2. Acoustics

Classification of Sound – decibel – Weber Fechner law – Sabine's formula – derivation using growth and decay method – Absorption Coefficient and its determination – factors affecting acoustics of buildings and their remedies. Methods of sound absorptions - absorbing materials - noise and its measurements, sound insulation and its measurement, impact of noise in multi-storeyed buildings.

Introduction

The branch of physics which deals with generation, reception, propagation and analysis of sound is called ***acoustics.***

The study of sound waves plays an important role in many engineering and non - engineering applications. The areas of acoustical studies and their applications include

Architectural acoustics - Study of sound waves in closed halls and buildings.

Musical acoustics - Physics of musical instruments

Engineering acoustics - Technology of sound production and recording, study of vibrations of solids and their control as well as noise control.

Bio-acoustics / Medical acoustics - Use of sound in medical diagnosis and therapy.

2.1 CLASSIFICATION OF SOUND

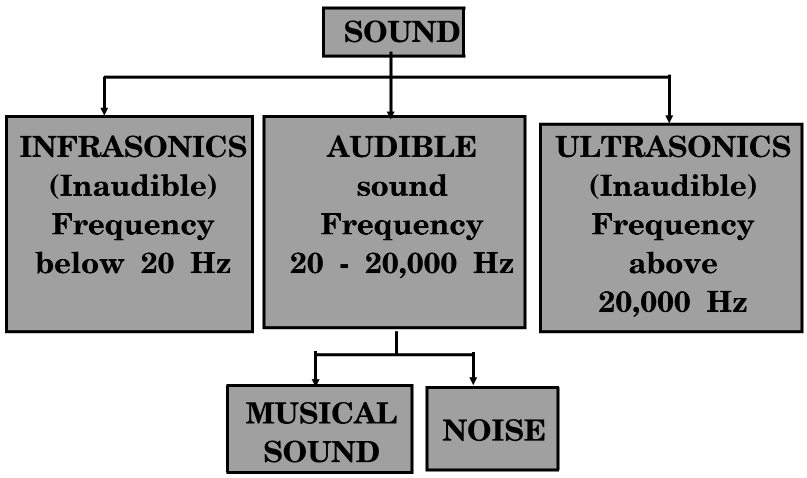
Sound waves are classified into three types based on their frequencies.

(a) **Infrasonics (Inaudible):** Sound waves of frequencies below **20 Hz** are called infrasonics. They are inaudible.

(b) **Audible sound:** Sound waves of frequencies between **20 Hz** and **20,000 Hz** are called audible sound. They are audible.

Audible sound is further classified as ***musical sound*** and ***noise***.

(c) **Ultrasonics (Inaudible):** Sound waves of frequencies above **20,000 Hz** or **20 kHz** are called ultrasonics. They are inaudible.



Musical Sound

Sound which produces a pleasant effect to our ears is called musical sound.

Example:

Sounds produced by the musical instruments like sitar, violin and piano are musical sounds.

Properties of musical sound

- Fig. 2.1. shows the wave forms of the different musical sounds.
- The waveform of musical sound has a regular shape.
- Musical sound has definite periodicity.
- There is no sudden change in amplitude.

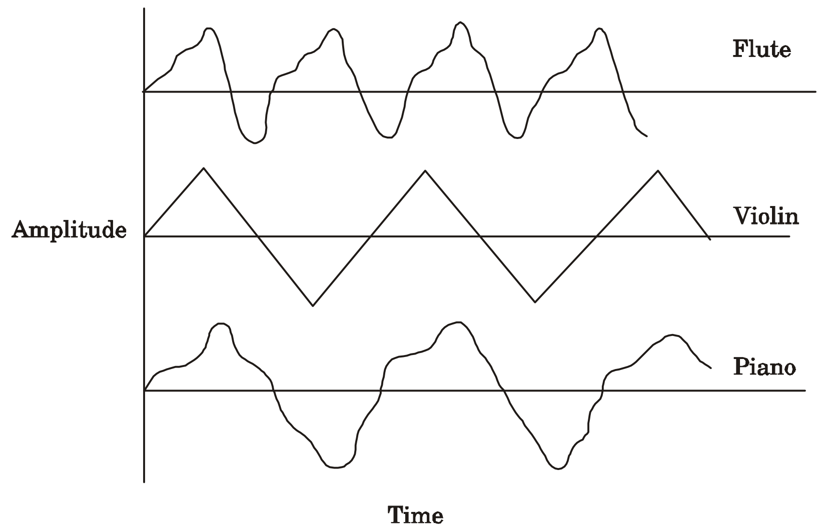


Fig. 2.1. Musical sound wave forms

Noise

Any unpleasant sound to our ears is called noise.

Noise causes irritation and strain to our ear. Noise of high intensity may cause permanent or temporary deafness.

Example: Movement of furniture, road traffic, explosion of bombs.

Properties of noise

- The wave form of noise is shown in fig. 2.2.
- The waveform of noise is irregular in shape

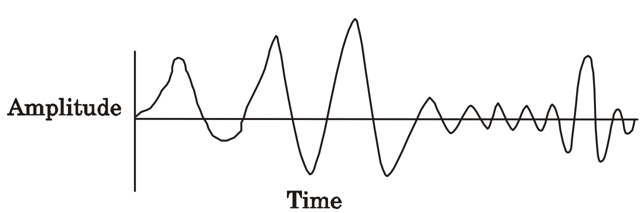


Fig. 2.2. Noise wave form

- It lacks periodicity
- It undergoes sudden changes in amplitude and frequency as shown in fig. 2.2

Characteristics of musical sound

The different musical sounds are distinguished from each other by the following three characteristics.

