity jet exhaust, became more efficient as the jet velocity increased. The noise generated by the aircraft also increased, approximately proportional to the eighth power of the jet velocity, and public complaints about aircraft noise increased accordingly.

As the problem of aircraft noise increased, it became apparent to a large number of international officials and aircraft manufacturers who held a conference on the subject in London, (UK International Noise Conf., 1966) that the aircraft noise problem should be addressed and that means of control were necessary to prevent the noise issue from becoming a major deterrent in the orderly development of the air transportation system. The seriousness of this potential constraint to the air transportation system was manifest in the attitude of airport neighbours, many of whom lived and worked in noise impact situations considered by most psychoacousticians to be environmentally unacceptable. In fact, the airport neighbours had in some cases been led to believe that aircraft noise could increase mortality rates among impacted people, as well as induce birth defects in unborn children, and also to cause excessive mental stress. The fact that these views have not been established as credible and the fact that physical demonstrations against airports have tended to diminish in recent years is attributed to the efforts of the early investigators, who at the time of the London Conference and afterwards recognized the seriousness of the aircraft noise problem and instituted programmes to ameliorate the impact of aircraft noise.

13.1.2 Elements of the Problem

Control of Aircraft Noise at the Source, Operationally, and at the Receiver

In some countries, virtually no new airports are being opened for operation and many improvements in airports are being inhibited largely because of environmental impacts, mostly attributable to public concern about aircraft noise. Faced with this constraint, it is apparent that aircraft noise is an environmental cost which should be an internalized cost recognized as part of the total operating costs of the air transportation system. Realizing this fact, there have been voluntary, as well as regulatory, attempts to control aircraft noise. Addressing this issue as an international problem, the International Civil Aviation Organization held a 'Special Meeting on Aircraft Noise in the Vicinity of Aerodromes' in 1969, which was the first attempt by an international body to develop standards for the control of aircraft noise. Initially, these standards addressed the conventional fleet of turbojet aircraft, which were beginning to dominate national airport noise exposure. Since the 1969 special meeting, the ICAO's Committee on Aircraft Noise has traditionally led in the development of standards for light and heavy propeller-driven aircraft, for supersonic transport aircraft, for helicopters, for STOL aircraft, and for auxiliary power units. All of these standards tend to seek a solution to the aircraft noise problem at source. Over the past 12 years, these source noise control measures have been extremely effective. It is estimated that the noise levels of aircraft entering the fleet could be from 15 to 20 decibels higher than those currently entering the fleet had not specific noise standards been established.

A second important element of the aircraft noise control problem is related simply to the manner in which the aircraft are operated. Operations of aircraft at airports should be controlled to reflect the proximity of the airport neighbours to the airport runways. In some cases, a rapid initial climb will provide better noise control than can be obtained by a low altitude thrust reduction with the accompanying lower noise levels.

Noise control operational procedures, in general, are a compromise with respect to the distribution of aircraft noise. In all cases, however, it is of primary importance to ensure that operational procedures are clearly demonstrated to have no advance impact on aircraft safety.

A third element of the aircraft noise problem can be controlled largely through the airport design and through land-use planning. It is this element of noise alleviation around airports which is usually the direct responsibility, though not necessarily completely under the control of the airport proprietor.

13.1.3 Control Measures Available to Airport Proprietors

Airport Community Planning Programme

In some countries the airport proprietor is the party solely legally responsible for the impact of aircraft noise. This reasoning is often based on the fact that the location of the airport, the type of operations, the geometric layout, and the size of the airport are all design decisions made by the airport proprietor. With this responsibility, the airport proprietor should have a reasonable number of prerogatives at his disposal for the control of aircraft noise. The airport developer should be involved in the community's long-range land use planning programme and should have the benefit of zoning restrictions to prevent the encroachment of airport communities on the airport after it has been built. The airport proprietor should also be in a position to acquire adequate land for noise impact control and should have available noise impact estimation procedures to assist in the appropriate layout and design of the airport. In this context, it is particularly desirable that the airport designers utilize all natural barriers, such as rivers, busy highways, or commercial areas as points of noise concentration, thus reducing the need for distribution of the noise to residential neighbourhoods.

13.2 AIRCRAFT NOISE GENERATION

To understand the problem of airport noise control, it is useful to have an understanding of aircraft noise generation. Different types of aircraft have noise sources which are uniquely characteristic of the type of propulsion system used by the aircraft. Many of the sources are common to all of the aircraft types, but contribute in different magnitude.

Extensive research and development efforts have been undertaken to understand the noise mechanisms and in some areas the control devices are fairly well advanced. In other areas, the mechanisms are not understood and the control process has just been initiated.

13.2.1 Jet Noise Source

The early turbojet aircraft produced a single-exhaust stream of hot gases, which provided thrust in proportion to the jet velocity and the mass flow of gas in the single-jet exhaust stream. The jet-exhaust noise sources result from the mixing of the hot-core exhaust stream with the surrounding environment, from

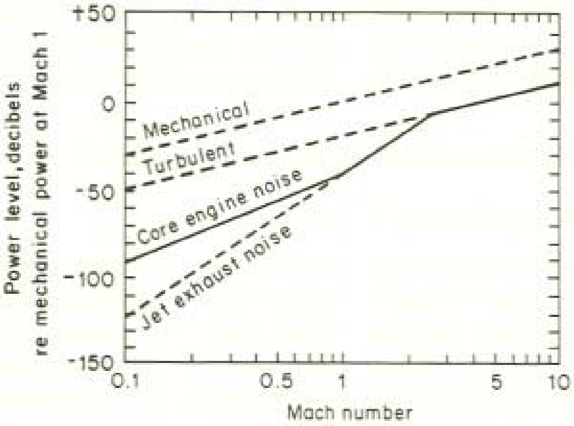
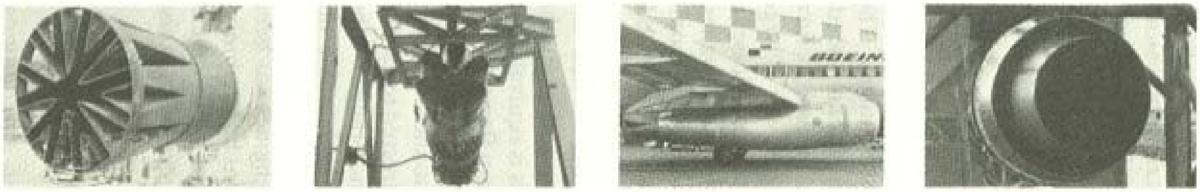


Figure 13.1 Variation of turbojet engine noise with jet Mach number

the shock associated noise when the flow is supersonic, from the core-engine noise, including combustion noise, and from aerodynamic noise resulting from the compressor or turbine systems. In Figure 13.1 (Powers, 1971), the relative engine noise source power levels are presented in decibels referenced to a turbojet's mechanical power at a Mach number of 1.0. It is noted that the mechanical energy varies with the third power of the jet Mach number and, hence, increases by 30 decibels for each order of magnitude increase in jet Mach number. The turbulent energy of the jet is approximately one percent of the mechanical energy and is shown at a 20 decibel reduced power level. Jet-exhaust noise theory predicts that the acoustical power varies with the eighth power of the jet velocity, which is equivalent to an 80 decibels change for each order of magnitude in Mach number. This power-law relationship has been substantiated by a large collection of experimental data; however, it is noted that core-engine noise tends to dominate in the lower jet velocity regions. Unfortunately, the core-engine noise source is difficult to control.

Since the predominant frequency in the jet is inversely proportional to the jet diameter, the larger diameter jets tend to produce a low-frequency dominated noise. With this fact in mind, early researchers attempted to shift the dominant frequencies of the jet spectra to higher values which were more rapidly attenuated by propagation through the atmosphere. This was accomplished by constructing exhaust nozzles, which were subdivided into many smaller individual nozzles or which had various forms of shutes and flutes designed to improve mixing of the exhaust flow with the external atmosphere. Several examples of jet-mixing suppressor designs are shown in Figure 13.2. In view of the complexity of the jet-suppressor designs shown in the figure, a design guide (Report No. FAA-RD-76-79, 1979) has been developed to identify the

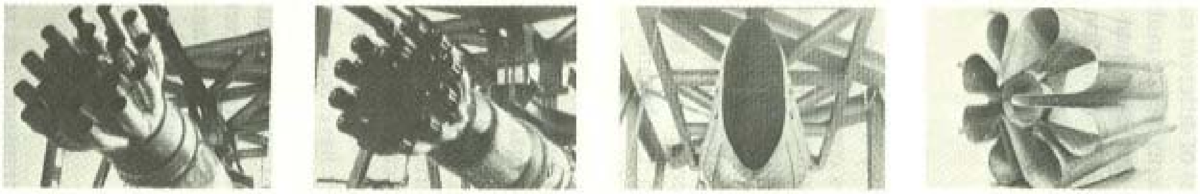


12-LOBE SUPPRESSOR

SIX LOBE SUPPRESSOR

SIX LOBE SUPPRESSOR FLIGHT TEST, 737 AIRPLANE

COAXIAL NOZZLE

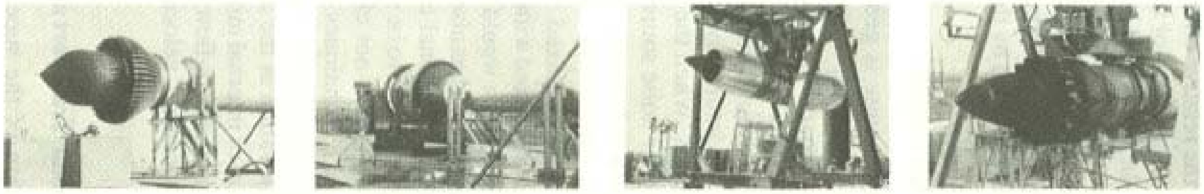


19-TUBE SUPPRESSOR

19-TUBE SUPPRESSOR WITH 10-LOBE NOZZLES

DIRECTIONAL NOZZLE

FAN AND PRIMARY



48-LOBE SUPPRESSOR

48-SUPPRESSOR WITH TWO-STAGE LINED EJECTOR

20-LOBE EJECTOR SUPPRESSOR FOR 727 AIRPLANE

LINED EJECTOR REMOVED TO SHOW 20-LOBE SUPPRESSOR

Figure 13.2 Examples of full-scale jet noise suppressor tests on JT8D engine (Courtesy of Boeing Airplane Company from Document D6–40613-K, April 1980) acoustic suppression phenomena involved and the impact of the suppressors on the thrust performance for different configurations. The design guide can be used to assess the relative effectiveness of different suppressor configurations, and is applicable for most of the concepts, (e.g., multiple-nozzle suppressors, shutes, etc.) when operated in either single- or dual-flow installations. These devices, in general, provide a moderate reduction of jet noise, but were constrained by the fact that the jet thrust was reduced correspondingly. In some cases, the loss of performance experienced by aircraft tended to offset the noise reduction provided by the exhaust nozzle configuration.

13.2.2 Turbofan Engines

Turbofan engine noise is generated by a combination of mechanisms. The number of fan and compressor blades combined with their rotational speeds generates the primary fundamental harmonics discrete-tones. The vortex flow around and shed by the blades produces the broadband noise over a large frequency range. An additional source of fan and compressor noise is generated by the interaction of the wakes from the rotor and stator vanes, which are in series. When the fan or compressor blades operate at supersonic tip speed, another noise source called 'combination-tone noise' is generated. The fundamental advantage of turbofan engines from the noise standpoint results from a two-stream mixing process, which takes place when the high-velocity core is mixed with a lower-velocity fan-flow and then the combined stream is mixed with the external flow. The net result is equivalent to a lower noise level than would be generated by the single-stream flow.

The turbofan engine has also advanced the development of sound absorbing material to reduce the tonal characteristics of engines. The sound-absorbing material has been shown to be very effective, but its design is directed towards a single frequency and is not effective over the entire frequency range of the turbofan engine. Techniques recently have been developed to increase the effective frequency range of sound absorbing materials.

A recent innovation in the control of noise from turbofan engines has been the introduction of internal mixers. The internal mixer functions by combining the fan-flow and the core-flow inside of the engine and produces a lower mean velocity and a control velocity profile, which can be optimized for noise control.

13.2.3 Supersonic Transport and Rotor Noise

The introduction of the supersonic transport has resulted in an additional problem for the airport proprietor. The thrust necessary for flight at supersonic speeds is most efficiently generated by pure jet engines and is considerably higher than the thrust needed for subsonic cruise aircraft. As a result, the take-off noise levels of supersonic transport aircraft tend to be very large. A related problem, which does not result in an airport noise impact, is the problem of SST's sonic boom. The sonic boom problem has been found to be controllable only through the use of operational restrictions on SST overflights.

Another dominant aircraft noise generating mechanism is the rotor noise of propeller-driven aircraft and helicopters. In this case, the general mechanism for the propeller-driven aircraft and helicopters is essentially similar, however, there are practical differences resulting from configurational design. Both noise sources are composed of the rotational component, which occurs at the fundamental blade-passing frequency and its harmonics. Additionally, the vortex noise and thickness noise provide the elements of a broadband structure which add to the total noise spectra. The helicopters have an additional noise source resulting from the interaction between blade-wakes and the advancing blade (Figure 13.3), (Foster, 1978). This interaction can occur between the forward and aft blades of a tandem rotor aircraft or between the main and tail rotors of a single main rotor helicopter. The control of rotor noise has not reached advanced technological stages as yet and most noise control emphasis is directed at the reduction of blade-tip Mach number. This means of achieving noise control unfortunately results in a performance loss and must be compensated for by increasing the blade solidity or changes in other design parameters.

13.2.4 Source Noise Control by Regulation

The Evolution of International Noise Standards

Following the 1966 London Conference, considerable effort was directed towards the development of international aircraft noise-control standards. While it is recognized that the noise-control standards themselves do not result in a reduction in noise generation, it is apparent that the aircraft designer must include control of noise as an important design parameter in the aircraft design. The standards developed in the 1969 time frame were generated under the guidelines that regulation should provide relief and protection to the public from unnecessary aircraft noise and that regulation should be consistent with safety, economically reasonable, and technically practicable. The initial standards were designed for subsonic turbojet aircraft. Consideration of the noise levels of existing aircraft, the fact that a new generation of high bypass-ratio turbofan engines was being developed, and that technical improvements in nacelle design could be achieved through the use of sound-absorbing materials resulted in the conclusion that appreciable reduction in existing noise levels could be accomplished. The standards were also designed to be compatible with airworthiness requirements and operational

Figure 13.3 Tip vortex interaction

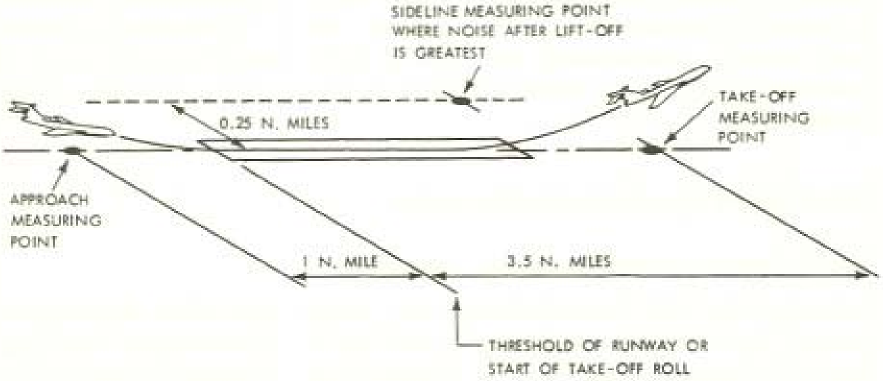


Figure 13.4 Noise measuring points for airplane type certification

practice, which lead to the stipulation of noise-level criteria achievable during normal airport flight operating conditions. The noise-level criteria were expressed in a newly developed unit called the Effective Perceived Noise Level (EPNL), which was designed to reflect public reaction to the noise of turbojet aircraft and to provide a regulatory incentive to aircraft designers to control the objectionable characteristics of aircraft noise. The noise levels were measured by a microphone array utilizing the three-point concept shown in Figure 13.4, which specified measurement point locations at specific distances for assessment of take-off, sideline and approach noise. These measurement point locations were considered to be representative of the airport-community interface and were intended to provide airport proprietors with useful guidance

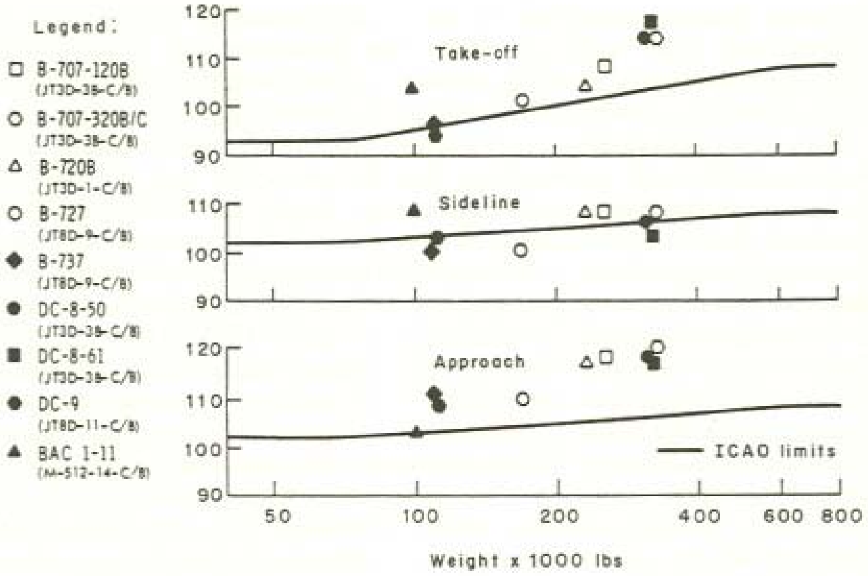


Figure 13.5 Uncertificated noise levels (EPNdB) (estimated)

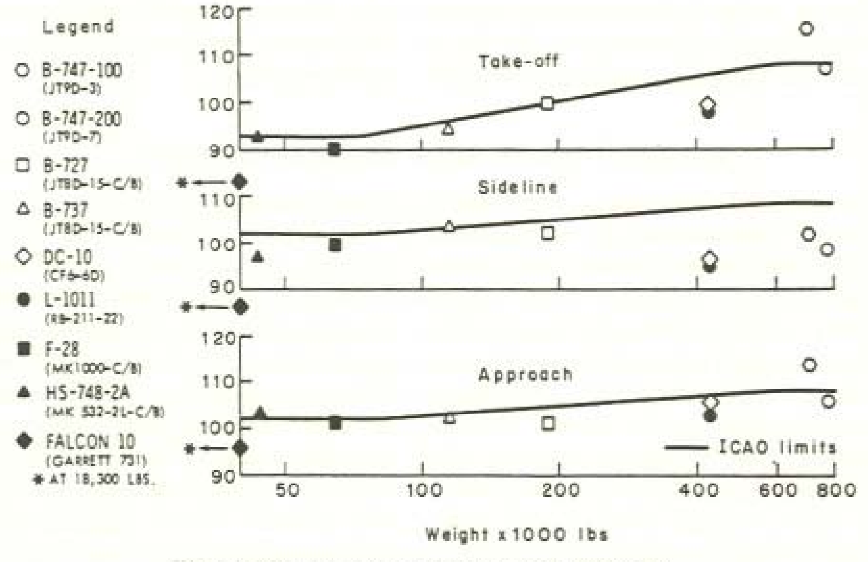


Figure 13.6 Certificated noise levels (EPNdB)

in the determination of acceptable aircraft for operation at their airports. Figures 13.5 and 13.6 show representative noise levels for aircraft designed prior to the establishment of the initial ICAO noise limits and the noise levels of some aircraft certificated to the ICAO standards (Convention on International Civil Aviation, 1978). The implementation of the initial international noise standards has resulted in aircraft which are approximately 10 to 15 decibels quieter than those designed without noise-level constraints.

Since the initial standards were promulgated, additional standards have been enacted which progressively broaden the scope and increase the stringency of the noise level requirements. In the mid-1970's, all newly produced aircraft were required to meet the initial noise standards. Internationally, many nations are in the process of requiring that all aircraft meet the initial ICAO standards by a specific date during the time period 1985–1990 as a condition for operation at their airports. Also in the late 1970's, a more stringent set of noise-level limits were promulgated which will require further reductions in allowable noise levels by 5 to 9 decibels for second generation aircraft designs. Additionally, international standards have been developed for the new design and new production of small and large propeller-driven aircraft, for civil supersonic aircraft, and are in the process of being finalized for civil helicopters. In many respects, aircraft complying with the international standards will be required to achieve the ultimate in source noise control available through the application of advanced acoustic technology. This is not to be construed as implying that all of these actions will in any way eliminate aircraft noise. Even when the optimum noise control technology is applied to aircraft designs, the remaining noise resulting from moving-off a substantial mass from the ground and into the air will create a residual noise-control problem which must be addressed by the airport proprietor.

13.3 CONTROL OF NOISE AROUND AIRPORTS

For many years, the basic concept that aircraft noise abatement is and must be a shared responsibility of all elements of the aviation industry has been articulated. In the United States, for example, that concept is the basis for the United States' Aviation Noise Abatement Policy (Dept. of Transportation, 1976), which has formally been in effect for approximately five years and has been in effect informally since the seriousness of the aircraft noise problem was initially realized. The contribution of the aircraft engine and airframe manufacturers to the control of noise has been reviewed in the previous section. The air-carrier segment of the aviation industry has also made substantial investments in the control of aircraft noise through the replacement of older, noisier aircraft with new quieter aircraft. These replacement programmes, because of the extreme financial burden involved, are necessarily long-term actions and, hence, the benefits come in small increments which are difficult for airport neighbours to fully appreciate. The airport proprietor, who is responsible for the noise impact, is not independently responsible for implementing the remaining measures for noise control. In many cases, implementation of the necessary noise control measures can only be accomplished in cooperation with the aircraft operators and the Federal authorities.

13.3.1 Operating Measures

Typical of such cooperative measures are the implementation of aircraft operational noise-control procedures in the airport vicinity, which require the co-operation of the air traffic and airspace managers, the operating airline, as well as the airport proprietor. The following are representative noise control operating measures.

