

CHAPTER 5

Aural Reception

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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

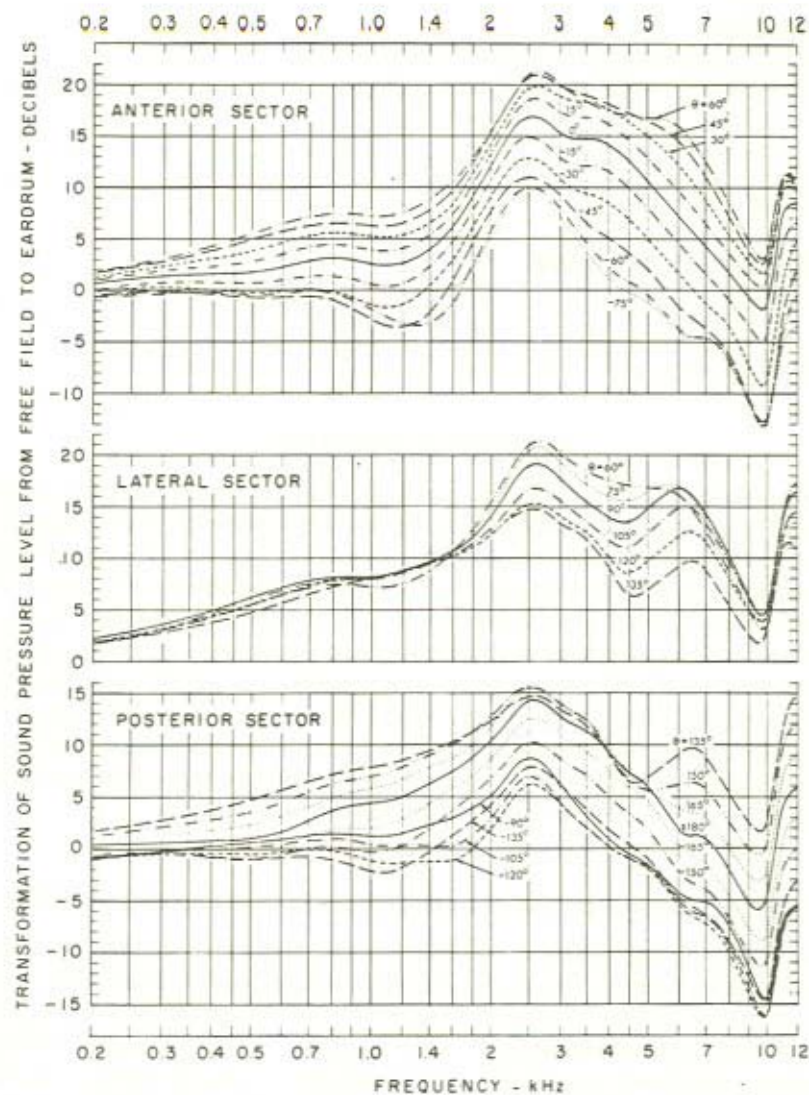


Figure 5.1 Average transformation of sound pressure level from free field to human eardrum as a function of frequency at 24 angles of incidence in the horizontal plane. Azimuth $\Theta = 0^\circ$ indicates frontal incidence. Azimuth 90° indicates that sound source is facing left ear. After Shaw (1974c)

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.

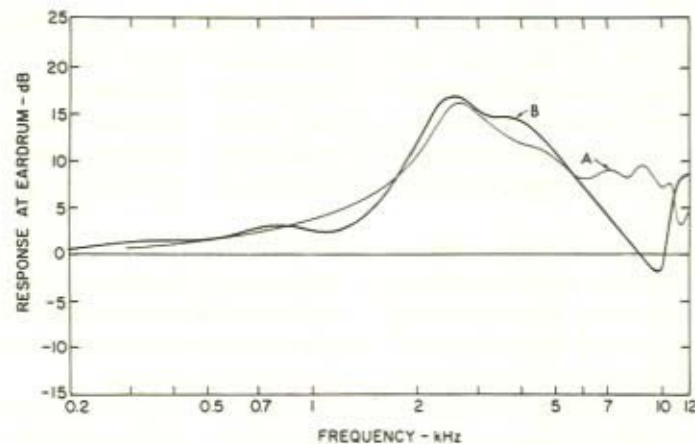


Figure 5.2 Curve A estimated average transformation of sound pressure level from diffuse (random-incidence) sound field to human eardrum as a function of frequency based on theoretical considerations and measurements with a model ear. After Shaw (1980). Curve B shows free field response with frontal incidence ($\Theta = 0^\circ$) 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