(i) Pitch or frequency
(ii) Quality or timbre
(iii) Intensity or loudness

(i) Pitch (or) frequency

Pitch is the characteristic of a sound which distinguishes between a shrill sound and a grave sound. The pitch of a musical note is the sensation conveyed to our brain by the sound waves falling on our ears.

Pitch depends directly on the frequency of the sound waves.

Example

- The voice of women and children has high pitch because the frequency of sound is high.
- The voice of an old man has low pitch because the frequency of sound is low.
- In guitars, thicker wires give a lower frequency and thinner wires give a length frequency.

(ii) Quality (or) Timbre

Quality or timbre of the sound wave is a characteristic which enables us to distinguish between musical notes emitted by different instruments or voices even though they have the same pitch and loudness.

(iii) Intensity of sound (I)

Intensity of a sound wave (I) at a point is defined as the amount of sound energy (*Q*) flowing per second per unit area held normally at the point to the direction of the propagation of sound wave.

Intensity of sound wave $\boxed{I = \frac{Q}{tA}}$

where Q - Amount of sound energy flowing
t - Time of flow
A - Area normal to the propagation of sound.

$$\text{Intensity, } I = \frac{P}{A} \qquad \left[\because \text{ Power, } P = \frac{Q}{t}\right]$$

Intensity is a measurable physical quantity. It is expressed in joule second^{-1} metre^{-2} or watt metre^{-2} (Wm^{-2}).

Loudness

Loudness of the sound is defined as the degree of sensation produced on the ear. It varies from one listener to another. Loudness is different from intensity of sound.

Loudness is a physiological quantity. It is difficult to measure because it depends upon the individual listener. However, it is measured as the logarithmic value of intensity.

2.2 WEBER - FECHNER LAW

(Relation between loudness and intensity of sound)

According to Weber - Fechner law, the loudness of sound varies with intensity of sound.

Statement

The law states that the loudness (L) produced is directly proportional to logarithm of intensity.

i.e.,
$$L \propto \log_{10} I$$

$$L = k \log_{10} I$$

where L – loudness

I – intensity

k – constant

$$\boxed{\frac{dL}{dI} = \frac{k}{I}}$$

The quantity $\frac{dL}{dI}$ is called sensitiveness of the ear. It decreases with an increase in the intensity of sound.

Sound Intensity Level

Absolute intensity of a sound wave is measured in Wm^{-2}. For all our practical purposes, we are interested in the measurement of relative intensity rather than absolute intensity.

Intensity of a sound is measured with reference to some standard intensity. The standard intensity $I_o = 10^{-12}\ Wm^{-2}$ is chosen for this purpose.

This is the lowest intensity of sound (at 1000 hertz) to which a normal human ear can respond. This standard intensity is known as threshold of audibility.

2.3 DECIBEL

Definition

The logarithmic ratio of intensity of a sound to standard intensity is known as sound intensity level or relative intensity of sound.

The, sound intensity level of a sound wave having intensity I is given by

$$\beta = \log_{10}\left[\frac{\text{Intensity of sound (I)}}{\text{Standard Intensity of sound (} I_o \text{)}}\right]$$

$$\boxed{\beta = \log_{10}\left[\frac{I}{I_o}\right]} \qquad \text{... (1)}$$

Here, standard intensity of sound is the minimum audible sound intensity heard by our ears.

The unit for sound intensity level is bel named in honour of Alexander Graham Bell, (inventor of telephone).

Sound intensity level, $\beta = \log_{10}\left[\frac{I}{I_o}\right]$ bel ...(2)

Consider sound intensity $I = 10\,I_o$

Sound intensity level in bel, $\beta = \log_{10}\left[\frac{10\,I_o}{I_o}\right]$ ...(3)

From equation (3), we get

$$\beta = \log_{10} 10$$

$$\beta = 1 \text{ bel}$$

If $I = 100\,I_o$, then $\beta = 2$ bel, and

If $I = 1000\,I_o$, then $\beta = 3$ bel.

Bel is the sound intensity level of a sound whose intensity is ten times the standard intensity.

In practice, bel is a larger unit. Hence, another unit known as decibel (dB) is more often used.

$$\boxed{\textbf{1 bel = 10 decibel}}$$

Hence, sound intensity level is measured in decibel

$$\boxed{\beta \text{ (in decibel)} = 10 \log_{10}\left[\frac{I}{I_o}\right]} \text{ dB}$$

Physical significance of a decibel

Let us find the physical significance of a decibel, i.e., what percentage change in intensity represents one decibel.

If sound intensity level increases by '1' dB,

(substituting intensity level in $dB = 1$)

$$1 = 10 \log_{10}\left(\frac{I}{I_o}\right)$$

$$\log_{10}\left(\frac{I}{I_o}\right) = \frac{1}{10} = 0.1$$

$$\frac{I}{I_o} = 1.26 \qquad (\because \text{ antilog of } 0.1 = 1.26)$$

$$I = 1.26\, I_o$$

Thus, an increase of sound intensity level by 1 dB would increase the intensity by 26%.

Normally, our ears can hear the sound intensity level between the range 0 dB to 120 dB. The maximum sound intensity level which our ears can tolerate without sensation of pain is 120 dB. This upper limit of hearing is called threshold of feeling or pain threshold.

ANNA UNIVERSITY SOLVED PROBLEMS

Problem 2.1

The intensity of sound produced by thunder is 0.1 Wm^{-2}. Calculate the intensity level in decibel.

(A.U. Jan 2014)

Given data

Intensity of sound produced by thunder,

$$I = 0.1\ Wm^{-2}.$$

Standard intensity $I_o = 10^{-12}\ Wm^{-2}$

Solution

Intensity level of sound $(\beta) = 10 \log_{10}\left[\frac{I}{I_o}\right]$

Substituting the given values, we have

$$= 10 \log_{10}\left[\frac{0.1}{10^{-12}}\right]$$

$$= 10 \log_{10} (10^{11}) = 10 \times 11 = 110\ dB$$

Hence, sound intensity level produced by thunder = 110 dB

Problem 2.2

The intensity of sound in a street during heavy traffic is 10^{-4} Wm^{-2}. Calculate intensity level in decibel.