A. Noise Preferential Runways

The noise preferential runway use system utilizes the runways which can take advantage of natural terrain around the airport, such as requiring approaches over rivers or industrialized areas to avoid the noise impact on residential communities. In cases where this is not possible because the airport is completely surrounded by residential communities, the possibility of distributing the noise burden through a rotating preferential runway use system may be explored. The preferential runway use system must be flexible to accommodate expected but varied meteorological conditions and in all cases must be implemented in a manner ensuring maximum safety.

B. Displaced Thresholds

In certain situations, if the runways are of sufficient length, the approach threshold can be displaced to require the aircraft to touch down at greater distances from the start of the runway and hence at a further distance from the airport boundary. This may require movement of ILS landing aids but can provide noise relief by maintaining a greater displacement between the aircraft and the airport residential neighbourhood.

C. Take-off Noise Abatement Procedures

The control of aircraft take-off noise can be accomplished by requiring thrust reduction relatively near to the ground at airports where the residential neighbourhoods are fairly close to the take-off ends of runways (Figure 13.7). The aircraft in this case would climb over the residential area at reduced power which would minimize the noise in the residential community being overflown. When the aircraft has passed the residential area, normal climb power can be re-applied until cruise altitude is reached. If the residential community is further displaced from the airport boundary, it is generally desirable to climb as

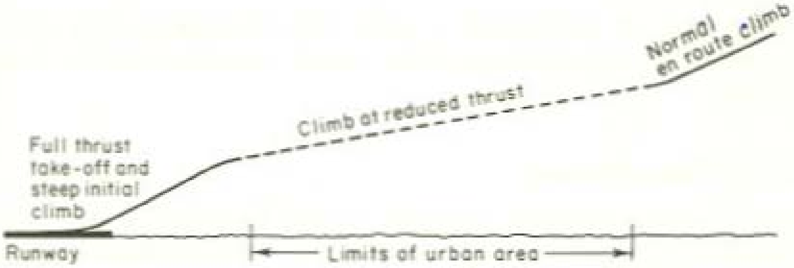


Figure 13.7 Noise abatement takeoff procedure

rapidly as possible to obtain the maximum altitude over the residential areas before reducing power. The steep-climb procedure is not effective if the residential neighbourhoods are close to the sidelines of the airport runway. In this case, it is desirable to reduce thrust soon after the aircraft comes out of the extra lateral attenuation phase, which is associated with the propagation of noise when the aircraft is near the ground. Standardization of noise abatement operational take-off climb procedures is considered highly important for effectivity, especially from a safety standpoint. Currently, the Operational Panel of the ICAO Airworthiness Committee is in the process of recommending standardized noise abatement departure procedures which take into account fuel conservation, as well as neighbourhood noise impact.

D. Approach Procedures

In the last ten years, probably more has been done to control approach noise than noise during other operational modes. The approach procedure some years ago consisted of an extended flight at approximately 1500-ft altitudes with the aircraft in the maximum approach flap configuration and, hence, maximum noise condition until it intercepted the normal 3 degree glide-slope and proceeded to touchdown. The 1500-ft approach is being replaced in the United States by a local-flow traffic management programme, which reduces the flying time at altitudes below 10,000 ft, eliminates holding, and provides the shortest practical route for the aircraft to take all the way to touchdown. The use of the minimum certificated approach flaps has also standardized approach procedures, which assist in reducing the noise. Other techniques used to control approach noise are identified as the decelerating approach and the flap-management approach. Both of these procedures control the noise on the ground by reducing the engine thrust levels during approach.

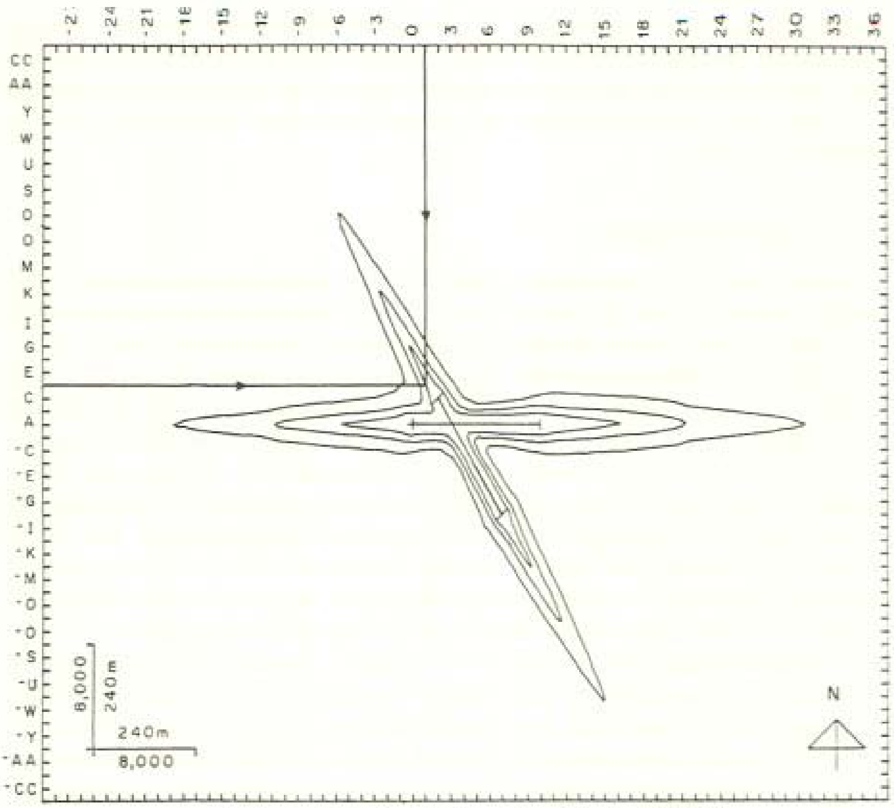
Operational procedures have been considered for many years to be one of the most promising methods of controlling aircraft noise; however, their effectiveness is generally airport specific. The desire for uniformity in operations, which is considered by most pilots to be essential for the highest degree of safety, has resulted in only limited support for the use of operational noise-control procedures. Additionally, there is a tendency for the operational procedures to be aircraft specific as well as airport specific and, therefore, standardization of procedures across all aircraft types is difficult to realize.

13.3.2 Land-Use Control

Land-use control is synonymous with long-range airport/community planning to ensure that the airport will be able to provide the required service with reasonable prospects for minimizing noise impact, both in the present and in the future. The mechanism used for assessing the aircraft noise impact in the vicinity of an airport in the United States has been identified as the Integrated Noise Model (INM) (Dept. of Transportation, 1979). This noise planning model can be used to evaluate different techniques for reducing the noise impact or can identify how operations at the airport must be controlled to prevent excessive impact in specific airport neighbourhoods. The INM consists of summing the annual aircraft movements in the vicinity of the airport to represent an annual average daily noise impact contour as shown in Figure 13.8. The airport noise impact can be expressed in a number of noise metrics depending on the preference of the user. Currently, the noise metrics available from the model are 'cumulative metrics', such as Noise Exposure Forecast (NEF), Day-Night Average Sound Level (L_{dn}), Equivalent Sound Level (L_{eq}), and Community Equivalent Level (CNEL). Noise contours in these units can be computed and printed at selected map scales. Additionally, the model automatically provides numerical listings of the calculated noise values at all intersecting points on a grid which encompasses the airport and surrounding neighbourhoods. For the land-use planner or airport developer, the INM may be used to identify controls necessary to bring about noise compatibility. These controls may be identified by comparing the noise impact contours for different aircraft types, varied fleet-mixes, different aircraft operation procedures and flight tracks, as well as alternative airport-use restrictions.

13.3.3 Monitoring

Aircraft noise monitoring is useful primarily as a deterrent against individual operations, which make excessive noise. Monitoring is not recommended as a device for violating individual airline flights, but as a means of identifying airline-by-airline average compliance with airport plans. These uses are differentiated because the first can result in the 'beat the box' syndrome or generally unsafe operational practices; whereas the second use identifies airlines as good airport neighbours, which stimulates quieter operations for



Federal aviation administation integrated noise Model 1.2

Figure 13.8 Example airport—NEF 30, 35 and 40

the public relation benefit available to the airline. The monitoring systems are also useful for checking the noise-exposure levels in any specific vicinity as a means of identifying problem areas which require special attention.

13.4 CONCLUDING REMARKS

It is clear that the burden of airport noise control will be the responsibility of the airport operators and proprietors for some time to come. The operator in his role as primary focal point for the control of airport noise may consider a large number of directly implementable options, many of which should be included in the initial airport development plan. (U.S. CFR 14, 1981, 1985). Further associated with the plan, if the airport proprietor has the authority, he can propose control of the use of land adjacent to the airport by zoning or other procedures. He can attempt to influence local building codes by advising that residential and public buildings in the vicinity of the airport be acoustically insulated and also be recommending a plan whereby future purchasers of real estate in the vicinity of the airport are made aware of the projected noise impact in areas of interest.

Working with other authorities and often with the support of financial institutions, the airport proprietor may seek to acquire land to ensure its future use for puposes compatible with the airport operations. If the land itself cannot be acquired, it may be possible to obtain air easement rights and to plan future runway developments in such a manner as to direct the noise to areas over which the proprietor has been able to acquire a degree of control. For site specific airports, some benefit may be gained by the construction of acoustic barriers or from the use of landscaping to modify the noise impact. These procedures often supply a minimum reduction of noise impact, but do provide an indication of concern by the airport proprietor for the welfare of the airport residents.

The operational procedures for noise-abatement control discussed above can be proposed by the airport proprietor as a means of noise control if it is endorsed by the national airworthiness authorities. Schemes consisting of use restrictions or noise-related landing fees may also be proposed if they are not in conflict with national prerogatives. Use restrictions could consist of limiting the number of operations per hour at different times during the day, of controlling the hours of operations, and of proposing specific evening and/or night-time curfews. Landing fees based on aircraft noise levels may prohibit operations of particular types or classes of noisy aircraft. While this set of options appears relatively straightforward, depending on the individual country's national regulations, the airport proprietor may find legal limitations to many of the use restrictions suggested. Guidelines on these limitations can only be general, but the limitations usually are legally acceptable if they are imposed equally and impartially and do not tend to discriminate against a particular class of aircraft operators. Care in application of use restrictions by the airport proprietor must be taken to ensure that the restrictions do not control the way aircraft are flown or do not constitute management of the navigable airspace. These functions are usually pre-empted by national governments. A final test of the viability of a use restriction is that it should not impose undue burden on interstate or foreign air commerce. Currently, the legal definition of undue burden has not been resolved and will undoubtedly be the subject of future legal decisions. In the meantime, as a general guideline the airport proprietor should keep in mind that use restrictions must be meaningful and non-arbitrary and that the noise control should be imposed equitably to all sources of noise in the vicinity of the airport.

In summary, while the burden of airport noise impact clearly falls on the airport proprietor, the means available to control that noise burden at any specific airport is limited by the airport's intended operational use. Obviously, it is considerably easier to control noise at new airports than to improve the noise situation at an existing airport, especially if that airport is operating at near capacity. The number of new airports which may be built, however, will be very much limited by public resistance unless the noise burden is reduced in magnitude and the cost of the burden generally internalized in the air transportation system. To accomplish this objective, all elements of the air transportation system must contribute to the control of airport noise to the maximum extent to ensure the orderly growth of one of the world's most important communicative resources.

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Noise Pollution
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CHAPTER 14

Solid-borne Noise Control in Buildings and Machinery

M. HECKL

14.1 THE NATURE OF 'NOISE' IN SOLIDS

The noise excited in solids may be of various types:

(a) Single impacts which are registered as separated events by the ear; examples are footsteps or door-slamming in buildings, pile driving, forge-hammer blows, punch presses, textile machines, etc.
(b) Periodic impacts that are interpreted by the ear as tones with harmonic content; examples are the piston slap in internal combustion engines or other periodic machinery, the many small impacts generated in the cutting process of a circular saw, etc.
(c) Almost harmonic as when fluctuating electromagnetic forces act in the body of a transformer or electric motor (cf. household appliances, elevators); other examples are in gear noise due to manufacturing inaccuracies (hence stressing the need for good *quality control*), or to gear-tooth resilience, or in the sometimes rather startling phenomena when feedback and/or resonance effects are involved (e.g. wheel squeal).
(d) More or less random, as in hydraulic systems such as in flushing cisterns, taps, pipes (cf. water-hammer) etc. arising from turbulence, cavitation or presence of 'air-locks'; in devices involving drilling, grinding or polishing; in movement of bodies over irregular surfaces (cf. trains passing over 'wavy-worn' tracks), etc.

The above examples indicate the many and varied sources of noise in solid structures and the sound energy involved is propagated by the different forms of wave-motion (see Chapter 1) which can exist in solids. On reaching the boundaries of the solid with other media, the continued transmission or reflection will depend upon the angle of wave incidence and the relative acoustic impedances of the boundary media. Any internal waves reaching an air-solid boundary will, in general, produce an outward or inward movement of the solid surface and this give rise to sound in the surrounding air.

This list, although incomplete, shows that solid-borne sound *excitation* is almost omnipresent and consequently also the *propagation* of solid-borne sound — or structure-borne sound as it is often called — plays an important role. Examples here are transmission of sound along flanking walls in buildings, propagation of bending waves or other wave types along structural beams, pipes etc., and the transmission of vibrations from machines via their mounting into neighbouring regions.

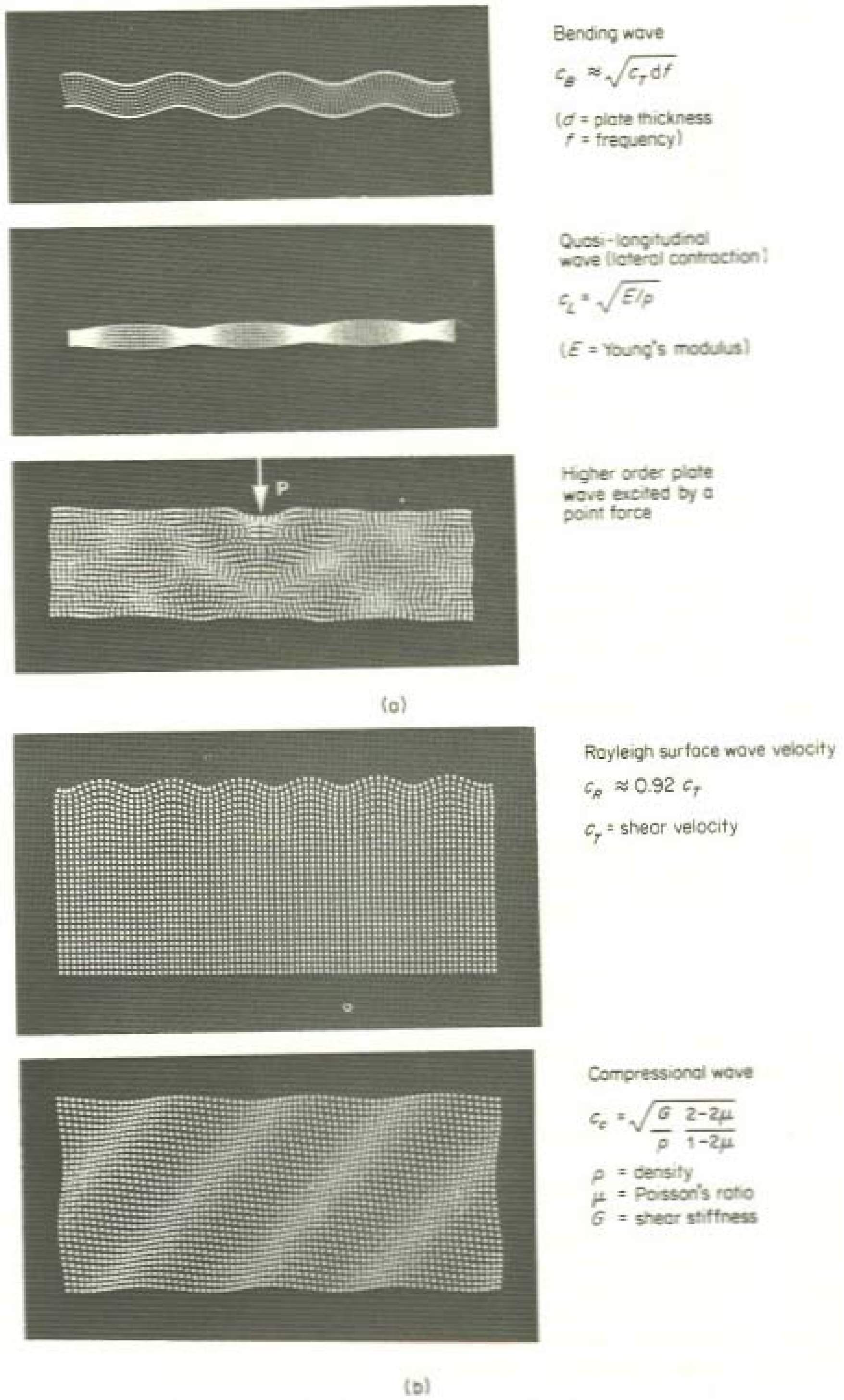
In the following, an attempt is made to describe (briefly) the important phenomena in solid-borne sound generation and propagation and to give the main hints on structure-borne sound reduction.

14.2 RESUMÉ OF DIFFERENT WAVE-TYPES IN SOLIDS

In gaseous or pure (i.e. non-viscous) liquid, media sound is propagated by compressional waves in the material. Solids, however, have not only a compressional stiffness but also a shear stiffness and consequently sound energy in solids may be transmitted via two types of wave that have different speeds and therefore give rise to some special effects that are unknown in gases or normal liquids. The two basic wave-types are the compressional waves and the shear waves, but rarely is one present alone and they combine with each other to give rise to more complicated wave-fields. Some of these combined waves have special names. The particle motion and the formulas for the speed of wave propagation motion for the various wave types are shown in Figure 14.1(a) and (b). It should be noticed that in some cases the wave speed depends on frequency thus giving rise to dispersion effects.

14.3 MEASURING TECHNIQUES

The quantity that usually is measured in the field of structure-borne sound is the motion in a direction perpendicular to the surface of the structure (only in a few cases is the motion parallel to the surface also of importance). A typical measuring set-up consists of a piezoelectric material backed by a little mass (see Figure 14.2). Such a device, when mounted rigidly to a vibrating surface, produces fluctuating electric charges that are proportional to the acceleration of the surface. Since the measuring devices are very small and light (typically 1–10 grams) — to avoid any mechanical loading of the vibrating object — the electrical signals are rather small, but with modern electronics the signals can easily be brought to a level which allows the use of all the data processing and



Bending wave

$c_B \approx \sqrt{c_T d f}$

(d = plate thickness
f = frequency)

Quasi-longitudinal wave (lateral contraction)

$c_L = \sqrt{E/\rho}$

(E = Young's modulus)

Higher order plate wave excited by a point force

Rayleigh surface wave velocity

$c_R \approx 0.92\, c_T$

c_T = shear velocity

Compressional wave

$c_c = \sqrt{\frac{G}{\rho}\,\frac{2-2\mu}{1-2\mu}}$

ρ = density
μ = Poisson's ratio
G = shear stiffness

Figure 14.1 Different wave types in solids

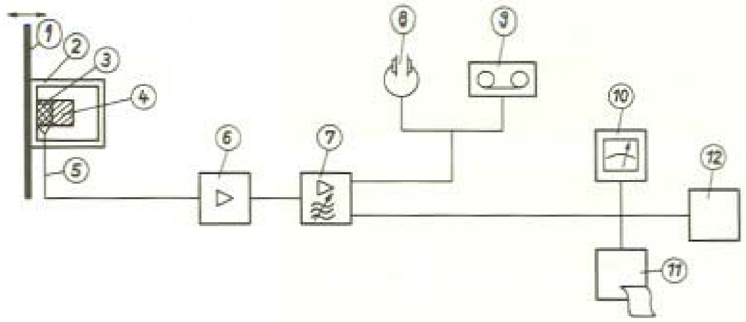


Figure 14.2 (1) vibrating object, (2) casing for accelerometer (not to scale), (3) piezoelectric material, (4) small mass, (5) cable, (6) preamplifier, (7) amplifier and filter, (8) earphones, (9) tape recorder, (10) scale instrument, (11) level recorder, (12) other data reduction (e.g. computer). Items (7)–(12) are the same as those used for normal sound signal processing

data reduction equipment (frequency filters, correlators, level recorders, etc.) that is available for normal sound signals. Figures 14.3(a) and (b) show some examples of measured structure-borne sound spectra. The data are given in terms of the velocity level which is appropriate for comparison with airborne sound data. It is defined as

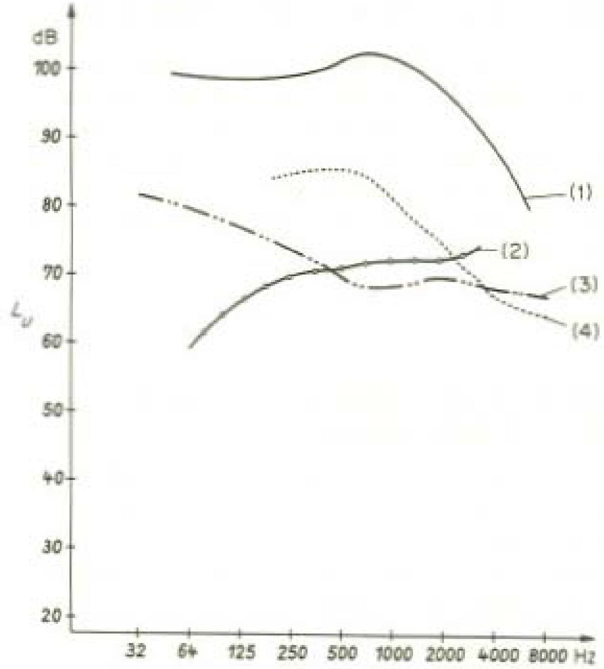
$$\text{Velocity level } L_U = 10 \log \frac{\bar{U}_2}{U_0^2}$$

Where $\bar{U}^2$ is the mean square value of velocity, and U_0 is a reference value. If the levels are given in term of spectra, the velocity level and the so-called acceleration level L_a are related by

$$L_U = L_a + 20 \log \frac{a_0}{2\pi f U_0}$$

where f is the centre frequency of the frequency band under consideration and a_0 is the reference value for the acceleration level. It should be noted, that the sound-*pressure* levels in front of a vibrating solid are hardly ever larger than the *velocity* levels as expressed in Figures 14.3(a) and (b).

