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Hearing and Psychological Effects

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Summary

In this chapter, first the characteristics of human hearing are discussed, including a brief description of the anatomy and function of the hearing mechanisms. Next, the frequency and loudness responses of the human hearing are explained, and then hearing loss causing permanent damage is described. Finally, the psychological response to noise is discussed by defining the indices, loudness (sones), noise-criteria curves, and sound level.

13.1 Introduction

This chapter considers the characteristics of human hearing. After a brief description of the anatomy and function of the hearing mechanism, those aspects of hearing that are important in noise control are discussed. The perception of sound by the human ear is a complicated process, dependent both on the frequency and pressure amplitude of the sound. We shall consider the structure of the ear and hearing mechanism. We will also briefly discuss various means of measuring the psychological effects of noise.

13.2 Structure and Function of the Ear [1]

The main components of the human ear are depicted in [Figure 13.1\(a\)](#). The ear is commonly divided into three main components: (1) the outer ear, (2) the middle ear, and (3) the inner ear.

The visible portion of the ear is called the *pinna*. Because of its small size compared with the primary wavelengths that we hear, the pinna serves only to produce a small enhancement of the sounds that arrive from the front of the listener as compared to those which arrive from behind; that is, the human sound reception system has a small frontal directivity. The remainder of the outer ear, which consists of the ear canal terminated in the ear drum, forms a resonant cavity at about 3 kHz. This resonant or near-resonant condition allows for a nearly reflection-free termination of the *ear canal* and thus a good impedance match of the *ear drum* to the air in which the sound wave was propagated.

The middle ear consists of three small *ear bones*, the hammer, anvil, and stirrup. The middle ear serves as an impedance transformer, which matches the low impedance of the air in which sound travels and in

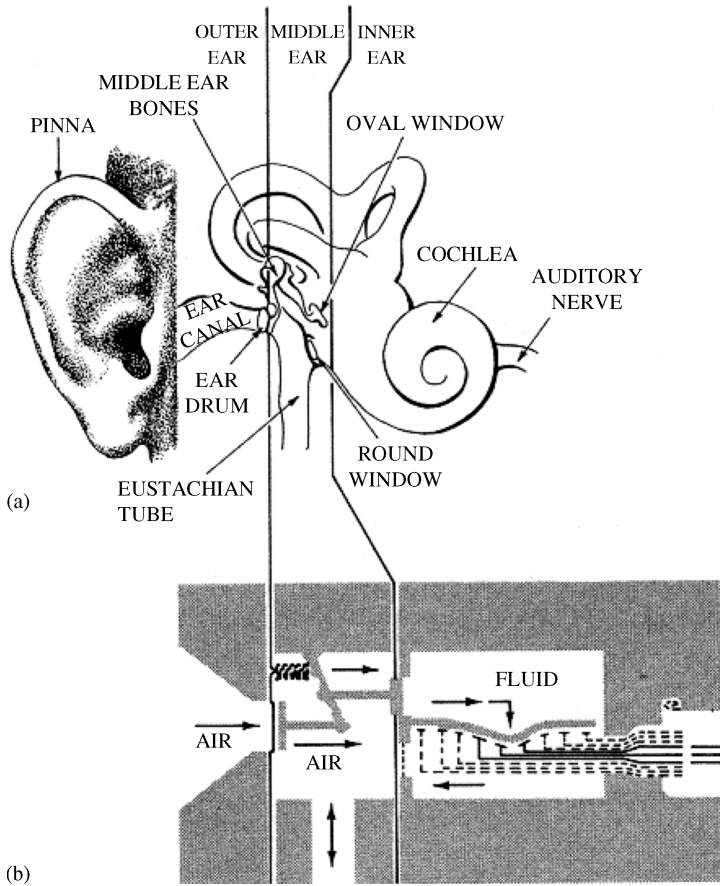


FIGURE 13.1 (a) Main components of the human ear; (b) functional diagram of the ear.

which the ear drum is located to the high impedance of the lymphatic fluid of the *cochlea* beyond the *oval window*. Without this impedance-matching transformation, a mismatch would occur, resulting in a loss of approximately 30 dB.

