Chapter 1

Noise and Its Measurement

Sound is a longitudinal wave in air, and wave is a traveling disturbance. Mass and elasticity of the air medium are primary characteristics for a wave to travel from the source to the receiver. A wave is characterized by two state variables, namely, pressure and particle velocity. These represent perturbations on the static ambient pressure and the mean flow velocity of wind, respectively. The perturbations depend on time as well as space or distance.

Noise is unwanted sound. It may be unwanted or undesirable because of its loudness or frequency characteristics. Excessive or prolonged exposure to noise may lead to several physiological effects like annoyance, headache, increase in blood pressure, loss of concentration, speech interference, loss of working efficiency, or even accidents in the workplace. Persistent exposure of a worker to loud noise in the workplace may raise his/her threshold of hearing.

The study of generation, propagation and reception of audible sound constitutes the science of Acoustics. There are several branches of acoustics, namely, architectural acoustics, electroacoustics, musical acoustics, underwater acoustics, ultrasonics, physical acoustics, etc. The field of industrial noise, automotive noise and environmental noise constitutes engineering acoustics or technical acoustics. This in turn comprises sub-areas like duct acoustics, vibro-acoustics, computational acoustics, etc.

The speed at which the longitudinal disturbances travel in air is called sound speed, $c$. It depends on the ambient temperature, pressure and density as follows.

$$c = (\gamma RT)^{1/2} = (\gamma p_0 / \rho_0)^{1/2}$$

(1.1)
Here $\gamma$ is the ratio of specific heats $C_p$ and $C_v$, $R$ is gas constant, $p_0$ is static ambient pressure, $\rho_0$ is mass density, and $T$ is the absolute temperature of the medium. For air at standard pressure ($\gamma = 1.4$, $R = 287.05 \text{ J/(kg.K)}$, $p_0 = 1.013 \times 10^5 \text{ Pa}$), it can easily be seen that

$$c \approx 20.05(T)^{1/2}$$

where $T$ is the absolute temperature in Kelvin.

Symbol $T$ is used for the time period of harmonic disturbances as well. It is related to frequency $f$ as follows:

$$T = \frac{1}{f} \text{ or } f = \frac{1}{T}$$

Frequency $f$ is measured in Hertz (Hz) or cycles per second. Wavelength $\lambda$ of moving disturbances, of frequency $f$, is given by

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

where $c$ denotes speed of sound.

### 1.1 Plane Wave Propagation

Plane waves moving inside a wave guide (a duct with rigid walls) are called one-dimensional waves. These are characterized by the following one-dimensional wave equation [1]:

$$\frac{\partial^2 p}{\partial t^2} - c^2 \frac{\partial^2 p}{\partial z^2} = 0$$

where $p$, $z$, and $t$ are acoustic pressure, coordinate along direction of wave propagation and time, respectively.

For harmonic waves, the time dependence is given by $e^{j\omega t}$ or $\cos(\omega t)$ or $\sin(\omega t)$, where $\omega = 2\pi f$ is the circular frequency in rad/s.

General solution of Eq. (1.5) may be written as

$$p(z,t) = (Ae^{-j\omega t} + Be^{j\omega t}) e^{j\omega \omega t}$$
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or as

\[ p(z,t) = A e^{i(\omega t - kz/c)} + B e^{i(\omega t + kz/c)} \]  

(1.7)

where \( k = \omega / c = 2\pi / \lambda \) is called the wave number.

It can easily be seen that \( A \) is amplitude of the forward progressive wave and \( B \) is amplitude of the reflected or rearward progressive wave. Algebraic sum of the two progressive waves moving in opposite directions is called a standing wave. Thus, Eq. (1.6) represents acoustic pressure of a one-dimensional standing wave. The corresponding equation for particle velocity is given by

\[ u(z,t) = \frac{1}{\rho_0 c} \left( Ae^{-jkz} - Be^{jkz} \right) e^{i\omega t} \]  

(1.8)

\( \rho_0 c \), product of the mean density and sound speed, represents the characteristic impedance of the medium.

For an ambient temperature of 25°C and the standard atmospheric pressure (corresponding to the mean sea level), we have

\[ p_0 = 1.013 \times 10^5 \text{ Pa}, \quad T = 298 \text{ K}, \quad \rho_0 = 1.184 \text{ kg/m}^3, \quad c = 346 \text{ m/s}, \quad \rho_0 c = 410 \text{ kg/(m}^2\text{s)} \]

One-dimensional wave occurs primarily in the exhaust and tail pipe of automotive engines and reciprocating compressors. These waves are characterized by a plane wave front normal to the axis of the pipe or tube, and therefore they are called plane waves.

The forward wave is generated by the source and the rearward wave is the result of reflection from the passive termination downstream. In particular, \( B/A = R \) is called the Reflection Coefficient, and may be determined from the termination impedance [1]. In particular, \( R = 0 \) for anechoic termination, \( 1 \) for rigid (closed) termination, and \( -1 \) for expansion into vacuum. In general, \( R \) is a function of frequency.

In view of the plane wave character of the one-dimensional waves, the acoustic power flux \( W \) of a plane progressive wave may be written as

\[ W = IS = \langle p \cdot u \rangle S = \langle p \cdot v \rangle, \quad v = Su \]  

(1.9)
where \( I \) is Sound Intensity defined as power per unit area in a direction normal to the wave front (in the axial direction for plane waves), \( S \) is area of cross-section of the pipe, and \( V \) is called the Volume Velocity.

Thus, the acoustic power flux associated with the incident progressive wave and the reflected progressive wave are given by

\[
W_i = \frac{|A|^2 S}{2 \rho_v c} \quad \text{and} \quad W_r = \frac{|B|^2 S}{2 \rho_v c}
\]

(1.10, 1.11)

Note that the factor of 2 in the denominator is due to the mean square values required in the power calculations. Thus, the net power associated with a standing wave is given by

\[
W = W_i - W_r = \frac{|A|^2 - |B|^2}{2(\rho_v c / S)} = \frac{|A|^2 - |B|^2}{2Y}
\]

(1.12)

where \( Y = \rho_v c_o / S \) is the Characteristic Impedance of plane waves, defined as ratio of acoustic pressure and volume velocity of a plane progressive wave along a tube of area of cross-section \( S \).

### 1.2 Spherical Wave Propagation

Wave propagation in free space is characterized by the following Three-Dimensional (3D) Wave Equation [1]

\[
\left[ \frac{\partial^2}{\partial r^2} - c^2 \nabla^2 \right] p = 0.
\]

(1.13)

where \( \nabla^2 \) is the Laplacian. In terms of spherical polar coordinates, neglecting angular dependence for spherical waves, Eq. (1.13) can be written as

\[
\frac{\partial^2 (rp)}{\partial t^2} - c^2 \frac{\partial^2 (rp)}{\partial r^2} = 0
\]

(1.14)
Comparison of Eqs. (1.5) and (1.14) suggests the following solution for spherical waves:

\[ p( r, t ) = \frac{1}{r} \left\{ A e^{-jk r} + B e^{ikr} \right\} e^{i\omega t} \quad (1.15) \]

Substituting it into the momentum equation

\[ \rho_0 \frac{\partial u}{\partial t} = - \frac{\partial p}{\partial r} \quad (1.16) \]

yields

\[ u( r, t ) = \frac{j}{\omega \rho_0 r} \left\{ - \left( jk + \frac{1}{r} \right) A e^{-jk r} + \left( jk - \frac{1}{r} \right) B e^{ikr} \right\} e^{i\omega t} \quad (1.17) \]