(A.U. Jan 2016)

Given data

Intensity of sound in the street, $I = 10^{-4}\ Wm^{-2}$

Standard intensity of sound $I_o = 10^{-12}\ Wm^{-2}$

Solution

Sound intensity level $(\beta) = 10 \log_{10}\left[\frac{I}{I_o}\right]$

Substituting the given values, we have

$$\beta = 10 \log_{10}\left[\frac{10^{-4}}{10^{-12}}\right]$$

$$\beta = 10 \log_{10}(10^{8}) = 10 \times 8 = 80 \text{ dB}$$

TABLE 2.1

Sound intensity levels of some familiar common sounds

S. No.	Sound	Sound intensity level in decibel (dB)	Nature
1.	Threshold of audibility	0	silence
2.	Rustle of leaves	10	feeble
3.	Whispering	20	feeble
4.	Radio at home	40	feeble
5.	Automobile sound	50	moderate
6.	Busy street traffic	70	loud
7.	Noisy factory	90	loud
8.	Orchestra	100	very loud
9.	Threshold of pain	120	very loud

Acoustics of buildings

The subject of physics which deals with the design and construction of rooms or halls so as to give the best sound effects is called acoustics of buildings or architectural acoustics.

The acoustical properties of a room or hall have considerable effect on the clarity and intelligibility of speech or music produced in the hall.

The acoustic properties of buildings were studied systematically by Prof. Wallace C. Sabine, Professor of Physics in Harvard University, U.S.A in the year 1900.

Now, the science of acoustics of buildings has a prominent role in the design of modern buildings.

2.4 ABSORPTION COEFFICIENT

When a sound wave strikes a surface, a part of its energy is absorbed, a part of it is transmitted and the remaining part is reflected.

The property of the surface to convert sound energy into other forms of energy is known as absorption.

The effectiveness of absorption of sound energy by the surface is expressed as absorption coefficient.

Absorption coefficient (a) is defined as the ratio of sound energy absorbed by its surface to that of total sound energy incident on the surface.

$$\boxed{a = \frac{\text{Sound energy absorbed by the surface}}{\text{Total sound energy incident on the surface}}}$$

Practical definition of absorption coefficient

In order to compare the relative sound absorption of different materials the open window is taken as standard reference since it is a perfect sound absorber.

It is because the whole of the sound energy passes through the open window and none is reflected.

Absorption coefficient of a surface is the ratio of sound energy absorbed by 1 m² of the surface to that absorbed by 1 m² of an open window.

$$\boxed{a = \frac{\text{Sound energy absorbed by 1m}^2\text{ of the surface}}{\text{Sound energy absorbed by 1m}^2\text{ of open window}}}$$

Clearly, the value of absorption coefficient varies between 0 and 1. (1 is being the maximum value of absorption coefficient).

Thus, absorption coefficient is measured in Open Window Unit and is written as O.W.U. or sabine / m^2.

For example, absorption coefficient of plastered wall is 0.03 O.W.U. It means that sound energy absorbed by 1 m^2 of plastered wall is 0.03 times that absorbed by 1 m^2 of an open window.

TABLE 2.2

Absorption coefficients of some common sound absorbing materials

S. No	Material	Absorption coefficient per m^2
1.	Open window	1.00
2.	Ventilators	0.10 to 0.50
3.	Plaster on wall surface	0.02
4.	Glass against solid surface	0.03
5.	Marble	0.01
6.	concrete floor	0.03
7.	Solid wooden floor	0.09
8.	Plywood on battens	0.17 to 0.26
9.	Window glazed	0.18
10.	Curtains in heavyfolds	0.40 to 0.75
11.	Metal	0.01
	Individual object	**Absorption units in m^2 - sabins**
1.	Audience, adults in wooden seat	0.46
2.	Plain seat	0.02
3.	Covered seat	0.10 to 0.20

2.5 SOUND ABSORBING MATERIALS

The special materials used to increase the absorption of sound waves or to reduce the reflection of sound waves in a room or hall are known as sound absorbing materials.

The important facts in connection with sound absorbing materials

- An ideal absorbing material should be economical in construction and maintenance, water-proof, fire-proof, sufficiently strong and good in appearance.
- In the hall treated with absorbing materials, the speech can be heard clearly and music can be fully enjoyed.
- All the absorbing materials are found to be soft and porous. They work on the principle that the sound waves penetrate into the pores and they are converted into other form of energy.
- The absorbing capacity of the absorbing materials depends on the thickness of the material, its density and frequency of sound.
- Great care should be exercised while prescribing the sound absorbing material so as to improve its appearance.
- It should be remembered that in a big hall, the audience is a major absorbing factor.

The requirements of a good acoustical material are as follows:

- It should be durable and should not be liable to be attacked by insects, termites, etc.
- It should be easily available at a reasonable cost.
- It should be efficient over a wide range of frequencies.
- It should be fire resistant.
- It should give pleasing appearance after fixing.

- It should have high coefficient of absorption.
- It should have sufficient structural strength.

Classification of sound absorbing materials

The sound absorbing materials are broadly classified into the following four categories:

(a) **Porous absorbents**

(b) **Cavity resonators**

(c) **Resonant absorbing or panel absorbers**

(d) **Composite types of absorbents.**

(a) ***Porous absorbents.*** When sound waves strike the porous material, a part of waves is reflected while the other enters the porous material.

The part that enters the porous material is converted into heat energy while the reflected part is reduced in energy.

Examples: fibre boards, soft plasters, rock wool, wood wool, mineral wools, glass silk, asbestos fibre spray, etc.

