1.1 BASIC QUANTITIES OF SOUND WAVES

Sound Waves and Noise

In the broadest sense, a sound wave is any disturbance that is propagated in an elastic medium, which may be a gas, a liquid, or a solid. Ultrasonic, sonic, and infrasonic waves are included in this definition. Most of this text deals with sonic waves, those sound waves that can be perceived by the hearing sense of a human being. Noise is defined as any perceived sound that is objectionable to a human being. The concepts basic to this chapter can be found in references 1–7. Portions are further expanded in Chapter 2.

Sound Pressure

A person who is not deaf perceives as sound any vibration of the eardrum in the audible frequency range that results from an incremental variation in air pressure at the ear. A variation in pressure above and below atmospheric pressure is called sound pressure, in units of pascals (Pa). A young person with normal hearing can perceive sound in the frequency range of roughly 15 Hz (hertz) to 16,000 Hz, defined as the normal audible frequency range.

Because the hearing mechanism responds to sound pressure, it is one of two quantities that is usually measured in engineering acoustics. The normal ear is most sensitive at frequencies between 3000 and 6000 Hz, and a young person can detect pressures as low as about 20 µPa, which, when compared to the normal atmospheric pressure (101.3 × 10^5 Pa) around which it varies, is a fractional variation of 2 × 10^−10.

*One pascal (Pa) = 1 newton/meter squared (N/m²) = 10 dynes/cm²*
BASIC ACOUSTICAL QUANTITIES: LEVELS AND DECIBELS

Pure Tone
A pure tone is a sound wave that can be represented by the equation,

\[ p(t) = p_0 \sin(2\pi ft) \]  

(1.1)

where \( p(t) \) is the instantaneous, incremental, sound pressure (above and below atmospheric pressure), \( p_0 \) is the maximum amplitude of the instantaneous sound pressure, and \( f \) is the frequency, that is, the number of cycles per second, expressed in hertz. The time \( t \) is in seconds.

Period
A full cycle occurs when \( t \) varies from zero to \( 1/f \). The \( 1/f \) quantity is known as the period \( T \). For example, the period \( T \) of a 500-Hz wave is 0.002 sec.

Root-Mean-Square Amplitude
If we wish to determine the mean value of a full cycle of the sine wave of Eq. (1.1) (or any number of full cycles), it will be zero because the positive part equals the negative part. Thus, the mean value is not a useful measure. We must look for a measure that permits the effects of the rarefactions to be added to (rather than subtracted from) the effects of the compressions.

One such measure is the root-mean-square (rms) sound pressure \( p_{\text{rms}} \). It is obtained, first, by squaring the value of the sound pressure disturbance \( p(t) \) at each instant of time. Next the squared values are added and averaged over one or more periods. The rms sound pressure is the square root of this time average. The rms value is also called the effective value. Thus

\[ p_{\text{rms}}^2 = \frac{1}{2} p_0^2 \]  

(1.2)

or

\[ p_{\text{rms}} = 0.707 p_0 \]  

(1.3)

In the case of nonperiodic sound pressures, the integration interval should be long enough to make the rms value obtained essentially independent of small changes in the length of the interval.

Sound Spectra
A sound wave may be comprised of a pure tone (single frequency, e.g., 1000 Hz), a combination of single frequencies harmonically related, or a combination of single frequencies not harmonically related, either finite or infinite in number. A combination of a finite number of tones is said to have a line spectrum. A combination of an infinite (large) number of tones has a continuous spectrum. A continuous-spectrum noise for which the amplitudes versus time occur with a
normal (Gaussian) distribution is called random noise. Three of these types of noise are shown by the frequency spectra in Figs. 1.1a–c. A combination of a line and a continuous spectrum, called a complex spectrum, is shown in Fig. 1.1d.

Regardless of which type of sound wave is considered, when propagating at normal sound pressure amplitudes (to avoid nonlinearity) in air over reasonably short distances (so that sound attenuation in the air itself, which becomes significant at frequencies above 1000 Hz, can be neglected), the waveform is unchanged. Thus, a violin heard at a distance of 30 m sounds the same as at 5 m, although it is less loud.

**Sound Intensity**

The second quantity commonly measured in engineering acoustics is sound intensity, defined as the continuous flow of power carried by a sound wave through an incrementally small area at a point in space. The units are watts per square meter (W/m²). This quantity is important for two reasons. First, at a point in free space, it is related to the total power radiated into the air by a sound source and, second, it bears at that point a fixed relation to the sound pressure.

Sound intensity at a point is directional (a vector) in the sense that the position of the plane of the incrementally small area can vary from being perpendicular
to the direction in which the wave is traveling to being parallel to that direction. It has its maximum value, \( I_{\text{max}} \), when its plane is perpendicular to the direction of travel. When parallel, the sound intensity is zero. In between, the component of \( I_{\text{max}} \) varies as the cosine of the angle formed by the direction of travel and a line perpendicular to the incremental area.

Another equation, which we shall develop in the next chapter, relates sound pressure to sound intensity. In an environment in which there are no reflecting surfaces, the sound pressure at any point in any type of freely traveling (plane, cylindrical, spherical, etc.) wave is related to the maximum intensity \( I_{\text{max}} \) by

\[
p_{\text{rms}}^2 = I_{\text{max}} \cdot \rho c \quad \text{Pa}^2
\]

where
- \( p_{\text{rms}} \) = rms sound pressure, Pa (N/m²)
- \( \rho \) = density of air, kg/m³
- \( c \) = speed of sound in air, m/s [see Eq. (1.7)]
- \( N \) = force, N

**Sound Power**

A sound source radiates a measurable amount of power into the surrounding air, called sound power, in watts. If the source is nondirectional, it is said to be a spherical sound source (see Fig. 1.2). For such a sound source the measured (maximum) sound intensities at all points on an imaginary spherical surface centered on the acoustic center of the source are equal. Mathematically,

\[
W_s = (4\pi r^2)I_s(r) \quad \text{W}
\]

where
- \( I_s(r) \) = maximum sound intensity at radius \( r \) at surface of an imaginary sphere surrounding source, W/m²
- \( W_s \) = total sound power radiated by source in watts, W (N · m/s)
- \( r \) = distance from acoustical center of source to surface of imaginary sphere, m

A similar statement can be made about a line source; that is, the maximum sound intensities at all points on an imaginary cylindrical surface around a cylindrical sound source, \( I_c(r) \), are equal:

\[
W_c = (2\pi rl)I_c(r) \quad \text{W}
\]

where
- \( W_c \) = total sound power radiated by cylinder of length \( l \), W
- \( r \) = distance from acoustical centerline of cylindrical source to imaginary cylindrical surface surrounding source

**Inverse Square Law**

With a spherical source, the radiated sound wave is spherical and the total power radiated in all directions is \( W \). The sound intensity \( I(r) \) must decrease with
BASIC QUANTITIES OF SOUND WAVES

The area of the wavefront is 4 times greater at d₂ (2 m)

Area of the wavefront at d₁ (1 m)

Distance in proportion to the sound pressure squared, that is \( W/4\pi r^2 \) [Eq. (1.5)]. Hence the name inverse square law. This is illustrated by the diagram in Fig. 1.2, where at a distance of 1 m the area of the wave front shown is \( a \) square meters and at 2 m it becomes 4\( a \) square meters. To preserve sound energy, the same amount of power flows through the larger area; thus Fig. 1.2 diagrammatically shows the intensity decreasing by a factor of 4, or, as shown later, 6 dB, from 72 to 66 dB.