Here \( r \) is the radial distance between the receiver and a point source. It may again be noted that the first component of Eqs. (1.15) and (1.17) represents the spherically outgoing or diverging wave and the second one represents the incoming or converging spherical wave. In practice, the second component is hypothetical; in all practical problems dealing with noise radiation from vibrating bodies one deals with the diverging wave only. The ratio of pressure and particle velocity for the diverging progressive wave may be seen to be

\[ \frac{p( r, t )}{u( r, t )} = \frac{\omega \rho_0}{\rho_0 c} = \frac{\rho_0 c}{1 - \frac{j}{kr}} \frac{jk r}{1 + jkr} \quad (1.18a) \]

It may be observed that unlike for plane progressive waves, this ratio is a function of distance \( r \). This indicates that for a spherical diverging wave, pressure and velocity are not in phase. However when the Helmholtz number \( kr \) tends to infinity (or is much larger than unity), then this ratio tends to \( \rho_0 c \). Physically, it implies that in the far field a spherical diverging wave becomes or behaves as a plane progressive wave. This also indicates that the microphone of the sound level meter should not be near the vibrating surface; it should be in the far field.

In the far field, Helmholtz number is much larger than unity \( (kr \gg 1) \) and then Eqs. (1.15), (1.17) and (1.18a) reduce to
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\[ p(r,t) = \frac{A}{r} e^{-\beta r} e^{i\omega t}, \quad u(r,t) = p(r,t) / (\rho_c c) \]  

(1.18 b, c)

and therefore, sound intensity and total power are given by

\[ I(r) = \frac{\text{Re}(p(r)u^*(r))}{2} = \frac{|p(r)|^2}{2\rho_c c} = \frac{\rho_c c |p(r)|^2}{2} = \frac{W}{4\pi r^2} \]  

(1.18 d-h)

where \(4\pi r^2\) is the surface area of a hypothetical sphere of radius \(r\) over which the total power \(W\) is divided equally to yield intensity \(I(r)\).

**Example 1.1** A bubble-like sphere of 5 mm radius is pulsating harmonically at a frequency of 1000 Hz with amplitude of radial displacement 1 mm in air at mean sea level and 25°C. Evaluate

(a) amplitude of the radial velocity of the sphere surface;

(b) amplitude of the acoustic pressure and particle velocity at a radial distance of 1 m.

**Solution**

(a) For harmonic radial motion, radial velocity \(u\) equals \(\omega\) times the radial displacement \(\xi\), where \(\omega = 2\pi f\). Thus, \(\omega = 2\pi \times 1000 = 6283.2\) rad/s

\[ |u| = |\omega| |\xi| = 6283.2 \times \frac{1}{1000} = 6.283 \text{ m/s} \]

(b) Wave number, \(k = \frac{\omega}{c} = \frac{6283.2}{346} = 18.16 \text{ m}^{-1}\)

Distance, \(r = 1\) m (given)

Helmholtz number, \(kr = 18.16\) at \(r = 1\) m, and 0.091 at \(r = 0.005\) m (i.e., on the surface). As per Eq. (1.17), for a diverging spherical wave in free field, \(B = 0\), and
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\[ |\mathbf{u}|_{\text{surface}} = \frac{(1 + k^2 r_0^2)^{1/2}}{\omega \rho_0 r_0^2} A \]

or

\[ A = |\mathbf{u}|_{\text{surface}} \frac{\omega \rho_0 r_0^2}{(1 + k^2 r_0^2)^{1/2}} = 6.283 \times 6283.2 \times 1.184 \times (0.005)^2 \left\{ 1 + (0.091)^2 \right\}^{1/2} \]

\[ = \frac{1.1685}{1.004} = 1.1638 \]

Substituting this value of \( A \) in Eq. (1.17) for \( r = 1 \text{m} \) yields

\[ |\mathbf{u}|_{1\text{m}} = A \left\{ \frac{(1 + k^2 r_0^2)^{1/2}}{\omega \rho_0 r_0^2} \right\}_{r=1\text{m}} = 1.1638 \times \left\{ 1 + (18.16)^2 \right\}^{1/2} = 2.845 \times 10^{-3} \text{ m/s} \]

Now, use of Eq. (1.15) yields

\[ |p|_{\text{1m}} = \frac{A}{r} = \frac{1.1638}{1} = 1.164 \text{ Pa} \]

Incidentally, sound pressure amplitude at 1 m may also be obtained by means of Eq. (1.18a):

\[ |p|_{\text{1m}} = |\mathbf{u}|_{\text{1m}} \rho_0 c \left\{ \frac{18.16}{1 + (18.16)^2} \right\}^{1/2} \]

\[ = |\mathbf{u}|_{\text{1m}} \rho_0 c \]

\[ = 2.845 \times 10^{-3} \times 410 = 1.166 \text{ Pa} \]

It is worth noting that
\[
\frac{P}{u} = \rho_0 c \times jkr \quad \text{at the surface, where } k r \ll 1, \\
\frac{P}{u} = \rho_0 c \quad \text{in the farfield, where } k r \gg 1,
\]

Thus, at the surface (or in the nearfield), sound pressure leads radial velocity by \(90^\circ\) (because \(j = e^{j\pi/2}\)), whereas in the farfield sound pressure is in phase with particle velocity.

### 1.3 Decibel Level

Human ear is a fantastic transducer. It can pick up pressure fluctuations of the order of \(10^{-5}\) Pa to \(10^3\) Pa; that is, it has a dynamic range of \(10^8\)! Therefore, a linear unit of measurement is ruled out. Instead, universally a logarithmic unit of decibels has been adopted for measurements of Sound Pressure Level, Intensity Level and Power Level. These are defined as follows [1-3]:

\[
SPL \equiv L_p = 10 \log \left( \frac{p_{rms}}{p_{th}} \right) = 20 \log \left( \frac{p_{rms}}{2 \times 10^{-5}} \right) \quad \text{dB} \quad (1.19)
\]

\[
IL \equiv L_I = 10 \log \left( \frac{I}{I_{ref}} \right) = 10 \log \left( \frac{I}{10^{-12}} \right) \quad \text{dB} \quad (1.20)
\]

\[
SWL \equiv L_w = 10 \log \left( \frac{W}{W_{ref}} \right) = 10 \log \left( \frac{W}{10^{-12}} \right) \quad \text{dB} \quad (1.21)
\]

where \text{log} denotes log to the base 10, and \(p_{th} = 2 \times 10^{-5}\) Pa represents the threshold of hearing. This standard quantity represents the root-mean-square pressure of the faintest sound of 1000 Hz frequency that a normal human ear can just pick up. The corresponding value of the reference intensity represents

\[
I_{ref} = \frac{p_{th}^2}{\rho_0 c} = \frac{(2 \times 10^{-5})^2}{400} = 10^{-12} \quad \text{W/m}^2 \quad (1.22)
\]
Similarly, \( W_{\text{ref}} = 10^{-12} W \).

Making use of Eqs. (1.15) and (1.17) in Eq. (1.20) indicates that in the far field the acoustical intensity is inversely proportional to the radial distance \( r \). This inverse square law when interpreted in logarithmic units becomes

\[
L_{r}(2r) - L_{r}(r) = 10 \log \frac{r^{2}}{(2r)^{2}} = -6 \text{ dB}
\]

(1.23)

This indicates that in the far field, the sound pressure level or sound intensity level would decrease by 6 decibels when the measurement distance from the source is doubled.