(b) ***Cavity resonators.*** A cavity resonator is a chamber or container having a small opening. When sound waves enter the resonator, the waves are absorbed due to multiple reflections.

(c) ***Resonant absorbents or Panel absorbers***. In this system, the absorbent materials is fixed on a framing (usually timber) with an air space between the framing and the wall. It acts as a panel absorber.

Examples: gypsum boards, wood and hard-board panels, suspended plaster ceilings, rigid plastic boards, windows, doors, etc.

(d) ***Composite absorbers***. When the functions of all the three types described above is combined in a single unit, then it is known as composite absorber.

The composite absorbers consist of a perforated panel fixed over an air space containing porous absorbent.

When sound waves strike the panel, they pass through it and damped by resonance of the air in the cavity.

Common types of sound absorbing materials:

1. Hairfelt

The average value of coefficient of absorption of 25 mm thick hairfelt is 0.60.

2. Acoustic plaster

This is also known as the *fibrous plaster* and it includes granulated insulation material mixed with cement. The acoustic plaster boards are also available. They can be fixed on the wall and their coefficient of absorption varies from 0.15 to 0.30.

3. Acoustical tiles

These are made in factory and sold under different trade names. The absorption of sound is uniform from tile to tile and they can be fixed easily.

4. Strawboard

This material can also be used as absorbent material.

5. Pulp boards

These are the soft boards which are prepared from the compressed pulp. They are cheap and can be fixed by ordinary panelling. The average value of coefficient of absorption is 0.17.

6. Compressed fiberboard

This material may be perforated or unperforated. The average coefficient of absorption for the perforated is 0.30.

7. Compressed wood particle board

This material is provided with perforations and it can also be painted. With a thickness of about 13 mm, the average coefficient of absorption is 0.40.

8. Perforated plywood

This material can be used by forming composite panels with mineral wool and cement asbestos or with mineral wool and hardboard. It is generally suspended from the trusses.

9. Wood wool board

This material is generally used with a thickness of 25 mm. The average value of coefficient of absorption is 0.20.

10. Quilts and mats

These are prepared from mineral wool or glass wool and are fixed in the form of acoustic blankets.

Reverberation

The sound which is produced in a hall, travels in all directions and undergo multiple reflections from the walls, floor and ceiling before it becomes inaudible (fig. 2.3).

A listener in the room continuously receives successive reflections of diminishing intensity of sound (a part of sound energy is lost at each reflection). Therefore, the listener hears a ***'roll of sound'*** instead of a single sharp sound.

This implies that the sound is heard continuously for short definite time interval even after the source of sound has stopped to emit the sound.

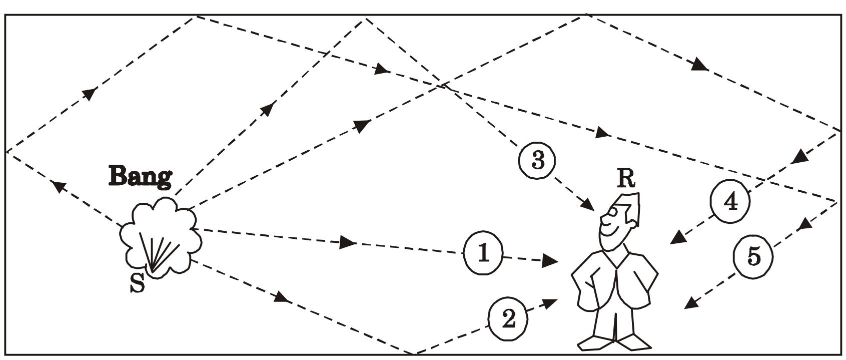


Fig. 2.3 Reverberation of sound in a room

The existence or prolongation or persistence of sound in a room (due to multiple reflections from surfaces) even after the source of sound has stopped to emit the sound is called reverberation.

This familiar phenomenon is experienced in vacant halls of a new building.

Reverberation Time

Definition

- **The time duration for which a sound persists even after the source of sound has stopped to emit the sound is called reverberation time.**
- **It is measured as the time taken by the sound to fall below the minimum audibility after source of sound has stopped to emit the sound.**

Standard reverberation time

- **Standard reverberation time is defined as time taken by the sound intensity to fall one - millionth (10^{-6}) of its initial intensity after the sound source has stopped to emit the sound.**
- **It is also defined as time taken by the sound intensity level to reduce by 60 decibels from its initial sound intensity level after the source of sound has stopped to emit the sound.**

If I_m is initial intensity, then I intensity of sound after the time interval corresponding to standard reverberation time 'T'

$$I = \frac{I_m}{10^6}$$

$$\boxed{\frac{I}{I_m} = 10^{-6}}$$

2.6 SABINE'S FORMULA FOR REVERBERATION TIME

Sabine derived a relation for the standard reverberation time.

It is given by $\boxed{T = \dfrac{0.167\ V}{\Sigma\, as}}$ second

ie.,

$$T = \frac{0.167\ V}{a_1 s_1 + a_2 s_2 + \ldots}$$

where V – Volume of the room or hall in $\mathbf{m^3}$

a – Absorption coefficients of surface areas of different materials present in the hall in **O.W.U.**

s – Surface areas of the different surfaces in $\mathbf{m^2}$

$\Sigma\, as$ – Total absorption of sound i.e., sum of the product of absorption coefficients and surface areas of the different surfaces present in the hall in **O.W.U.** m ^{2} **or sabine**

It is popularly known as ***Sabine's formula for reverberation time***.

2.7 DERIVATION USING GROWTH AND DECAY METHOD

Let us assume that the sound energy is uniformly distributed throughout the hall. It does not depend on frequency.

We shall calculate the rate at which the sound energy is incident upon the walls and hence the rate at which the sound energy is being absorbed.