In the inner ear, the cochlea is the main component where the actual reception of sound takes place. The schematic extended structure of the cochlea is depicted in Figure 13.1(b). The cochlea, which is located in extremely hard temporal bone, is divided almost its entire length by the *basilar membrane*. At the end of the cochlea, the two canals are connected by the *helicotrema*, which allows for the flow of the *lymphatic fluid* between the two sections. The basilar membrane, which is about 3 cm long and 0.02 cm wide, has about 24,000 nerve ends terminated in *hair cells* located on the membrane. The motion of the oval window is transmitted to the basilar membrane and its associated sensing cells. This motion is sensed as sound.

13.3 Frequency and Loudness Response

The threshold of hearing, defined for binaural listening, is that sound pressure in the free field which one can just still hear as the signal is decreased. The threshold of hearing, for what is considered normal hearing, is shown in Figure 13.2. As seen from the curve, human hearing is most sensitive in the range of 2000 to 5000 Hz; furthermore, we note that the response in this range is very close to 0 dB, or 20×10^{-6} Pa. At the other end of the scale, there is the threshold of pain, which is usually taken as about 135 to 140 dB. Thus, there is a dynamic range of normal hearing of approximately 140 dB.

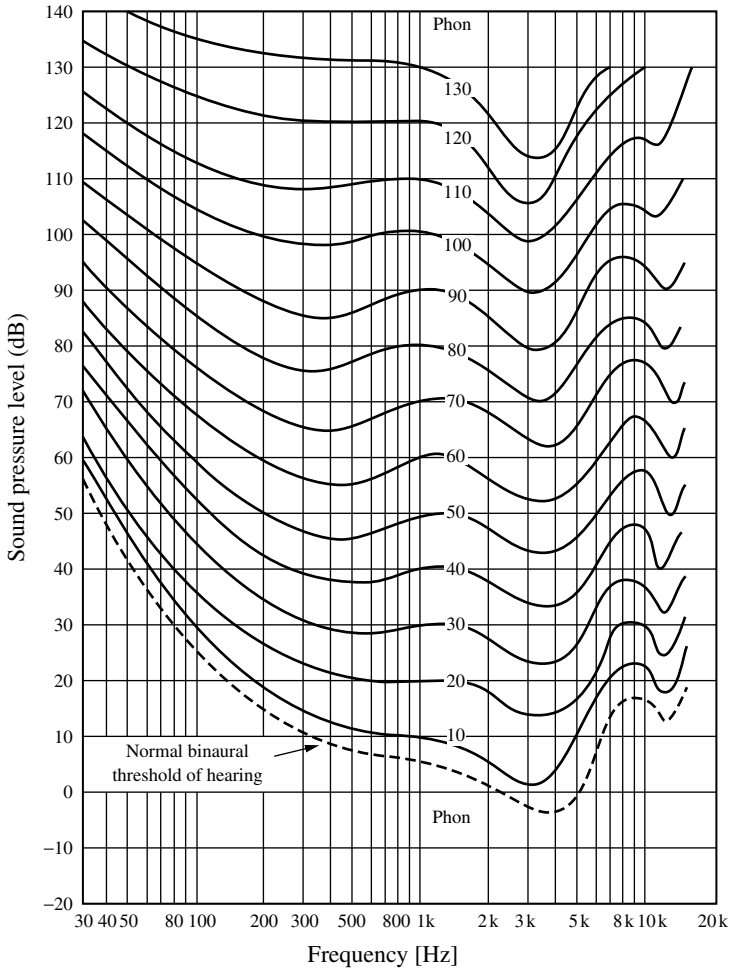


FIGURE 13.2 Equal-loudness contour for free-field binaural listening.