Figure 14.3 (a) Examples of velocity levels per third octave. Reference value $5 \cdot 10^{-8}$ m/s: (1) Diesel engine on elastic mounts running at full load (2,500 Hp) at 1,700 r.p.m.; (2) Standard tapping machine acting on a 12 cm concrete floor; (3) Electric motor on elastic mounts running at 1,400 r.p.m.; (4) Gasoline engine on elastic mounts running at full load (4 Hp) at 4,000 r.p.m; (b) Examples of velocity levels per third octave. Reference value $5 \cdot 10^{-8}$ m/s. (1) Subway rail when train is passing at 60 km/h; (2) Maximum values of an elastically mounted elevator for six persons; (3) Wall of a house when a street-car is passing with 45 km/h at a distance of 13 m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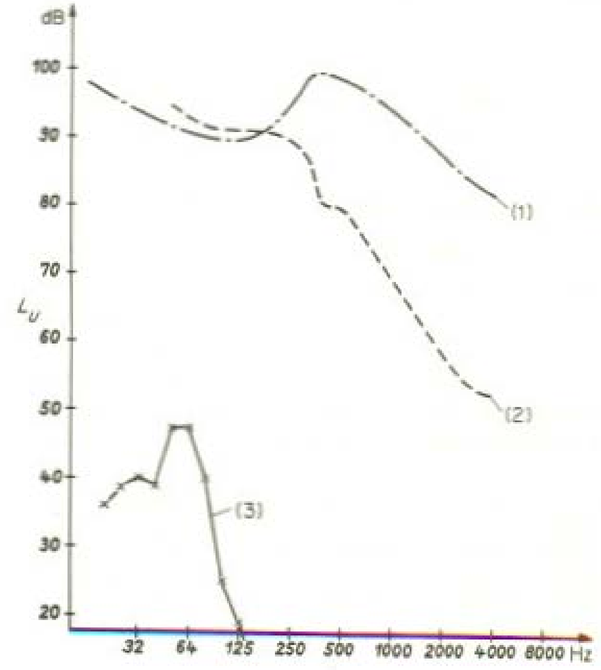
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14.4 REDUCTION OF STRUCTURE-BORNE NOISE AT ITS ORIGIN

The so-called primary noise control — is usually more effective and more economic than noise control which leaves the noise-excitation mechanisms unchanged but reduces the sound propagation by damping materials, enclosures, isolator shields, etc. (the so-called secondary noise control).

There are cases even where primary noise control shows some additional benefits* because there is no law of nature that states that good noise control has to be paid for by some sort of disadvantage.

The most common methods of primary noise control in the field of structure-borne sound are as follows:

14.4.1 Reduction of the Fluctuating Forces and Motions which are Basically Responsible for the Sound Generation.

This can be done by lowering the speed, by using very smooth surfaces when one body rolls over another one, by reducing the mass of those parts that have to undergo high acceleration.

An interesting case in this respect is the development of the typewriter. Originally, the rather heavy platen had to be accelerated and decelerated whenever a letter was typed. As a next step the letters were placed on a light sphere and only the sphere had to be moved. Nowadays the sphere is replaced by a very thin plastic disc which has a weight of less than 1 gram. The next step seems to be that the only moving parts are minute droplets of ink which are sprayed in such a way onto the paper that letters or other symbols are formed. Thus in the development process the mass of the moving parts has been reduced from kilograms to less than milligrams.

14.4.2 Modification of the Time History of a Process

In this case sudden changes, which are responsible for the annoying high frequency sound, are avoided.

Examples are cam drives that are designed in such a way that discontinuities in the motion or in its first derivative cannot occur. Other examples are found in gearboxes where the teeth are inclined to cause a smooth transmission of the force or in many other instances where a suitable mechanical design of a system allows for a smooth transition. All these methods rely on the fact that usually it

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* It is known, for example, that sudden impacts cause a lot of noise, they also cause wear, thus if impacts are made smoother, the life time of a machine is likely to increase. Similarly, reduction of unbalanced masses in machinery rotating at high speeds decreases the noise and helps to avoid damage in bearings. As a third example, one may mention the fact that small clearances between the moving parts of machine tools reduce any rattling noise and at the same time improve the precision of the product. In short, quiet machines are better machines.

is not the magnitude of a force or a displacement which is responsible for the sound generation but its rate of change (i.e. the suddeness of an event). Quite often small alterations that are restricted to a few milliseconds of an event can have a remarkable effect on the noise production, provided that discontinuities are smoothed out. Modern flush toilets as compared to those that were built twenty years ago give a good example how noise control at the origin can effectively reduce the sound.

14.4.3 Detuning of Resonances and/or Interruption of Feedback Loops

Sometimes structural noise sources generate an almost harmonic tone with an amplitude that is much higher than the rest of the spectrum. Examples are resonances of electric motors or generators, large pipes, double walls, etc. and stick slip phenomena that generate screech sounds, rattling of lathes, etc. Since, in such cases, resonance effects and feedback mechanisms are involved noise reduction can be achieved by detuning the system or by interrupting the feedback loop. Unfortunately, this is said much more easily than it is done. The reason for this is that — apart from electric machinery where the situation is fairly well understood — an exact prediction of resonances and feedbacks is almost impossible. Therefore, one is compelled to design those structures that are apt to cause difficulties according to the best of the existing knowledge but allow for some changes whenever a prototype is available. A rather novel and effective method to improve resonating constructions is the so-called modal analysis. This method which usually consists of an impact excitation of a structure and many subsequent velocity or acceleration measurements gives the resonance frequencies as well as the nodal patterns of a vibrating structure. Thus it is possible to find out the frequencies that do not give rise to resonances and those points that have the least motion (i.e. nodal points) and which therefore are the most suitable as mounting points. Good results are also obtained when modal analysis is combined with the finite element method or when holographic methods are applied to study the vibration patterns of structures.

14.4.4 Compensation of Fluctuating Forces or Motions by their Opposite

Noise in solids usually can be described by some linear differential equations, i.e. the principle of linear superposition holds. Thus if a force F causes a velocity v, a force $(-F)$ causes a velocity $(-v)$, or in other words if both forces are present simultaneously the velocity vanishes. This principle can be applied in noise control whenever it is possible to make some lever arrangement that replaces fluctuating forces by fluctuating moments. There are even some attempts to add an artificial — usually electrodynamic — force generator that acts as an anti-noise source, which if properly phased reduces the total noise output.

14.5 REDUCTION OF SOLID-BORNE NOISE DURING PROPAGATION

It is a general principle in environmental engineering that a pollutant can be controlled the easier the nearer this is done to the source. It is also known that a single well-defined pollutant can be handled much better than mixture of many — possibly unknown — contributers to a pollution situation.

Applied to structure-borne noise control, this means that one should bring all methods of secondary noise control, such as damping, isolation, etc., as close to the original sound source as possible; it also means that a source which generates just one wave type at one frequency (so to say one noise pollutant) can be reduced much easier than one that produces many wave types in a random manner over the whole frequency range.

14.5.1 Resilient Layers

Resilient layers, such as rubber elements, springs, etc. are the most common way of reducing structure borne sound transmission. Figure 14.4 gives a few examples. They may act in two ways. If they are close to the noise source (e.g. floating floors, carpets or other resilient layers in buildings) they reduce the suddeness of impacts and thereby avoid high frequency noise excitation. If they are at some distance from the source (more than half a wavelength) they reflect the incoming structure-borne sound energy. Resilient engine mounts, the rubber elements separating the wheels and bogies of modern subway coaches, resilient clamps in piping-systems or suspended ceilings (spring damping) are examples. The efficiency of such devices can be quite high (20 dB or more) provided they are applied very close to the original source; and provided they are resilient.

As a rough rule of satisfactory resilience one may take that the resilient mount has to be much softer than those parts of the adjacent structure that lay within a quarter of a wavelength.

14.5.2 Vibration Damping (Thermal)

There are several materials, especially high polymers, that generate heat when they are vibrating. The amount of vibratory energy that is transformed into heat by this way, i.e. the structure-borne sound damping can be quite substantial. Materials are available that transform more than fifty percent of the vibratory energy into heat within one cycle. Unfortunately such materials have no structural strength therefore they are combined with other load carrying structural elements. Some constructions obtained this way are shown in Figure

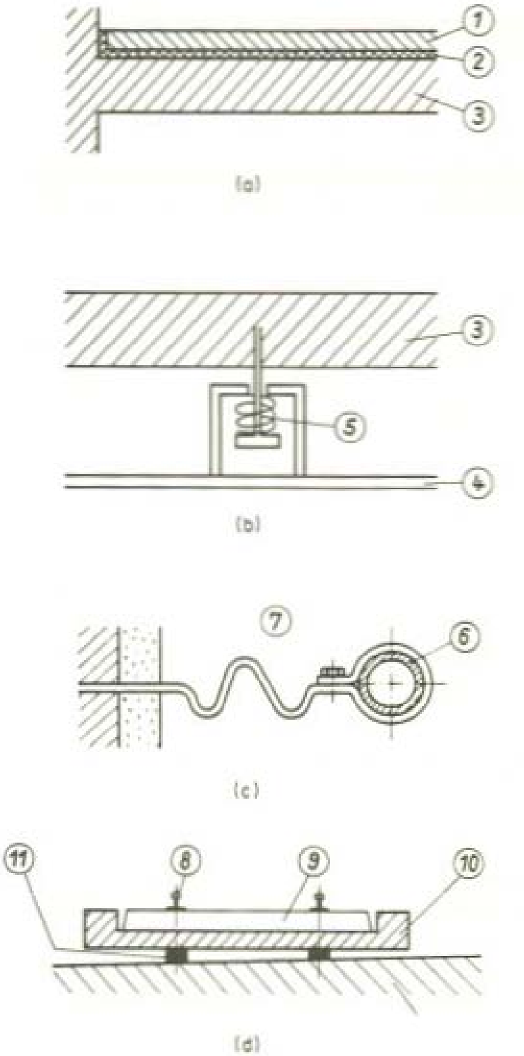

Figure 14.4 Application of resilient layers. (a) Floating floor; (b) Suspended ceiling on springs; (c) Flexible pipe clamp; (d) Resilient track mounting. (1) floating floor, (2) fibrous material appr. 10-mm thick, (3) structural floor, (4) suspended ceiling, (5) spring, (6) pipe, (7) resilient clamp, (8) rail, (9) sleeper, (10) heavy concrete beam, (11) elastomer mounts

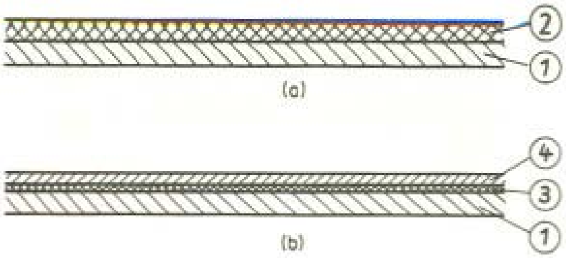

Figure 14.5 Application of vibration damping. (a) Constrained layer; (b) Sandwich plate. (1) base plate, (2) damping layer consisting of a highly damped material with rather high elasticity, (3) thin shear layer, optimum thickness depends on thickness of base plate and cover plate, (4) cover plate

14.5. Other ways of structure-borne sound damping incorporate the friction in materials like sand (especially in architectural acoustics) or the viscosity of thin layers of air or oil between two thin plates (Figure 14.5). Vibration damping devices give a considerable reduction of resonant amplitudes and very effectively attenuate structure-borne sound over longer distances. When applied to constructions that consist of many different parts, they often are of limited use in the vicinity of the sound source.

14.5.3 Added Masses and Other Discontinuities

Structure-borne sound waves are reflected to a smaller or larger degree whenever they come to a discontinuity. Thus any change in cross section or material, any change in the direction of propagation (sound around corners and bends), as well as added masses give a certain reduction of structure-borne sound propagation. Usually the improvements obtained this way are rather small (e.g. the reduction at wall-joints in building is of the order of 3–10 dB). Only heavy added masses are of practical importance as noise-control devices. They give good results when they are applied to thin structures near the sound source and when the frequencies of interest are fairly high. Noticable improvements are achieved if an added mass is heavier than the surrounding structure within a quarter-wavelength.

14.6 FUTURE TRENDS

It is the opinion of this author, that in the near future research in structure-borne sound will concentrate on getting a better understanding of the different sound-excitation mechanisms. Such a better understanding will certainly help to find new ways of noise control at the origin. In many cases such investigations will incorporate the study of nonlinear effects, a subject that hardly has been touched in structure-borne sound. It may also be that such sophisticated methods as the use of antisound sources will be applied more and more.

With regard to structure-borne sound propagation, there are still many open questions with respect to buildings consisting of many prefabricated, large elements. It seems to be possible to design this type of buildings in such a way that the sound isolation is good; but the design rules are not yet quite clear. Another promising aspect is the availability of resilient materials (elastomers) that can withstand very high loads. With such materials it is possible to isolate very heavy machinery, complete buildings, and long stretches of subway or railway tracks.

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CHAPTER 15

Impact Machinery Noise — Prediction and Control

E. J. Richards

15.1 INTRODUCTION

The noise energy emanating from a machine can be as little as 10^{-7} (in the case of a gear-train) or as large as 10^{-3} (in a drop hammer) of the energy used by the machine. In either case, it is small and any improvement we can make is not likely to improve directly the efficiency of production or of operation. It is related more closely to the vibration level of the machine or to that of the air emission associated with the machine, but even so, the relationship is tenuous, and the impression has grown that 'noise' is some sort of mysterious and indeterminate adjunct to vibration and that the best thing to do is 'to box the machine in' if its noise is excessive.

Apart from the noise created by industrial jets and blow-off valves, most excessive noise occurs as a result of sharp impacts or discontinuities in the machine system, and in such cases, surprisingly simple laws can be enunciated (Richards *et al.*, 1979a, 1979b, 1981) which can be very helpful to machinery designers who do not wish to concern themselves with very elaborate computations (which as often as not just stop short of being realistic) but who, nevertheless, need basic diagnostic rules to tell them whether they are moving acoustically in the direction of quietness in their machine design work.

The first rule of machinery noise control is 'vibration seeks its own paths away from the source'. Thus, reduction of machinery noise becomes difficult, the further the treatment is from the source.

The second rule to state is that noise meters are, in most cases, integrators of noise energy over short periods of a second or less and that the noise level measured from repetitive impact machines will be the same as that measured scientifically by an integrating dosemeter for a single impact and corrected for the number of impacts per second. Thus, from an engineering design point of view, it is often more sensible to predict the noise emanating from a

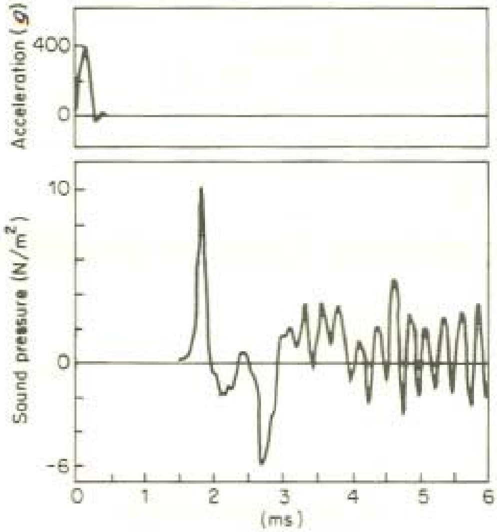

Figure 15.1 Typical acceleration and sound pressure signals from colliding cylinders

single-machine cycle (since this relates directly to the machine process) and to correct for the repetition rate.

The third rule arises from the fact that the radiated noise energy per event consists basically of two components (Figure 15.1), that arising from the transient or forced motion associated with the work process and its time history (acceleration noise), the other (ringing noise) arising from the fact that the vibrational energy left in the machine after it has done its work must be dissipated either as heat (internal damping) or as radiated sound (acoustic damping). The aim must therefore be to maximize the first, and minimize the second.

15.2 ACCELERATION NOISE

Dealing first of all with acceleration noise (which often determines the instantaneous peaks) it has been shown (Richards *et al*, 1979a) that a body coming to rest instantaneously radiates into the far field an amount of energy equal to half that in a bag of air of the same shape travelling at the same initial speed. This is a maximum and it falls off with the time of deceleration. Indeed a master curve (Figure 15.2) can be drawn of the actual acoustic energy radiated as a fraction of this maximum against the distance this transient sound wave travels during the impact time as a fraction of the body size $\delta = ct_0/\mathrm{vol}^{1/3}$*. It is therefore possible to predict limits of acceleration noise from such bodies as

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* (vol) is the body volume which changes its velocity from v to zero in the impact time t_0.

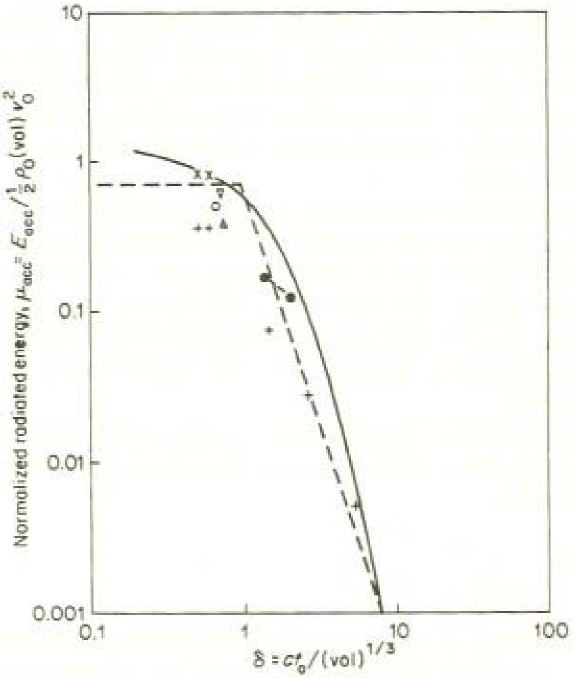

Figure 15.2 Normalized sound energy μ_{acc} vs δ. ○, 75-mm diameter cylinders; + 100-mm diameter cylinders; × 150-mm diameter cylinders; ● 100-mm diameter spheres; △ cones point to point; ▽, cones base to base; — theoretical curve for spheres

drop stamps, impacting bottles, cavitation bubbles, combustion, gears, and so on. Figure 15.2 shows the fall in

$$\mu_{acc}\left(=\frac{E_{acc}}{\frac{1}{2}\rho_0 v^2(\text{vol})^*}\right) \quad \text{with} \quad \delta\left(=\frac{ct_0}{(\text{vol})^{1/3}}\right)$$

for the classical case of two spheres impacting on each other, the theoretical curve agreeing excellently with the actual measured noise for different geometries. The maximized curve provides a satisfactory guide to the amplitude of the acceleration noise, once the impact time and velocity are known.

15.3 RINGING NOISE

It has also been shown (Richards *et al*, 1979b) that on bodies of less solidity which have one or two dimensions much greater than the third, *slow bending* waves can take the work energy away from the work area, leaving the machine after impact in a state of considerable vibration. Under these circumstances, acceleration noise is less important than the noise radiated during this ringing phase, and the problem of noise prediction ceases to be related directly to the initial impact, but to the amount of energy stored as vibration and the fraction of this radiated as sound.

For a very poorly damped structure, all this energy E is radiated acoustically (i.e., $E_{\mathrm{rad}} = E_{\mathrm{escape}}$), but on most fabricated machinery the majority of the vibrational energy is absorbed as heat, leaving only a small remainder E_{rad} to be radiated acoustically. This must obviously depend upon the efficiency of acoustic radiation σ_{rad}, the structural damping factor η_s, and the bulkiness, d, of the machine (obviously damping depends upon volume, radiation upon surface movements).

The ratio of that energy radiated as sound to the energy entering the machine as vibration at frequency f can be written simply for steel structures (Richards *et al.*, 1981) in the form

$$\frac{E_{\mathrm{rad}}(f)}{E_{\mathrm{escape}}(f)} = \frac{\sigma_{\mathrm{rad}}(f)}{\sigma_{\mathrm{rad}}(f) + 1.17\eta_s d \cdot f}$$

where d is an average thickness in centimetres. For undamped structures, $E_{\mathrm{rad}}(\mathrm{f}) = E_{\mathrm{escape}}(f)$ and we need only evaluate $E_{\mathrm{escape}}(f)$ in any frequency band to establish $E_{\mathrm{rad}}(f)$ in the same bandwidth. In most fabricated machines, σ_{rad} is small at low frequencies, and there is no great loss of generality in writing

$$E_{\mathrm{rad}}(f) = E_{\mathrm{escape}}(f) \times \frac{\sigma_{\mathrm{rad}}(f)}{1.17\eta_s d \cdot f}$$

or in logarithmic form and correcting for the A weighting with frequency,

$$\underset{\substack{\uparrow \\ \text{Deafness} \\ \text{contribution} \\ \text{per event}}}{L_{\mathrm{eq}}(A)\,(f)\,(\Delta f)} = \underset{\substack{\uparrow \\ \text{Total escape} \\ \text{energy into} \\ \text{structure}}}{10 \log E_{\mathrm{escape}}(\mathrm{total})} + \underset{\substack{\uparrow \\ \text{Fraction of} \\ \text{total in} \\ \text{frequency} \\ \text{band being} \\ \text{considered}}}{10 \log (\mathrm{s} \cdot \mathrm{c})} +$$

$$+ \underset{\substack{\uparrow \\ A\text{ weighted} \\ \text{and freq.} \\ \text{sensitive joint} \\ \text{radiation/} \\ \text{damping} \\ \text{efficiency}}}{10 \log \left(\frac{A\sigma_{\mathrm{rad}}}{f}\right)} - \underset{\substack{\uparrow \\ \text{Damping} \\ \text{level}}}{10 \log \eta_s} - \underset{\substack{\uparrow \\ \text{Machine} \\ \text{bulkiness} \\ \text{or solidity}}}{10 \log d} + \text{Constant}$$

15.4 NOISE REDUCTION : DESIGN CHANGES

If the structure is very lightly damped the noise energy and the vibrational energy are the same (i.e., we can ignore all but the first two terms, and the problem of noise reduction equates to that of reducing the vibrational energy left in the machine after impact or fracture). Most machinery structures are fabricated and contain a significant degree of structural damping; under such circumstances, noise reduction in any frequency band requires the modification of one or several of the terms in the above equation. Thus, noise reduction can result from a reduction in the quantity E_{escape}, in reducing the modified radiation efficiency term $A\sigma_{\mathrm{rad}}/f$, allowance being made for both the effects of A-weighting and length of ringing, in increasing the damping factor η_s or in increasing the thickness 'd' (i.e., in making the structure more 'solid').