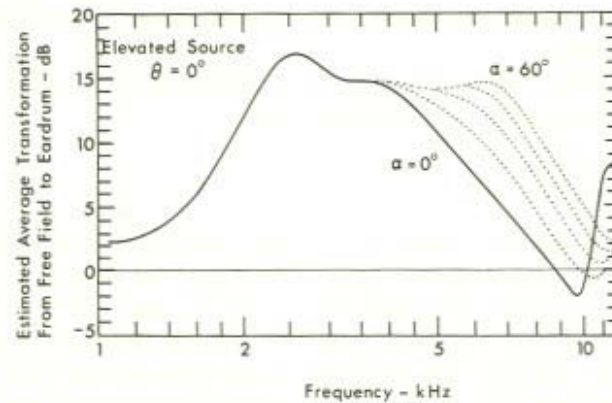


Figure 5.3 Estimated average transformation of sound pressure level from free field to eardrum as a function of frequency in symmetry plane of head at source elevations $\alpha = 0^\circ, 15^\circ, 30^\circ, 45^\circ$ and 60° . From Shaw (1974a) with permission

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 monaural spectral factor come into play in typical situations.

The nature of the monaural 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 $\theta = 60^\circ$ to $\theta = 135^\circ$. 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 ($\theta = 45^\circ, \theta = -45^\circ$). Families of difference curves are presented elsewhere (Shaw, 1974c). As can be seen, for $\theta = 45^\circ$

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 μ s. 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

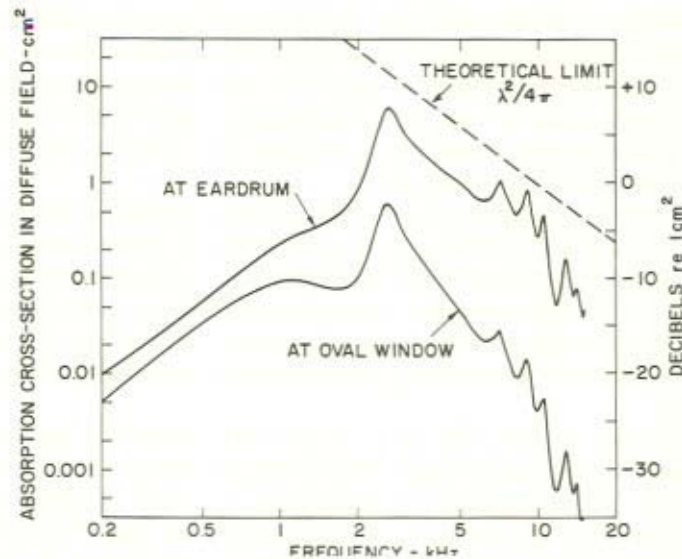


Figure 5.4 Calculated absorption cross section of human ear as a function of frequency at eardrum (upper curve) and at oval window of cochlea (lower curve) based on network representation of middle ear and on measurements with physical model of external ear. Broken line shows theoretical limit as a function 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 1/3 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

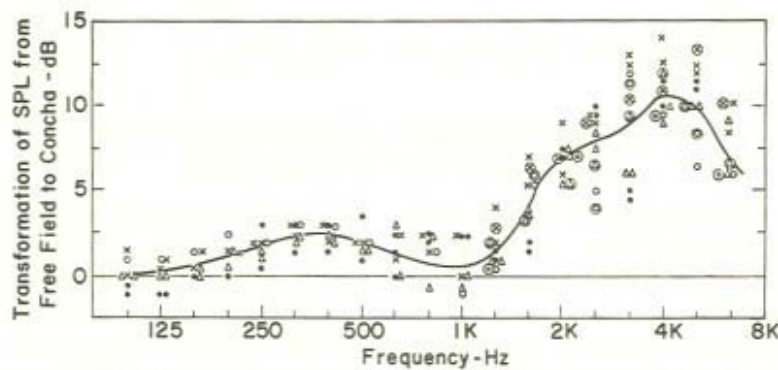


Figure 5.5 Measured transformation of sound pressure level from free field (0° azimuth, horizontal plane) to cavum of external ear as a function of frequency for four adult male subjects. After Brammer and Piercy (1977)

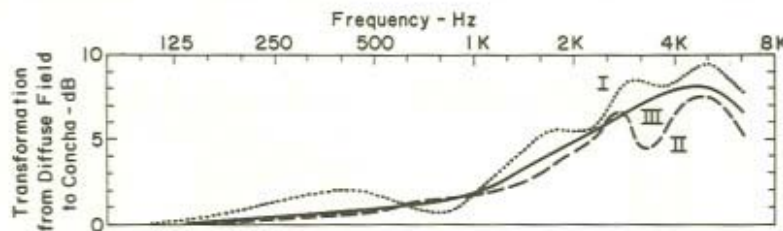


Figure 5.6 Estimates of average transformation of sound pressure level from diffuse (random-incidence) sound field to cavum of external ear as a function of frequency. Curve I: From Figures 5.2 and 5.5. Curve II: From Fig. 2 and Shaw (1974c). Curve III: Smooth curve proposed for practical use