One also readily notes from the curve of Figure 13.2 that the threshold of hearing is a function of frequency. For example, with normal hearing, one would just be able to hear a 2000 Hz tone at a 0 dB level. However, one would require a pressure level of about 15 dB to be able to barely hear a 200 Hz tone. Thus, in describing the subjective loudness of sound, it is necessary to consider the characteristics of the human ear. This concept of loudness is quantized by the loudness level.

The *loudness* level of a particular sound is determined by the subjective comparison of the loudness of the sound to that of a 1000 Hz pure tone. The level, measured in *phons*, is equal numerically to the sound pressure level, in dB, of the 1000 Hz tone, which was regarded to be of equal loudness. A set of internationally standardized equal loudness contours is plotted in Figure 13.2. In keeping with the definition of loudness level, note that at 1000 Hz, all the equal loudness contours are equal in phons to the sound pressure level in dB.

Example 13.1

Determine the sound pressure level of a 100 Hz tone with a loudness level of 30 phon.

Solution

From Figure 13.2, we find the sound pressure level to be 44 dB.

13.4 Hearing Loss

Excessive and prolonged noise exposure causes permanent hearing loss. Various theories have been put forth in an effort to characterize and predict the possible damage that might be caused by a given exposure. Absolute proof of any theory concerning such a complex biological phenomenon is virtually impossible to achieve. However, reliable data have been collected, which deal with situations where workers have been continuously exposed to more or less the same noise environment for many years.

It is well established that excessive noise exposure causes permanent hearing damage by destroying the auditory sensor cells. These cells are hair cells located on the basilar membrane. Furthermore, other types of inner ear damage include harm to the auditory neurons, as well as damage to the structure of the organ of Corti. In all, the various theories and data have been taken advantage of establishing the noise-exposure criteria set forth in the noise exposure regulations.

13.5 Psychological Effects of Noise

In this section, certain generally accepted aspects of the psychological effects of noise will be discussed and quantified. Various indexes have been proposed that quantify the psychological effects of noise. However, only a few of indices, *loudness (sones)*, *noise-criteria (NC) curve*, and *sound level*, are introduced in the following presentation.

13.5.1 Loudness Interpretation

As was discussed relating to [Figure 13.2](#), loudness level is measured in phons, and the related quantity, loudness, is measured in *sones*. A sone is defined as the loudness of a 1000 Hz pure tone with a sound pressure level of 40 dB. On recalling the definition of loudness level, or by referring to [Figure 13.2](#), one notes that 40 phon have a loudness equal to 1 sone. This relationship may be simply expressed as

$$S = 2^{(L_L - 40)/10} \text{ sone} \quad (13.1)$$

where S = loudness (sones), L_L = loudness level (phons), or conversely

$$L_L = 33.2 \log S + 40 \text{ phon} \quad (13.2)$$

Example 13.2

Make the following two conversions using the appropriate equation (Equation 13.1 or Equation 13.2):

(1) convert 80 phon to sone, (2) convert 100 sone to phon.

Solution

1. To convert phons to sones, use Equation 13.2:

$$S = 2^{(L_L - 40)/10} = 2^{(80 - 40)/10} = 2^4 = 16 \text{ sone}$$

2. To convert sones to phons, use Equation 13.2:

$$L_L = 33.2 \log S + 40 = 33.2 \log 100 + 40 = 66.4 + 40 = 106.4 \text{ phon}$$

How should we determine the “total loudness” (sones), when the sound is composed of multiple frequency components? Probably the most widely used method for establishing the loudness of a complex noise is that developed by Stevens [2]. The method is based on the measurement of the 1-octave, 1/3-octave, or 1/2-octave band pressure levels. The measured band pressure levels are used