For spherically diverging waves the sound pressure level at a distance \( r \) from a point source is related to the total sound power level as follows [2]:

\[
L_{p}(r) = L_{w} + 10 \log \left( \frac{Q}{4\pi r^{2}} \right), \text{ dB}
\]

(1.24)

where \( Q \) is the locational directivity factor, given by [2, 3]

\[
Q = 2^{n_{s}}.
\]

(1.25)

Here, \( n_{s} \) is the number of surfaces touching at the source. Thus, \( n_{s} = 0 \) for a source in mid air (or free space),

1 for a source lying on the floor,

2 for a source located on the edge of two surfaces, and

3 for a source located in a corner (where three surfaces meet).

Specifically, for a source located on the floor in the open, Eq. (1.24) yields

\[
L_{p}(r) = L_{w} - 10 \log \left( 2\pi r^{2} \right), \text{ dB}
\]

(1.26)

### 1.4 Frequency Analysis

The human ear responds to sounds in the frequency range of 20 Hz to 20,000 Hz (20 kHz), although the human speech range is 125 Hz to 8000
Hz. Precisely, male speech lies between 125 Hz to 4000 Hz, and female speech is one octave higher, that is, 250 Hz to 8000 Hz.

The audible frequency range is divided into octave and 1/3-octave bands. For an octave band,

$$ f_u / f_l = 2 \quad \text{and} \quad f_m = (f_u f_l)^{1/2} \quad \text{(1.27)} $$

so that

$$ f_l = \frac{f_m}{2^{1/2}} = 0.707 f_m \quad \text{and} \quad f_u = f_m 2^{1/2} = 1.414 f_m \quad \text{(1.28)} $$

Similarly, for a one-third octave band,

$$ f_u / f_l = 2^{1/3} \quad \text{and} \quad f_m = (f_u f_l)^{1/3} \quad \text{(1.29)} $$

so that

$$ f_l = \frac{f_m}{2^{1/6}} = 0.891 f_m \quad \text{and} \quad f_u = f_m 2^{1/6} = 1.1225 f_m \quad \text{(1.30)} $$

In Eqs. (1.27) to (1.30), subscripts \( l \), \( u \) and \( m \) denote lower, upper and mean, respectively. It may be noted that three contiguous 1/3-octave bands would have the combined frequency range of the octave band centered at the centre frequency of the middle 1/3-octave band.

1000 Hz has been recognized internationally as the standard reference frequency, and the mid frequencies of all octave bands and 1/3-octave bands have been fixed around this frequency. Table 1.1 gives a comparison of different octave and 1/3-octave bands.

Incidentally, the standard frequency of 1000 Hz happens to be the geometric mean of the human speech frequency range; that is,

$$ 1000 = (125 \times 8000)^{1/2} \quad \text{(1.31)} $$

It may also be noted that

$$ 2^{1/3} = 1.26 \quad \text{and} \quad 10^{1/10} = 1.259 \quad \text{(1.32)} $$
Table 1.1 Bandwidth and geometric mean frequency of standard octave and ⅓-octave bands [12].

<table>
<thead>
<tr>
<th>Lower cutoff frequency (Hz)</th>
<th>Center frequency (Hz)</th>
<th>Upper cutoff frequency (Hz)</th>
<th>Lower cutoff frequency (Hz)</th>
<th>Center frequency (Hz)</th>
<th>Upper cutoff frequency (Hz)</th>
</tr>
</thead>
<tbody>
<tr>
<td>22</td>
<td>31.5</td>
<td>44</td>
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<td>88</td>
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<td>141</td>
</tr>
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<td>500</td>
<td>447</td>
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</tr>
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</table>

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Thus, for practical purposes, $2^{1/3} = 10^{1/10}$. That is why working either way around 1000 Hz, 100 Hz, 200 Hz, 500 Hz, 2000 Hz, 5000 Hz, 10,000 Hz represent the mean frequencies of the respective 1/3-octave bands. It may also be noted that the center frequencies indicated in the 2nd and 5th columns of Table 1.1 are internationally recognized nominal frequencies and may not be precise.

It may also be noted that the octave band and 1/3-octave band filters are constant percentage band–width filters. The percentage bandwidth of an n-octave filter may be written as

$$bw_n = \frac{f_u - f_l}{f_m} \times 100 = \left[ 2^{n/2} - 2^{-(n/2)} \right] \times 100$$  \hspace{1cm} (1.33)

Thus, for an octave filter (n = 1), bandwidth is 70.7% and for a one-third octave filter (n = 1/3), the bandwidth is 23.16% of the mean or centre frequency of the particular filter.

Power spectral density represents acoustic power per unit frequency as a function of frequency. Power in a band of frequencies represents area under the curve within this band. For example, for a flat (constant power) spectrum, the power in a frequency band would be proportional to the bandwidth in Hertz. As the bandwidth of an octave band doubles from one band to the next, the sound pressure level or power level would increase by $10 \log 2 = 3$ dB. Similarly, the SPL or SWL of a 1/3-octave band would increase by $10 \log 2^{1/3} = 1$ dB, as we move from one band to the next. As a corollary of the phenomenon, SPL in an octave band would be equal to the logarithmic sum of the SPLs of the three contiguous 1/3-octave bands constituting the octave band.

1.5 Weighted Sound Pressure Level

The human ear responds differently to sounds of different frequencies. Extensive audiological surveys have resulted in weighting factors for different purposes. Originally, A-weighting was for sound levels below 55 dB, B-weighting was for levels between 55 and 85 dB, and C-weighting was for levels above 85 dB. These are shown in Fig. 1.1.
Significantly, however the A-weighting network is now used exclusively in most measurement standards and the mandatory noise limits.

![Approximate electrical frequency response of the A-, B-, and C-weighted networks of sound level meters](image)

Table 1.2 contains a listing of the corrections in decibels to be added algebraically to all frequency bands. The A-weighted sound pressure level is denoted as $L_{pA}$, dB or $L_p$, dBA

$$L_{pA}, \text{ dB} \quad \text{or} \quad L_p, \text{ dBA}$$

(1.34)

The former notation is more logical. However, the latter continues to be in wide use. Incidentally, symbol dBA is often written as dB(A).

The second column in Table 1.2 indicates octave numbers in popular use among professionals.

### 1.6 Logarithmic Addition, Subtraction and Averaging

The total sound power level of two or more incoherent sources of noise may be calculated as follows:
Table 1.2  Sound level conversion chart from flat response to A, B, and C weightings.