Figure 15.3 shows the values of $10 \log A\sigma_{\mathrm{rad}}/f$ for plates, solids and rods or beams of various typical sizes. It is a recognised characteristic in all these curves that they peak at frequencies which depend upon size, or cross-sectional dimensions, and that it is obviously wise to keep the vibrational energy in the system to frequencies well below or well above these values. Indeed, the process of optimization of noise control can be illustrated in the diagram shown as Figure 15.4. As at any frequency, logarithmic additions are equivalent to multiplication, whereas the energy in each frequency band is summed linearly to obtain the total $L_{\mathrm{eq}}(A)$, the process of noise reduction must reduce to that of mis-matching of frequencies as much as that of reducing E_{escape} and increasing the damping coefficient η_s.

Figure 15.5 shows a form of heavy-duty container or bin in which all these terms have been reduced compared with those occurring in a heavy standard steel container. The reduction in $L_{\mathrm{eq}}(A)$ so obtained is 29 dB(A) equivalent roughly to a reduction in radiated noise energy to a one-thousandth of the original figure for the same velocity of drop.

This formation of the relationship between noise and vibration helps considerably in the process of understanding exactly how the noise energy is created by a machine, and permits us to indicate the limits of noise reduction achievable by practical design changes.

For example, in the case referred to at the beginning of this chapter of the noise from a good gear-train producing as little as 10^{-6} to 10^{-7} of its throughput energy as noise, we can now break this down to a progressive study of the fraction of the throughput energy going into vibration and of that, the fraction going into noise. Depending upon the quality of manufacture, loading, wear of a gear, for example, some 10^{-2} to 10^{-3} of the energy passing through the gear is dissipated as vibrational energy of which only about 10^{-1} to 10^{-2} is in the frequency range which radiates sound efficiently. Of this 10^{-4} to 10^{-5} vibrational energy, most of it goes into heat, only a small fraction going into sound. For hard impacts this fraction

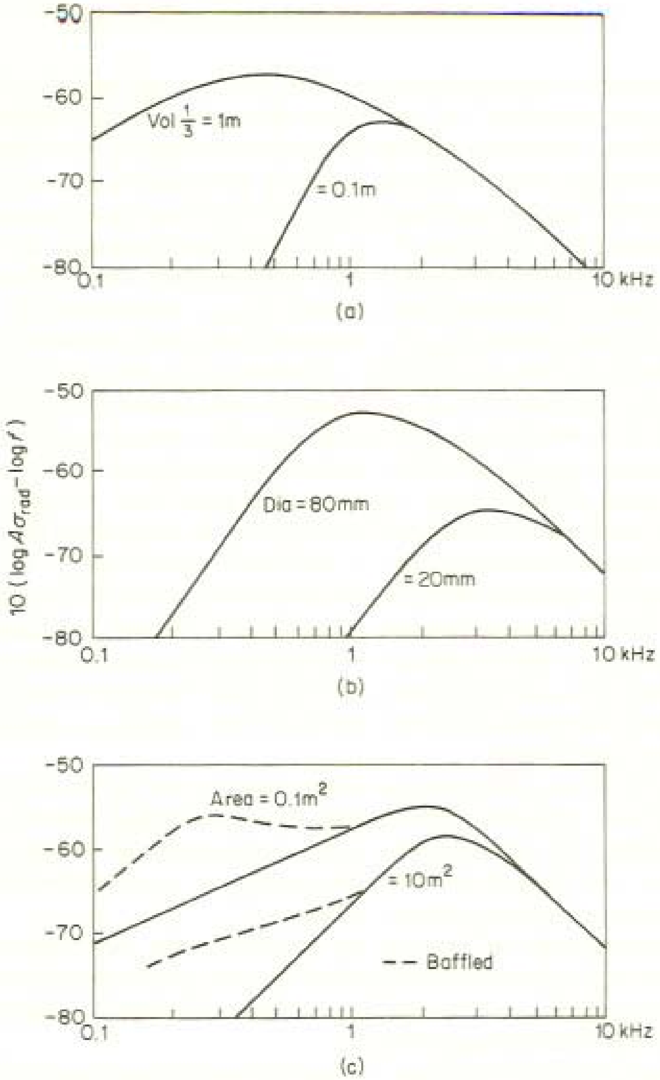

Figure 15.3 The variation of 'modified' radiation efficiency of various bodies plates and beams with frequency. (a) Oscillating bodies; (b) Circular cylinders in flexural vibration; (c) 12.7 mm thick square plate simply supported

of the vibrational energy converted into acoustical energy in the frequency range in which radiation is efficient is 1/1.7 $d\eta f$, i.e., about 10^{-2} at 1 kHz and if $\eta_s = 0.1$. Thus, 10^{-6} to 10^{-7} of the transmitted energy is turned into sound.

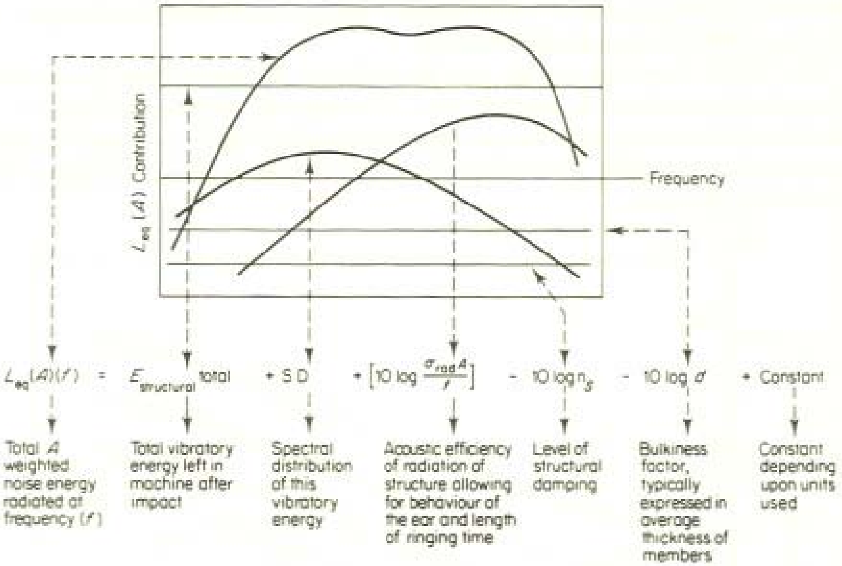

Figure 15.4 The make-up of machinery noise at any particular frequency (f)

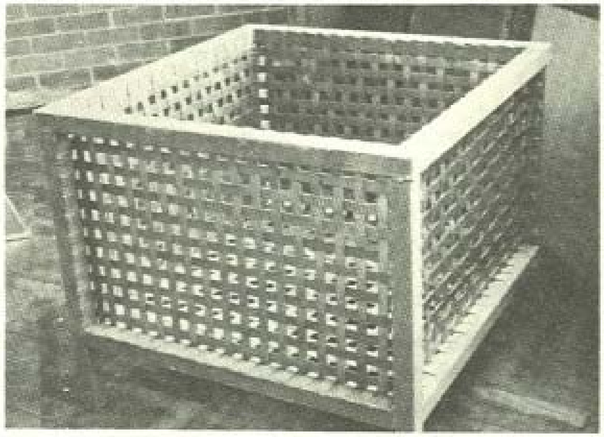

Figure 15.5 Woven stillage

To reduce this, we need to reduce the vibration excitation level and the fraction of this contained in the frequency range in which high radiation efficiency occurs; we need to increase the structural damping, i.e., the fraction which goes into heat as opposed to sound and we need to provide as much bulk as possible, i.e., as low a surface vibration level as possible. Thus gear noise can be reduced by providing good meshing under load and very little wear: the fraction of vibration in the high frequency range is decreased by reducing the sharpness of impact, either by using spiral gears, a wide lowly loaded gear, or by using a softer non-metallic material.

The noise from the casing can be reduced by preventing the sharply fluctuating loads from reaching it, i.e., by using soft and damped bushes, by thickening the casing cross section near the bearings, and by adding structural damping to the casing. An indication of this change is shown in Figure 15.6 from work by Opitz.

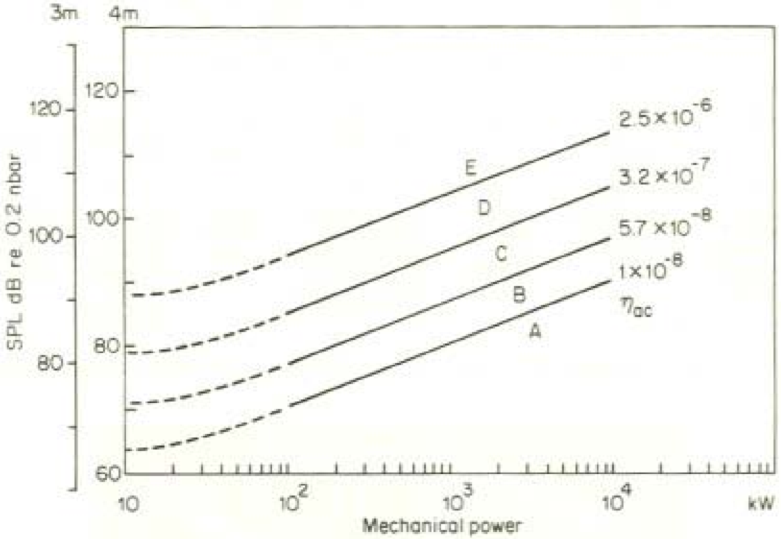

Figure 15.6 Noise levels to be expected from various classes of gears at 3 and 4 metres. Classification of gears: Class A—Very fine finish: impossible to maintain; B—Extremely high accuracy; C—High manufacturing tolerance; D—Normal tolerance; E—Poor quality η_{ac} = acoustical efficiency = acoustical power/mechanical power

15.5 NOISE AND ITS RELATION TO FORCE DERIVATIVES

The second useful form for the above relationship between noise and vibration when no metal deformation occurs is obtained by replacing the first two terms (i.e., the expression for 10 log E_{escape}), by an expression for the work done by the applied external force during the impact. This can be put into the form of a (force)^2 times a structural mobility or more usefully from a *diagnostic* point of view in the form of the square of the rate of change of force multiplied by a relevant point receptance term. In this form, the equation for the A-weighted noise radiated per second takes the form

$$L_{\text{eq}}(A, f, \Delta f) = 10 \log N + 10 \log \left[|F'(f)|^2 \right] + 10 \log \text{Re}\left[\frac{H(f)}{j} \right]$$

$$+ 10 \log \frac{A\sigma_{\text{rad}}}{f} - 10 \log \eta_s - 10 \log d + 10 \log \frac{\Delta f}{f} + \text{Constant}$$

N is the number of impacts per second, $[F'(f)]^2$ is an impulse shaping term which will depend in magnitude of the square of the sum of the rates of change of force, and $\mathrm{Re}[H(f)/j]$ is the imaginary part of the structure response term at a point and is defined in the frequency plane by $V(f) = H(f) \cdot F'(f)$. Thus a typical noise spectrum will be made up of the various terms typically as shown in Figure 15.7.

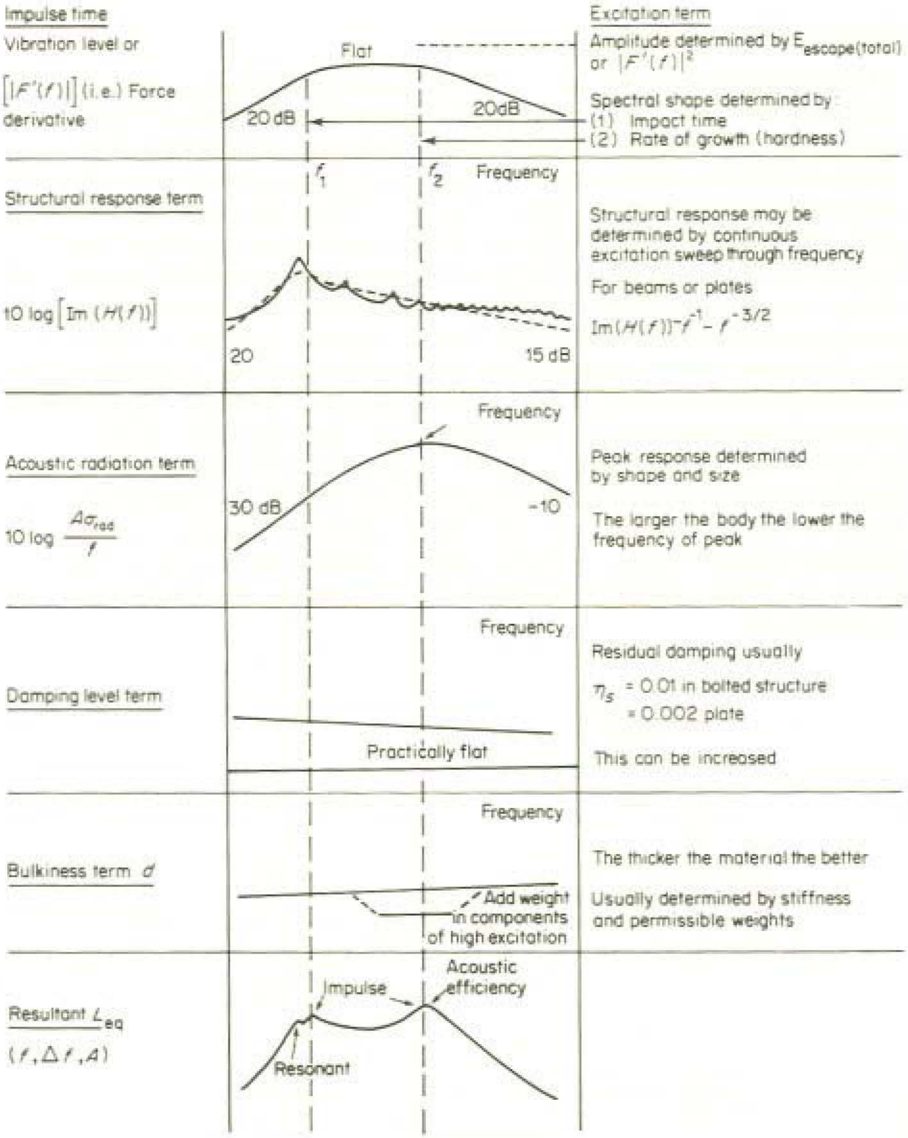

Figure 15.7 Summation of contributions to L_{eq}

15.5.1 Application Examples

Three examples of the value of this formulation can be given, the first, concerning the noise from a damped plate-like structure representative of a gear casing, flywheel or machine cover subject to impact loads, the second, concerning itself with the effects of changes in tool design on noise from a punch press, the third, with diesel engine noise.

Damped Plate-like Structures

As part of the general validation process associated with using such diagnostic formulae, we have examined the noise radiated from a damped plate-like structure which is subject to a series of impulsive loads. The damping factors η_s associated with any frequency of vibration has been measured Figure 15.8, the modified radiation efficiency term 10 log $A\sigma_{\mathrm{rad}}/f$ has been calculated (Richards *et al.*, 1979b), the structural response term has been measured using sinusoidal loading and has been shown to agree with that predicted from power flow theory; the value of 10 log $F'(f)^2$ has been both measured and calculated for metal to metal and soft impact pulse shapes respectively (Figure 15.9(a), (b), (c). The noise energy radiated from the plate has been calculated from the above equation for a series of third-octave bands, and has been compared with that measured from a series of microphones surrounding the finite plate. It may be seen from Figure 15.10(a) that the agreement between estimation and measurement is very gratifying and that the noise reduction obtained both from changing impact shape (Figure 15.10 (b)) and from changing the level of damping (Figure 15.10 (c)), is close to that expected from the theory. The use of the above noise radiation equations are therefore of considerable practical diagnostic use.

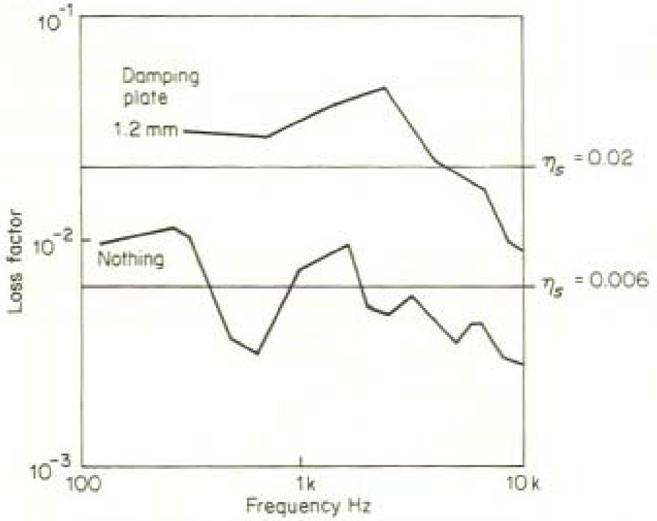

Figure 15.8 Damping factor for test plate

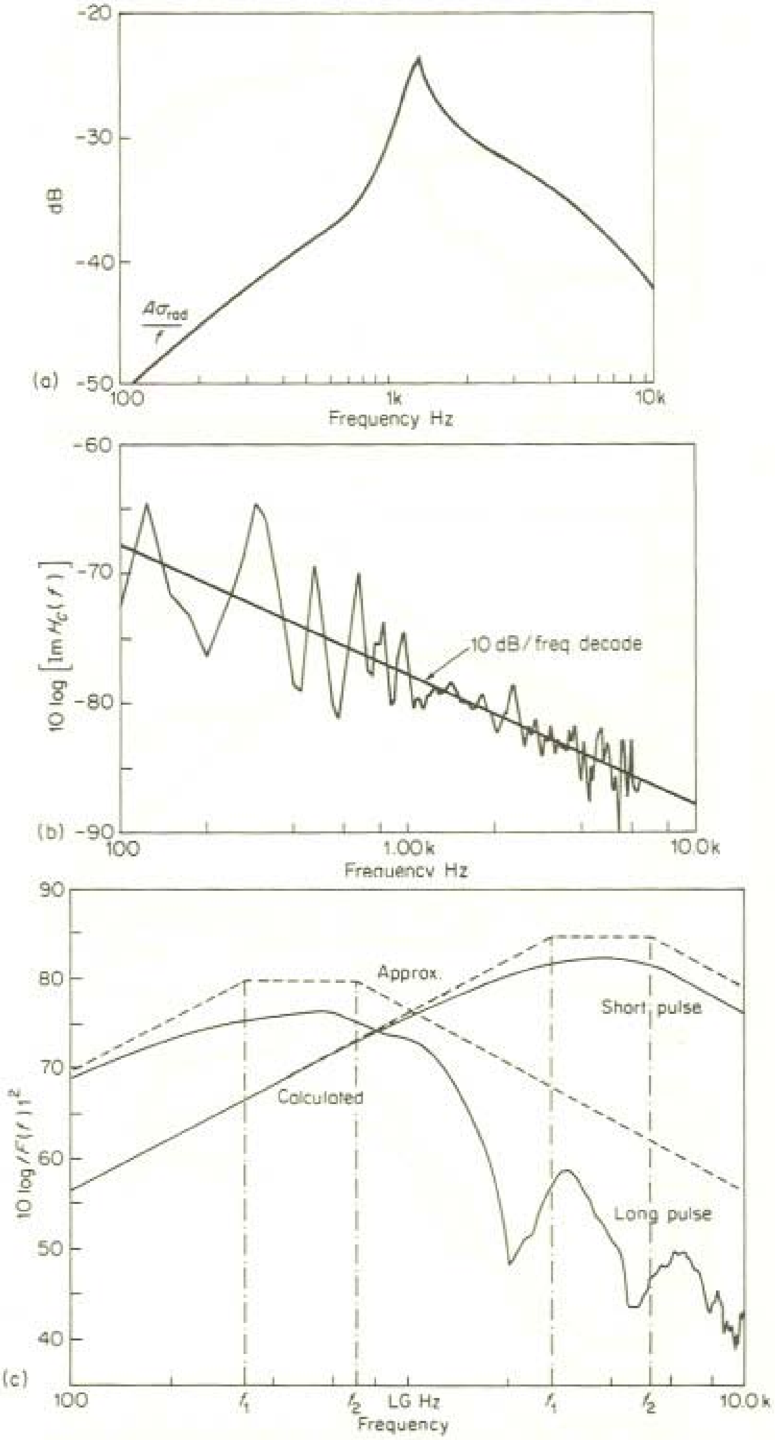

Figure 15.9 Radiation efficiency curves for test plate

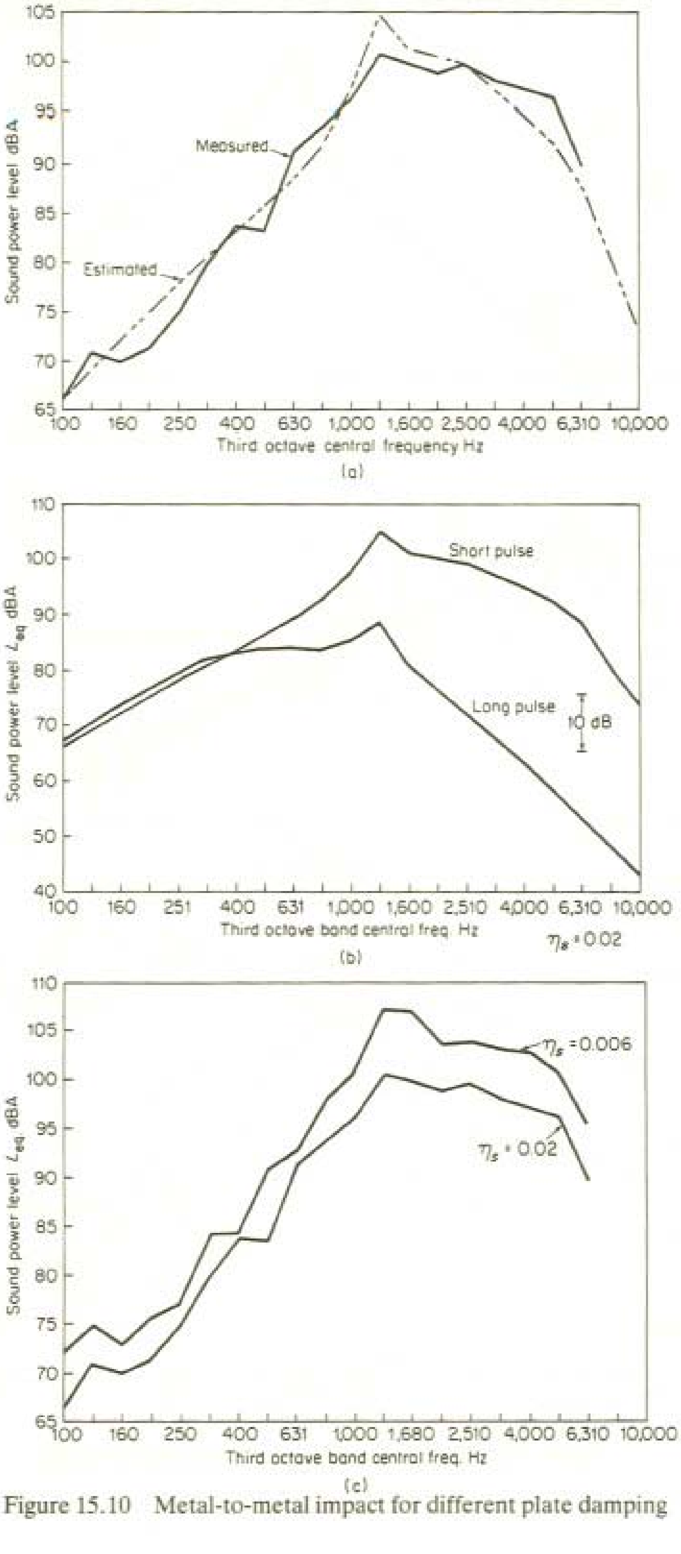

Figure 15.10 Metal-to-metal impact for different plate damping

Punch Press

It can be shown that the rate of change of force occurring during the fracture process on a punch press is not sufficiently impulsive to allow us to assume that the term $F' (f)^2$ is constant with frequency at the frequency at which the 'modified' radiation efficiency is at a maximum, but that $[F' (f)]^2$ can be so considered. Evensen (Evensen, 1980) shows that the magnitude of this term can be equated to $\Sigma f'^{2}_{\max} (t)$ where $f(t)$ is the force being exerted by the punch at any time t, and that this consists of a series of impulses associated with the various impacts occurring during the operation. For any machine in which there is no modification of geometry or damping but a change only of tooling or workpiece thickness (and hence of the rates of change of force in the punch), the L_{eq} per event (or the sound-pressure level for a fixed punch rate) is given by

$$\mathrm{SPL} = E + 10 \log \Sigma[f'_{\max}(t)]^2 = E + L_{\dot{F}}$$

The methods available to us to reduce the rate of change of force are many, including reducing the punch penetration to minimize the strain energy left in the punch area as fracture occurs, using a sheared punch to increase the gradualness of the fracture, using a lower percentage clearance to increase the amount of cutting and reducing the thickness of fracture, using an eccentric die to vary the percentage clearance around the punch, coupling punching with coining, or providing hydraulically an equal and opposite force derivative to the machine at points as near to the punch as possible.