Consider a small element *ds* on a plane wall AB in the hall as shown in fig. 2.4.

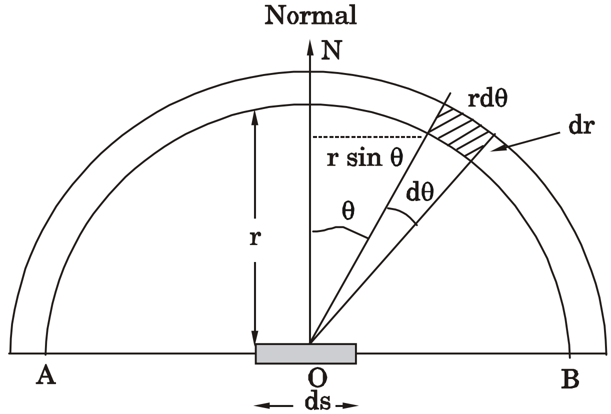


Fig. 2.4 Sound absorption on a plane wall

It is assumed that the element ds receives sound energy. Taking O as a mid point on ds, two semicircles are drawn with radii r and $r + dr$.

Now, consider a small shaded portion between the circles lying between two radii r and $r + dr$ drawn at angles θ and $\theta + d\theta$ with normal ON as shown in fig. 2.4.

Radial length of the shaded portion $= dr$

Arc length of the shaded portion $= r\, d\theta$

Area of this shaded portion $= r\, d\theta\, dr$ ...(1)

Imagine, the whole figure is rotated about the normal through an angle $d\phi$ (radius of the rotating shaded portion being $r \sin\theta$).

The shaded portion travels through a small distance dx (circumferential length) and thus, traces out an elemental volume dV (Fig. 2.5).

Distance travelled by this shaded portion,

$$dx = r \sin \theta\, d\phi$$

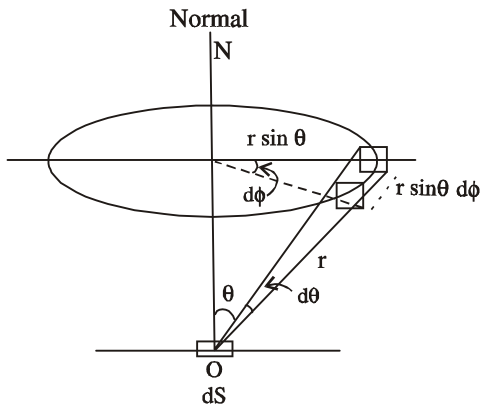


Fig. 2.5

∴ Volume traced by the shaded portion,

$$dV = \text{area} \times \text{distance travelled}$$

$$dV = r\,d\theta\,dr \times r\sin\theta\,d\phi$$

$$dV = r^2 \sin\theta\,d\theta\,dr\,d\phi \qquad ...(2)$$

If E is the sound energy density i.e., sound energy per unit volume, then,

Sound energy present within the elemental volume dV

$$= E \times dV$$

On substituting eqn (2), we have

$$= Er^2 \sin\theta\,dr\,d\theta\,d\phi \qquad ...(3)$$

This sound energy from elemental volume is travelling equally in all directions in total solid angle of 4 π.

∴ Sound energy travels the volume dV per unit solid angle

$$= \frac{EdV}{4\pi} = \frac{Er^2 \sin\theta\,dr\,d\theta\,d\phi}{4\pi} \qquad ...(4)$$

In this case, the solid angle subtended by the area ds at this elemental volume dV

$$= \frac{ds \cos\theta}{r^2}$$

Hence, sound energy from the elemental volume dV towards 'ds' is given by

$$= \frac{\mathrm{E}r^2 \sin\theta \, d\theta \, dr \, d\phi}{4\pi} \times \frac{ds \cos\theta}{r^2}$$

$$= \frac{\mathrm{E}ds}{4\pi} \sin\theta \cos\theta \, d\theta \, d\phi \, dr \qquad \ldots(5)$$

Since sound energy is falling on ds from all directions, θ changes from 0 to $\pi/2$ and ϕ changes from 0 to 2π.

Further, to get total sound energy received per second, r changes from 0 to v, where v is the velocity of sound (since sound existing within the distance of 0 to v metre from ds reaches ds in one second).

∴ Total sound energy falling on ds per second

$$= \frac{\mathrm{E}ds}{4\pi} \int_0^{\pi/2} \sin\theta \cos\theta \, d\theta \int_0^{2\pi} d\phi \int_0^{v} dr$$

$$= \frac{\mathrm{E}ds}{4\pi} \times \frac{1}{2} \times 2\pi \times v$$

$$= \frac{\mathrm{E}v \, ds}{4} \qquad \ldots(6)$$

Note:

Solid angle is an angle formed at the vertex of a cone or subtended at the point of intersection of two or more planes. (Fig. 2.6)

Solid angle subtended by an area *ds* about any point P at a distance '*r*' is given by

$$d\omega = \frac{\text{Normal component of area}}{\text{Square of the distance}} = \frac{ds \cos\theta}{r^2}$$

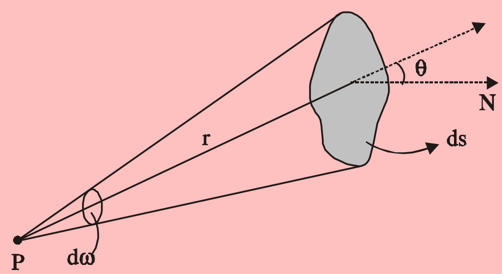


Fig. 2.6 Solid angle

where θ is angle between the normal to the area *ds* and *r* (line joining the point P and the surface *ds*)

Total solid angle subtended by the sphere of radius *r* is given by

$$\omega = \frac{\text{Surface area of the sphere}}{r^2} = \frac{4\pi r^2}{r^2} = 4\pi$$

Unit for solid angle is steradian (Sr).