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 dosimeter 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

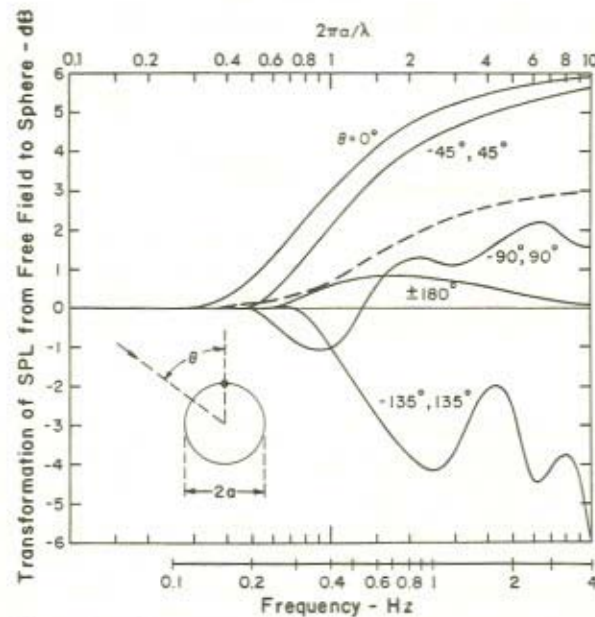


Figure 5.7 Calculated transformation of sound pressure level from free field to a point on a hard sphere of radius a as a function of $2\pi a/\lambda$ for various values of azimuth θ of incident plane waves. After Shaw (1974a). Frequency scale at bottom is for a sphere of radius 13.7 cm representing 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 ($\theta = 0, 45^\circ$ and -45°) and comparatively little change in level at grazing incidence ($\theta = \pm 90^\circ$). On the 'dark' side of the sphere (e.g. $\theta = \pm 135^\circ$) there are decreases in level except for the 'bright spot' at the centre of the dark side ($\theta = \pm 180^\circ$) 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 bottom 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

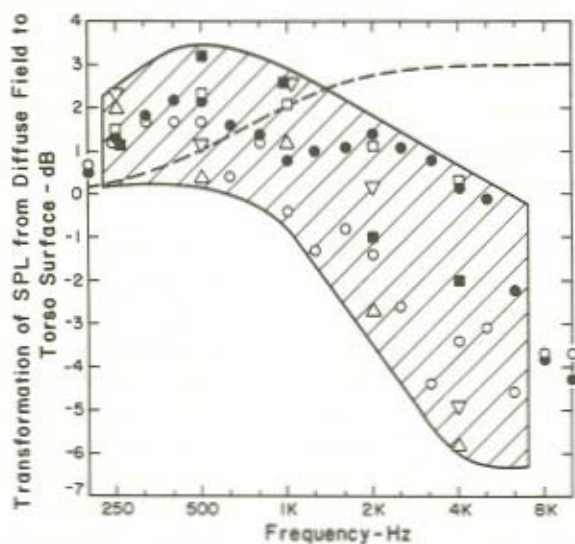


Figure 5.8 Transformation of sound pressure level from diffuse (random-incidence) sound field to torso surface as a function of frequency. Broken line shows theoretical curve for a hard sphere of radius 13.7 cm based on Kuhn (1979). Experimental points show data adapted from five experimental studies with human subjects and a mannikin clothed with shirts or jackets. Shaded area probable range of values. From Shaw (1982b)

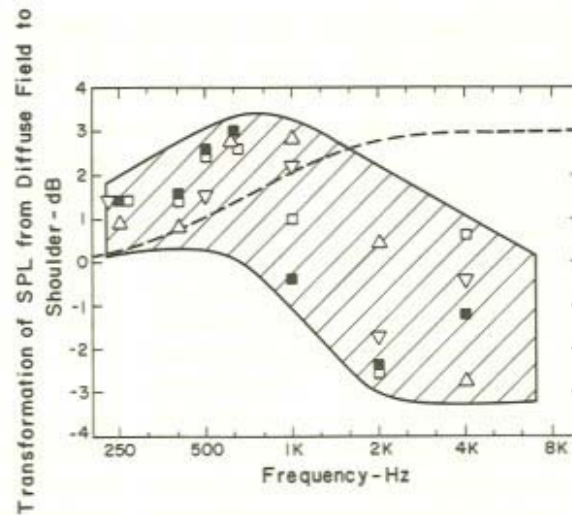


Figure 5.9 Transformation of sound pressure level from diffuse (random-incidence) sound field to shoulder as a function of frequency. Broken line shows theoretical curve for a hard sphere of radius 13.7 cm based on Kuhn (1979). Experimental points show data adapted from two experimental studies with 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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