Particle Velocity

Consider that the surface of the spherical source of Fig. 1.2 is expanding and contracting sinusoidally. During the first half of its sinusoidal motion, it pushes the air particles near its surface outward. Because air is elastic and compresses, the pressure near the surface will increase. This increased pressure overcomes the inertia of the air particles a short distance away and they move outward. That outward movement causes the pressure to build up at this new distance and, in turn, pushes more removed particles outward. This outward movement of the disturbance takes place at the speed of sound.

In the next half of the sinusoid, the sinusoidally vibrating spherical source reverses direction, creating a drop of pressure near its surface that pulls nearby
air particles toward it. This reverse disturbance also propagates outward with
the speed of sound. Thus, at any one point in space, there will be sinusoidal
to-and-fro movement of the particles, called the particle velocity. Also at any
point, there will be sinusoidal rise and fall of sound pressure.

From the basic equations governing the propagation of sound, as is shown in
the next chapter, we can say the following:

1. In a plane wave (approximated at a large distance from a point source)
propagated in free space (no reflecting surfaces) the sound pressure and
the particle velocity reach their maximum and minimum values at the same
instant and are said to be in phase.
2. In such a wave the particles move back and forth along the line in which the
wave is traveling. In reference to the spherical radiation discussed above,
this means that the particle velocity is always perpendicular to the imagi-
nary spherical surface (the wave front) in space. This type of wave is called
a longitudinal, or compressional, wave. By contrast, a transverse wave is
illustrated by a surface wave in water where the particle velocity is per-
pendicular to the water surface while the wave propagates in a direction
parallel to the surface.

**Speed of Sound**

A sound wave travels outward at a rate dependent on the elasticity and density
doing the air. Mathematically, the speed of sound in air is calculated as

\[ c = \sqrt{\frac{1.4P_s}{\rho}} \text{ m/s} \]  

where \( P_s \) = atmospheric (ambient) pressure, Pa
\( \rho \) = density of air, kg/m\(^3\)

For all practical purposes, the speed of sound is dependent only on the absolute
temperature of the air. The equations for the speed of sound are

\[ c = 20.05\sqrt{T} \text{ m/s} \]  \( (1.8) \)
\[ c = 49.03\sqrt{R} \text{ ft/s} \]  \( (1.9) \)

where \( T \) = absolute temperature of air in degrees Kelvin, equal to 273.2
plus the temperature in degrees Celsius
\( R \) = absolute temperature in degrees Rankine, equal to 459.7 plus the
temperature in degrees Fahrenheit

For temperatures near 20°С (68°F), the speed of sound is

\[ c = 331.5 + 0.58°\text{С} \text{ m/s} \]  \( (1.10) \)
\[ c = 1054 + 1.07°\text{F} \text{ ft/s} \]  \( (1.11) \)
Wavelength

Wavelength is defined as the distance the pure-tone wave travels during a full period. It is denoted by the Greek letter $\lambda$ and is equal to the speed of sound divided by the frequency of the pure tone:

$$\lambda = \frac{c}{f} \text{ m}$$  \hspace{1cm} (1.12)

Sound Energy Density

In standing-wave situations, such as sound waves in closed, rigid-wall tubes, rooms containing little sound-absorbing material, or reverberation chambers, the quantity desired is not sound intensity, but rather the sound energy density, namely, the energy (kinetic and potential) stored in a small volume of air in the room owing to the presence of the standing-wave field. The relation between the space-averaged sound energy density $D$ and the space-averaged squared sound pressure is

$$D = \frac{p_{\text{av}}^2}{\rho c^2} = \frac{p_{\text{av}}^2}{1.4 P_s} \text{ W} \cdot \text{s/m}^3 \text{ (J/m}^3 \text{ or simply N/m}^2)$$  \hspace{1cm} (1.13)

where $p_{\text{av}}^2$ = space average of mean-square sound pressure in a space, determined from data obtained by moving a microphone along a tube or around a room or from samples at various points, Pa$^2$

$P_s$ = atmospheric pressure, Pa; under normal atmospheric conditions, at sea level, $P_s = 1.013 \times 10^5$ Pa

1.2 SOUND SPECTRA

In the previous section we described sound waves with line and continuous spectra. Here we shall discuss how to quantify such spectra.

Continuous Spectra

As stated before, a continuous spectrum can be represented by a large number of pure tones between two frequency limits, whether those limits are apart 1 Hz or thousands of hertz (see Fig. 1.3). Because the hearing system extends over a large frequency range and is not equally sensitive to all frequencies, it is customary to measure a continuous-spectrum sound in a series of contiguous frequency bands using a sound analyzer.

Customary bandwidths are one-third octave and one octave (see Fig. 1.4 and Table 1.1). The rms value of such a filtered sound pressure is called the one-third-octave-band or the octave-band sound pressure, respectively. If the filter bandwidth is 1 Hz, a plot of the filtered mean-square pressure of a continuous-spectrum
FIGURE 1.3 Power spectral density spectra showing the linear growth of total mean-square sound pressure when the bandwidth of noise is increased. In each case, $p_1^2$ is the mean-square sound pressure in a band 1 Hz wide.

FIGURE 1.4 Frequency response of one manufacturer's octave-band filter. The 3-dB down points for the octave band and for a one-third-octave-band filter are indicated.
TABLE 1.1 Center and Approximate Cutoff Frequencies (Hz) for Standard Set of Contiguous-Octave and One-Third-Octave Bands Covering Audio Frequency Range