If a is the absorption coefficient of the wall AB of which ds is a part, then sound energy absorbed by *ds* in one second

$$= \frac{Ev\, ds\, a}{4}$$

∴ Total sound energy absorbed per second by the whole enclosure (entire hall)

$$= \frac{Ev\,\Sigma\,a\,ds}{4}$$

$$= \frac{Ev\,A}{4} \qquad \text{...(7)}$$

where $A = \Sigma\,a\,ds$ is total absorption of sound by all the surfaces inside the hall on which sound energy is incident.

Growth and decay of sound energy

If P is sound power output, ie., rate of emission of sound energy from the source and V is the total volume of the hall, then,

Total sound energy in the hall at a given instant 't' $= EV$

where E is the sound energy density at that instant.

∴ Rate of growth or increase in energy per second

$$= \frac{d\,(EV)}{dt} = V\frac{dE}{dt} \qquad \text{...(8)}$$

[∵ Volume of the hall (V) is constant.]

Rate of emission of sound energy by the source	=	Rate of growth of sound energy in the room	+	Rate of absorption of sound energy by the walls

ie., $$P = V\frac{dE}{dt} + \frac{EvA}{4} \qquad \text{...(9)}$$

When steady state is reached, $\frac{dE}{dt} = 0$, Steady-state energy density is denoted as E_m and it is expressed as

$$P = \frac{E_m \, v \, A}{4}$$

$$\therefore \qquad \boxed{E_m = \frac{4\,P}{v\,A}}$$

Dividing equation (9) by V, we have

$$\frac{dE}{dt} + \frac{EvA}{4V} = \frac{P}{V} \qquad \text{...(10)}$$

Substituting $\frac{vA}{4V} = \alpha$, eqn (10) is written as

$$\frac{dE}{dt} + E\alpha = \frac{4P\,\alpha}{v\,A} \qquad \left(\because \frac{1}{V} = \frac{4\alpha}{vA} \right)$$

Multiplying with $e^{\alpha t}$ on both sides of the above equation, we get

$$\left[\frac{dE}{dt} + E\alpha \right] e^{\alpha t} = \frac{4\,P\alpha\, e^{\alpha t}}{vA}$$

$$\frac{d}{dt}(Ee^{\alpha t}) = \frac{4P\alpha\, e^{\alpha t}}{vA}$$

Integrating on both sides, we obtain

$$\int \frac{d}{dt}(Ee^{\alpha t}) = \int \frac{4P\alpha\, e^{\alpha t}}{vA} = \frac{4P\alpha}{vA} \int e^{\alpha t} \qquad \left[\because \int e^{\alpha t} = \frac{e^{\alpha t}}{\alpha} \right]$$

$$Ee^{\alpha t} = \frac{4P\alpha\, e^{\alpha t}}{vA\,\alpha} + K$$

$$\boxed{Ee^{\alpha t} = \frac{4P\, e^{\alpha t}}{vA} + K} \qquad \text{...(11)}$$

where K is a constant of integration. The value of K is determined by considering the boundary conditions.

Growth of Sound Energy

Sound energy grows from the instant the source begins to emit sound at $t = 0$ and $E = 0$

Applying this condition to equation (11), we get

$$0\,e^{0} = \frac{4P\,e^{0}}{vA} + K \qquad \left[\because e^{0} = 1\right]$$

$$\therefore \quad K = \frac{-4P}{vA} \qquad \text{...(12)}$$

Using eqn (12) in eqn (11), we get

$$Ee^{\alpha t} = \frac{4P}{vA} e^{\alpha t} - \frac{4P}{vA}$$

$$E = \frac{4P}{vA} \frac{e^{\alpha t}}{e^{\alpha t}} - \frac{4P}{vA\,e^{\alpha t}}$$

$$E = \frac{4P}{vA} - \frac{4P}{vA} e^{-\alpha t}$$

$$E = \frac{4P}{vA} (1 - e^{-\alpha t})$$

$$\boxed{E = E_m (1 - e^{-\alpha t})} \qquad \text{...(13)}$$

$[\because E_m = \frac{4P}{vA}$ is the maximum sound energy density.$]$

The equation (13) represents the growth of sound energy density E with time t. A graph is plotted between sound energy density and time (t). It is a rising exponential curve as shown in fig. 2.7.

This indicates that E increases with t, and when $t \to \infty$, $E = E_m$.

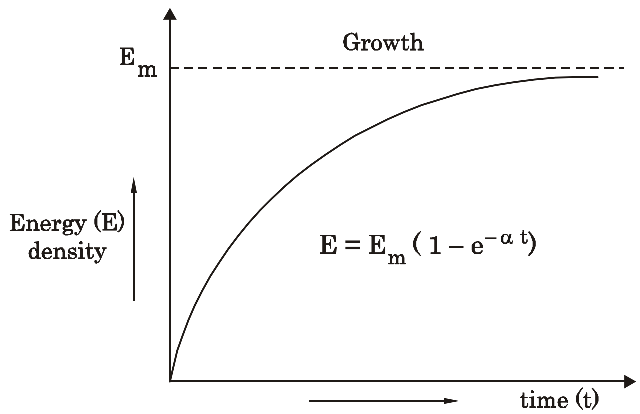


Fig. 2.7. Growth of sound with time

Decay of Sound Energy

Assume that when sound energy has reached its steady (maximum value) state E_m, source of sound is cut off.

