Sound

Lecture No. 9

Topics: Units of sound intensity: Decibel and other units

Variation of sound intensity with distance, Architectural Acoustics

Teacher's name: Dr. Mehnaz Sharmin

Measurement of Intensity of Wave

- Intensity of wave is the amount of energy transfer per unit area per second which is given by, $I=2\pi^2n^2a^2\rho v$
- The intensity of sound wave is the quantity of sound energy that flows through a unit area in a unit time and the direction of flow being perpendicular to the area.
- **Intensity** is a definite **physical** quantity, whereas **loudness** is a **physiological degree of sensation**. Loudness depends on intensity, but the dependence is not linear.
- According to Weber-Fecher law "**Loudness produced is proportional to the logarithm of sound intensity**".
- If S is the loudness and I is the intensity, then $S \propto log I$ *Or,* $S = K\, log I$ (K=constant) Or, $\frac{dS}{dI} = \frac{K}{I}$
- $\frac{dS}{dI}$ is the sensitiveness of the ear which decreases with the increases of intensity of sound.
- In practical measurements, relative intensity is more important than the absolute intensity. Hence, the intensity of sound is often measured as its ratio to a standard intensity I_o. Standard intensity corresponds to the lowest audible sound 100 Hz (threshold of hearing).

Unit of intensity

Bell: (Introduced by Alexander Graham Bell)

If a sound is 10, 100 and 1000 times more intense than other, A. G. Bell called the former to be 1 unit, 2 unit or 3 units higher than the later. This unit was balled Bell and denoted by "bel".

In general it can be said that if a sound is 10^p times more intense than another the former is p times higher than the later.

Suppose, dS is the change perceived in loudness when dI is the change produced in original intensity I, then we have, $dS \propto \frac{dI}{I}$

or, $dS = K\frac{dI}{I}$ (K=constant)

After integrating the equation, $S = K\log_{10} I + A$

Let S is the loudness for an intensity I and S_o is that for an intensity I_o, then $S_o = K\log_{10} I_o + A$

The intensity level (L) is the difference in loudness. So, $L = S - S_o = K\log_{10} I - K\log_{10} I_o = K\log_{10}\frac{I}{I_o}$

When, $K=1$, $L = \log_{10}\frac{I}{I_o}$

Here, the unit of L is "bel". In practice, bel is a large unit. Hence, 1/10th of a bel is called decibel (dB) is generally used.

$L = 10\log_{10}\frac{I}{I_o}$ in dB

Let, the intensity level is changed 1dB, then $1 = 10\log_{10}\frac{I}{I_o} \Rightarrow \frac{I}{I_o} = 1.26$ That means L alters by 1 when I changes by $\left(\frac{1.26-1}{1} \times 100\%\right)$=26%.

The intensity levels of different sound

Source	Intensity (W/m^2)	Intensity Level (dB)
Threshold of hearing	1×10^{-12}	0
Rustling leaves	1×10^{-11}	10
Whisper/ quiet room	1×10^{-10}	20
Quiet radio	1×10^{-8}	40
Normal conversation	1×10^{-6}	60
Busy street traffic, Noisy office	1×10^{-5}	70
Vacuum cleaner, Loud radio, classroom lecture	1×10^{-4}	80
Inside a heavy truck	1×10^{-3}	90
Large Orchestra	6.3×10^{-3}	98
Walkman at Maximum level, Noisy factory, siren at 30 m	1×10^{-2}	100
Front rows of rock concert	1×10^{-1}	110
The range of human audibility	1	120 dB
Threshold of pain	1×10^{1}	130
Military jet takeoff	1×10^{2}	140
Instant perforation of eardrum	1×10^{4}	160

Damage from prolonged exposure

Damage from 8 h per day exposure

Damage from 30 min per day exposure

severe pain, damage in seconds

❑ Phon:

- During defining dB the assumption was taken that the loudness is independent of the pitch or frequency, but actually it depends on both intensity and frequency.
- So, a new unit named "Phon" was defined. The measure of loudness in Phon is the intensity level in dB for an equally loud pure tone of frequency 1000 Hz. Thus, the dB scale and Phon scale agree for the frequency 1000 Hz but differ for other frequencies.
- Phon = sound pressure level in dB at the frequency of 1000 Hz
- Let a frequency 3000 Hz and intensity 70 dB gives the same loudness as a standard source of frequency 1000 Hz at the intensity level 67 dB. Then the intensity level of the tone at 3000 Hz is 67 Phon.

❑ Limits of audibility:

- The sensation of sound depends upon both frequency and intensity.
- Audibility limit varies from person to person.
- Audibility limit in terms of frequency 20 to 20,000 Hz. (For aged person it reduces to 12,000 Hz)
- Frequency and intensity ranges of audibility both are important in detection of sound.
- For a particular frequency within the range there is a minimum intensity for audibility. This is called threshold of audibility.

Architectural acoustics

- Before the Beginning of 20th century constructions (rooms or buildings or halls) were designed without any consideration for their suitability from the acoustic point of view. That is why most of the constructions had bad sound quality.
- In the year 1910, Wallace Clement Sabine (an American physicist) stated that the building materials are poor absorber of sound. As a result, a large fraction of sound energy in a room is reflected possibly about some hundreds of times before being completely absorbed. The consequence of these repeated reflections is that appreciable amount of sound intensity persists even after the source stops emitting sound.

❑ **Reverberation:**

"The persistence of sound in the audible range after the sound source has ceased is called **reverberation** and it is responsible mainly for the bad acoustics of a room or a hall."

❑ **Reverberation time:**

The **time of reverberation** or **reverberation time** is defined as the time taken by the sound intensity to fall from its value called threshold of audibility." It is also known as the time taken by the sound intensity to fall through one-millionth of its value or 60 dB of intensity.

- **Things those affects the acoustics of a building:** 1. Un-optimized reverberation time, 2. Very low sound or very high loudness, 3. Interference of sound caused by improper focusing to a particular area, 4. Echoes produced inside the buildings, 5. Resonance caused due to matching of sound waves, 6. Noise roaming outside or inside the building.

- **Reduction of Reverberation:** Reverberation can be reduced by covering the walls, ceiling and floors with suitable absorbent materials. The absorbing power of an absorbent is measured by the fraction of the total sound energy which it can absorb in a single incidence. It depends somewhat on the frequency of the source.

Table: Absorption co-efficient of various materials determined by Sabine for the source of frequency 500 Hz

Materials	Absorption co-efficient (Sabines)
Brick, Plaster, Marble, etc.	0.01 to 0.03
Carpets and curtains	0.15 to 1.00
Felt	0.7
Person	0.2
Open window	1.00

Open window behaves as a perfect absorber of sound

- The **absorption coefficient of a surface** is defined as the ratio of sound energy absorbed by a certain area of the surface to that of an open window of same area. The absorption coefficient is measured in open window unit (O.W.U) or Sabines.

- Optimization of reverberation time is very important. If it is longer it will reduce the intelligibility while if it is lower it will make the sound level of the room very low.

Sabine's Reverberation Formula

Sabine developed the reverberation formula to express rise and fall of sound in a auditorium. The basic assumptions are-

- The average energy per unit volume is uniform.
- The energy is not lost in the auditorium except due to the absorption of the materials of the walls, ceiling, open windows and ventilators.