<table>
<thead>
<tr>
<th>Octave</th>
<th>Lower Band Limit</th>
<th>Lower Band Center</th>
<th>Lower Band Limit</th>
<th>Upper Band Limit</th>
<th>Upper Band Center</th>
<th>Upper Band Limit</th>
</tr>
</thead>
<tbody>
<tr>
<td>12</td>
<td>11</td>
<td>16</td>
<td>22</td>
<td>14.1</td>
<td>16</td>
<td>17.8</td>
</tr>
<tr>
<td>13</td>
<td></td>
<td></td>
<td></td>
<td>17.8</td>
<td>20</td>
<td>22.4</td>
</tr>
<tr>
<td>14</td>
<td></td>
<td></td>
<td></td>
<td>22.4</td>
<td>25</td>
<td>28.2</td>
</tr>
<tr>
<td>15</td>
<td>22</td>
<td>31.5</td>
<td>44</td>
<td>28.2</td>
<td>31.5</td>
<td>35.5</td>
</tr>
<tr>
<td>16</td>
<td></td>
<td></td>
<td></td>
<td>35.5</td>
<td>40</td>
<td>44.7</td>
</tr>
<tr>
<td>17</td>
<td></td>
<td></td>
<td></td>
<td>44.7</td>
<td>50</td>
<td>56.2</td>
</tr>
<tr>
<td>18</td>
<td>44</td>
<td>63</td>
<td>88</td>
<td>56.2</td>
<td>63</td>
<td>70.8</td>
</tr>
<tr>
<td>19</td>
<td></td>
<td></td>
<td></td>
<td>70.8</td>
<td>80</td>
<td>89.1</td>
</tr>
<tr>
<td>20</td>
<td></td>
<td></td>
<td></td>
<td>89.1</td>
<td>100</td>
<td>112</td>
</tr>
<tr>
<td>21</td>
<td>88</td>
<td>125</td>
<td>177</td>
<td>112</td>
<td>125</td>
<td>141</td>
</tr>
<tr>
<td>22</td>
<td></td>
<td></td>
<td></td>
<td>141</td>
<td>160</td>
<td>178</td>
</tr>
<tr>
<td>23</td>
<td></td>
<td></td>
<td></td>
<td>178</td>
<td>200</td>
<td>224</td>
</tr>
<tr>
<td>24</td>
<td>177</td>
<td>250</td>
<td>355</td>
<td>224</td>
<td>250</td>
<td>282</td>
</tr>
<tr>
<td>25</td>
<td></td>
<td></td>
<td></td>
<td>282</td>
<td>315</td>
<td>355</td>
</tr>
<tr>
<td>26</td>
<td></td>
<td></td>
<td></td>
<td>355</td>
<td>400</td>
<td>447</td>
</tr>
<tr>
<td>27</td>
<td>355</td>
<td>500</td>
<td>710</td>
<td>447</td>
<td>500</td>
<td>562</td>
</tr>
<tr>
<td>28</td>
<td></td>
<td></td>
<td></td>
<td>562</td>
<td>630</td>
<td>708</td>
</tr>
<tr>
<td>29</td>
<td></td>
<td></td>
<td></td>
<td>708</td>
<td>800</td>
<td>891</td>
</tr>
<tr>
<td>30</td>
<td>710</td>
<td>1,000</td>
<td>1,420</td>
<td>891</td>
<td>1,000</td>
<td>1,122</td>
</tr>
<tr>
<td>31</td>
<td></td>
<td></td>
<td></td>
<td>1,122</td>
<td>1,250</td>
<td>1,413</td>
</tr>
<tr>
<td>32</td>
<td></td>
<td></td>
<td></td>
<td>1,413</td>
<td>1,600</td>
<td>1,778</td>
</tr>
<tr>
<td>33</td>
<td>1,420</td>
<td>2,000</td>
<td>2,840</td>
<td>1,778</td>
<td>2,000</td>
<td>2,239</td>
</tr>
<tr>
<td>34</td>
<td></td>
<td></td>
<td></td>
<td>2,239</td>
<td>2,500</td>
<td>2,818</td>
</tr>
<tr>
<td>35</td>
<td></td>
<td></td>
<td></td>
<td>2,818</td>
<td>3,150</td>
<td>3,548</td>
</tr>
<tr>
<td>36</td>
<td>2,840</td>
<td>4,000</td>
<td>5,680</td>
<td>3,548</td>
<td>4,000</td>
<td>4,467</td>
</tr>
<tr>
<td>37</td>
<td></td>
<td></td>
<td></td>
<td>4,467</td>
<td>5,000</td>
<td>5,623</td>
</tr>
<tr>
<td>38</td>
<td></td>
<td></td>
<td></td>
<td>5,623</td>
<td>6,300</td>
<td>7,079</td>
</tr>
<tr>
<td>39</td>
<td>5,680</td>
<td>8,000</td>
<td>11,360</td>
<td>7,079</td>
<td>8,000</td>
<td>8,913</td>
</tr>
<tr>
<td>40</td>
<td></td>
<td></td>
<td></td>
<td>8,913</td>
<td>10,000</td>
<td>11,220</td>
</tr>
<tr>
<td>41</td>
<td></td>
<td></td>
<td></td>
<td>11,220</td>
<td>12,500</td>
<td>14,130</td>
</tr>
<tr>
<td>42</td>
<td>11,360</td>
<td>16,000</td>
<td>22,720</td>
<td>14,130</td>
<td>16,000</td>
<td>17,780</td>
</tr>
<tr>
<td>43</td>
<td></td>
<td></td>
<td></td>
<td>17,780</td>
<td>20,000</td>
<td>22,390</td>
</tr>
</tbody>
</table>

\(^a\)From Ref. 6.

Sound versus frequency is called the power spectral (or spectrum) density spectrum. Narrow bandwidths are commonly used in analyses of machinery noise and vibration, but the term “spectral density” has no meaning in cases where pure tones are being measured.

The mean-square (or rms) sound pressure can be determined for each of the contiguous frequency bands and the result plotted as a function of frequency (Fig. 1.3e).
Bandwidth Conversion. It is frequently necessary to convert sounds measured with one set of bandwidths to a different set of bandwidths or to reduce both sets of measurements to a third set of bandwidths. Let us imagine that we have a machine that at a point in space produces a mean-square sound pressure of $p_1^2 = 10^{-6} \text{ Pa}^2$ in a 1-Hz bandwidth between 999 and 1000 Hz (Fig. 1.3a). Now imagine that we have a second machine the same distance away that radiates the same power but is confined to a bandwidth between 1000 and 1001 Hz (Fig. 1.3b). The total spectrum now becomes that shown in Fig. 1.3c and the total mean-square pressure is twice that in either band. Similarly, 10 machines would produce 10 times the mean-square sound pressure of any one (Fig. 1.3d).

In other words, if the power spectral density spectrum in a frequency band of width $\Delta f$ is flat (the mean-square sound pressures in all the 1-Hz-wide bands, $p_1^2$, within the band are equal), the total mean-square sound pressure for the band is given by

$$p_{\text{tot}}^2 = p_1^2 \frac{\Delta f}{\Delta f_0} \text{ Pa}^2$$

where $\Delta f_0 = 1 \text{ Hz}$.

As an example, assume that we wish to convert the power spectral density spectrum of Fig. 1.3e, which is a plot of $p_1^2(f)$, the mean-square sound pressure in 1-Hz bands, to a spectrum for which the mean-square sound pressure in 100-Hz bands, $p_{\text{tot}}^2$, is plotted versus frequency. Let us consider only the 700–800-Hz band. Because $p_1^2(f)$ is not equal throughout this band, we could painstakingly determine and add together the actual $p_1^2$'s or, as is more usual, simply take the average value for the $p_1^2$'s in that band and multiply by the bandwidth. Thus, for each 100-Hz band, the total mean-square sound pressure is given by Eq. (1.14), where $p_1^2$ is the average 1-Hz band quantity throughout the band. For the 700–800-Hz band, the average $p_1^2$ is $5.5 \times 10^{-6}$ and the total is $5.5 \times 10^{-6} \times 100 \text{ Hz} = 5.5 \times 10^{-4} \text{ Pa}^2$.