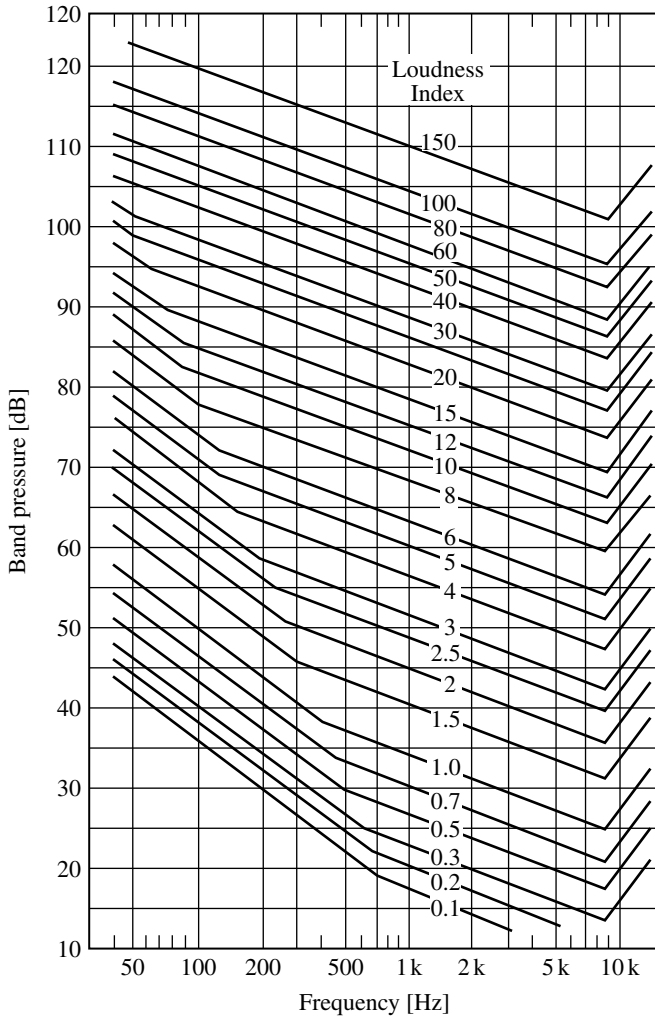


FIGURE 13.3 Equal loudness index contour [2].

in conjunction with the equal loudness index contours shown in Figure 13.3 to determine the loudness or loudness level by means of a simple calculation.

A step-by-step outline of the procedure is as follows:

1. Measure the band pressure levels (1-octave, 1/2-octave, or 1/3-octave) over the frequency range of interest. Usually, the range chosen is from about 50 to 10,000 Hz.
2. Enter the center frequency and band pressure level for each band in the contour of Figure 13.3, and determine the loudness index for each band.
3. Calculate the total loudness, S_t , in sones, by using

$$S_t = I_m(1 - K) + K \sum_{i=1}^n I_i \text{ (sone)} \tag{13.3}$$

where S_t = the total loudness (sones), I_m = the largest of the loudness indices, I_i = the loudness indices, including I_m , K = weighting factor for the bands chosen. $K = 0.3$ for 1-octave bands, $K = 0.2$ for 1/2-octave bands, $K = 0.15$ for 1/3-octave bands.

- If so desired, one may calculate the loudness level in phons using Equation 13.2, or one may convert to loudness level by means of the conversion curve of Figure 13.3.

Example 13.3

A particular complex noise was measured to yield the one-octave band pressure given in the following table

Center Frequency (Hz)	Band Pressure Level (dB)	Loudness Index (sone)
63	66	2.5
125	63	3.2
250	65	4.8
500	70	7.5
1000	73	10.6
2000	76	15.2
4000	81	25.1
8000	79	29.0

Compute the loudness level using the procedure described before.