That all these techniques can be used to provide noise reductions is shown in Figure 15.11 which contains points associated with different material hardness, different thicknesses, different percentage clearances, different eccentricities and different tool penetration. It may be seen that the measured overall noise levels (aggregated into a dB(A) level) is a function only of the measured $\Sigma f'_{\max}(t)$ and that the standard deviation from a curve with slope of 1.02 (compared with a predictable unity) is only ±1.2 dB(A). This fact gives us confidence in assuming that any machine-tool modification which lowers the sharp rates of change of force will reduce noise predictably, and that this will be true, not only of impact force derivatives associated with punch mechanisms, but also those associated with internal backlash or other mechanisms which provide sharp metal-to-metal impacts in handling or manipulation of materials. This general conclusion is clearly applicable to swaging machines, crushing machines, shuttle mechanisms, conveyor systems and a host of machines involving clatter of cans, stamping and cutting.

Diesel Engine

The third example consists of noise radiated from a diesel engine with its complicated structure, and one which is difficult to discuss in simple terms.

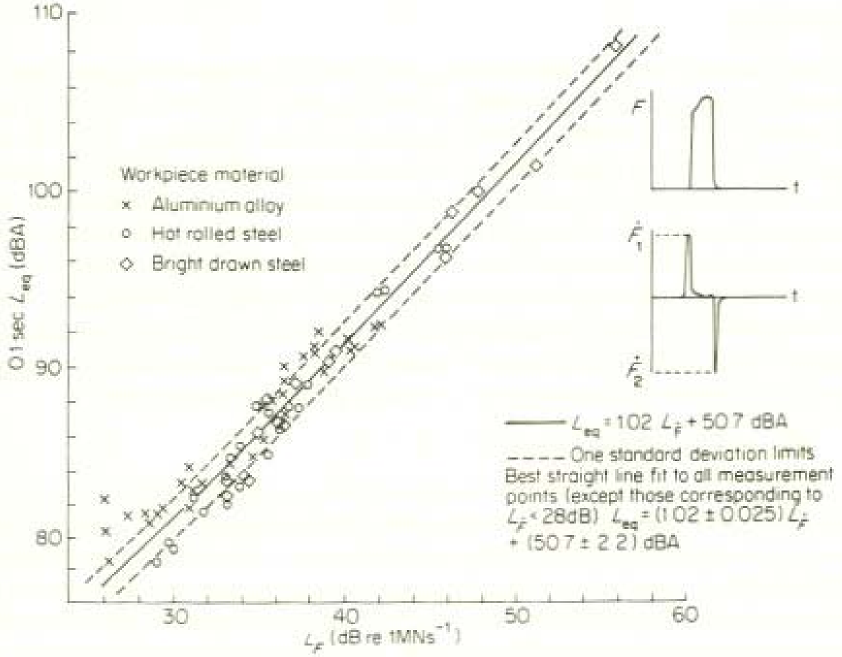

Figure 15.11

Apart from the noise emanating from the exhaust and from the fan or fuel pump, the predominating noise arises from two basic mechanisms, the vibration caused by the sharp increase in cylinder pressure when the fuel already in the cylinder ignites, and that which follows the sharp piston slap occurring when the side-load on the piston causes it to impact on the cylinder wall liners.

Looking at the various terms in the above equation, the pressure in the cylinder can be measured and the value of $F'\ (f)^2$ can be compiled both in magnitude and its spectral shape. In fact, it falls approximately at a rate of 10 dB per decade of increase in frequency and the response of the structure to the cylinder pressure will also be expected to fall at between 10 and 15 dB per decade.

Thus we can expect an $L_{eq}\ (f)$ spectrum which will reflect the shape of 10 log $A\sigma_{rad}/f$ but with a downward tilt of between 20 and 25 dB per decade.

Modelling the cylinder block respectively as a vibrating solid body, as a plate in a small baffle, and as a long cylinder gives vibrations of 10 log $A\sigma_{rad}/f$ which all have one thing in common, a gradual growth to a frequency dependent upon the size, and a subsequent fall-off of 10 dB per decade; Figure 15.12 shows these spectral curves skewed by 22 dB per frequency decade, together with an experimental measurement of the noise from an engine of the size under consideration. It may be seen that the

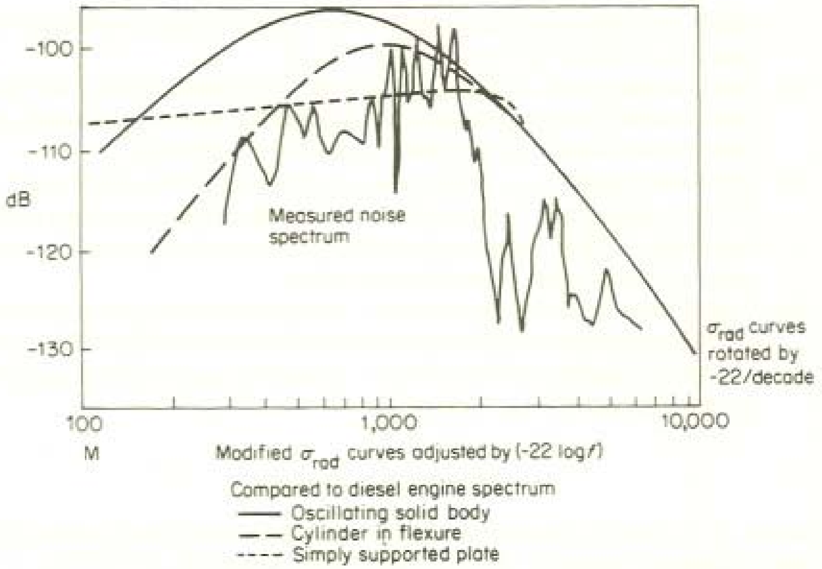

Figure 15.12

estimated shape and that measured is qualitatively the same and that some simple lessons can be learnt.

First, it is clear that the basic approach to noise reduction must consist (a) of smoothing out the sharpness of the pressure jump with time, (b) that the longstroke engine will have the lowest internal cylinder area and consequently the lowest force to excite the upper engine, (c) that metal should be used optimally to prevent any surface area from carrying excessive surface vibration, and (d) the addition of internal damping is advantageous. All these techniques are used in modern design, together with the use of complete isolated covers over highly vibrating surfaces, and the use of light limp isolated lower frame covers even though they can accept low frequency vibration.

15.6 CONCLUSION

The lessons to be learnt from this formulation are many, but can be listed for convenience as follows:

(a) The vibration level left in the structure will vary as some function of the rate of change of force, so that the strongest noise reduction technique available to us is to reduce $f_{max}(t)$ to a minimum.

(b) If the machine process requires a large rate of change of force, this should be arranged, by the use of resilient inserts, to reach as little of the highly radiative surfaces as possible so as to decouple in frequency the peaks in 10 log $F'(f)^2$ and 10 log $A\sigma_{rad}/f$.

(c) The damping term 10 log η_s should be maximized, but in view of the considerable damping already occurring in fabricated structures, large increases are necessary to achieve significant reductions.

(d) Depending upon size, 10 log $A\sigma_{rad}/f$ will peak between 800 and 2,000 Hz. It is important to prevent high-level vibrations occurring at these frequencies. Thus softening the impact to excite frequencies out of the range of such maxima should be aimed at.

(e) Wall thickness is often determined by requirements of stress levels and stiffness requirements. It can be shown that some configurations, while providing adequate stiffness for work accuracy, are nevertheless too thin and frail for good noise control.

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Noise Pollution
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CHAPTER 16

Building Noise Control: The Main Problems, Available Technology and Future Trends

THEODORE J. SCHULTZ

16.1 INTRODUCTION

When the subject of noise pollution is discussed, people generally think of the noises of transportation, building construction and industry. Such noises obviously strongly impact those people who are outdoors with these sources; but such noise also penetrates into dwellings and office buildings to disturb their occupants. In addition, there are indoor sources of noise that have little effect on people outdoors but that constitute a source of serious disturbance and annoyance to people within the dwelling or office.

Thus, building noise control is clearly a fitting matter for discussion in the context of *noise pollution*. Indeed, we are quite accustomed to solving technical building acoustics problems and reporting the results at symposia and congresses concerned with noise pollution.

But it is important to realize that there are major acoustical problems that do not necessarily need *technological* solutions, and, in my view, the main problems in building acoustics today fall into that category. The necessary technology already exists to cope with most building acoustics problems, at least in the industrialized countries. (Newman *et al.*, U.S. Dept. of Health, 1975; Beranek, 1971; Doelle, 1972). The real problem is how to apply that technology effectively.

We should, therefore, perhaps, be speaking not of technical acoustics, but of *political acoustics* and *social acoustics*, because the route to successful achievement of an improved acoustical environment in buildings passes through the realms of politics and social concern.

16.2 THE MAIN PROBLEM: FIRST-ORDER SOLUTIONS TO FIRST-ORDER PROBLEMS

Like air and water pollution, *noise pollution* comes mostly from having made particular technological choices without fully considering their impact on people who have to live with them. Technology, to date, has typically advanced by satisfying 'first-order' needs with 'first-order' solutions—for example, creating transportation facilities (the automobile and the highway system) to increase our mobility. Such conventional 'first-order' solutions have gradually come to defeat the purposes for which they were made: we now have traffic congestion instead of mobility, and we also have air and noise pollution as well. Specific problems have been considered in isolation, rather than anticipating the sociological effects of the solution; it has simply built systems, rather than designing them with an awareness of their potential impact on society.

So long as we attend only to first-order solutions, our technology is clearly not so advanced as we have sometimes boasted.

Now, with respect to noise, we have all read of the detrimental effects of intrusive noise on our health and welfare and there is no doubt that, in the long run, these repeated intrusions generate in the community the helpless feeling that something of great value—the quality of the environment, the right to quiet enjoyment of our homes, and the value of our residential property—has been taken away from us by 'somebody else', who cannot even be identified and blamed or enjoined to stop the disturbances: we find ourselves victimized by 'the system'.

These comments are relevant to the noise problems of the industrialized countries of the world, where the facts are already a matter of history. After years of heedless pollution, several countries are just beginning to achieve effective control of environmental noise.

To those of us who have lived through some of these problems, and who hope to have learned that prudence and restraint are necessary with respect to insults to the environment, it is distressing to see the same mistakes repeated in the developing industrial countries ... and mostly for the same reasons.

In the developing *pre*-industrial countries, matters are worse still. Building isolation is technically almost impossible in tropical countries where natural ventilation is the rule. Moreover, motivation for noise abatement is non-existent in the face of poverty and overpopulation.

Acoustical scientists from some of the developing countries have just begun speak of these matters (for example, in the recent Tenth ICA* in Sydney (1980), and it is clear that their problems are very great, indeed.

The question, as usual, is one of motivation *vs* economy. The contrast is between societies that are comfortably housed and overfed and those that are ill-housed and living in poverty and hunger. Inadequate privacy between dwellings is not important when three or four families are living in a single room.

Only a politician or a sociologist, can solve that kind of problem. Instead, we will deal with some acoustical problems for which we can begin to glimpse the

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* International Compression Acoustics.

solutions, hoping that the day will come when we will learn more from history than that history teaches us nothing. I am concerned primarily with the impact of noise in our dwellings.

16.3 PRIVACY AS AN AMENITY

'Of all the complaints owners throughout the country hear about postwar apartments, lack of soundproofing heads the list most frequently. There isn't even a close second' (*Symposium on Noise In Multifamily Dwellings*, New York, May 1963) (Rose, 1964).

'Major property management firms report that noise transmission is one of the most serious problems facing managers of apartment buildings throughout the country. Managers and owners of apartments readily admit that market resistance is not only increasing as a result of excessive noise transmission but also that lack of acoustical privacy and noise control are the greatest drawbacks to apartment living.' (Harold B. Finger, Assistant Secretary for Research and Technology, HUD*, in a *Symposium on the Performance Concept in Buildings*, Philadelphia, May 1972) (U.S. Dept. of Commerce, 1972).

'No longer can noise problems only be associated with low-income apartment units. According to the Federal Housing Administration, both low and high income apartment building residents register the same number of complaints about bother-some noise.' (Cosimo Caccavari, U.S. Environmental Protection Agency, in NOISEXPO, Chicago, 1980) (Caccavari *et al.*, 1980).

This seriousness of noise intrusion and lack of privacy in dwellings has thus been evident for more than a decade and in the U.S.A. there has been a movement to do something about the noise. This has involved the United Nations, the Federal, State and local governments, as well as science, industry, the legal profession and citizens. However, the same issue remains important in the 1980's.

It is not a new movement; the issues were known and widely discussed in the 1960's and early 1970's. In the absence of substantial progress, the same issues remain important in the 1980's.

16.4 HOW TO ACHIEVE PRIVACY FROM NOISE

The first difficulty lies in the dual nature of urban noise.

1. It acts as a pollutant, an undesired product of somebody else's activity that imposes a cost upon third parties who are not partners to the action and may receive no direct benefit from it.

   Market forces alone, at present, are not strong enough to restrain the producers of unwanted noise; therefore, the control of these noisy activities is usually assumed to lie in the public domain. Unfortunately, regulatory action against noise pollution is slow in finding its way into law.

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* Housing and Urban Development.

2. On the other hand, urban noise has a desirable effect: namely, the continuous low hum of traffic and ventilation noise provides a neutral acoustic background that helps mask out undesired *intermittent* intrusions, such as auto horns, neighbours' speech, TV, radio, etc. Without this continuous background of 'acoustic perfume', it would be quite beyond our technical capability to provide privacy in multifamily dwellings at a cost we can afford.

   We immediately see that the task of noise abatement is delicate: we do not dare simply to eradicate the noise (even if we could). Instead, we must control it, bring it into balance, and manipulate it to serve our purposes.

The technical reader will observe that this is a statement of a technical acoustics problem. As such, he is likely prepared to understand the balance between noise control and background noise that is required.

But try putting this into the framework of political and social acoustics. The image is not nearly vivid enough! *If* a goal can be simply-stated, it is easy to persuade people (or their representatives or the press) to support the project: 'Cut down that tree'; 'Build a bridge across a river'. It is impossible to win support to cut a tree down, but not all the way; to build a bridge *almost* to the other side of the river! It is equally difficult to get agreement on the question of *how much* noise, and *which* noise, must go.

We are presented with a double problem. The increase in population in urban centres means more and more noisy activity. For this reason alone, we need to improve the sound attenuation of *existing* construction, in order to preserve the present standards of comfort, such as they are. But, at the same time we must provide growing numbers of people with *new* housing, designed for better sound isolation and hopefully costing and weighing less. These are traditionally incompatible objectives; it is very hard to circumvent the acoustical mass law which says, 'Increased sound isolation requires greater mass.'

However, our most pressing need is not for novel technical production methods nor for magic new materials, but rather for the *proper application* of existing, traditional methods of building. The reasons are these:

(i) Considerations other than acoustics are given priority in determining the basic type of building structure, the method of assembly, and even the surface finishing materials.

(ii) Even if the acoustical requirements *have* been considered early in the building design and suitable noise control structures have been selected, a structure that is acoustically good in itself can be spoiled by failure to work out the architectural details carefully so that 'leaks' and 'flanking transmission' do not by-pass the intrinsic isolation that the structure can potentially achieve.

(iii) Even though the architect has chosen acoustically good building constructions and has developed details that avoid flanking transmission, the ultimate success of the building depends on the work of men with no knowledge of, and no interest in, acoustical problems: the contractor and individual trades people.

Carpenters and plumbers do not 'think acoustically'. They may be counted upon to introduce on-site changes from the specified construction for any number of reasons: habit, personal convenience, cost-savings, unavailability of specified materials, simple ignorance or flagrant indifference. Though these changes may appear harmless to the workmen, they frequently undermine the acoustical design of the building.

16.5 BUILDING CODES AS A MEANS OF DEALING WITH THE MAIN PROBLEM

No amount of ingenuity in the development of novel building techniques and new acoustical materials will transcend this problem of unthinking construction workers. No break through in acoustical isolation methods will be of any use whatever, unless a corresponding break through is made in assuring constant attention to construction details and continuous, effective on-site supervision. No matter what construction techniques and materials are used, an essential step toward improving noise isolation on dwellings will be to persuade contractors, builders, and trades people of the extreme importance of the details of proper construction, and also to motivate them to accept the responsibility for better supervision during construction.

Under the present set-up of the building construction industry (at least in the United States) this latter break through seems unlikely to occur in response to market demands alone. Ten years ago, it was a seller's market in the building construction industry; housing was needed too badly for the consumer to be very critical of details such as noise isolation.

Nowadays, *anything* that adds to the cost of the building will be scrutinized very critically before being approved. Clearly, it will not be easy, in this atmosphere, to attract the attention of the housing construction industry to acoustical matters.

The questions raised here are not technical but social; and, since the problems are far-reaching, their solutions (when they come) will have profound social consequences. They will require one or the other of two drastic changes in the building industry:

1. A thorough-going re-education and motivation of the contractors and trades involved in on-site construction, to require them to take as much care in achieving adequate noise isolation as they do now in providing suitably

strong structures and adequate heating and plumbing. Such an approach implies a major change in our handling of noise control in building codes.

2. The design, from the beginning, of complete and most prefabricated housing systems with final assembly procedures so simple and foolproof as to be practical for unskilled labour in the field; the noise isolation must be 'built in'.

The second choice seems feasible to organize on a large scale under purely commercial motivation. The scheme is by no means unheard of; in fact, the foundations already exist in the 'mobile home' industry. These are experimental 'apartment houses' built in the southern United States by stacking house trailers into a suitable structural framework that includes provision for electrical and plumbing facilities as well as access stairways.

This approach would entail, however, a very significant social change, namely, the ultimate transition in the building construction trade from a local 'craft industry' to more-or-less centralized machine production.

For the time being, a more practical approach is the first choice: the adoption and the effective enforcement of noise control requirements in our building codes.

Such requirements are included in the building codes of a number of countries, particularly in Europe, but unfortunately these requirements do not prevent complaints of inadequate privacy from the tenants of the buildings to which the codes apply. Figure 16.1 shows the means of building code enforcement in Europe; routine tests in the finished buildings (see line 6) are uncommon, except in West Germany when Government loans are involved.

For a number of European countries, there is a discouraging record of failure which can be expected when no special incentives are offered to encourage the effective enforcement of building noise control. Line 3 shows the typical failure rates.

The main trouble comes during construction, where poorly executed details of assembly allow serious flanking transmission and sound leaks.

The outlook is brightened somewhat by recent data from the Netherlands (van Os, 1981). Both in 1973/74 and in 1979/80 large-scale field-test programmes were carried out measuring the sound insulation in dwellings; the percentages of tests that met the Dutch minimum requirement for airborne sound insulation were as follows:

	1973/74	*1979/80*
Between living rooms:	29%	90%
Between sleeping rooms:	21%	80%

Evidently, a vigorous enforcement programme *can* have beneficial effects!