<table>
<thead>
<tr>
<th>Frequency (Hz)</th>
<th>Octave band number</th>
<th>A weighting (dB)</th>
<th>B weighting (dB)</th>
<th>C weighting (dB)</th>
</tr>
</thead>
<tbody>
<tr>
<td>20</td>
<td></td>
<td>-50.5</td>
<td>-24.2</td>
<td>-6.2</td>
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<td>+1.2</td>
<td>-0.4</td>
<td>-0.5</td>
</tr>
<tr>
<td>4000</td>
<td>7</td>
<td>+1.0</td>
<td>-0.7</td>
<td>-0.8</td>
</tr>
<tr>
<td>5000</td>
<td></td>
<td>+0.5</td>
<td>-1.2</td>
<td>-1.3</td>
</tr>
<tr>
<td>6300</td>
<td></td>
<td>-0.1</td>
<td>-1.9</td>
<td>-2.0</td>
</tr>
<tr>
<td>8000</td>
<td>8</td>
<td>-1.1</td>
<td>-2.9</td>
<td>-3.0</td>
</tr>
<tr>
<td>10000</td>
<td></td>
<td>-2.5</td>
<td>-4.3</td>
<td>-4.4</td>
</tr>
<tr>
<td>12500</td>
<td></td>
<td>-4.3</td>
<td>-6.1</td>
<td>-6.2</td>
</tr>
<tr>
<td>16000</td>
<td></td>
<td>-6.6</td>
<td>-8.4</td>
<td>-8.5</td>
</tr>
<tr>
<td>20000</td>
<td></td>
<td>-9.3</td>
<td>-11.1</td>
<td>-11.2</td>
</tr>
</tbody>
</table>

\[ W_i = \sum_{i=1}^{n} W_i \]  \hspace{1cm} (1.35)

or
Noise and Its Measurement

Here \( n \) denotes the total number of incoherent sources like machines in a workshop or different sources of noise in an engine, etc. Similarly, the corresponding total SPL at a point is given by

\[
L_{p,t} = 10 \log \left[ \sum_{i=1}^{n} 10^{0.1L_{w,i}} \right]
\]  

Incidentally, Eqs. (1.35) – (1.37) would also apply to logarithmic addition of SPL or SWL of different frequency bands in order to calculate the total level. The logarithmic addition of power levels or sound pressure levels have some interesting implications for noise control. It may easily be verified from Eqs. (1.36) and (1.37) that

\[
100 \oplus 100 = 103 \text{ dB}
\]
\[
100 \oplus 90 = 100.4 \text{ dB}
\]
\[
x \oplus x = x + 3 \text{ dB}
\]

Similarly, 10 identical sources of \( x \) dB would add up to \( x + 10 \) dB.

Perception wise,

- 3 dB increase in SPL is hardly noticeable;
- 5 dB increase in SPL is clearly noticeable; and
- 10 dB increase in SPL appears to be twice as loud.

Similarly, 10 dB decrease in SPL would appear to be half as loud, indicating 50% reduction in SPL. Therefore, it follows that:

(i) In a complex noisy situation, one must first identify all significant sources, rank them in descending order and plan out a strategy for reducing the noise of the largest source of noise first, and then only tackle other sources in a descending order.

(ii) While designing an industrial layout or the arrangement of machines and processes in a workshop, one must identify and locate the noisiest machines and processes together in one corner, and isolate this area acoustically from the rest of the workshop or factory.
(iii) It is most cost effective to reduce all significant sources of noise down to the same desired level.

Addition of the sound pressure levels of the incoherent sources of noise may be done easily by making use of Fig. 1.2 which is based on the following formula:

$$\Delta L = L_{p2} - L_{p1} = 10 \log \left[ 1 + 10^{-0.1(L_{p2} - L_{p1})} \right], \text{ dB}$$  \hspace{1cm} (1.38)

It may be noted that the addition $\Delta L$ to the higher of the two levels is only 0.4 dB when the difference of the levels $(L_{p1} - L_{p2})$ equals 10 dB. Therefore for all practical purposes, in any addition, if the difference between the two levels is more than 10 decibels, the lower one may be ignored as relatively insignificant.

If one is adding more than two sources, one can still use Fig. 1.2, adding two at a time starting from the lowest, as shown Fig. 1.2.

The concept of addition can also be extended to averaging of sound pressure level in a community location. Thus, the equivalent sound pressure level during a time period of 8 hours may be calculated as an average of the hourly readings; that is,

$$L_{p,8h} = 10 \log \left[ \frac{1}{8} \sum_{i=1}^{8} 10^{0.1L_{pi}} \right], \text{ dB}$$  \hspace{1cm} (1.39)

This averaging is done automatically in an integrating sound level meter or dosimeter used in the factories in order to ensure that a worker is not subjected to more than 90 dBA of equivalent sound pressure level during an 8 hour shift. Similarly, one can measure $L_d$, the day time average (6 AM to 9 PM) and $L_n$, the night time average (9 PM to 6 AM). Making use of the fact that one needs quieter environment at night, the day-night average (24-hour average) is calculated as follows:

$$L_{dn} = 10 \log \left[ \frac{1}{24} \left\{ 15 \times 10^{0.1L_d} + 9 \times 10^{0.1(L_n + 10)} \right\} \right], \text{ dB}$$  \hspace{1cm} (1.40)
It may be noted that the $L_n$ has been increased by 10 dBA in order to account for our increased sensitivity to noise at night.

An illustration

Fig. 1.2 Logarithmic addition of two SPLs, $L_{p1} \oplus L_{p2}$. 

100 dB
Example 1.2 For a reasonably flat frequency spectrum with no sharp peaks or troughs, the band is nearly equal to the sum of the sound powers in the three contiguous one-third octave bands. Make use of this fact to evaluate sound pressure level of the 500 Hz band if the measured values of the 400-Hz, 500-Hz and 630-Hz 1/3-octave bands are 80, 90 and 85 dB, respectively.

Solution It may be noted from Table 1.1 that the frequency range of
400-Hz 1/3-octave band is 355 – 447 Hz, 
500-Hz 1/3-octave band is 447 – 562 Hz, 
630-Hz 1/3-octave band is 562 – 708 Hz, and 
500-Hz 1/1-octave band is 355 – 710 Hz
Thus, the 500-Hz octave band spans all three contiguous 1/3-octave bands. Therefore making use of Eq. (1.37),
\[ L_p(500 \text{ Hz octave band}) = 10 \log \left( 10^{80/10} + 10^{90/10} + 10^{85/10} \right) \]
\[ = 91.5 \text{ dB} \]

1.7 Directivity

Most practical sources of noise do not radiate noise equally in all directions. This directionality at distance \( r \) in the far field is measured in terms of a directivity index \( DI \), or directivity factor \( DF \), as follows:
\[ DI_\theta (r) = L_{p,\theta} (r) - L_{p,av} (r) = 10 \log (DF_\theta), \text{ dB} \quad (1.41) \]

The average sound pressure level \( L_{p,av} \) is calculated from the total sound power level by
\[ L_{p,av} (r) = L_w - 10 \log \left( 4\pi r^2 \right) \quad (1.42) \]

The average sound pressure level can be evaluated by averaging the measured sound pressure levels at different angles at the same distance \( r \) around the source, making use of the formula
If all the levels around the machine are within 5 dB of each other, then instead of Eq. (1.43) one can take the arithmetic average of SPLs and add 1 dB to it in order to get a reasonably approximate value of the average sound pressure level.

**Example 1.3** Sound pressure levels at four points around a machine are 85, 88, 92 and 86 dB when the machine is on. The ambient SPL at the four points (when the machine is off) is 83 dB. Calculate the average SPL of the machine alone (by itself).