If mean-square sound pressure levels have been measured in a specific set of bandwidths such as one-third-octave bands, it is possible to present accurately the data in a set of wider bandwidths such as octave bands by simply adding together the mean-square sound pressures for the component bands. Obviously, it is not possible to reconstruct a narrower bandwidth spectrum accurately (e.g., one-third-octave bands) from a wider bandwidth spectrum (e.g., octave bands.) However, it is sometimes necessary to make such a conversion in order to compare sets of data measured differently. Then the implicit assumption has to be made that the narrower band spectrum is continuous and monotonic within the larger band. In either direction, the conversion factor for each band is

$$p_B^2 = p_A^2 \frac{\Delta f_B}{\Delta f_A}$$

where $p_A^2$ is the measured mean-square sound pressure in a bandwidth $\Delta f_A$ and $p_B^2$ is the desired mean-square sound pressure in the desired bandwidth $\Delta f_B$. 
Conversion of octave-band mean-square sound pressures into third-octave-band mean-square sound pressures. Such conversion should be made only where necessary under the assumption that the third-octave-band mean-square pressure levels decrease monotonically with band midfrequency. The sloping solid curve is the assumed-correct converted spectrum.

As an example, assume that we have measured a sound with a continuous spectrum using a one-octave-band filterset and have plotted the intensity for the contiguous bands versus the midfrequency of each band (see the upper three circles in Fig. 1.5). Assume that we wish to convert to an approximate one-third-octave-band spectrum to make comparisons with other data possible. Not knowing how the mean-square sound pressure varies throughout each octave band, we assume it to be continuous and monotonic and apply Eq. (1.15). In this example, approximately, $\Delta f_B = \frac{1}{3} \Delta f_A$ for all the bands (see Table 1.1), and the mean-square sound pressure in each one-third-octave band with the same midfrequency will be one-third that in the corresponding one-octave band. The data would be plotted versus the midfrequency of each one-third-octave band (see Table 1.1 and Fig. 1.5). Then the straight, sloping line is added under the assumption that the true one-third-octave spectrum is monotonic.
Complex Spectra

The mean-square sound pressure resulting from the combination of two or more pure tones of different amplitudes \( p_1, p_2, p_3 \) and different frequencies \( f_1, f_2, f_3 \) is given by

\[
p_{\text{rms}}^2(\text{total}) = p_1^2 + p_2^2 + p_3^2 + \cdots \quad (1.16)
\]

The mean-square sound pressure of two pure tones of the same frequency but different amplitudes and phases is found from

\[
p_{\text{rms}}^2(\text{total}) = p_1^2 + p_2^2 + 2p_1p_2 \cos(\theta_1 - \theta_2) \quad (1.17)
\]

where the phase angle of each wave is represented by \( \theta_1 \) or \( \theta_2 \).

Comparison of Eqs. (1.16) and (1.17) reveals the importance of phase when combining two sine waves of the same frequency. If the phase difference \( \theta_1 - \theta_2 \) is zero, the two waves are in phase and the combination is at its maximum value. If \( \theta_1 - \theta_2 = 180^\circ \), the third term becomes \(-2p_1p_2\) and the sum is at its minimum value. If the two waves are equal in amplitude, the minimum value is zero.

If one wishes to find the mean-square sound pressure of a number of waves all of which have different frequencies except, say, two, these two are added together according to Eq. (1.17) to obtain a mean-square pressure for them. Then this mean-square pressure and the mean-square pressures of the remainder of the components are summed according to Eq. (1.16).

1.3 LEVELS

Because of the wide range of sound pressures to which the ear responds (a ratio of \(10^5\) or more for a normal person), sound pressure is an inconvenient quantity to use in graphs and tables. This is also true for the other acoustical quantities listed above. Early in the history of the telephone it was decided to adopt logarithmic scales for representing acoustical quantities and the voltages encountered in associated electrical equipment.

As a result of that decision, sound powers, intensities, pressures, velocities, energy densities, and voltages from electroacoustic transducers are commonly stated in terms of the logarithm of the ratio of the measured quantity to an appropriate reference quantity. Because the sound pressure at the threshold of hearing at 1000 Hz is about 20 \( \mu \text{Pa} \), this was chosen as the fundamental reference quantity around which the other acoustical references have been chosen.

Whenever the magnitude of an acoustical quantity is given in this logarithmic form, it is said to be a level in decibels (dB) above or below a zero reference level that is determined by a reference quantity. The argument of the logarithm is always a ratio and, hence, is dimensionless. The level for a very large ratio, for example the power produced by a very powerful sound source, might be given with the unit bel, which equals 10 dB.
**Power and Intensity Levels**

**Sound Power Level.** Sound power level is defined as

\[ L_W = 10 \log_{10} \frac{W}{W_0} \text{ dB re } W_0 \]  

(1.18)

and conversely

\[ W = W_0 \text{antilog}_{10} \frac{L_W}{10} = W_0 \times 10^{L_W/10} \text{ W} \]  

(1.19)

where \( W \) = sound power, \( W \) (watts)

\( W_0 \) = reference sound power, standardized at \( 10^{-12} \) W

As seen in Table 1.2, a ratio of 10 in the power \( W \) corresponds to a level difference of 10 dB regardless of the reference power \( W_0 \). Similarly, a ratio of 100 corresponds to a level difference of 20 dB. Power ratios of less than 1 are allowable: They simply lead to negative levels. For example (see Table 1.2), a power ratio of 0.1 corresponds to a level difference of \(-10\) dB.

Column 4 of Table 1.2 gives sound power levels relative to the standard reference power level \( W_0 = 10^{-12} \) W in watts.

Some sound power ratios and the corresponding sound-power-level differences are given in Table 1.3. We note from the last line that the sound power level for the product of two ratios is equal to the sum of the levels for the two ratios. For example, determine \( L_W \) for the quantity \( 2 \times 4 \). From Table 1.3,

**TABLE 1.2 Sound Powers and Sound Power Levels**

<table>
<thead>
<tr>
<th>Radiated Sound Power ( W ), watts</th>
<th>Sound Power Level ( L_W ), dB</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Usual Notation</strong></td>
<td><strong>Equivalent Exponential Notation</strong></td>
</tr>
<tr>
<td>100,000</td>
<td>( 10^5 )</td>
</tr>
<tr>
<td>10,000</td>
<td>( 10^4 )</td>
</tr>
<tr>
<td>1,000</td>
<td>( 10^3 )</td>
</tr>
<tr>
<td>100</td>
<td>( 10^2 )</td>
</tr>
<tr>
<td>10</td>
<td>( 10^1 )</td>
</tr>
<tr>
<td>1</td>
<td>1</td>
</tr>
<tr>
<td>0.1</td>
<td>( 10^{-1} )</td>
</tr>
<tr>
<td>0.01</td>
<td>( 10^{-2} )</td>
</tr>
<tr>
<td>0.001</td>
<td>( 10^{-3} )</td>
</tr>
<tr>
<td>0.000,1</td>
<td>( 10^{-4} )</td>
</tr>
<tr>
<td>0.000,01</td>
<td>( 10^{-5} )</td>
</tr>
<tr>
<td>0.000,001</td>
<td>( 10^{-6} )</td>
</tr>
<tr>
<td>0.000,000,1</td>
<td>( 10^{-7} )</td>
</tr>
<tr>
<td>0.000,000,01</td>
<td>( 10^{-8} )</td>
</tr>
<tr>
<td>0.000,000,001</td>
<td>( 10^{-9} )</td>
</tr>
</tbody>
</table>
### TABLE 1.3  Selected Sound Power Ratios and Corresponding Power-Level Differences