Then, the rate of emission of sound energy

$$P = 0$$

Eqn (11) is written as $\quad Ee^{\alpha t} = K$

Substituting the boundary conditions

$E = E_m$ at $t = 0$ and $P = 0$ in equation (11), we get

$$E_m e^0 = 0 + K$$

$$K = E_m \qquad \text{...(14)}$$

From eqns (11) and (14), we get

$$Ee^{\alpha t} = E_m$$

$$E = \frac{E_m}{e^{\alpha t}} = E_m e^{-\alpha t}$$

$$\boxed{E = E_m e^{-\alpha t}} \quad ...(15)$$

Equation (15) represents the decay of sound energy density with time after the source is cut off. A graph is plotted between sound energy density and time. It is an exponentially decreasing curve as shown in fig. 2.8.

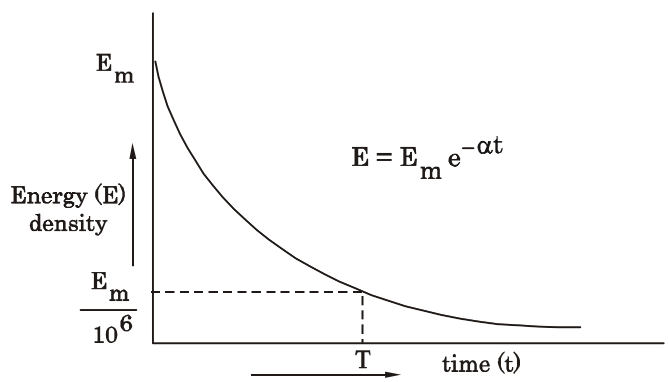


Fig. 2.8 Decay of sound with time

Expression for reverberation time

We know that standard reverberation time *T* is the time taken by the sound to fall of its intensity to one-millionth of its initial value after the source is cut off.

Now the sound energy density before cut off is E_m. At standard reverberation time, it reduces to

$$E = \frac{E_m}{10^6}$$

[Since E is proportional to I, $\frac{I}{I_m} = \frac{E}{E_m} = 10^{-6}$]

Hence, to calculate T,

$$\text{we put } E = \frac{E_m}{10^6} = E_m\, 10^{-6}$$

$$\text{and} \quad t = T \text{ in eqn (15)}$$

$$E_m\, 10^{-6} = E_m\, e^{-\alpha T}$$

$$e^{-\alpha T} = 10^{-6}$$

$$e^{\alpha T} = 10^{6}$$

Taking log on both sides, we have

$$\log_e e^{\alpha T} = \log_e 10^6$$

$$\alpha T = 6 \log_e 10 = 6 \times 2.3026 \times \log_{10} 10$$

$$T = \frac{6 \times 2.3026 \times 1}{\alpha}$$

Substituting $\alpha = \frac{vA}{4V}$, we get

$$T = \frac{6 \times 2.3026 \times 1}{\frac{vA}{4V}}$$

$$= \frac{6 \times 2.3026 \times 4V}{vA}$$

Taking the velocity of the sound, $v = 330\ \text{ms}^{-1}$

we have, $$T = \frac{6 \times 2.3026 \times 4V}{330 \times A}$$

or $$T = \frac{0.167V}{A}$$

i.e., Reverberation Time = $$\boxed{T = \frac{0.167V}{\Sigma as}} \qquad (\because A = \Sigma as)$$

This equation is in agreement with the experimental values obtained by Sabine.

ANNA UNIVERSITY SOLVED PROBLEMS

Problem 2.3

A cinema hall has a volume of 7500 m^3. The total absorption in the hall is 825 O.W.U. m2. What should be the reverberation time? ***[A.U. Dec 2010]***

Given data

Total absorption $\Sigma as = 825$ O.W.U.m^2

Volume of the hall $V = 7500$ m^3

Solution

Reverberation time $$T = \frac{0.167\,V}{\Sigma as}$$

Substituting the given values, we have

$$= \frac{0.167 \times 7500}{825} = 1.52 \text{ second}$$

Problem 2.4

The volume of an auditorium is 12000 m^3. Its reverberation time is 1.5 second. If the average absorption coefficient of interior surfaces is 0.4 sabine m^{-2}. Find the area of interior surfaces. ***[A.U. May 2015]***

Given data

Volume of the hall $V = 12000\ m^3$

Reverberation time $T = 1.5$ second

Average absorption coefficient $\bar{a} = 0.4$ sabine m^{-2}

Solution

We know that $T = \dfrac{0.167\ V}{\Sigma\, as}$

$$T = \frac{0.167\ V}{\bar{a}\, S} \qquad [\because\ \Sigma\, as = \bar{a}\, S]$$

$\bar{a}$ – average absorption coefficient

S – total surface area inside the hall

$$S = \frac{0.167\ V}{\bar{a}\, T}$$

Substituting the given values, we get

$$S = \frac{0.167 \times 12000}{0.4 \times 1.5} = 3340\ m^2$$

2.8 METHODS OF SOUND ABSORPTION

When a sound wave strikes one of the surfaces of a room, some of the sound energy is reflected back into the room and some penetrates the surface.

The parts of the sound wave energy are absorbed by conversion to heat energy in the material, while the rest is transmitted through the material.

The level of energy converted to heat energy depends on the sound absorbing properties of the material.

Room acoustics describes how sound behaves in a space. That means the listener and the sound source are in the same room.

If the room has nearly no sound absorbing surfaces (wall, roof and floor), the sound will bounce between the surfaces and it takes a long time before the sound dies out.

The listener in this kind of room will then have a problem registering the speaker because he hears both the direct sound and repeated reflected sound waves.