**Solution**

Making use of Eq. (1.43),

\[
L_{p,av} = 10 \log \left[ \frac{1}{n} \sum_{i=1}^{n} 10^{0.1L_{p,i}} \right], \, dB
\]

\[
(1.43)
\]

\[
L_{p,av}(\text{machine + ambient}) = 10 \log \left[ \frac{1}{4} \left( \frac{85 + 88 + 92 + 86}{10^{10} + 10^{10} + 10^{10} + 10^{10}} \right) \right]
\]

\[
= 88.6 \, dB
\]

Incidentally, the arithmetic average of the SPLs at the four points works out to be

\[
\frac{1}{4} (85 + 88 + 92 + 86) = 87.7 \, dB
\]

So, the logarithmic average is quite close to the arithmetic average plus 1 dB.

Now, logarithmically subtracting the ambient SPL we get

\[
L_{p,av}(\text{machine alone}) = 10 \log \left(10^{88.6/10} - 10^{83/10}\right)
\]

\[
= 87.5 \, dB
\]
1.8 Measurement of Sound Power Level

A more precise method of measuring the average sound pressure level and the total power level of a source consists in making use of an anechoic room. This is a specially constructed room to simulate free field environment. Its walls as well as the floor and the ceiling are lined with long thin wedges of acoustically absorbent material with power absorption coefficient of 0.99 (99%) or more in the frequency range of interest. Low frequency noise is not absorbed easily. The lowest frequency upto which the absorption coefficient is at least 0.99 is called the cut-off frequency of the anechoic room. Such rooms are used for precise measurements as per international standards.

However, it is logistically very difficult to mount large and heavy test machines on suspended net flooring. Therefore the Engineering Method of measurement of sound pressure level of a machine to a reasonable accuracy is to make use of a hemi-anechoic room where one simulates a hemi-spherical free field. This is like testing a machine on the ground in an open ground. In such a room the floor is acoustically hard (highly reflective) while all the four walls and the ceiling are lined with highly absorbent acoustical wedges as indicated above for an anechoic room.

Table 1.3 Co-ordinates of the 12 microphone locations.

<table>
<thead>
<tr>
<th>Location No.</th>
<th>$x/r$</th>
<th>$y/r$</th>
<th>$z$</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>1</td>
<td>0</td>
<td>1.5 m</td>
</tr>
<tr>
<td>2</td>
<td>0.7</td>
<td>0.7</td>
<td>1.5 m</td>
</tr>
<tr>
<td>3</td>
<td>0</td>
<td>1</td>
<td>1.5 m</td>
</tr>
<tr>
<td>4</td>
<td>-0.7</td>
<td>0.7</td>
<td>1.5 m</td>
</tr>
<tr>
<td>5</td>
<td>-1</td>
<td>0</td>
<td>1.5 m</td>
</tr>
<tr>
<td>6</td>
<td>-0.7</td>
<td>-0.7</td>
<td>1.5 m</td>
</tr>
<tr>
<td>7</td>
<td>0</td>
<td>-1</td>
<td>1.5 m</td>
</tr>
<tr>
<td>8</td>
<td>0.7</td>
<td>-0.7</td>
<td>1.5 m</td>
</tr>
<tr>
<td>9</td>
<td>0.65</td>
<td>0.27</td>
<td>0.71 r</td>
</tr>
<tr>
<td>10</td>
<td>-0.27</td>
<td>0.65</td>
<td>0.71 r</td>
</tr>
<tr>
<td>11</td>
<td>-0.65</td>
<td>-0.27</td>
<td>0.71 r</td>
</tr>
<tr>
<td>12</td>
<td>0.27</td>
<td>0.65</td>
<td>0.71 r</td>
</tr>
</tbody>
</table>
Fig. 1.3 Microphone locations on a hypothetical hemi-spherical surface.

Radius of hemisphere: $r$
Alternatively, one can use the so-called Survey Method where measurements are made at discrete microphone locations on the parallelepiped shown in Fig. 1.4.

If $S_m$ is the area of the hypothetical measurement surface in $m^2$, then

$$L_w = L_{p,av} + 10 \log(S_m)$$

(1.44)

For a hemispherical hypothetical surface shown in Fig. 1.3, the measurement surface area $S_m = 2\pi r^2$, and for the parallelepiped surface of Fig. 1.4,

$$S_m = 2a \times 2b + 2(2a+2b)c = 4(ab + bc + ca), \ m^2$$

(1.45)

Example 1.4 The overall dimensions of a diesel generator (DG) set are $3m \times 1.5m \times 1.2m$ (height). The A-weighted sound pressure levels at 1 m from the five (4+1) radiating surfaces are 100, 95, 93, 102 and 98 dBA, respectively. Assuming that the contribution from the four walls and ceiling for the DG room is negligible, and making use of the Survey method, evaluate the sound power level of the DG set.
Solution  With reference to Fig. 1.4,

\[ l_1 = 3m, \quad l_2 = 1.5m, \quad l_3 = 1.2m \quad \text{and} \quad d = 1m \]

Thus,
\[ 2a = 3 + 2 \times 1 = 5 \, m, \]
\[ 2b = 1.5 + 2 \times 1 = 3.5 \, m, \]
\[ c = 1.2 + 1 = 2.2 \, m \]

Using Eq. (1.45), surface area of the hypothetical measurement surface is given by
\[
S_m = 4(ab + bc + ca) \\
= 4\left(\frac{5}{2} \times \frac{3.5}{2} + \frac{3.5}{2} \times 2.2 + 2.2 \times \frac{5}{2}\right) \\
= 54.9 \, m^2
\]

Average value of the SPL may be calculated by means of Eq. (1.43):
\[
L_{p, av} = 10 \log \left[ \frac{1}{5} \left( 10^{0.0/10} + 10^{9.5/10} + 10^{9.3/10} + 10^{10.2/10} + 10^{9.8/10} \right) \right] \\
= 98.3 \, dBA
\]

Finally, the power level of the DG set is given by Eq. (1.44). Thus,
\[
L_{W, A} = 98.3 + 10 \log (54.9) \\
= 115.7 \, dBA
\]

1.9 Loudness

Loudness index \( S \) is measured in terms of sones and the loudness level \( P \) in phons. They are related to each other as follows:
\[
L = 2^{(P - 40)/10}, \quad P = 40 + 33.3 \log S \tag{1.46}
\]
The band loudness index for each of the octave bands is read from Fig. 1.5, and then the composite loudness level, \( L \) (sones) is determined by [4]

\[
L = S_{\text{max}} + B \sum_i S_i
\]

(1.47)

where \( S_i \) is the loudness of the \( i^{th} \) band and \( S_{\text{max}} \) is the maximum of these values. Constant \( B = 0.3 \) for octave band analysis and 0.15 for 1/3-octave band analysis. The summation does not include \( S_{\text{max}} \).

**Example 1.5** If the measured values of the SPLs for the octave bands with mid-frequencies of 63, 125, 250, 500, 1000, 2000, 4000 and 8000 Hz are 100, 95, 90, 85, 80, 75, 70 and 65 dB, respectively, calculate the total loudness level in sones as well as phons.

**Solution** The exercise is best done in a tabular form shown below.
The measured values of SPL are entered in the first row of the table. The band loudness index $S_i$ for each octave band is read from Fig. 1.5 and entered in the second row of the Table. It may be noted that the maximum value of the loudness index, $S_{max}$, is 28 sones. Constant $B = 0.3$ for octave bands. Thus, making use of Eq. (1.47), the composite loudness index, $L$, is calculated as follows:

$$L = 28 + 0.3(25 + 22 + 19 + 17 + 14 + 13 + 11)$$

$$= 28 + 0.3 \times 121 = 64.3 \text{ sones}$$

Now use of Eq. (1.46) yields the loudness level in phons:

$$P = 40 + 33.2 \log 64.3$$

$$= 100.0 \text{ phons}$$

### 1.10 Noise Limits in India

The Ministry of Environment and Forests (MOEF) of the Government of India, on the advice of the National Committee for Noise Pollution Control (NCNPC) has been issuing Gazette Notifications prescribing noise limits as well as rules for regulation and control of noise pollution in the urban environment. These are summarized below.