<table>
<thead>
<tr>
<th>Sound Power Ratio $W/W_0, R$</th>
<th>Sound-Power-Level Difference $10 \log W/W_0, L_W$ (dB)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1000</td>
<td>30</td>
</tr>
<tr>
<td>100</td>
<td>20</td>
</tr>
<tr>
<td>10</td>
<td>10</td>
</tr>
<tr>
<td>9</td>
<td>9.5</td>
</tr>
<tr>
<td>8</td>
<td>9.0</td>
</tr>
<tr>
<td>7</td>
<td>8.5</td>
</tr>
<tr>
<td>6</td>
<td>7.8</td>
</tr>
<tr>
<td>5</td>
<td>7.0</td>
</tr>
<tr>
<td>4</td>
<td>6.0</td>
</tr>
<tr>
<td>3</td>
<td>4.8</td>
</tr>
<tr>
<td>2</td>
<td>3.0</td>
</tr>
<tr>
<td>1</td>
<td>0.0</td>
</tr>
<tr>
<td>0.9</td>
<td>−0.5</td>
</tr>
<tr>
<td>0.8</td>
<td>−1.0</td>
</tr>
<tr>
<td>0.7</td>
<td>−1.5</td>
</tr>
<tr>
<td>0.6</td>
<td>−2.2</td>
</tr>
<tr>
<td>0.5</td>
<td>−3.0</td>
</tr>
<tr>
<td>0.4</td>
<td>−4.0</td>
</tr>
<tr>
<td>0.3</td>
<td>−5.2</td>
</tr>
<tr>
<td>0.2</td>
<td>−7.0</td>
</tr>
<tr>
<td>0.1</td>
<td>−10</td>
</tr>
<tr>
<td>0.01</td>
<td>−20</td>
</tr>
<tr>
<td>0.001</td>
<td>−30</td>
</tr>
</tbody>
</table>

$R_1 \times R_2 = L_{W_1} + L_{W_2}$

*To the nearest 0.1 dB.

$L_W = 3.0 + 6.0 = 9.0$ dB, which is the sound power level for the ratio 8. Similarly, $L_W$ for a ratio of 8000 equals the sum of the levels for 8 and 1000, that is, $L_W = 9 + 30 = 39$ dB.

**Sound Intensity Level.** Sound intensity level, in decibels, is defined as

$$\text{Intensity level} = L_I = 10 \log \frac{I}{I_{ref}} \text{ dB re } I_{ref}$$

(1.20)

where $I =$ sound intensity whose level is being specified, W/m²

$I_{ref} =$ reference intensity standardized as $10^{-12}$ W/m²

Sound power levels should not be confused with intensity levels (or with sound pressure levels, which are defined next), which also are expressed in decibels. Sound power is a measure of the total acoustical power radiated by a source in watts. Sound intensity and sound pressure specify the acoustical “disturbance”
produced at a point removed from the source. For example, their levels depend on
the distance from the source, losses in the intervening air path, and room effects
(if indoors). A helpful analogy is to imagine that sound power level is related to
the total rate of heat production of a furnace, while either of the other two levels
is analogous to the temperature produced at a given point in a dwelling.

**Sound Pressure Level**

Almost all microphones used today respond to sound pressure, and in the public
mind, the word *decibel* is commonly associated with sound pressure level or A-
weighted sound pressure level (see Table 1.4). Strictly speaking, sound pressure
level is analogous to intensity level, because, in calculating it, pressure is first
squared, which makes it proportional to intensity (power per unit area):

\[
\text{Sound pressure level} = L_p = 10 \log \left( \frac{p(t)}{p_{\text{ref}}} \right)^2 \]

\[
= 20 \log \frac{p(t)}{p_{\text{ref}}} \text{ dB re } p_{\text{ref}} \quad (1.21)
\]

where \( p_{\text{ref}} \) = reference sound pressure, standardized at \( 2 \times 10^{-5} \) N/m\(^2\) (20 µPa)
for airborne sound; for other media, references may be 0.1 N/m\(^2\)
(1 dyn/cm\(^2\)) or 1 µN/m\(^2\) (1 µPa)

\( p(t) \) = instantaneous sound pressure, Pa

Note that \( L_p \) re 20 µPa is 94 dB greater than \( L_p \) re 1 Pa.

As we shall show shortly, \( p(t)^2 \) is only proportional to sound intensity if its
mean-square value is taken. Thus, in Eq. (1.21), \( p(t) \) would be replaced by \( p_{\text{rms}} \).

The relations among sound pressure levels (re 20 µPa) for pressures in the
meter-kilogram-second (mks), centimeter-gram-second (cgs), and English sys-
tems of units are shown by the four nomograms of Fig. 1.6.

### 1.4 DEFINITIONS OF OTHER COMMONLY USED LEVELS
AND QUANTITIES IN ACOUSTICS

Analogous to sound pressure level given in Eq. (1.21), *A-weighted sound pressure
level* \( L_A \) is given by

\[
L_A = 10 \log \left( \frac{p_A(t)}{p_{\text{ref}}} \right)^2 \text{ dB} \quad (1.22)
\]

where \( p_A(t) \) is the instantaneous sound pressure measured using the standard
frequency-weighting A (see Table 1.4).
### TABLE 1.4  A and C Electrical Weighting Networks for Sound-Level Meter