In USA and many other countries, the owners and tenants have no part in the selection of the building materials. When they suffer from inadequate privacy, they cannot therefore apply market pressure to the manufacturers for

Procedure \ Country	Belgium	Denmark	France	W. Germany	Netherlands	Sweden	Switzerland	U.K.[¶]	U.S.A.	Spain	E. Germany
1. Inspection of drawings	?	×●	×●[*]	×●	×●	×●	?	×●	×●	×	×●
2. Suggestion (or requirement) to use approved constructions		×		×	×	×	×	×	×		×
3. Exploiting market advantage			×[†]								
4. Giving financial bonus for higher quality			×[†]		△[‡]						
5. Imposing market penalty (lowered rent)		○		○							
6. Test in finished building to demonstrate compliance	?	△	[†] ○ ○	△ [‡] ●	○ (<1%)	△	?	○ √			△
7. Corrective measures if building fails test		△ √		△ √	○	●					○
8. Pilot test of novel constructions				●	△	●		△			△

Key: ×—Officially required, permitted, or provided.
●—Always or usually done.
△—Sometimes done.
√—Done only when complaints arise.
○—Seldom done.

[*] Applies only to Government Subsidized Homes (HLM); no requirements in other buildings, and sound insulation is usually poor.

[†] In cases where the Acoustic Comfort Label is required.

[‡] If built with Government loan.

[¶] Except inner London.

Figure 16.1 Means of Enforcing Code Requirements more realistic involvement throughout the construction process. The builders and architects who select the products almost never suffer from the acoustical consequences of faulty construction and hence, the design–construction–completion loop is never closed, as it should be.

The only way to break out of this situation is to focus on the quality of the finished product. The industry needs a complete package, comprising adequate incentive for seeking improved acoustical quality, reliable tools to achieve it (for example, simple and reliable test procedures and a code that works), and initial assistance (money and instruction) to help get started on a fresh approach to noise control in buildings.

Incentive can be provided by the local adoption of a building code that requires acoustical tests of a certain percent of the completed dwelling units, in order to demonstrate compliance with code requirements for noise isolation between dwellings, and that requires remedial action on the part of the builder in case of failure.

The necessary tools include a recently-developed simple test procedure (ASTM E597–77T) for measuring sound isolation between dwellings in terms of A-weighted sound levels; it is both reliable enough to demonstrate compliance credibly and simple enough to be performed by relatively untrained staff. This procedure requires a standard sound source and a simple sound level meter.

The final tool is a set of new noise control provisions for a model building code, which EPA* has recently completed. These include a performance specification for adequate sound isolation, to be demonstrated by acoustical tests in the finished building.

The practical advantage of training and education for the building trades is well illustrated in the following case history.

16.6 PERSUASION OF PEOPLE TO ACCEPT TESTS FOR COMPLIANCE WITH A SPECIFICATION

It is possible that there may be general opposition to the introduction of mandatory tests of acoustical performance in finished buildings; not simply because this approach introduces changes in an already established procedure, but because the architect, the owner and builder have no guarantee at the time the permit to build is granted, that the finished building will be approved for occupancy. Understandably, they may regard it as a considerable risk to go ahead with the project. On the other hand, when they *do* go ahead, they will undoubtedly be strongly motivated to provide good supervision all along the line, in order to prevent acoustical accidents during the construction.

As an illustration, we cite a case history from the San Francisco Bay area that arose from a particular historical incident. In the early 1960's, a great deal of

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* Environmental Protection Agency (USA).

low-to-moderate-cost housing was financed by local insurance companies. Partly for budgetary reasons and partly because there was no tradition of concern with the provision of sound isolation in the buildings, no special attention was given to these matters. As a result, it developed that the insurance companies were stuck with a great many unrentable housing units, because of the poor acoustical isolation between dwellings.

Here an enterprising acoustical consultant entered the picture. He persuaded the insurance companies to adopt the following programme in the construction of future housing:

1. He would advise the architects on the choice of suitable constructions for party walls and floor/ceilings, and would provide further guidance on how to detail the structure so as to avoid damaging flanking transmission: avoidance of back-to-back electrical outlets and bathroom wall cabinets, proper sealing and caulking of floor and ceiling joints, avoidance of duct and pipe-runs between dwellings, etc.
2. When a project was partially completed, he would conduct acoustical tests on a small number of the units to determine that the desired acoustical isolation was being achieved. The results of these tests, on average, became the *de facto* acoustical performance specifications for the rest of the project. An important feature of these and subsequent tests was that the construction trades persons that worked on the project were required to attend the tests and to observe what was at fault when failures were discovered. An immediate result was that they became quite interested in achieving good sound isolation and even came up with suggetions for doing a better job with less cost or greater ease.
3. When the project was finished, about 10% of the remaining units were tested for compliance with the *de facto* specifications established in the pilot tests. These tests, as well as the pilot tests, were paid for by the insurance companies.

   At this point some flexibility in procedure was admitted. If all the tested units were in compliance, it was assumed that, by and large, the entire project was satisfactory. If many failures were found, further tests would be made, etc.
4. The contractor was required (by agreement in his original contract) to undertake remedial work on the units that failed to pass, and then to pay for the subsequent acoustical testing to demonstrate the success of this treatment. (At this point, the advantage of *de facto* performance standards, *established in that very project*, became obvious, in contrast to 'abstract' standards specified in some legal document. The contractor could offer no legitimate excuse for failure if it occurred: a mistake was clearly a mistake!)

The upshot of this programme was nearly 100% compliance with the requirements for adequate acoustical performance in these housing projects: a boon for the insurance companies, the owners and their tenants. In addition, the contractors involved soon won a reputation for being able to produce acoustically trouble-free housing and were much in demand for other jobs.

An important feature was that there was not a significant long-term increase in cost. At first there were some mistakes; and the cost of the acoustical testing had to be borne by the insurance companies. But this was preferable to coping with unrentable housing, and soon the contractors and their trades learned how to put up the buildings without mistakes, and the required number of acoustical tests could be reduced.

As far as I know, this is the only example where the loop from acoustical specification to demonstrated compliance in the finished buildings has been successfully closed in a routine manner in the United States. It illustrates the singular virtue of enlisting the cooperation of *all* the people involved, from the beginning of the project!

In the absence of such a 'historical incident', however, we may expect some opposition to the new code approach from people mistrustful of change.

16.7 COUPLING NOISE CONTROL WITH ENERGY CONSERVATION

There is, under the Energy Policy and Conservation Act of 22 December 1975 (PL 94–163, Sec. 362), authorization for grants to States from the US Federal Government, up to $50 million per year for three years, to support a number of energy conservation measures. These may include the provision in building codes of conservation requirements for new and renovated buildings.

Of special interest is the installation of thermal insulation for conserving energy. The means to improve the thermal insulation of a dwelling are similar to those for increasing the acoustical isolation from outdoor noises. Therefore, the opportunity exists, under the new energy conservation laws, for achieving energy conservation in such a way as to get also improved sound isolation of the exterior walls and windows, with virtually no added cost.

Such an advantage could be made the subject of co-operative demonstrations, nationwide, to show that better protection against community noise intrusion can be had for a bargain.

One such demonstration programme is being carried out at the present time in Chelsea, Mass., under the joint direction of the US Environmental Protection Agency, the Department of Energy, the Department of Housing and Urban Development and the National Bureau of Standards. It is called the Energy Conservation and Noise Control Demonstration Program for the Decade of the 1980's (Keast and Berman, 1979).

16.8 CONCLUSION

The hopeful plans and projects described in the last sections reflect the mood of the 1970's, which assumed that persistent effort and public education would evantually lead to both acceptance of a reasonable and economic improvement in the acoustical environment in our communities, and the funds to achieve it.

The 1980's look considerably more bleak. A sagging economy and increased energy costs are not favourable to the development of new ways to tackle old problems.

In the 1960's, the scientific personnel at sponsoring Government Agencies had the money and the authority to support good new ideas for promising research, and these were quickly and adequately funded. In the 1970's, government funding for research has been severely cut back. Where promising Federal programmes of noise abatement had been planned, they were falteringly implemented.

From the viewpoint of this survey, namely, the inadequacy of 'first-order' solutions, the present position with respect to building acoustics in industrial countries is as follows. The need has been seen for housing with more adequate noise control. In order to achieve this objective that attention to better noise control was needed, laboratory and field methods have been developed for measuring and rating sound insulation and isolation with considerable refinement. These matters are well known only in the technological community, but so far have not successfully involved the planners, architects, construction engineers and building trades in collaborating toward a balanced solution to the problem of noise control in buildings.

It appears that suitable enforcement tools have recently been developed and some progress is looked for in the near future.

But it is *also* the responsibility of industrialized countries to discuss technological progress in acoustics and noise control and to acknowledge the need for progress in political acoustics and social acoustics.

Finally, it is the duty of the acoustician to watch for, and to avoid, the deceptive attraction of the 'first-order' solution. Wherever it is possible, developing countries should be warned of the pitfalls that can lie in the path of the obvious first-order approach.

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Noise Pollution
Edited by A. Lara Sáenz and R. W. B. Stephens

CHAPTER 17

Noise Pollution Control: Present Possibilities of Controlling Noise inside Buildings

G. L. Fuchs

17.1 INTRODUCTION

The physical principles that control the behaviour of acoustical materials and systems as isolators of airborne- and structure-borne sound are well established, but so far only limited success has been achieved in improving the acoustical quality of the human habitat.

In our experience this failure originates from the main factors quoted below.

- —Tendency of the public to pay and appreciate more the aesthetic rather than the acoustic qualities of enclosures.
- —Resistance to the use of acoustical materials and devices on the part of the builders.
- —A failure of Buildings Codes and Legislation to impose the attainment of acoustic quality, still considered a sort of luxury in urban environments.

In this chapter we shall assume that the physical principles of noise generation, propagation and reception have been adequately reviewed (Part I) and that physiological and psychological reactions have also been analysed (Part II). The main sources of noise emission such as traffic, machinery and vehicles have been discussed (Chapters 12 to 15). Codes of practice and regulations have been reviewed and their applications and results evaluated (Egan 1972)

17.2 DESIGN CRITERIA

To design an acoustically acceptable environment, we have to know the main *activities* to be performed and the corresponding human *sensibility*. In spite of the fact that too many acoustical indices have been proposed to cover every special situation, it is considered to be accurate enough for design purposes to

1		2	
Functions	Acoustic related activities	Sensibility to noise	Criteria dB(A)[*]
Industrial plants (machinery)	Communication and warning	Low	<70
Arts and crafts Business and administration Urban services Social activities	Simple mental tasks	Medium	50–60
Creative work Learning and cultural	Complex mental tasks	High	40–50
(a) Health care (b) Sleep (c) Sound recording and playing	Recovery periods listening	Critical	<40

[*] Statistical levels (≥8 hr/day).

Figure 17.1 Proposed acoustical design criteria. After Lara and Fuchs

reduce the sensibility levels to just four (Figure 17.1). A more detailed analysis of the requirements for each activity and type of environment has allowed the determination of complete lists of average advisable levels for each case (Figure 17.2). It has been demonstrated that individual reactions to noise vary throughout a wide range and it does not seem reasonable to design for the most sensitive people (who will be annoyed by the slightest interference) or for the extremely insensitive subjects who will endure almost any noise situation without complaints.

We would like to concentrate on the design with present-day available materials and technology, of acoustically acceptable environments. Building materials and methods vary considerable from country to country, but we shall only mention here those most widely known and used.

The basis for an adequate acoustical control of interiors is founded on a correct estimation of the noise inmission in the building which depends on the external environmental noise climate surrounding it. Such noise climate is related to the urban location of the building site.

17.3 URBAN PLANNING

Typical urban areas include: residential, commercial, downtown, industrial, airports and recreational areas. These are mostly mixed, making the demarca-

		Inside			Outside		
Location	Meas.	Activ. Interf.	H.L. risk	Both effects	Activ. interf.	H.L. risk	Both effects
Outside	L_{dn}	45		45	55		55
	L_{eq} (24)		70			70	
Inside	L_{dn}	45		45			
	L_{eq} (24)		70				
Commercial	L_{eq} (24)		70	70		70	70
Inside vehicles	L_{eq} (24)		70				
Industries	L_{eq} (24)		70	70		70	70
Hospitals	L_{dn}	45		45	55		55
	L_{eq} (24)		70			70	
Education	L_{eq} (24)	45		45	55		55
	L_{eq} (24)		70			70	
Recreation areas	L_{eq} (24)		70	70		70	70
Rural areas	L_{eq} (24)					70	70

(All values in dB(A).)

Figure 17.2 Recommended design equivalent noise levels to protect public health and welfare. After E.P.A.

tion of boundaries a difficult task. But approximations can reasonably be made and L_{dn} levels attached to the area under study (Figure 17.3).

Complete acoustical urban planning is seldom feasible except when new towns are purposely so designed. Grouping of the various activities according to their noise generating capabilities is the simplest (though not always realizable) planning scheme (Figure 17.4). Partial improvements can be achieved through zoning or by moving noise sources away from residential areas.

In existing towns it is always possible to improve unfavourable situations by the use of natural or artificial barriers such as those already mentioned (Chapters 3, 12) or using other buildings as barriers.

When barriers cannot be interposed economically or whenever city authorities do not resort to them for general urban noise limitation, the next possible control of noise emission at the site is to erect a local barrier or enclosing wall. The use of vegetation is aesthetically good but properly designed fence-walls are more efficient as attenuators of sound. In downtown areas, where façades and roofs are the only protection against surface and air traffic, the design of these enclosing elements becomes a priority in the control of exterior noise emission.

Façades in down-town streets generally oppose each other on both sides of high-rise buildings and generate a quasi-reverberant field at almost all levels giving rise to the so called 'canyon effect'. Absorption is not easy to apply on the

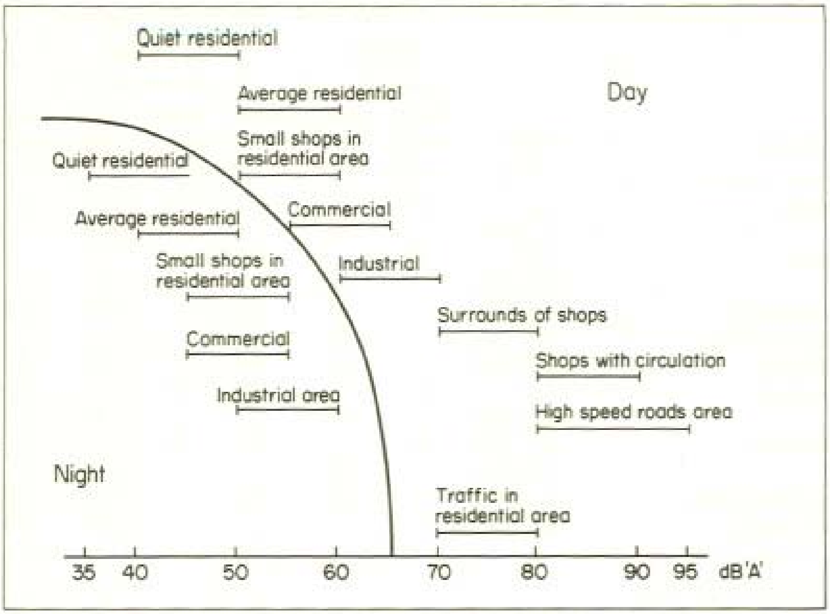


Figure 17.3 Day and night levels in different U.S. City Areas (Shuth, 1970)

outside of façades because of weather and maintenance reasons. Though some improvement has been achieved by applying it below protecting surfaces, mainly under balcony overhangs. The receding front line is also a good defence against street noise and the canyon effect.

The most reliable way of evaluating acceptable noise levels at the outside of buildings is by statistical measurements. Many surveys have been carried out to propose general design values. But, from our experience, the particular conditions vary so widely (reflections, weather, urban-layout of the surrounds, etc.) that even a quick measurement at peak hours of representative days and/or seasons may be more reliable for special cases. The most widely used unit for measurement is the equivalent level (L_{eq}) which is an energy integrating index rather than an actual level. The day–night level (L_{dn}) which is based on the L_{eq} compensated by 10 dB for the night hours (generally 10 p.m. to 6 a.m.) is also a convenient figure to relate exterior noise to design target levels. L_{eq} for urban purposes is computed or sampled over the 24 hours (Chapter 1).

17.4 AIRBORNE AND SOLID-BORNE NOISE

Airborne noise is the most widely encountered type of noise inmission into buildings, though vibration is not to be neglected as a primary source of interior noise.

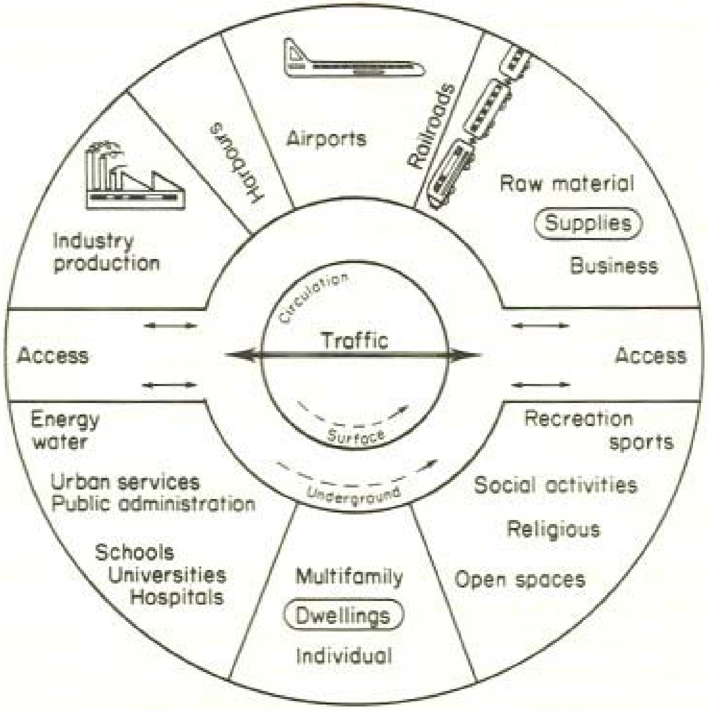


Figure 17.4 Model of urban zoning to minimize noise interference. After Fuchs

Re-emission from structural elements, especially from flexural vibrations propagated by plates (concrete slabs and the like), may generate strong standing waves inside enclosures which at low frequencies and in regularly-shaped enclosures can be noticeable and annoying.

From the urban planning point of view, passing subway trains generate the strongest low frequency vibrations. Surface traffic noise also propagates through the ground as P and S waves that reach the foundation slabs and piles of buildings, even from considerable distances (Cremer and Heckl, 1973). The propagation pattern is difficult to predict from site measurements but minimum distances from these sources (trains, highway and street traffic, etc.) have been proposed as design figures (Figure 17.5). If these distances cannot be achieved there is not much else that can be done at the receiving points, except perhaps interrupt the continuity of the concrete frame by structural joints. This presents some serious difficulties to engineers when shearing forces are present at the prospective discontinuities. Supporting elements such as column bases and platforms may be partially isolated by adding a resilient layer horizontally between a base slab and the load-bearing one but only for relatively small structures. The specific loads at such points are so high that only layers of lead or steel reinforced polymers can be used. The resilient layer

Noise source	There is a possibility of excessive noise due to this source if the building site is:
Highway	Within 300 m of any major roadway
Railroad	Within 1000 m of any railway line
Aircraft	Within the distances given below:

1. International airport		2. Commercial or military airport		3. General aviation airport	
to side of runway	to end of runway	to side of runway	to end of runway	to side of runway	to end of runway
≤5 km	≤24 km	≤4 km	≤15 km	≤2 km	≤8 km

From: NBS-BS 584.

Figure 17.5 Minimum acceptable distances for transportation noise sources. From NBS-BS 584

is dimensioned from knowledge of the specific load applied on it and the corresponding static deflection due to the load.

The use of resilient materials as vibration isolators is widely spread (Figure 17.6). Each has a frequency range of maximum efficiency. The transmissibility of vibrations is minimized by selecting the optimum damping and ratio of forcing to natural frequencies (Figure 17.7).

Springs are only used below machinery and their calculation requires specialized knowledge. New elastomers are constantly developed for multiple vibration isolation usage in buildings.

17.5 FAÇADES AND ROOFS

As mentioned above, the weakest link between exterior noise emission and noise protecting enclosing surfaces (façades and roofs) is the insulating properties of these building elements. Façades, which in classical architecture consisted mostly of thick brick walls with relatively small openings, have evolved into non-load-bearing elements, mostly crystal windows (windowalls) or light hollow brick walls, between load-bearing columns. Glass walls, even with good weather-stripping, afford little isolation from traffic noise, especially in the low frequencies. Except in air conditioned buildings with fixed windows, the latter are kept open in the warmest season, reducing the insulation to some 10 dB (Figure 17.8). Doors are similarly insulated.