#### 1.10.1 The noise pollution (regulation and control) rules, 2000 [5]

These rules make use of Table 1.4 for the ambient air quality standards. These are more or less the same as in Europe and USA.
Table 1.4  Ambient air quality standards in respect of noise [7].

<table>
<thead>
<tr>
<th>Category of Area/Zone</th>
<th>Limits in Leq (dBA)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Day Time</td>
</tr>
<tr>
<td>Industrial area</td>
<td>75</td>
</tr>
<tr>
<td>Commercial area</td>
<td>65</td>
</tr>
<tr>
<td>Residential area</td>
<td>55</td>
</tr>
<tr>
<td>Silence zone</td>
<td>50</td>
</tr>
</tbody>
</table>

Note:
1. Day time shall mean from 6:00 a.m. to 10:00 p.m.
2. Night time shall mean from 10:00 p.m. to 6:00 a.m.

(i). A loud speaker or a public address system shall not be used except after obtaining written permission from the authority.
(ii). A loud speaker or a public address system or any sound producing instrument or a musical instrument or a sound amplifier shall not be used at night time except in closed premises for communication within, like auditoria, conference rooms, community halls, banquet halls or during a public emergency.
(iii). The noise level at the boundary of the public place, where loudspeaker or public address system or any other noise source is being used, shall not exceed 10 dB(A) above the ambient noise standards for the area (see Table 1.4) or 75 dB(A) whichever is lower.
(iv). The peripheral noise level of a privately owned sound system or a sound producing instrument shall not, at the boundary of the private place, exceed by more than 5 dB(A) the ambient noise standards specified for the area in which it is used.
(v). No horn shall be used in silence zones or during night time in residential areas except during a public emergency.
(vi). Sound emitting fire crackers shall not be burst in silence zone or during night time.
(vii). Sound emitting construction equipments shall not be used or operated during night time in residential areas and silence zones.
1.10.2 **Permissible noise exposure for industrial workers**

In keeping with the practice in most countries, India has adopted the international limit of 90 dBA during an 8-hour shift for industrial workers.

<table>
<thead>
<tr>
<th>Duration/day (h)</th>
<th>Sound Level (dBA)</th>
</tr>
</thead>
<tbody>
<tr>
<td>16</td>
<td>87</td>
</tr>
<tr>
<td>8</td>
<td>90</td>
</tr>
<tr>
<td>4</td>
<td>93</td>
</tr>
<tr>
<td>2</td>
<td>96</td>
</tr>
<tr>
<td>1</td>
<td>99</td>
</tr>
<tr>
<td>0.5</td>
<td>102</td>
</tr>
<tr>
<td>0.25 or less</td>
<td>105</td>
</tr>
</tbody>
</table>

As shown in Table 1.5, for every 3 dB increase in the A-weighted sound level, the permissible maximum exposure has been reduced to half. Dosimeters have been provided to the factory inspectors and also to the traffic police. The technicians working on noisy machines or in noisy areas are provided with ear muffs or ear plugs, and are required to use them compulsorily.

The total daily dose, $D$, is given by

$$D = \frac{C_1}{T_1} + \frac{C_2}{T_2} + \ldots + \frac{C_n}{T_n}$$

(1.48)

where

$C_i = $ Total actual time of exposure at a specified noise level, and

$T_i = $ Total time of exposure permitted by the table above at that level.

Alternatively, if we want to evaluate the maximum time that a technician may be asked to work in a noisy environment without risking him to over exposure, we may make use of an integrating sound level meter to evaluate the 8-hour average of the A-weighted SPL as follows:
Noise and Vibration Control

\[ L_{\text{Aeq,8h}} = 10 \log \left[ \frac{1}{8} \int_{0}^{T} 10^{\frac{SPL(t)}{10}} \, dt \right] \]  
(1.49)

where \( t \) is in hours. Then, the maximum allowed exposure time to an equivalent SPL, \( L_{\text{Aeq,8h}} \), would be given by

\[ T_{\text{allowed}} = \frac{8}{D} \]  
(1.50)

where \( D \), the daily noise dosage with reference to the base level criterion of 90 dBA is given by

\[ D = 2^{\frac{(L_{\text{Aeq,8h}} - 90)}{3}} \]  
(1.51)

Here, constant 3 represents the decibel trading level which corresponds to a change in exposure by a factor of two for a constant exposure time (10 log 2 = 3). For use in USA, this constant would be replaced with 5.

**Example 1.6** The operator of a noisy grinder in an Indian factory is to be protected against over-exposure to the work station noise by rotation of duties. The operator’s ear level noise is 93 dBA near the grinder and 87 dBA in an alternative work place. What is the maximum duration during an 8-hour shift that the worker may work on the grinder?

**Solution**

Referring to Table 1.5,

\( T_1 \) for 93 dBA is 4 hours, and \( T_2 \) for 87 dBA is 16 hours.

Let the worker operate the grinder for \( x \) hours, and work in the quieter location for the remaining duration of 8-\( x \) hours.

Use of Eq. (1.48) yields

\[ \frac{1}{4} + \frac{8-x}{16} = 1 \]

whence

\[ x = \frac{8}{3} = 2.67 \text{ hours.} \]

Therefore, the technician should not be made to operate the grinder for more than 2.67 hours during an 8-hour shift.
1.10.3 Noise limit for diesel generator sets

India has the problem of power scarcity although the government has set up a number of thermal power plants, hydropower plants and atomic power plants. Therefore, most of the manufacturers have their own captive power plants based on diesel engines. The relevant gazette notification of the MOEF prescribes as follows [6].

- The maximum permissible sound pressure level for new diesel generator (DG) sets with rated capacity upto 1000 KVA shall be 75 dB(A) at 1 metre from the enclosure surface, in free field conditions.
- The diesel generator sets should be provided with integral acoustic enclosure at the manufacturing stage itself.

Noise limits for diesel generator sets of higher capacity shall be as follows [7].

- Noise from DG set shall be controlled by providing an acoustic enclosure or by treating the room acoustically, at the user’s end.
- The acoustic enclosure or acoustic treatment of the room shall be designed for minimum 25 dB(A) insertion loss or for meeting the ambient noise standards, whichever is on the higher side. The measurement for Insertion Loss may be done at different points at 0.5 m from the acoustic enclosure/room, and then averaged.
- The DG set shall be provided with a proper exhaust muffler with insertion loss of minimum 25 dB(A).
- The manufacturer should offer to the user a standard acoustic enclosure of 25 dB(A) insertion loss, and also a suitable exhaust muffler with IL of at least 25 dB(A).