<table>
<thead>
<tr>
<th>Frequency, Hz</th>
<th>A-Weighting Relative Response, dB</th>
<th>C-Weighting Relative Response, dB</th>
</tr>
</thead>
<tbody>
<tr>
<td>10</td>
<td>−70.4</td>
<td>−14.3</td>
</tr>
<tr>
<td>12.5</td>
<td>−63.4</td>
<td>−11.2</td>
</tr>
<tr>
<td>16</td>
<td>−56.7</td>
<td>−8.5</td>
</tr>
<tr>
<td>20</td>
<td>−50.5</td>
<td>−6.2</td>
</tr>
<tr>
<td>25</td>
<td>−44.7</td>
<td>−4.4</td>
</tr>
<tr>
<td>31.5</td>
<td>−39.4</td>
<td>−3.0</td>
</tr>
<tr>
<td>40</td>
<td>−34.6</td>
<td>−2.0</td>
</tr>
<tr>
<td>50</td>
<td>−30.2</td>
<td>−1.3</td>
</tr>
<tr>
<td>63</td>
<td>−26.2</td>
<td>−0.8</td>
</tr>
<tr>
<td>80</td>
<td>−22.5</td>
<td>−0.5</td>
</tr>
<tr>
<td>100</td>
<td>−19.1</td>
<td>−0.3</td>
</tr>
<tr>
<td>125</td>
<td>−16.1</td>
<td>−0.2</td>
</tr>
<tr>
<td>160</td>
<td>−13.4</td>
<td>−0.1</td>
</tr>
<tr>
<td>200</td>
<td>−10.9</td>
<td>0</td>
</tr>
<tr>
<td>250</td>
<td>−8.6</td>
<td>0</td>
</tr>
<tr>
<td>315</td>
<td>−6.6</td>
<td>0</td>
</tr>
<tr>
<td>400</td>
<td>−4.8</td>
<td>0</td>
</tr>
<tr>
<td>500</td>
<td>−3.2</td>
<td>0</td>
</tr>
<tr>
<td>630</td>
<td>−1.9</td>
<td>0</td>
</tr>
<tr>
<td>800</td>
<td>−0.8</td>
<td>0</td>
</tr>
<tr>
<td>1,000</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>1,250</td>
<td>+0.6</td>
<td>0</td>
</tr>
<tr>
<td>1,600</td>
<td>+1.0</td>
<td>−0.1</td>
</tr>
<tr>
<td>2,000</td>
<td>+1.2</td>
<td>−0.2</td>
</tr>
<tr>
<td>2,500</td>
<td>+1.3</td>
<td>−0.3</td>
</tr>
<tr>
<td>3,150</td>
<td>+1.2</td>
<td>−0.5</td>
</tr>
<tr>
<td>4,000</td>
<td>+1.0</td>
<td>−0.8</td>
</tr>
<tr>
<td>5,000</td>
<td>+0.5</td>
<td>−1.3</td>
</tr>
<tr>
<td>6,300</td>
<td>−0.1</td>
<td>−2.0</td>
</tr>
<tr>
<td>8,000</td>
<td>−1.1</td>
<td>−3.0</td>
</tr>
<tr>
<td>10,000</td>
<td>−2.5</td>
<td>−4.4</td>
</tr>
<tr>
<td>12,500</td>
<td>−4.3</td>
<td>−6.2</td>
</tr>
<tr>
<td>16,000</td>
<td>−6.6</td>
<td>−8.5</td>
</tr>
<tr>
<td>20,000</td>
<td>−9.3</td>
<td>−11.2</td>
</tr>
</tbody>
</table>

*These numbers assume a flat, diffuse-field (random-incidence) response for the sound-level meter and microphone.

Average sound level \(L_{av,T}\) is given by

\[
L_{av,T} = 10 \log \left( \frac{1}{T} \int_0^T \frac{p^2(t)}{p_{ref}^2} \, dt \right) \text{ dB} \tag{1.23}
\]

where \(T\) is the (long) time over which the averaging takes place.
DEFINITIONS OF OTHER COMMONLY USED LEVELS AND QUANTITIES IN ACOUSTICS

Average A-weighted sound level $L_{A,T}$ (also called $L_{eq}$, equivalent continuous A-weighted noise level) is given by

$$L_{A,T} = L_{eq} = 10 \log \left( \frac{1}{T} \int_0^T p_A^2(t) \, dt \right) \frac{p_{ref}^2}{p^2_{ref}} \text{ dB} \quad (1.24)$$

The time $T$ must be specified. In noise evaluations, its length is usually one to several hours, or 8 h (working day), or 24 h (full day).

Day–night sound (noise) level $L_{dn}$ is given by

$$L_{dn} = 10 \log \frac{1}{24} \left[ \int_{07:00}^{22:00} \frac{p_A^2(t)}{p_{ref}^2} \, dt + \int_{22:00}^{07:00} 10 \frac{p_A^2(t)}{p_{ref}^2} \, dt \right] \text{ dB} \quad (1.25)$$

where the first term covers the “daytime” hours from 07:00 to 22:00 and the second term covers the nighttime hours from 22:00 to 07:00. Here, the nighttime noise levels are considered to be 10 dB greater than they actually measure. The A-weighted sound pressure $p_A$ is sampled frequently during measurement.
A-weighted sound exposure $E_{A,T}$ is given by

$$E_{A,T} = \int_{t_1}^{t_2} p_A^2(t) \, dt \quad \text{Pa}^2 \cdot s$$

This equation is not a level. The term $E_{A,T}$ is proportional to the energy flow (intensity times time) in a sound wave in the time period $T$. The period $T$ starts and stops at $t_1$ and $t_2$, respectively.

A-weighted noise exposure level $L_{E,A,T}$ is given by

$$L_{E,A,T} = 10 \log \left( \frac{E_{A,T}}{E_0} \right) \quad \text{dB}$$

where $E_0$ is a reference quantity, standardized at $(20 \, \mu\text{Pa})^2 \cdot s = (4 \times 10^{-10} \, \text{Pa})^2 \cdot s$. However, the International Organization for Standardization standard ISO 1999:1990-01-5, on occupational noise level, uses $E_0 = (1.15 \times 10^{-5} \, \text{Pa})^2 \cdot s$, because, for an 8-h day, $L_{E,A,T}$, with that reference, equals the average A-weighted sound pressure level $L_{A,T}$. The two reference quantities yield levels that differ by 44.6 dB.

For a single impulse, the time period $T$ is of no consequence provided $T$ is longer than the impulse length and the background noise is low.

Hearing threshold for setting “zero” at each frequency on a pure-tone audiometer is the standardized, average, pure-tone threshold of hearing for a population of young persons with no otological irregularities. The standardized threshold sound pressure levels at the frequencies 250, 500, 1000, 2000, 3000, 4000, 6000, and 8000 Hz are, respectively, 24.5, 11.0, 6.5, 8.5, 7.5, 9.0, 8.0, and 9.5 dB measured under an earphone. An audiometer is used to determine the difference at these frequencies between the threshold values of a person (the lowest sound pressure level of a pure tone the person can detect consistently) and the standardized threshold values. Measurements are sometimes also made at 125 and 1500 Hz.

Hearing impairment (hearing loss) is the number of decibels that the permanent hearing threshold of an individual at each measured frequency is above the zero setting on an audiometer, in other words, a change for the worse of the person’s threshold of hearing compared to the normal for young persons.

Hearing threshold levels associated with age are the standardized pure-tone thresholds of hearing associated solely with age. They were determined from tests made on the hearing of persons in a certain age group in a population with no otological irregularities and no appreciable exposure to noise during their lives.

Hearing threshold levels associated with age and noise are the standardized pure-tone thresholds determined from tests made on the hearing of individuals who had histories of higher than normal noise exposure during their lives. The average noise levels and years of exposure were determined by questioning and measurement of the exposure levels.