Solution

As a first step, the loudness indices are determined from Figure 13.3 and recorded in tabular form with the band pressure levels. Next, we note that one-octave bands have been used. Therefore $K = 0.3$ in Equation 13.3, and

$$S_t = I_m(1 - 0.3) + 0.3 \sum_{i=1}^8 I_i$$

From the table above, we find that $I_m = 29.0$ sone and, summing up, find $\sum I_i = 97.9$ sone. Therefore,

$$S_t = 29(1 - 0.3) + 0.3(97.9) = 49.67 \text{ sone}$$

We find that the loudness, $S_t \cong 50$ sone. The loudness level may now be calculated by means of Equation 13.2 as

$$L_L = 33.2 \log S_t + 40 = 33.2 \log 50 + 40 = 96.4 \text{ phon}$$

Therefore, L_L , the loudness level, is 96 phon.

13.5.2 Noise-Criteria Curves

Noise-criteria curves, which are neglected here, were established in 1957 for rating indoor noise. The curves have been utilized as one method of rating background noise level in a room. Each curve specifies the maximum octave-band sound pressure level for a given NC rating. If the octave band levels for a given noise spectrum are known, the rating of that noise in terms of the NC curves is given by plotting the noise spectrum on the set of NC curves to determine the point of highest penetration.

In 1971, some objections to the NC curves led to their modification. The new curves, which are shown in Figure 13.4, are called the *preferred noise-criteria* (PNC) curves. Although these curves differ from the NC curves, they are used in exactly the same manner.

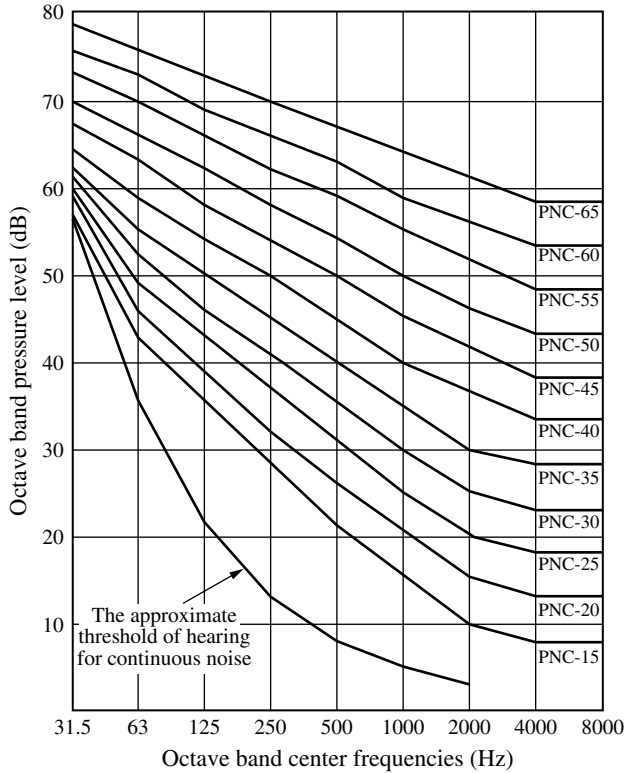


FIGURE 13.4 1971 preferred noise-criteria curves.

Example 13.4

Determine the PNC rating for the octave-band noise spectrum tabulated below.

Center frequency (Hz)	63	125	250	500	1000	2000	4000	8000
Band pressure level (dB)	65	60	60	63	55	50	45	40

Solution

The highest penetration is found at 500 Hz on PNC-60. Hence, the answer is PNC-60.

13.5.3 Sound Level

Sound levels are sound pressure levels that have been weighted according to a particular weighting curve. Three weightings, A, B, and C, and associated sound levels, have been developed as a method to subjectively evaluate the impact of noise upon the human ear, in a proper manner. The frequency response and decibel conversions from a flat response for each of these weightings are given in Figure 13.5 and Table 13.1, respectively.

The A-weighting network is now used almost exclusively in measurements that relate directly to the human response to noise, both from the viewpoint of hearing damage and of annoyance. Such measurements are referred to as sound level measurements. Sound level is designated by L and the designated unit is the dBA. Similarly, dBB and dBC are used to designate sound level weighted by B weighting and C weighting networks, respectively.