1.10.4 Noise limit for portable gensets

Most shops and commercial establishments have their kerosene-start, petrol-run portable gensets with power range of 0.5 to 2.5 KVA. The relevant gazette notification for such small portable gensets prescribes as follows [7].
• Sound power level may be determined by means of the Survey method [8] (see Fig. 1.4).
• The A-weighted sound power level of the source in the case of the Direct Method is calculated from the equation

\[ L_{WA} = L_{PA} - K + 10 \log \left( \frac{S}{S_0} \right) \]  

(1.52)
where
- \( K \) is the environmental correction, \( 10 \log (1+4S/A) \)
- \( S \) is the area of the hypothetical measurement surface, \( \text{m}^2 \)
- \( S_0 = 1 \text{ m}^2 \)
- \( A \) is the room absorption, \( \text{m}^2 \) (see Eq. (4.13) in Chapter 4).
• The prescribed limit of sound power level of portable gensets is 86 dBA.
• This noise limit may necessitate use of acoustic hoods in most cases.

### 1.10.5 Noise limit for fire crackers

The Indian Society is a mix of different racial and religious communities. Each community has its festivals that are usually celebrated by means of sound emitting fire crackers. Most of the time, these crackers are fired in hand, and therefore the chance of body damage, particularly to the hearing for the players as well as on-lookers standing nearby, is high. Therefore, the government has mandated as follows [9].

• The manufacture, sale or use of fire-crackers generating noise level exceeding 125 dB(A) or 145 dB(C) peak at 4 meters distance from the point of bursting shall be prohibited.
• For individual fire-cracker constituting a series (joined fire-crackers), the above mentioned limit be reduced by \( 5 \log (N) \), where \( N \) = number of crackers joined together.
• The measurements shall be made on a hard concrete surface of minimum 5 meter diameter or equivalent.
• The measurements shall be made in free field conditions, i.e., there shall not be any reflecting surface upto 15 meter distance from the point of bursting.
1.10.6 **Noise limit for vehicles**

Table 1.6 Noise limits for vehicles at manufacturing stage applicable since 1\textsuperscript{st} April 2005 [10].

<table>
<thead>
<tr>
<th>Sl. No.</th>
<th>Type of Vehicle</th>
<th>Noise Limits dB(A)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Two-wheelers</td>
<td></td>
<td></td>
</tr>
<tr>
<td>1</td>
<td>Displacement upto 80 cc</td>
<td>75</td>
</tr>
<tr>
<td>2</td>
<td>Displacement more than 80 cc but upto 175 cc</td>
<td>77</td>
</tr>
<tr>
<td>3</td>
<td>Displacement more than 175 cc</td>
<td>80</td>
</tr>
<tr>
<td>Three-wheelers</td>
<td></td>
<td></td>
</tr>
<tr>
<td>4</td>
<td>Displacement upto 175 cc</td>
<td>77</td>
</tr>
<tr>
<td>5</td>
<td>Displacement more than 175 cc</td>
<td>80</td>
</tr>
<tr>
<td>Four-wheelers</td>
<td></td>
<td></td>
</tr>
<tr>
<td>6</td>
<td>Vehicles used for the carriage of passengers and capable of having not more than nine seats, including the driver’s seat</td>
<td>74</td>
</tr>
<tr>
<td></td>
<td>Vehicles used for carriage of passengers having more than nine seats, including the driver’s seat, and a maximum Gross Vehicle Weight (GVW) of more than 3.5 tonnes</td>
<td></td>
</tr>
<tr>
<td>7</td>
<td>With an engine power less than 150 kW</td>
<td>78</td>
</tr>
<tr>
<td>8</td>
<td>With an engine power of 150 kW or above</td>
<td>80</td>
</tr>
<tr>
<td></td>
<td>Vehicles used for carriage of passengers having more than nine seats, including the driver’s seat \ vehicles used for the carriage of goods</td>
<td></td>
</tr>
<tr>
<td>9</td>
<td>With a maximum GVW not exceeding 2 tonnes</td>
<td>76</td>
</tr>
<tr>
<td>10</td>
<td>With a maximum GVW greater than 2 tonnes but not exceeding 3.5 tonnes</td>
<td>77</td>
</tr>
<tr>
<td></td>
<td>Vehicles used for the transport of goods with a maximum GVW exceeding 3.5 tonnes</td>
<td></td>
</tr>
<tr>
<td>11</td>
<td>With an engine power less than 75 kW</td>
<td>77</td>
</tr>
<tr>
<td>12</td>
<td>With an engine power of 75 kW or above but less than 150 kW</td>
<td>78</td>
</tr>
<tr>
<td>13</td>
<td>With an engine power of 150 kW or above</td>
<td>80</td>
</tr>
</tbody>
</table>
Environmental noise of vehicles is measured in a pass-by noise test [10] as shown in Fig. 1.6. The vehicle approaches line A-A at a steady speed corresponding to 3/4 times the maximum power speed of the engine. As the vehicle front end reaches point $C_1$, the accelerator is pushed to full open throttle position and kept so until the rear of the vehicle touches line B-B at point $C_2$. The maximum SPL reading is recorded at the two microphone locations shown in Fig. 1.6. The test is repeated with the vehicle moving in the opposite direction. This is repeated three times. The average of the peak SPL readings represents the pass-by noise of the vehicle. Detailed operating instructions as well as test conditions are given in Ref. [10].

![Fig. 1.6 Measurement of passby noise of an automobile [10].](image)

Table 1.6 gives the pass-by noise limits for vehicles at the manufacturing stage [11] applicable since April 2005. These limits are similar to those prescribed in Europe since 1996. The limits are enforced by the Automotive Research Association of India (ARAI, Pune) during
the type testing of the new vehicles for establishing their road-worthiness.

1.11 Masking

Often environmental noise masks a warning signal. Masking is the phenomenon of one sound interfering with the perception of another sound. This is why honking has to be considerably louder than the general traffic noise around. It has been observed that masking effect of a sound of a particular frequency is more at higher frequencies than at the lower frequencies. Thus if we want to mask ambient sound of 500 Hz to 2000 Hz then we should introduce sound in the 500 Hz one-third octave band. In fact, the masking effect of a narrow band noise is more than that of a pure tone at the centre frequency of the band. The amount of masking is such that a tone which is a few decibels above the masking noise appears to be as loud as it would sound if the masking noise were not present. Masking can be put to effective use in giving acoustic privacy to intellectuals located in open cubicles in large call centers or similar large offices under the same roof. Playing of soft instrumental music in the background is enough to mask the conversation in the neighboring cubicles.

1.12 Sound Level Meter

The basic components of a portable sound level meter are microphone, pre-amplifier, weighting network, amplifier, rectifier, the output quantity calculator, and display unit.

The microphone is a transducer for conversion of acoustic signal into a voltage signal. Pre-amplifier is an impedance matching unit with high input impedance and low output impedance. The waiting network relates to A-weighting or C-weighting; B-weighting is rarely used these days. The display unit is essentially a sensitive digital voltmeter, pre-calibrated in terms of sound pressure levels in decibels. For convenience, the attenuators are usually arranged in 10 dB steps. The dynamic range is generally 60 or 80 decibels. There is invariably a meter response
function labeled as slow, fast and impulse with averaging time constants of 1 sec, 100 ms and 35 ms, respectively.

The Sound level meter is classified as Class I or Class II (also termed as Type I and Type II), depending on accuracy. Class I sound level meter is a precision sound level meter intended for accurate measurements whereas Class II sound level meter is a general purpose sound level meter intended for field use.