Noise-induced permanent threshold shift (NIPTS) is the shift in the hearing threshold level caused solely by exposure to noise.
1.5 REFERENCE QUANTITIES USED IN NOISE AND VIBRATION

American National Standard

The American National Standards Institute has issued a standard (ANSI S1.8-1989, Reaffirmed 2001) on “Reference Quantities for Acoustical Levels.” This standard is a revision of ANSI S1.8-1969. The authors of this book have been surveyed for their opinions on preferred reference quantities. Table 1.5 is a combination of the standard references and of references preferred by the authors. The two references are clearly distinguished. All quantities are stated in terms of the International System of units (SI) and in British units.

Relations among Sound Power Levels, Intensity Levels, and Sound Pressure Levels

As a practical matter, the reference quantities for sound power, intensity, and sound pressure (in air) have been chosen so that their corresponding levels are interrelated in a convenient way under certain circumstances.

The threshold of hearing at 1000 Hz for a young listener with acute hearing, measured under laboratory conditions, was determined some years ago as a sound pressure of $2 \times 10^{-5}$ Pa. This value was then selected as the reference pressure for sound pressure level.

Intensity at a point is related to sound pressure at that point in a free field by Eq. (1.14). A combination of Eqs. (1.4), (1.20), and (1.21) yields the sound intensity level

$$L_I = 10 \log \frac{I}{I_{ref}} = 10 \log \frac{p^2}{\rho c I_{ref}}$$

$$= 10 \log \frac{p^2}{p_{ref}^2} + 10 \log \frac{p_{ref}^2}{\rho c I_{ref}}$$

$$L_I = L_P - 10 \log K \quad \text{dB re} \ 10^{-12} \ \text{W/m}^2 \quad (1.28)$$

where $K = \text{const} = I_{ref} \rho c / p_{ref}^2$, which is dependent upon ambient pressure and temperature; quantity $10 \log K$ may be found from Fig. 1.7, or,

$$K = \rho c / 400$$

The quantity $10 \log K$ will equal zero, that is, $K = 1$, when

$$\rho c = \frac{p_{ref}^2}{I_{ref}} = \frac{4 \times 10^{-10}}{10^{-12}} = 400 \text{ mks rayls} \quad (1.29)$$

We may also rearrange Eq. (1.28) to give the sound pressure level

$$L_P = L_I + 10 \log K \quad \text{dB re} \ 2 \times 10^{-5} \ \text{Pa} \quad (1.30)$$
### TABLE 1.5 Reference Quantities for Acoustical Levels from American National Standard ANSI S1.8-1989 (Reaffirmed 2001) and As Preferred by Authors

<table>
<thead>
<tr>
<th>Name</th>
<th>Definition</th>
<th>Preferred Reference Quantities</th>
<th>SI</th>
<th>British</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sound pressure level (gases)</td>
<td>$L_I = 20 \log_{10}(p/p_0)$ dB</td>
<td>$p_0 = 20 \mu Pa = 2 \times 10^{-5} \text{ N/m}^2$</td>
<td>$2.90 \times 10^{-9} \text{ lb/in.}^2$</td>
<td></td>
</tr>
<tr>
<td>Sound pressure level (other than gases)</td>
<td>$L_I = 20 \log_{10}(p/p_0)$ dB</td>
<td>$p_0 = 1 \mu Pa = 10^{-6} \text{ N/m}^2$</td>
<td>$1.45 \times 10^{-10} \text{ lb/in.}^2$</td>
<td></td>
</tr>
<tr>
<td>Sound power level</td>
<td>$L_W = 10 \log_{10}(W/W_0)$ dB</td>
<td>$W_0 = 1 \text{ pW} = 10^{-12} \text{ N-m/s}$</td>
<td>$8.85 \times 10^{-12} \text{ in.-lb/s}$</td>
<td></td>
</tr>
<tr>
<td>Sound intensity level</td>
<td>$L_I = 10 \log_{10}(I/I_0)$ dB</td>
<td>$I_0 = 1 \text{ µW} = 10^{-6} \text{ N-m/s}$</td>
<td>$5.71 \times 10^{-15} \text{ lb/in.-s}$</td>
<td></td>
</tr>
<tr>
<td>Vibratory force level</td>
<td>$L_F = 20 \log_{10}(F/F_0)$ dB</td>
<td>$F_0 = 1 \text{ µN} = 10^{-6} \text{ N}$</td>
<td>$2.25 \times 10^{-7} \text{ lb}$</td>
<td></td>
</tr>
<tr>
<td>Frequency level</td>
<td>$N = 10 \log_{10}(f/f_0)$ dB</td>
<td>$f_0 = 1 \text{ Hz}$</td>
<td>$1.00 \text{ Hz}$</td>
<td></td>
</tr>
<tr>
<td>Sound exposure level</td>
<td>$L_E = 10 \log_{10}(E/E_0)$ dB</td>
<td>$E_0 = (20 \mu \text{Pa})^2 \cdot s = (2 \times 10^{-5} \text{ Pa})^2 \cdot s$</td>
<td>$8.41 \times 10^{-18} \text{ lb}^2/\text{in.}^4$</td>
<td></td>
</tr>
</tbody>
</table>

The quantities listed below are not officially part of ANSI S1.8. They either are listed there for information or are included here as the authors’ choice.

- **Sound energy level given in ISO 1683:1983**
  $L_E = 10 \log_{10}(e/e_0)$ dB
  $e_0 = 1 \text{ pJ} = 10^{-12} \text{ N-m}$
  $8.85 \times 10^{-12} \text{ lb-in.}$

- **Sound energy density level given in ISO 1683:1983**
  $L_D = 10 \log_{10}(D/D_0)$ dB
  $D_0 = 1 \text{ pJ/m}^3 = 10^{-12} \text{ N/m}^2$
  $1.45 \times 10^{-16} \text{ lb/in.}^2$

- **Vibration acceleration level**
  $L_a = 20 \log_{10}(a/a_0)$ dB
  $a_0 = 10 \text{ µm/s}^2 = 10^{-5} \text{ m/s}^2$
  $3.94 \times 10^{-4} \text{ in./s}^2$

- **Vibration acceleration level in ISO 1683:1983**
  $L_a = 20 \log_{10}(a/a_0)$ dB
  $a_0 = 1 \text{ µm/s}^2 = 10^{-6} \text{ m/s}^2$
  $3.94 \times 10^{-4} \text{ in./s}^2$

- **Vibration velocity level**
  $L_v = 20 \log_{10}(v/v_0)$ dB
  $v_0 = 10 \text{ mm/s} = 10^{-8} \text{ m/s}$
  $3.94 \times 10^{-7} \text{ in./s}$

- **Vibration velocity level in ISO 1683:1983**
  $L_v = 20 \log_{10}(v/v_0)$ dB
  $v_0 = 1 \text{ mm/s} = 10^{-9} \text{ m/s}$
  $3.94 \times 10^{-8} \text{ in./s}$

- **Vibration displacement level**
  $L_d = 20 \log_{10}(d/d_0)$ dB
  $d_0 = 10 \text{ pm} = 10^{-15} \text{ m}$
  $3.94 \times 10^{-10} \text{ in.}$

**Notes:** Decimal multiples and submultiples of SI units are formed as follows: $10^{-1}$ = deci (d), $10^{-2}$ = centi (c), $10^{-3}$ = milli (m), $10^{-6}$ = micro (µ), $10^{-9}$ = nano (n), and $10^{-12}$ = pico (p). Also $J = \text{ joule} = \text{ W-s(N-m)}$, $N = \text{ newton}$, and $\text{Pa} = \text{ pascal} = 1 \text{ N/m}^2$. Note that 1 lb = 4.448 N.