Hollow bricks, as is well known from the mass-law are poor insulating elements which seldom provide enough insulation. The frequency dependency of partitions (Figure 17.9) is complex and has been studied in detail but double

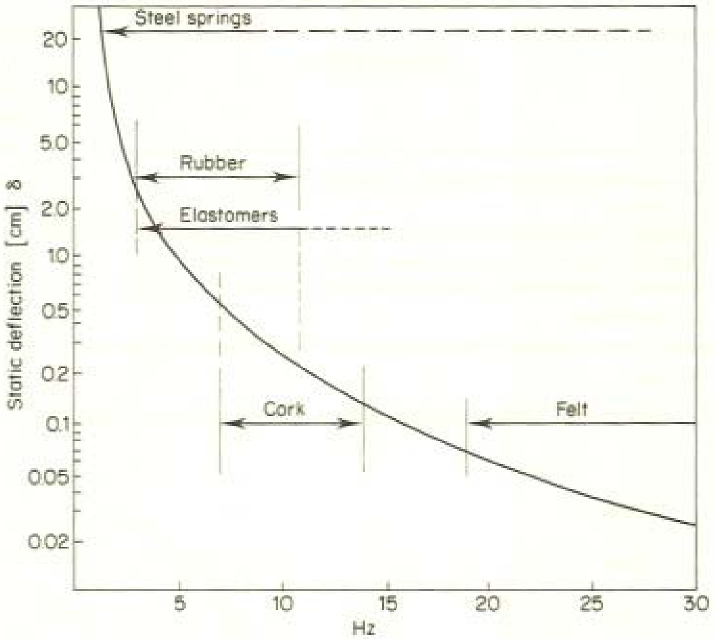


Figure 17.6 Application ranges of elastic mountings

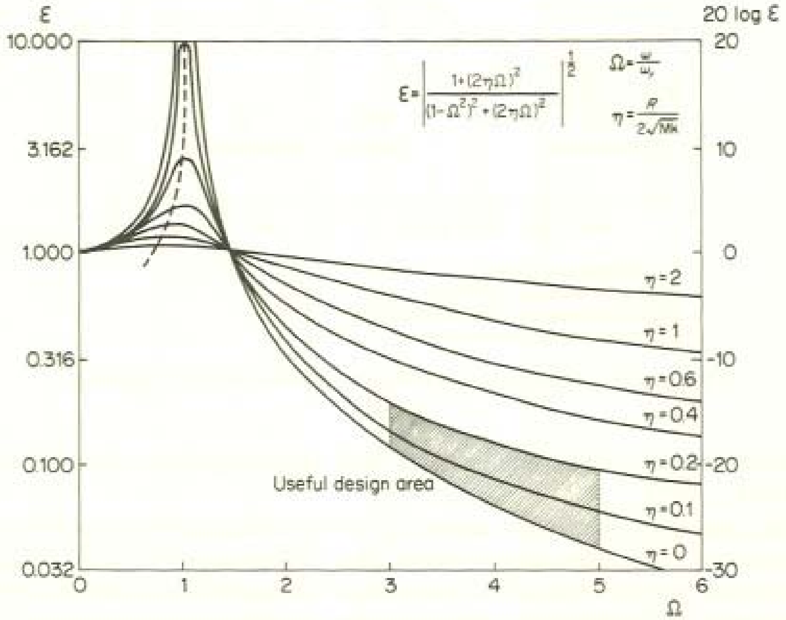


Figure 17.7 Design chart for optimum damping of elastic supports. After Fuchs and Lara

WINDOWS

Pos.	Window type	Airborne insulation index-I_a,dB
1	Low-priced, single window, no sealing, glass 2–8 mm	10–20
2	Double (house type) double frame with sealing glass 2 × 2–5 mm	20–30
3	Special insulating several glass sheets and frames	30–40
4	Double-framed with glass between 4–8 mm thick, 15 cm separation	35–45

From: A. Lauber.

Figure 17.8 Typical isolation for windows. After A. Lauber

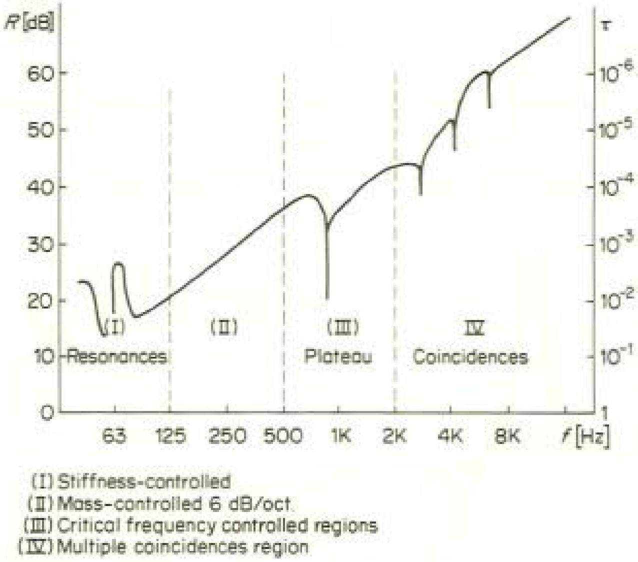


Figure 17.9 Behaviour of partitions isolation versus frequency

partitions are still more complicated in their frequency dependence (Cremer and Heckl, 1973).

What, one may ask, is the answer to this problem posed by present-day architecture? Architects seem to have taken a firm stand for preserving the 'visual transparency' of façades. One alternative, certainly not inexpensive, is the doubling of the glass panes but to be effective they must be separated by at least 15 cm and carefully sealed. The use of glazing of different thicknesses for the inside and outside sheets, increases the insulation by changing the resonant frequencies between the sheets. Rubber gaskets, double-contact carpentry and non-paralellism of glass panes (whenever possible) are useful aids to increase the insulation of double windows.

Windowless façades have been tried successfully both from the architectural and the acoustical point of view; depending on the function of the building. This alternative generates a subjective disadvantage to the users due to the lack of direct daylighting and landscape view. Internal 'patios', elaborate lighting schemes, air conditioning and functional music may compensate, albeit partially, our instinctive desire to 'look outside'.

Roofing can vary from very light metal or asbestos sheet shells to heavy concrete slabs. In factories, noise emission from aircraft noise is rarely important because internal noise masks by more than 10 dB the levels due to this source, which rarely exceeds 80 dB at roof level.

In multifamily condominiums the top storey is generally roofed with massive concrete slabs plus water-proofing treatment and even topsoil for roof gardens or swimming pools, so reducing the noise to that created by sporadic helicopter flights.

The roofings of least insulation are found in individual light frame dwellings (wooden frames of inclined roofs with tiles or shingles). Special enclosures, particularly television, broadcasting, dubbing or film studios require higher roof insulation as they are generally placed in tall independent buildings. They require roofings consisting of double or even triple slabs to attain the 40-dB insulation necessary to reduce the background noise to acceptable performing levels. Individual dwellings have roofing of poorer sound insulation than any of the walls and so aircraft noise can intrude directly from on top, being especially intense in the vicinity of airports where taking-off and landing aircraft flyover at very low altitudes. Levels of 90–100 dB(A) have been often measured. The addition of airtight and heavy ceilings may attenuate the required extra 20 dB. In countries where house roofings are generally heavier (horizontal tiled concrete where there is no snow overload) there are fewer complaints and most of the aircraft noise enters by way of windows and openings rather than the roof.

Other than by improving on the outer shell of the building, the designer can sometimes control exterior noise by orienting it correctly within the site, that is, away from the loudest sources such as airports, freeways, factories, etc. Neighbouring high-rise buildings may increase by multiple reflection the street and aircraft noise.

Multifamily condominiums are generally erected in a large site where these measures can be taken. But row or terrace housing and even individual residential units must rely mostly on fencing walls and the location of bedrooms, studios and rest places away from the loudest noise sources.

Within a building itself, the rooms can often be distributed according to their noisiness or requirements of quiet. Kitchen, bathrooms and utility rooms should be grouped away from bedrooms and similar rest spaces. Buffer spaces can be created by more noisy environments (living or playrooms, garages, passages or lobbies).

17.6 INTERIOR NOISE SOURCES

In any type of enclosure there are two kinds of noise sources: (a) inside the enclosure itself and (b) that coming from next door. The particular case of enclosures opening on the façade had already been dealt with, except for the room's own or neighbouring noises. Own sources can only be controlled by the user (buying quiet equipment or operating radios and TV sets at reasonable levels).

Household appliances, boilers or heaters and similar machinery may be selected from the most silent brands.

In multiple-unit buildings, the elevator machinery is a serious source of solid-borne noise, and although it should be easy to isolate both the machinery and the rest of the moving and supporting gearing yet it is often difficult to do successfully after the completion of building. This noise is readily transmitted by way of the structure, sometimes through many storeys. The same applies to motors, pumps and burners, which are generally located in the cellars. Unavoidably noisy machinery may be enclosed in absorbing-insulating capsules or protection should be afforded to individuals around the machine with ear muffs or plugs.

There is not much that we can do about controlling noise at the source once it is *installed*. Improvements in the *design* of the sources, (air conditioning, machinery, exhaust silencers, home appliances, etc.) are being actively pursued by the manufacturers and reductions of the order of 20 dB are being achieved. So *selection* of the most silent source on designing either a static or a dynamic habitat can do a lot towards lowering noise levels inside enclosures. But as we mentioned earlier, solid propagation from the sources must be controlled before noise is radiated into the enclosure as airborne sound.

Besides the above-mentioned means, applicable to the noise-radiating areas themselves, there is another possibility of noise reduction close to the source and that is by the use of *mounting* devices and systems. They can vary from springs of various types combined with dampers, to elastic layers of several materials from lead through cork to elastomers, etc. There is one requirement to make mountings efficient and that is the calculation of the natural and forcing oscillation frequencies, the damping and radiation constants. Unfortunately, these relatively simple means of reducing noise close to the source are often neglected by designers.

Pipings and conduits of all descriptions which nowadays form an unavoidable network in any static or dynamic habitat, are another example of neglected noise control, both at the design and the construction stages. It is not difficult to isolate their supports or crossings with structures by simple elastic rings, cladding or hanging bracings. Their efficiency is obvious and many laboratories have investigated and designed this type of solid-to-air noise insulation, now commercially available. Besides the technical knowhow of designers and builders there is a non-technical factor that contributes to this failure: inclusion of this requirement in Building Codes and the political decision to make technical inspection and enforcement effective and systematic.

Returning to the difficult problem of interaction of waves and structures we should mention that insulation is not an easy problem for two main reasons:

1. Materials are frequency and mass dependent in their capacity to insulate and their application must take both these factors into consideration at the design stage (Figure 17.9). Theoretically these properties have been exhaustively investigated and can be expressed in comparatively simple formulae.
2. The above-mentioned properties bring about very serious consequences when the partition is forced into oscillations close to the coincidence frequencies both in the mass controlled and the stiffness controlled region (Figure 17.9).

A partition isolated from a structure can behave in the above-mentioned complicated manner, but it is seldom the actual situation, both in static and dynamic structures (buildings, ships, etc.) because these plates are not infinite and unclamped at the edges. Rather they have limited dimensions, mass and degree of clamping to adjacent plates, beams and columns. This brings about solid interactions which may have serious consequences in the secondary generation of solid and airborne waves. An outstanding case is that of flexural waves. A finite plate set into flexural oscillation is a powerful generator because both horizontal and vertical partitions are plates of considerable area and mass.

17.7 PARTITION INSULATION

Insulation from other ambients due to a vertical or horizontal partition, sometimes called transmission loss (TL) refers to the insulation properties of the partition, but flanking paths even from non-adjacent ambients may alter in-situ measurements of this noise reduction.

Privacy (Egan, 1972) is a modern criterion for evaluating acoustical quality and is a function of isolation and not of the mere insulation properties of closing elements. It involves subjective evaluation of comfort produced by a certain reduction (R) physically computed.

The weakest links are the air leakages or currents letting noise in from other rooms or ducts.

The computation of isolation may be made with the aid of: (a) Tables or charts giving the combined insulation of the partitioning elements and doors or windows; and (b) Computation of noise levels by direct noise paths such as slits and air conditioning openings.

The floor, walls and roofing (or ceiling) of an enclosure may become a noise source by re-emission of flanking sound arriving as vibrations transmitted by structural elements of any type which excite the boundaries of the enclosure as flexural waves. It is important to keep in mind that stopping airborne noise is just one part of the acoustical problem. Solid-borne noise is as common and easier to propagate at unexpected distances by structural elements (Cremer, 1979). In dynamic environments such as aircraft, trains, etc. solid-borne noise is very often the predominant source in the enclosure. But even buildings have plenty of solid-borne noises and vibrations re-emitted to the air in all types of enclosures (Figure 17.10).

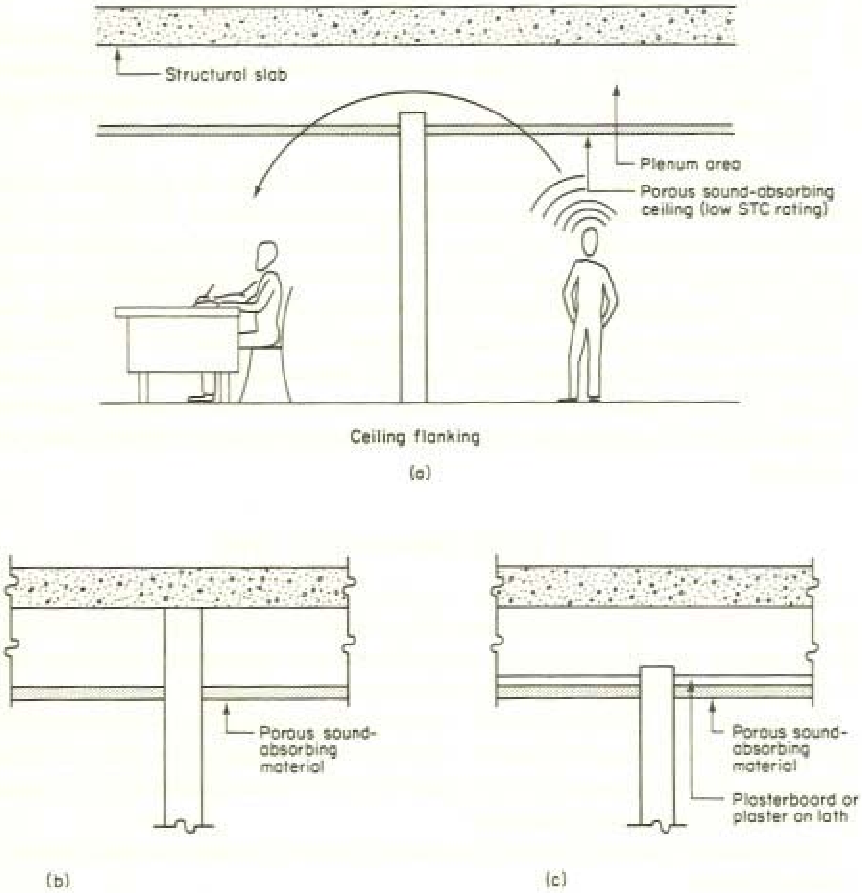


Figure 17.10 Sound insulation of acoustical ceilings

Radiation efficiency, the theoretical problem of the *interaction of sound waves and structures* has been extensively studied and some effective means of minimizing radiation efficiency of solids as well as the undesirable 'coincidence effect' which sets structures into flexural oscillation of great radiation capacity have been analytically solved. However, the practical problems of avoiding both are far from solved, but useful approximations have been achieved to date such as the appropriate combination of materials, mass and damping of partitions (single or multiple) to displace or annul coincidences where the insulation is minimized.

Similar combinations of mass-damping thicknesses and materials may optimize the attenuation of impacts such as footsteps on floors. Here again flexural waves radiate into the lower room when impacted by footsteps or similar point shocks. This constitutes one of the critical problems of privacy in multistorey buildings in which there are technical means of control, but few applications are actually seen to date as mentioned in our introductory words.

To conclude this part, we should mention the transmission of sound overhanging ceilings, the most important failure of insulation in office rooms. The space between slab from upper floor and ceiling is a plenum which allows sound to pass from the source room to the receiving side (Figure 17.10). A barrier should be interposed above the vertical partition and extra absorption added in the plenum, even if the ceiling is acoustically absorbent.

17.8 OTHER INTERIOR NOISE SOURCES

Besides walls, partitions, floorings and ducts, there are the electromechanical and sanitary installations which are often neglected by contractors and ignored by architects.

Let us start with the cold- and hot-water distribution systems. The piping, especially in vertical stretches, generates the typical 'water hammer' (hydraulic ram) impact noise which can be structurally carried by the piping walls and re-emitted into the rooms, even many storeys away from the source. The water-taps, unless well designed to avoid turbulence, are a considerable source of noise. These noises can be effectively prevented by using gradually closing taps which are elastically connected to the piping.

Wash-basins, tubs and showers are rarely elastically suspended, so generating noise both on filling and emptying. These noises can be effectively prevented by using gradually closing taps which are elastically connected to the piping.

Most multistorey buildings have now a space for all vertical supply and distribution of hot and cold water. But on branching out through walls a careful packing (fibreglass or rubber gaskets) should wrap the piping all through solid contacts with masonry or structure.

Most aerodynamic sources of noise such as ventilation ducts can be effectively reduced by decoupling duct from structure and by operating at the minimum flow speed. Ducts not properly treated may affect the privacy of multifamily units by transmitting conversation.

To conclude, most of these problems can be solved by adequate engineering design plus strict specifications and careful *in-situ* inspections after completion. Failures observed in practice are due to overlooking any or all of these steps.

17.9 THE SOUND FIELD INSIDE ENCLOSURES

An enclosure is a space partially or totally enclosed by more or less rigid facing surfaces of various configurations. The type of activities for which the enclosure is created, demand certain acoustic qualities. Even a successful design of the noise emission and control of the internal sources does not make an enclosure acoustically *good*.

The purpose for which the enclosure was designed may have (see Figure 17.2 at the beginning) widely varying requirements. From merely understanding voices or transmitted orders or warnings, or listening to the correct operation of machinery (for instance in a factory), the purpose of an enclosure may be to understand speech or discussions in meetings, classes or business quarters; ranging through various degree of activities and sensitivities down to the most exacting ones of mental concentration, health recovery, relaxation and/or sleep.

So the acoustical *quality* of an interior space depends on factors other than mere airborne or vibration isolation.

It has been proved that total silence is *not* a desideratum. Man is used to living in a certain background of noise which for certain activities and even for pleasure must be well above the threshold of hearing.

Research has proved that a 'state of arousal' is needed for optimum mental and physical productivity.

It is rather the ratio of signal-to-noise (S/N) that should be optimized by the interior design of the room.

Criteria of room 'quality' for various purposes have been proposed since the beginning of the century when the concept of reverberation time was suggested by Wallace Sabine.

The main parameters which can be controlled in an enclosure are:

1. Volume and shape.
2. Interior areas of the facing surfaces.
3. Type of source(s).
4. The transfer function of the room.

17.10 VOLUME AND SHAPE

Once the volume of a room has been fixed, based on optimum conditions of performance, the shape has to be decided upon.

The simplest shapes are paralelepipedic, creating regular and plane boundary conditions for the sound field. The study of these cases gave rise to what is known as 'wave acoustics'.

Irregular shapes complicate the field boundary and field conditions, originating statistical distributions which can only be evaluated by two methods: (a) a simplified one called geometrical or ray-tracing acoustics; and (b) statistical computation of the resulting field.

Our purpose in this chapter was not to develop the theoretical basis for design but rather to enumerate 'what can be done' to avoid acoustically poor environments, based on that theoretical knowledge.

Referring to the 'wave acoustics' approach we should mention that in the simplest case, the geometrical parameters: length, width and height may be arranged in such a way as to avoid 'standing waves' patterns which, especially at low frequencies, produce noticeable irregularities in the frequency response of the room. At infrasonic frequencies this effect may be annoying, causing a sensation of pulsed noise undetectable by the usual sound level meters.

To avoid normal modes as these patterns are called, Bolt (1946) established ideal combinations of (l, w, h) which result in optimized uniformity of the room response. This resource has a limited (Figure 17.11) range of validity frequency-wise, but is helpful as a basic design (or correction tool).

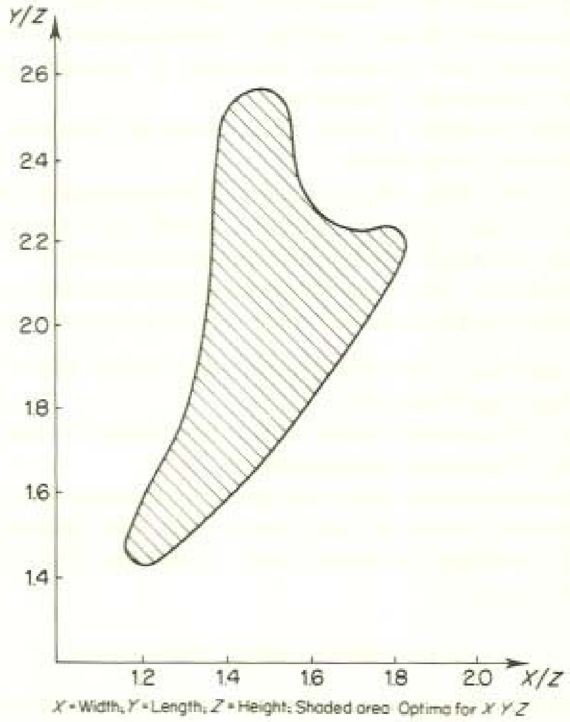


Figure 17.11 Chart for geometrical dimensioning of enclosures with optimal normal modes distribution

Geometrical acoustics has been very useful in graphical 'ray tracing' to locate and eliminate to a first approximation the gross faults of a room (especially for music) such as: echoes, focalizations, 'dead spots' and with the aid of models, has helped in the design of reasonably good rooms.

Statistical acoustics has helped in the direction of attaining better listening conditions by computing (or measurement in existing rooms) the Reverberation Time which is a good indicator of quality. Later refinements have added the possibility of better designing for interior absorbing and reflecting surfaces. Diffusion is a desirable quality that can be achied by irregularity of the bounding surfaces. But its value to improve the room response is still not well established.

The foremost researches in the last decade (Schroeder, Kuttruff, Reichardt, Beranek, etc.) have resorted to many acoustic solutions to achieve 'perfect' acoustics of an enclosure.

But this aim involves very complex subjective parameters that make this goal most controversial.

Computers have come to the aid of designers by allowing the modelling of rooms and prediction of their acoustic response (Schroeder, 1967).

To summarize, room design is still not an exact operation, but with the aid of the above design and correction methods, it permits the design and construction of 'acceptable' enclosures.

The materials available permit the erection of reflecting, diffusing and absorbing materials and systems.

Absorption is one of the critical parameters in room quality and we shall only mention here the main types of absorbers, which vary throughout the world according to the materials and industrial process available.

Generally speaking, absorption is a frequency dependent property and the mechanisms of absorption known to date may be summarized as follows:

- Porous absorbers (fibreglass, rock wool, wood fibres, polyurethane, etc.). Wide range absorption.
- Resonance absorbers (Helmholtz type) or treated cavities and slits. High 'Q' quality (Narrow range absorption).
- Membrane absorbers, which are based on the absorption of sound in a treated cavity behind an elastic membrane. The geometry and fixation varies its absorbing frequency range. Generally low- to mid-frequency absorption range.

17.11 CONCLUDING REMARKS

A description has been given of the resources that acoustical theory has provided for engineers, architects and acoustical consultants, in order to ensure that acoustically acceptable environments are properly designed and built.

The emphasis has been placed on buildings (or otherwise expressed 'static habitats') but the very same principles, methods and materials are applicable to 'dynamic' enclosures such as trains, airplanes, ships, etc. The only difference is generally the design criteria. Lower sensitivities are applicable to dynamic enclosures where communication and warning is the maximum acoustic requirement. Vibration is in general more severe and difficult to isolate and some aerodynamic noise and infrasound influences the acoustics of the interior of vehicles.