1.13 Microphones

There are several types of microphones. Three major types in common use are described here. The most precise microphone consists of a diaphragm which serves as one electrode of condenser and a polarized backing plate separated from it by a very narrow air gap which serves as the other electrode. The condenser is polarized by means of a bound charge so that small variations in the air gap due to pressure induced displacement of the diaphragm result in corresponding variations in the voltage across the condenser. Condenser microphone has relatively flat frequency response, which makes it very desirable for precise measurements.

In a piezo-electric microphone sound incident upon the diaphragm tends to stress or unstress the piezo-electric element which in return induces a bound change across its capacitance. Piezo-electric microphones are also called ceramic microphones.

<table>
<thead>
<tr>
<th>Sl. No.</th>
<th>Microphone type</th>
<th>Sensing element</th>
<th>Typical frequency range (Hz)</th>
<th>Temperature and humidity stability</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Condenser</td>
<td>Capacitor</td>
<td>2-20000</td>
<td>Fair</td>
</tr>
<tr>
<td>2</td>
<td>Ceramic</td>
<td>Piezolectric</td>
<td>20-10000</td>
<td>Good</td>
</tr>
<tr>
<td>3</td>
<td>dynamic</td>
<td>Magnetic coil</td>
<td>25-15000</td>
<td>Good</td>
</tr>
</tbody>
</table>

Dynamic microphones produce an electrical signal by moving a coil which is connected to a diaphragm through a magnetic field. Obviously, a dynamic microphone must not be used in the vicinity of devices that
create magnetic fields; e.g., transformers, motors and alternators. The relative performance of these microphones is given in Table 1.7.

### 1.14 Microphone Sensitivity

Microphone sensitivity is essentially the ratio of electrical output to acoustical input. In logarithmic units it is defined as

\[
S = 20 \log \left( \frac{E}{E_{\text{ref}}} \frac{p_{\text{ref}}}{p} \right), \quad dB \tag{1.53}
\]

where \( E_{\text{ref}} \), the reference voltage is generally 1 volt and \( p_{\text{ref}} \) the reference pressure which can be 1 Pa or 0.1 Pa (1 microbar). Eq. (1.53) may be rearranged as

\[
S = 20 \log E - L_p + 94, \quad dB \tag{1.54}
\]

where \( E \) is in volts and \( L_p \) is the sound pressure level (re 20 micropascal) on the microphone. Typical values of microphone sensitivities range between \(-25 \) and \(-60 dB \) re 1V/Pa.

Generally there is a trade-off between frequency response and sensitivity. For example, 6-mm diameter microphones have flat frequency response over a wide range of frequencies but they have less sensitivity, as compared to the corresponding 25-mm diameter microphones. Therefore 12-mm diameter microphones are used commonly on most portable sound level meters.

**Example 1.7** A condenser microphone with sensitivity of \(-30 dB \) re 1.0 V Pa\(^{-1}\) is used as the transducer on a portable sound level meter. What would be the SPL reading on the meter if the internal electronic noise is 10 \( \mu \)V?

**Solution**

Use of (1.54) yields

\[-30 = 20 \log \left(10 \times 10^{-6}\right) - SPL + 94\]
whence

\[ SPL = 30 - 100 + 94 \]
\[ = 24 \text{ dB} \]

As the internal electronic noise level is 24 dB, and 24 ⊕ 30 = 31, this sound level meter cannot be used to measure SPL of less than 30 dB with an accuracy of ±1 dB.

### 1.15 Intensity Meter

Intensity is defined as the time average of the product of acoustic pressure and normal particle velocity. As per the momentum equation, particle velocity is proportional to pressure gradient. Therefore, an intensity probe consists of two microphones with an acoustically transparent spacer in between. The acoustic pressure is then the average of the pressures picked up by the two microphones individually. Particle velocity is proportional to the difference of the two pressures divided by the distance \( d \) between the two (equal to spacer length). Thus,

\[
I = \frac{1}{4\omega\rho_0 d} \left( |p_1|^2 - |p_2|^2 \right)
\]

For this equation to represent the real intensity flux normal to a surface, the intensity probe must be held near the surface in such a way that the axis of the two microphones is perpendicular to the surface. The output of both the microphones is fed to the intensity meter which is calibrated to measure intensity directly in terms of decibels as per Eq. (1.20). Often a good intensity meter has provision for measurement of sound pressure levels and velocity level too. The sound intensity meter is also programmed for the octave and 1/3-octave frequency analysis.

### References


Problems in Chapter 1

Problem 1.1 Often, an approximate value of characteristic impedance \(Z_0 = \rho_0 c\) of air is taken as a round figure of 400 kg/(m\(^2\) s). What temperature does this value correspond to? Adopt the mean sea level pressure.

[Ans.: 40\(^\circ\)C]

Problem 1.2 What are the amplitudes of the particle velocity and sound intensity associated with a plane progressive wave of 100 dB sound pressure level? Assume that the medium is air at mean sea level and 25\(^\circ\)C.

[Ans.: 6.9 mm/s and 9.76 mW/m\(^2\)]
Problem 1.3 A bubble-like pulsating sphere is radiating sound power of 0.1 Watt at 500 Hz. Calculate the following at a farfield point located 1.0 m away from the centre of the sphere:

a) intensity level and sound pressure level  
b) rms value of acoustic pressure  
c) rms value of the radial particle velocity  
d) phase difference between pressure and velocity  

[Ans.: (a) both 99.0 dB, (b) 1.78 Pa, (c) 4.37 mm/s, (d) 6.3°]  

Problem 1.4 Sound pressure levels at a point near a noisy blower are 115, 110, 105, 100, 95, 90, 85 and 80 dB in the 63, 125, 250, 500, 1000, 2000, 4000 and 8000 Hz octave bands, respectively. Evaluate the total $L_p$ and $L_{pA}$.

[Ans.: $L_p = 116.6$ dB, $L_{pA} = 102.4$ dBA]  

Problem 1.5 Sound pressure levels measured in free space at 12 equispaced locations on a hypothetical hemi-spherical surface of radius 2m around a small portable genset lying on an acoustically hard floor are: 70, 72, 74, 76, 78, 80, 81, 79, 77, 75, 73 and 71 dB, respectively.

(a). Evaluate the sound power level of the portable genset.  
(b). What is the directivity factor for the locations where SPL is maximum and where SPL is minimum?  

[Ans.: (a) 90.5 dB, (b) 5.62 and 0.562]  

Problem 1.6 At a point in a particular environment, the octave-band sound pressure levels are 80, 85, 90, 85, 80, 75, 70 and 65 dB in the octave bands centered at 63, 125, 250, 500, 1000, 2000, 4000 and 8000 Hz, respectively. Evaluate the loudness index in sones for each of these eight octave bands, and thence calculate the total loudness level in sones and phons.

[Ans.: 49.6 sones and 96.5 phons]  

Problem 1.7 If the hourly A-weighted ambient SPL in an Indian workshop during an 8-hour shift are recorded as 85, 86, 87, 88, 90, 93, 93, 91 dBA, evaluate (a) the daily noise dose of the technicians
employed in the workshop, and (b) the maximum permissible exposure time according to the industrial safety standards.

[Ans.: (a) 0.93 and (b) 8.6 hours]

Problem 1.8 The technical specification sheet of a condenser microphone has been misplaced. In order to measure sensitivity of the microphone, it is subjected to SPL of 90 dBA in the 1000-Hz octave band. The output voltage is measured to be 1.0 millivolt. Find the sensitivity of the microphone.

[Ans.: $-56\ dB\ re\ 1\text{V/Pa}$]