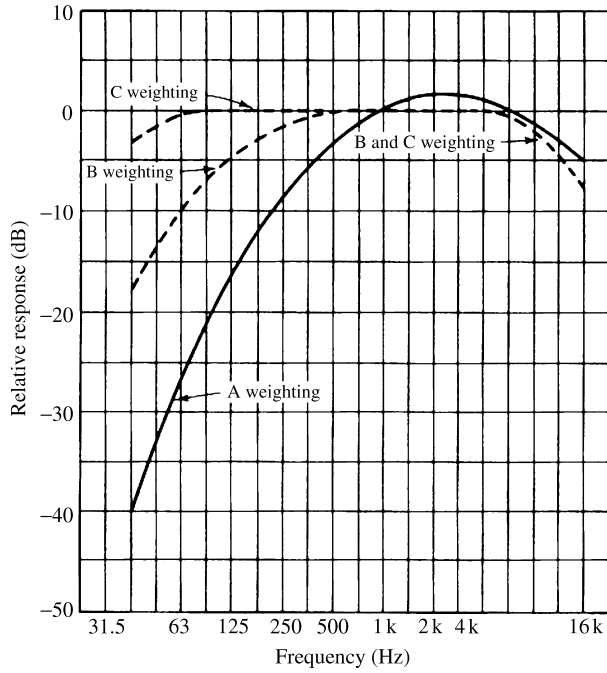


FIGURE 13.5 Frequency response for the A, B, and C weighting networks.

TABLE 13.1 Sound Level Conversion Chart from Flat Response to A Weighting

Frequency (Hz)	A Weighting (dB)
50	-30.2
63	-26.2
80	-22.5
100	-19.1
125	-16.1
160	-13.4
200	-10.9
250	-8.6
315	-6.6
400	-4.8
500	-3.2
630	-1.9
800	-0.8
1,000	0
1,250	+0.6
1,600	+1.0
2,000	+1.2
2,500	+1.3
3,150	+1.2
4,000	+1.0
5,000	+0.5
6,300	-0.1
8,000	-1.1
10,000	-2.5
12,500	-4.3
16,000	-6.6

TABLE 13.2 Octave-Band Sound Pressure Levels

f_c (Hz)	L_{flat} (dB)	ΔL_A (dB)	$L_A = L_{flat} + \Delta L$ (dB)	I_{iA}
63	74	-26.2	47.8	0.60×10^5
125	71	-16.1	54.9	3.09
250	61	-8.6	52.4	1.74
500	60	-3.2	56.8	6.31
1000	62	0	62.0	1.585×10^6
2000	60	1.2	61.2	1.318
4000	62	1.0	63.0	1.995
8000	69	-1.1	67.9	6.166
Sum				12.238×10^6

Note:

- f_c : band center frequency
- L_{flat} : sound pressure level with flat weighting
- ΔL_A : A-weighting level
- I_{iA} : sound pressure intensity with A weighting.

In noise-abatement problems, it is often necessary to convert calculated a 1-octave-band or 1/3-octave-band sound pressure level to a total sound level in dBA. Table 13.1 gives sound level conversion by A weighting from flat response pressure.

Example 13.5

Determine the total A weight sound level, L , of the set of octave-band sound pressure levels given in Table 13.2.

Solution

Refer Table 13.1 for the dB conversion from a flat response level, L_{flat} , for each of the octave bands to a sound pressure intensity with A weighting I_{iA} , and then the sum of I_{iA} . Finally, the total sound level with A weighting $L_{total,A}$ is given by

$$L_{total,A} = 10 \log \sum_{i=1}^n I_{iA} = 10 \log 12.238 \times 10^6 = 70.9 \text{ (dB)}$$

References

1. Irwin, J.D. and Graf, E.R. 1979. *Industrial Noise and Vibration Control*, Prentice Hall, Englewood Cliffs, NJ.
2. American National Standard USAS S3.4-1968. 1968. *Procedure for the Computation of Loudness of Noise*, America National Standards Institute, New York, NY.