A block diagram (Figure 17.12) gives the acoustic design process in its broadest possible sense.

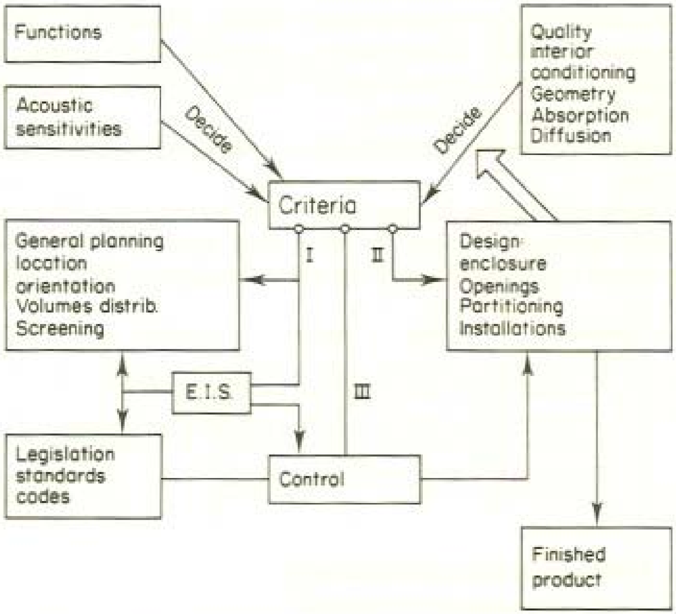


Figure 17.12 Diagram of the acoustical design process of man's habitat. After Fuchs

A 'habitat' of any type, that is, a dynamic or a static enclosure with elastic boundaries contains internal sources of various kinds. In its interior, activities of any type may be assumed to take place and partitions may divide partially, or entirely, the enclosure. Absorption, diffusion and vibration isolation receive consideration and when the functions to be performed, and their corresponding sensitivities are determined, a certain design criterion is decided upon.

The noise emission should be determined (traffic, street, air or underground activities), as well as that noise emitted to neighbouring environments which, in turn, may be sources which affect the total emission of the enclosure under study. This determines the design goal based on the adopted criterion.

The required acoustic quality determines the interior conditioning and geometry of the enclosure. Prior to adopting the criterion and computing the emission we can study the urban location and optimize the orientation, maximum noise screening, ideal volumes distributions, etc.

The details of design such as internal finishing materials, shapes, openings partitions, should then be worked out.

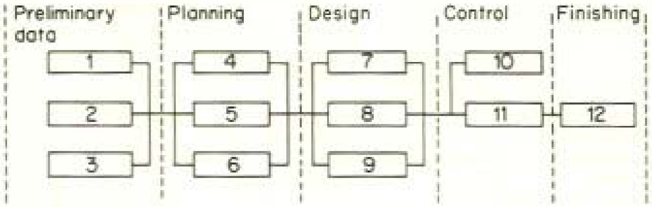
The installation must be carefully controlled not to affect the previously determined conditions.

Local legislation, Standards and Codes must be taken into account throughout this process and when the authorities so require it, an Environmental Impact Statement should be prepared.

The final stages of the process of obtaining a finished product with the desired acoustical quality is dependent not only on all the above mentioned technical steps but should include an effective supervision and control at all stages of the design and construction.

The sequential stages of acoustic design are presented in block diagram form (Figure 17.13).

Computation allows automation of many of these stages. Recently, as has been already mentioned, even the acoustical 'quality' of a room can be modelled, tested and modified with the aid of a computer (Schroeder, 1967).



1. Define functions and related activities
2. Select criteria based on sensitivities
3. Compute environmental inmision
4. Locate and orientate construction
5. Decide internal distribution
6. Plan installations and supplies
7. Choose internal partitions and openings
8. Design enclosing walls
9. Design installation isolation
10. Control actual insulation
11. Internal conditioning of enclosure quality
12. Finished product check-up

Figure 17.13 Sequential stages of acoustical design. After Lara and Fuchs

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CHAPTER 18

Judicial and Legal Aspects of Noise Control

W. AECHERLI

18.1 INTRODUCTION

The struggle against noise excess in the environment is frequently considered to be a matter of education and of science, but it is only the law which has the means to oppose effectively the lack of consideration of 'homo faber', of 'homo economicus' and of 'homo primitivus', who are largely responsible for the state of affairs today.

Noise, looked at from the lawyer's point of view, is in the first place a fact that has to be looked at from the physiological and psychological points of view. The technical side, in particular, has the task of informing the lawyer about the possibilities of avoiding excessive noise. However, on the medical side, it is damaging to health and has a marked influence on the wellbeing of man.

It has been estimated that 15% of the population of the member countries of the O.E.C.D. (Organization of Economic Co-operation and Development), i.e. of over 100 million people, are exposed to an external noise (apart from the noise in the place of work) exceeding 55 dBA.

Opinion polls have shown that inhabitants of towns consider noise one of the strongest exposures in their everyday life. If there is no strong declaration against a further intensification of noise, people should be prepared for the fact that from now until the year 2,000, the number of people exposed to noise exceeding 65 dB(A) would increase from 15 to 20%.

The causes of the intensification of noise are, foremost the constant development of motor transport, then follows more leisure time for the workers, increase in tourism, etc.

The street traffic which constantly grows will remain also in the future the strongest and the most compelling source of noise. Although this is the first priority, efforts at fighting other numerous sources of noise, mainly air transport, should not be neglected.

Fighting against noise is an essential part of the policy of natural environment protection and therefore it should be effectively introduced into the general concept of environmental protection. Co-ordination of means employed by various state, regional and local institutions responsible for controlling noise could be improved by general rules, orders of the administration, as well as comprehensive central programmes of appropriate actions. Fighting of noise requires one and substantial declaration of the aims. It is necessary firstly to establish a schedule for particular subdivisions, whereby also economic data and requirements should be also taken into account.

18.2 JUDICIAL BASIS OF NOISE CONTROL LEGISLATION

18.2.1 Foundations in Civil Law

The foundations for noise abatement in civil law are mostly contained in environmental regulations. The central point of protection against noise emission is the matter of its harmful effect on man. In order to decide whether the emission of noise is excessive in law, the courts normally 'weigh-up' conflicting interests. There is no exact limit of tolerance for noise, rather that each case is judged on its merits. Local conditions, economic considerations and social aspects for example are all significant. In civil actions the prosecution has roughly the following possibilities at its disposal:

- —the normal complaints about environmental defence and claims for damages;
- —claims of disturbance to property due to forbidden interference; a complaint of this nature can often be won in a summary action;
- —a complaint about the freedom of property (actio negatoria).

18.2.2 Administrative Foundations

Most countries have the possibilities of acting against the effects of noise according to the law of the land and independent of the possibilities of civil action just discussed.

Accordingly, the police or the administration of the communities, etc., have the possibility of taking the necessary measures, provided these are within the framework of the law and taken after proper examination of the facts, to protect public safety and order from general or specific dangers. Specifically, one may point out the right to expropriation. This does not directly pursue the aim of noise abatement, but, where there are corporations and institutions of public law and others legally entitled to expropriate those producing excessive emission—including unavoidable noise— it gives the possibility of assigning damages to the neighbour so afflicted. In this case, the afflicted has no right to defend himself against excessive noise. The right to expropriate may help noise abatement because it is in a position to have a prophylactic effect on noise.

18.2.3 Foundations in the Penal Code

Although the police law contains a veritable arsenal of suitable regulations and measures, there is still a point in making use of the experiences of the civil law as regards protection from noise emission. Let us point out particularly the consequences of tolerating the disturbances over a long period, the economic and social aspects, and most of all the concept of excessive noise above a limit of tolerance with regard to the protection of peace and quiet, particularly at night, and therefore the protection of health, etc.

In the face of such duplication in the fight against noise, one must keep in mind that in the first place it is up to the police to proceed. The civil courts are only able to act in a private prosecution against emission if a complainant takes on the action at his own expense and at his own risk. Without anybody following this procedure there is no help, however much the emission is against the law. The police, on the other hand, have a duty either because of what it has noticed itself, or because of a complaint to act against the production of excessive noise—whereby it is immaterial whether it is emission or other disturbances—even though nobody has made a complaint in civil law, and independent of it. The policy have to intervene all the more, if they are asked to help.

Motivation for intervening by the police in the public interest does not mean that the police only have to fight noise when a considerable number of people are being disturbed; on the contrary, the nuisance to a few or even only one person may be a sufficient reason for action.

There is no doubt that the police are competent to act in the face of excessive noise, however this noise was caused, be it by preventive or repressive measures, irrespective of whether or not there is a specific regulation regarding the way the noise in question is produced: if not, then the competence of the police to intervene is dependent on a clause in the general police regulations which is based according to the constitution on law or on general usage, i.e. the police are empowered to maintain general peace and quiet, security and order.

In many districts, however, where people and machines are active, the fight against noise by police hardly functions at all. This is the more to be regretted, since this reproach has been made in public for decades again and again. Not only has it had little success, but it does not seem to activate the police in the face of new sources of acute noise. Other than through this failure of the police, these orgies of noise which have become the scourge of modern life, cannot be explained.

Police law is based on a measure of reasonableness where interference is concerned. The police may not treat minor infringements with measures out of all proportion. It is in the nature of police law to limit freedom of action. For the police to restrict the fight against noise give freedom to the inconsiderate. Too much consideration in the matter of noise emission and other disturbances that the police could deal with, always has the effect of rewarding and encouraging lack of consideration.

18.3 SOME NATIONAL REGULATIONS ON THE LEGAL STRUCTURE OF NOISE

18.3.1 U.S.A.

Noise-abatement in the USA is based on the Noise Control Act of 1972. The Quiet Community Act, which is concerned with domestic and environmental noise, was passed by Congress in 1978. The activities were carried out by the United States Environmental Protection Agency (EPA), which, with the help of these laws, has developed a financial and technical procedure to support the individual states in their fight against noise but the Agency was discontinued in 1982. Apart from enlightening public opinion, it trained certain civil servants to deal with the noise problem.

18.3.2 Great Britain

The Control of Pollution Act 1976 came into effect on 1st January 1976 and included resolutions for fighting the main sources of noise. Street, aviation, railway and helicopter noise are dealt with. The appropriate authorities enforce regulations concerning the sound protection of dwellings and against noisy building works, and they draw up plans for protection zones. There are two fundamental aspects which form the basis of British legislation: adaptation of national standards to international standards; and delegations of responsibility for noise abatement to local level, where it is possible to adapt most quickly to local conditions.

18.3.3 Holland

The Ministry of Health and Environmental Protection introduced a wide-scale campaign against noise in the summer of 1976. The starting point was the fact that noise was a social problem and that each person should decide for himself when he considered the noise level unacceptable. Thus the problem can be solved only through co-operation. After a wide-scale public campaign in the spring of 1979 Parliament resolved unanimously to legislate against noise as the first step in the field of environmental protection.

18.3.4 German Federal Republic

In the G.F.R. legal measures for noise abatement are present both in federal acts and in more local legislation. By an amendment to the basic Act of 12th April 1972, federal authorities have been granted legislative rights in the field of removing waste, maintaining air purity and fighting against noise.

18.3.4 Austria

A constitutionally guaranteed right for environmental protection, especially for protection against noise, does not exist in Austria. There is no single body dealing with protection from noise or with combating noise, since these are not considered separate matters, but are generally dealt together with other matters that require controls. When the control of noise is not a matter for the employer, it is dealt with primarily by that section of the administration which deals with the field where the noise originates, (i.e. places of commerce, industry, building sites, power stations, etc.)

18.3.5 Switzerland

In Switzerland the control of noise is tied to Article 24 of the Constitution of the Federation. A law for the protection of the environment came into effect on 1st Jan. 1985.At Canton level there are regulations for combating noise. Heavy lorries may not be moved on Sundays or at night. Supersonic flying over Switzerland by civil aircraft is not permitted. Zurich and Geneva airports do not allvate flying between 10 p.m. and 6 a.m. From 1 November, 1980, these airports have charged an additional landing fee for excessive noise, depending on the type of plane.

18.3.6 German Democratic Republic

The central trade union for protection from noise of the Chamber of Science has in its executive and in ten trade unions many-sided specialists in the field of noise abatement.

Amongst other things, it has tried to make accessible to a large circle the results of research and the experience of individual factories and institutions, for which there is much interest and which have many users, but which cannot yet be sufficiently specified to be able to use them for standardization in form of regulations.

Looking at the plans for 1984–85, one may assume that the regulations will be taken more seriously. The requirements have to be estimated in the plans. Manufacturers, importers, and uses of machinery, installations and vehicles as well as those planning building works are obliged to apply for exemption if limits of noise are exceeded. The corresponding organizations for control are asked to make use of their right to examine, prosecute and punish offenders.

18.4 NOISE ABATEMENT LEGISLATION

18.4.1 Traffic Noise

The Tenth International Congress of the 'Association Internationale contre le bruit' held in Baden-Baden from 2 October to 6 October 1982 has shown the following:

A. The Effect of Traffic Noise on Human Beings

Without taking into account the physiological effects of noise, there is no question of getting used to this noise. This may exist psychologically, but it must be noted that getting psychologically adapted to noise may pose a permanent physical risk by obscuring physiological reactions to which one cannot become accommodated.

A group of researchers have proposed the following guidelines for maximum noise levels:

Environment	Day	Night		
Leisure or rest	55	45	L_{eq}	all values in dB(A)
Living accommodation	60	50		
Living on main roads	65	55		

For an environment without acoustic objections it would be desirable that all figures should be reduced by 10 dB(A).

B. Technical and Planning Matters

Measures for minimizing traffic noise in the future looked at both from the scientific and the planning aspect can be sudividied as follows:

- —purely technical measures for noise abatement,
- —measures for controlling the traffic to reduce noise,
- —noise abatement through planning,
- —an increased consciousness by the car driver that noise needs to be kept down, so that noise reduction becomes a more significant factor in buying a car,
- —information about the quality of noise from a vehicle,

- gradually adapted national and international technical guidelines about the emission of noise from vehicles,
- examination of the basis for taxation which so far favours noisy vehicles.

The following may be considered as measures for guiding the traffic to minimize noise:

- pedestrian zones;
- zones of quiet traffic;
- limitations of traffic by time and locality;
- speed restrictions;
- turning off hooters at night.

C. Legislative Aspects and Matters of Co-operation by the Citizen

By differentiating between quiet and noisy vehicles or aircraft when making traffic restrictions be it through bye-laws or regulations, one can make it attractive for the manufacturers to speed up the development of quiet machines. One can further use the law through taxation, where the present tax system based on the stroke volume works in the opposite way.

18.4.2 At the Work Place

On the occasion of the Eleventh Congress AICB* in October 1980, it was revealed that great numbers of men in all countries live and work under conditions detrimental to their health. Hence, it was recommended that an attempt be made on an international, as well as on a national level, to bring about better co-ordination of all the efforts being made in the field of noise suppression, and of the relevant interdisciplinary fields, to ensure better compliance with the following recommendations.

The legal aspect calls for the completion and codification of the existing system of standards and specifications and their verification from the point of view of their continued purposefulness and effectiveness. The standards and regulations should have a firm scientific and experimental basis. During the completion and codification of legal and technical standards an attempt should be made for their unification, and possibly broad co-ordination, at an international level. The regulations in the developed countries are assumed to form the basis for this unification. Special legal regulations should be issued concerning the purposeful employment of workers and employers suffering from an illness caused by noise and/or vibration.

Special sanctions should be provided for in case of bodily injuries caused by

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* Association Internationale Centre le Bruit (International Association Against Noise)

noise and vibration, as well as for the threat to human health, through a fault of the employer.

It has been recommended that special state and social organizations should be established in the course of finalizing the existing standards and regulations. These bodies should be responsible for the effective implementation of the existing methods and means.

When issuing supplementary regulations, special attention should be paid to regulations and technical specifications concerning the design, acceptance and operation of machines and equipment which are likely to produce appreciable noise and vibration, such as various forms of transportation and of constructional machinery.

From the technical aspect the organizations and institutions responsible for the study programmes of higher schools and colleges should give more consideration to disciplines connected with noise and vibration and to their suppression.

There should be a continuing endeavour to improve manufacturing processes and machinery so as to reduce the level of noise, with particular reference to the engineering industry.

Futher attention should be directed to improving unified methods of measuring noise levels. It is essential from the medical point of view that the limiting values of the noise levels should be well defined both as regards the machinery itself, its location and how the measurements are made. These conditions should be clearly specified in certificates issued with all machines.

18.5 INTERNATIONAL CO-OPERATION

The worldwide extensive international exchange of goods and the increased intensity of international travel emphasise the need for international co-operation in noise control in order to harmonize policies. (OECD, 1980 Paris).

This international co-operation should be dynamic, i.e. should contribute to a continuing progress in the field of noise control.

It should include:

—A unified and stricter limit for the emission of noise from motor vehicles.

—The harmonizing of measuring methods, marking of products with values of the noise emission and of standards referring to reliability and durability of noise control devices.

—A normalized method of testing the motor vehicles while operating in traffic.

—The efforts to devise a common measuring technique must avoid any weakening of stricter limiting noise values.

—There should be an exchange of experience and information and a regular critical evaluation of costs and the effectiveness of the strategy of noise control.

18.6 ECONOMIC IMPLICATIONS

In Switzerland as a practical approach to the problem of costing the provision of noise abatement measures an approximate evaluation was made of the application of these measures to a network of streets, motorways and railways.

An estimate was made of the order of magnitude of a national noise-abatement programme which includes replacement of existing windows by special noise-damping windows along streets with a sound level exceeding certain limits.

The estimated cost is given in the following table:

	Abatement costs along roads		
	Urban areas‡	Non-urban areas	Total
Sound levels†	10^6 SFr.[§]	10^6 SFr.	10^6 SFr.
75 dB(A)	35.0	0.4	35.4
70 dB(A)	395.2	123.8	519.0
65 dB(A)	977.1	773.6	1750.7

† Costs include all street sections in populated areas with noise exceeding these sound levels.
‡ Cities with a population in excess of 10,000 inhabitants.
[§] Fr. 1 (Swiss. $ 0.5 (US))

The estimation procedure was in two stages:

Stage 1: Calculation of lengths of street-sections above the considered equivalent continuous sound levels (L_{eq}) = 65 dB(A), 70 dB(A) and 75 dB(A), hereafter called 'problem sections'. These calculations were performed separately for urban and non-urban areas, that is four different types of settlement densities: downtown areas, central metropolitan areas, suburban areas and non-urban areas. These four types of settlement densities are defined and can be found on maps prepared by the Federal Office of Statistics.

Stage 2: Calculation of costs of noise-abatement measures along roads with high noise immissions along which windows need soundproofing (problem sections). Along roads the main means considered to reduce noise emissions were noise-damping windows, along motorways noise-damping walls were considered.

18.6.1 Calculation of noise-abatement costs

The calculation of the costs per kilometer of noise-abatement measures in Switzerland is based on the survey of settlement-densities in the immediate neighbourhood of streets. Such surveys can be repeated for any country and depend on the quality of the maps available.

The number of windows per street-kilometer is a function of the numbers of floors and the average ratio of the surface of windows to the exposed housefronts. These data are statistically registered in Switzerland. By comparison of such statistical figures with analogue figures of another country, structural differences can be quantified and included in the calculations. If necessary, windows could be counted the same way as it was done in Switzerland, namely along a representative sample of streets. The cost of noise-damping windows and of noise-absorbing walls will require to be found for the various countries from the industries concerned. When the problem-section and noise-abatement costs per kilometer are known, the overall costs of noise-abatement can be calculated for all the areas exceeding the sound levels of $L_{eq} = 65$ dB(A), = 70 dB(A) and 75 dB(A).

18.7 MEDICO-LEGAL ASPECTS

In order to protect the health of an ever greater number of workers exposed to harmful noise produced by machines, a general expression forthcoming from the Eleventh Congress of AICB was that the equipment, regulations, specifications and instructions concerning noise encountered at the workbench in all countries should be more strictly obeyed to than heretofore.

The sanitary and technical control of noise in the existing industrial works and plants should be improved. At the workbench, where the binding limiting values are still exceeded, because of technical reasons, the working conditions should be such as to ensure the safety of the working personnel. The workers should be provided with means of individual ear protection, if required.

The aim of all these precautions in the field of safety of work is the prevention of functional disturbances caused by noise, as well as to avoid a drop in productivity.

Especially important in the determination of the extent of the harmful influence of noise are the clinic examinations of great numbers of workers with the objective of determining preliminary pathological states and diagnostics of early forms of illness.

The determination of limit values of noise, permissible from the hygienic point of view, should be based upon hygienic physiological and clinical parameters. When determining standard optimum values from the hygienic point of view, attention should be paid both to harmful influence of noise to human ears, as well as to the other organs of the human body.

The kind of work should be additionally taken into account, special attention being devoted to activities which require considerable neuro emotional strain, or are connected with a considerable psychosensory strain.

During the research and development work and implementation of its results, the following factors should be taken into account:

- —The exposure to harmful noise not only leads to morbid circulations symptoms, and other neurovegetative reactions, but also can lead to a greater risk of some other diseases in case of a prolonged exposure to the action of a strong or even moderate noise.
- —Investigations of a combined effect of noise together with the influence of some other harmful factors, such as vibrations, elevated temperature, toxical substances, dust, mental strain and other stress factors, should be continued on a broader base than heretofore.
- —More attention should be paid to infrasonic and ultrasonic vibrations, and namely to the methods of measurements, frequency and intensity of these vibrations aimed at the determination of the values decisive for the transmission of these vibrations through the human body and the air.
- —When checking the effect of impact noise the peak values of this noise should always be taken into account. Special attention should be given to the determination of correction coefficients of limit values in case of workers exposed to vibrations who are in the early stages of vibration illness. A special set of instructions should be provided for workers who are exposed to noise and vibration in excess of the permissible levels. Working areas demanding closer attention to noise suppression are those of the metallurgical and textile industries.
- —Should the noise level exceed 120 dB then industrial workers must wear special body protective clothing, in addition to aural protection.
- —Because of the complexity of the problems of noise suppression attenuation should also be paid to community sources of noise, since they can also exert a harmful influence on human health and efficiency of working.

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Author Index

Subject Index