Analytical treatment of reverberation:-

Let E be the energy supplied by the source per second to a room having volume V. Then the energy supplied per unit volume is E/V. If I be the intensity, a the absorption co-efficient and n the number of reflection per unit second, then the energy absorbed per unit second is *Ian.*

The rate of change of energy per unit volume is given by,

$$\frac{dI}{dt} = \frac{E}{V} - Ian \qquad (12.10)$$

(a) Growth of intensity: The equation (12.10) can be written as, $\frac{dI}{\frac{E}{V} - Ian} = dt$

$$\int \frac{dI}{\frac{E}{V} - Ian} = \int dt$$

Or, $-\frac{1}{an} log_e\left(\frac{E}{V} - Ian\right)$ = t+k [k= constant of integration]

Choosing initial conditions: At t=0, I=0 from equation (12.10) we get, $-\frac{1}{an} log_e\left(\frac{E}{V}\right)$ = k

So, $-\frac{1}{an} log_e\left(\frac{E}{V} - Ian\right) = t - \frac{1}{an} log_e\left(\frac{E}{V}\right) \Rightarrow -\frac{1}{an} log_e\left(\frac{E}{V} - Ian\right) + \frac{1}{an} log_e\left(\frac{E}{V}\right) = t$

Or, $-\frac{1}{an}\left[log_e\left(\frac{E}{V} - Ian\right) - log_e\left(\frac{E}{V}\right)\right] = t$

Or, $-\frac{1}{an}\left[log_e\left\{\left(\frac{E}{V} - Ian\right) / \left(\frac{E}{V}\right)\right\}\right] = t$

Or, $-\frac{1}{an}\left[log_e\left(1 - \frac{Ian}{E/V}\right)\right] = t \qquad \Rightarrow log_e\left(1 - \frac{Ian}{E/V}\right) = -ant$

Or, $1 - \frac{Ian}{E/V} = e^{-ant} \qquad \Rightarrow \frac{Ian}{E/V} = 1 - e^{-ant}$

$$\therefore I = \frac{E}{anV}(1 - e^{-ant}) \qquad (12.11)$$

The equation (12.11) shows that I attains its maximum value (I_o) when t is infinity.

So, $I_o = \frac{E}{anV}$ (12.12)

(b) **Decay of intensity:** When the source ceases to emit sound, $E=0$ and hence equation (12.10) reduces to,

$$\frac{dI}{dt} = -Ian \qquad (12.13)$$

Or, $\frac{dI}{I} = -andt$

Or, $\int \frac{dI}{I} = -an \int dt$

Or, $log_e I = -ant + k'$ (12.14)

Here, k'= constant of integration

Counting the time from just when the source ceases, we have $t=0, I=I_o$

Putting these values in equation (12.14),

$log_e I_o = k'$

Therefore, equation (12.14) can be written as

$log_e I = -ant + log_e I_o$

Or, $log_e I - log_e I_o = -ant \Rightarrow log_e \frac{I}{I_o} = -ant$

Or, $\frac{I}{I_o} = e^{-ant} \Rightarrow I = I_o e^{-ant}$ (12.15)

Equation (12.15) shows theoretically I will be zero after an infinite time.

Jaeger shows by statistical methods that

n=cS/4V

Where, c = velocity of sound, S= Surface area of the room.

Substituting n in the equation (12.15),

$$I = I_o e^{-acSt/4V} \qquad (12.16)$$

If T= reverberation time, putting $I/I_o = 10^{-6}$ in equation (12.16) we get,

$10^{-6} = e^{-acST/4V}$; Now, taking log_{10} on both sides

$6 = \frac{acS}{4V} T \, log_{10} e$

$\therefore T = \frac{24V}{340 \times log_{10} e \times aS} = 0.16 \frac{V}{aS}$ (SI unit) [c=340 m/s]

$\therefore T = \frac{24V}{1100 \times log_{10} e \times aS} = 0.05 \frac{V}{aS}$ (CGS unit) [c=1100 ft/s]

When, different portion of the room has different absorption coefficient, aS in the equation should be replaced by ΣaS.

So, $T = 0.16 \frac{V}{\Sigma aS}$ (SI unit) or, $T = 0.05 \frac{V}{\Sigma aS}$ (CGS unit)