Although some international standards differ, in this text, to avoid confusion between power and pressure, we have chosen to use $W$ instead of $P$ for power; and to avoid confusion between energy density and voltage, we have chosen $D$ instead of $E$ for energy density. The symbol lb means pound force.

In recent international standardization $\log_{10}$ is written lg and $20 \log_{10}(a/b) = 10 \log (a^2/b^2)$, i.e., “20” is never used.
TABLE 1.6 Ambient Pressures and Temperatures for Which $\rho c$ (Air) = 400 mks rayls

<table>
<thead>
<tr>
<th>$p_s$, Pa</th>
<th>m of Hg, $0^\circ$C</th>
<th>in. of Hg, $0^\circ$C</th>
<th>Ambient Temperature $T$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$0.7 \times 10^5$</td>
<td>0.525</td>
<td>20.68</td>
<td>$-124.3$</td>
</tr>
<tr>
<td>$0.8 \times 10^5$</td>
<td>0.600</td>
<td>23.63</td>
<td>$-78.7$</td>
</tr>
<tr>
<td>$0.9 \times 10^5$</td>
<td>0.675</td>
<td>26.58</td>
<td>$-27.0$</td>
</tr>
<tr>
<td>$1.0 \times 10^5$</td>
<td>0.750</td>
<td>29.54</td>
<td>$+30.7$</td>
</tr>
<tr>
<td>$1.013 \times 10^5$</td>
<td>0.760</td>
<td>29.9</td>
<td>$38.9$</td>
</tr>
<tr>
<td>$1.1 \times 10^5$</td>
<td>0.825</td>
<td>32.5</td>
<td>$94.5$</td>
</tr>
<tr>
<td>$1.2 \times 10^5$</td>
<td>0.900</td>
<td>35.4</td>
<td>$164.4$</td>
</tr>
<tr>
<td>$1.3 \times 10^5$</td>
<td>0.975</td>
<td>38.4</td>
<td>$240.4$</td>
</tr>
<tr>
<td>$1.4 \times 10^5$</td>
<td>1.050</td>
<td>41.3</td>
<td>$322.4$</td>
</tr>
</tbody>
</table>

FIGURE 1.7 Chart determining the value of $10 \log (\rho c/400) = 10 \log K$ as a function of ambient temperature and ambient pressure. Values for which $\rho c = 400$ are also given in Table 1.6.

In Table 1.6, we show a range of ambient pressures and temperatures for which $\rho c = 400$ mks rayls. We see that for average atmospheric pressure, namely, $1.013 \times 10^5$ Pa, the temperature must equal $38.9^\circ$C ($102^\circ$F) for $\rho c = 400$ mks rayls. However, if $T = 22^\circ$C and $p_s = 1.013 \times 10^5$ Pa, $\rho c \approx 412$. This yields
a value of \(10 \log(\rho c/400) = 10 \log 1.03 = 0.13 \text{ dB}\), an amount that is usually not significant in acoustics.

Thus, for most noise measurements, we neglect \(10 \log K\) and in a free progressive wave let

\[ L_p \approx L_I \]  

(1.31)

Otherwise, the value of \(10 \log K\) is determined from Fig. 1.7 and used in Eq. (1.28) or (1.30).

Under the condition that the intensity is uniform over an area \(S\), the sound power and the intensity are related by \(W = IS\). Hence, the sound power level is related to the intensity level as follows:

\[
10 \log \frac{W}{10^{-12}} = 10 \log \frac{I}{10^{-12}} + 10 \log \frac{S}{S_0} \\
L_W = L_I + 10 \log S \text{ dB re } 10^{-12} \text{ W} 
\]

(1.32)

where \(S = \text{area of surface, m}^2\)
\(S_0 = 1 \text{ m}^2\)

Obviously, only if the area \(S = 1.0 \text{ m}^2\) will \(L_W = L_I\). Also, observe that the relation of Eq. (1.32) is not dependent on temperature or pressure.

## 1.6 Determination of Overall Levels from Band Levels

It is necessary often to convert sound pressure levels measured in a series of contiguous bands into a single-band level encompassing the same frequency range. The level in the all-inclusive band is called the overall level \(L(OA)\) given by

\[
L_p(OA) = 20 \log \sum_{i=1}^{n} 10^{f_i/20} \text{ dB} 
\]

(1.33)

\[
L_p(OA) = 10 \log \sum_{i=1}^{n} 10^{f_i/10} \text{ dB} 
\]

(1.34)

The conversion can also be accomplished with the aid of Fig. 1.8. Assume that the contiguous band levels are given by the eight numbers across the top of Fig. 1.9. The frequency limits of the bands are not important to the method of calculation as long as the bands are contiguous and cover the frequency range of the overall band. To combine these eight levels into an overall level, start with any two, say, the seventh and eighth bands. From Fig. 1.8 we see that whenever the difference between two band levels, \(L_1 - L_2\), is zero, the combined level is 3 dB higher. If the difference is 2 dB (the sixth band level minus the new level of 73 dB), the sum is 2.1 dB greater than the larger (75 + 2.1 dB). This procedure is followed until the overall band level is obtained, here, 102.1 dB.
DETERMINATION OF OVERALL LEVELS FROM BAND LEVELS

FIGURE 1.8 Nanogram for combining two sound levels $L_1$ and $L_2$ (dB). Levels may be power levels, sound pressure levels, or intensity levels. Example: $L_1 = 88$ dB, $L_2 = 85$ dB, $L_1 - L_2 = 3$ dB. Solution: $L_{\text{comb}} = 88 + 1.8 = 89.8$ dB.

If we set $L_{\text{comb}} - L_1 = A$, then $A$ is the number to be added to $L_1$ (the larger) to get $L_{\text{comb}}$.

It is instructive to combine the bands in a different way, as is shown in Fig. 1.10. The first four bands are combined first; then the second four bands are combined. The levels of the two wider band levels are then combined. It is seen that the overall level is determined by the first four bands alone. This example points up the fact that characterization of a noise by its overall level may be completely inadequate for some noise control purposes because it may ignore a large
portion of the frequency spectrum. If the data of Fig. 1.10 represented a genuine noise control situation, the 102.1 overall level might be meaningless for some applications. For example, the sound pressure levels in the four highest bands might be the cause of annoyance or interference with speech communication, as is discussed in Chapter 19.

Finally, it should be remembered that in almost all noise control problems, it makes no sense to deal with small fractions of decibels. Rarely does one need a precision of 0.2 dB in measurements, and quite often it is adequate to quote levels to the nearest decibel.

REFERENCES