If the surfaces instead are covered with sound absorbing material, the reflected sound will decrease much quicker and the listener will only hear the direct sound. Also, the general sound level in the room will decrease. (Fig. 2.9)

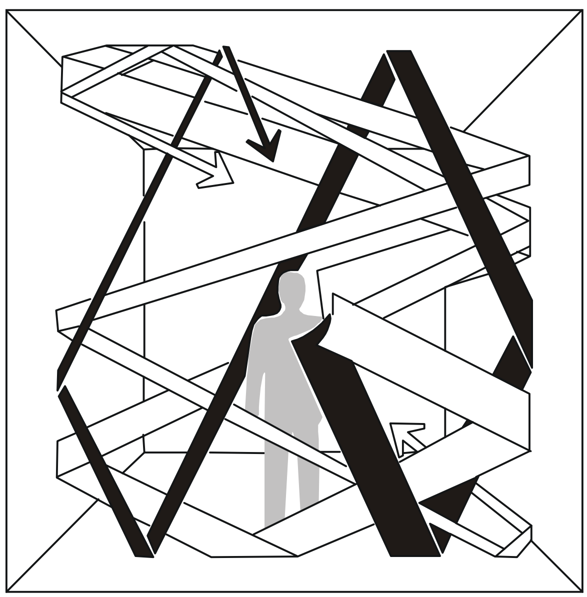


Fig. 2.9 Methods of sound absorption

2.9 DETERMINATION OF ABSORPTION COEFFICIENT

The absorption co-efficient of the sound absorbing material is measured in terms of reverberation time.

Consider a hall of volume V and surface area *s*.

First, without fixing any sound absorbing material in the hall, reverberation time T_1 is measured (Fig. 2.10 (a))

$$\text{Reverberation time } T_1 = \frac{0.167\ V}{\Sigma\, as} \qquad ...(1)$$

$$\text{i.e.,} \quad \frac{1}{T_1} = \frac{\Sigma\, as}{0.167\ V} \qquad ...(2)$$

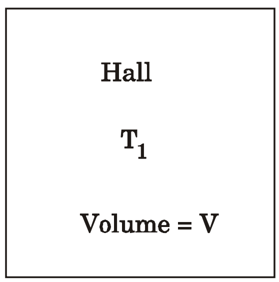


Fig. (a) Reverberation time measured without absorbing material

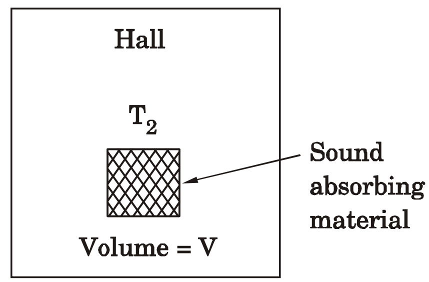


Fig. (b) Reverberation time measured with absorbing material

Fig. 2.10 Measurement of absorption coeficient

After fixing absorbing material inside the hall (Fig. 2.10 (b)), the corresponding reverberation time is noted and is given by

$$T_2 = \frac{0.167\ V}{\Sigma\, as + a_1 s_1} \qquad ...(3)$$

where a_1 – absorption coefficient of the absorbing material

s_1 – surface area

$$\frac{1}{T_2} = \frac{\Sigma\, as + a_1 s_1}{0.167\ V} \qquad ...(4)$$

subtracting eqn (2) from eqn (4), we get

$$\frac{1}{T_2} - \frac{1}{T_1} = \frac{\Sigma\, as + a_1 s_1}{0.167\ V} - \frac{\Sigma\, as}{0.167\ V}$$

$$\frac{1}{T_2} - \frac{1}{T_1} = \frac{\Sigma\, as + a_1\, s_1 - \Sigma\, as}{0.167\ V}$$

$$\frac{1}{T_2} - \frac{1}{T_1} = \frac{a_1 s_1}{0.167\ V} \qquad \text{...(5)}$$

From eqn (5), the absorption coefficient of the sound absorbing material is given by

$$a_1 = \frac{0.167\ V}{s_1}\left[\frac{1}{T_2} - \frac{1}{T_1}\right] \qquad \text{...(6)}$$

or

$$\boxed{a_1 = \frac{0.167\ V}{s_1}\left[\frac{T_1 - T_2}{T_1\, T_2}\right]} \qquad \text{...(7)}$$

By knowing the surface area of the absorbing material s_1, volume of the hall V, T_1 and T_2, absorption coefficient of the material is determined using eqn. (7).

2.10 FACTORS AFFECTING ACOUSTICS OF BUILDINGS AND THEIR REMEDIES

The factors affecting the acoustics of a building are:

1. **Optimum reverberation time**
2. **Loudness**
3. **Focussing**
4. **Echoes**
5. **Echelon effect**
6. **Resonance**
7. **Noises**

1. Optimum reverberation time

If reverberation time in a hall is too large, there is an overlapping of successive sounds which results in a loss of clarity and echo.

On the other hand, if reverberation time is very small, loudness is not sufficient. The speaker may find no response from the audience. Such a hall is considered as ***dead*** by the speaker.

Thus, it is very important that reverberation time in a hall should not be too long or short.

A satisfactory or preferred value of the reverberation time is called ***optimum reverberation time***.

The satisfactory reverberation times required are:

Speeches	–	0.5 second
Music	–	1 to 2 second
Theatres	–	1.1 to 1.5 second

Remedy

Optimum reverberation time is obtained by the following ways:

- Providing many windows and ventilators
- Covering a part of the ceiling, walls and even the back of chairs with suitable sound absorbing materials like felt, fibre board, glass, wool etc. (that is why cinema theatres have false ceilings, walls and interior decorations)
- Using curtains with folds
- Covering the floor with carpets and having graded ceiling tops.
- Having a good-size of audience
- Decorating the walls with pictures and maps.

2. Loudness

Loudness is the degree of sensation produced on the ear. If the intensity of sound is weak, loudness may go below the level of audibility.

Sufficient loudness in every part of the hall is important for satisfactory hearing.

Remedy

The loudness of sound is increased by the following ways:

- To achieve good loudness, maximum reflection of sound from the stage is desirable so that there is no loss of sound energy. This can be done by using a large sounding board behind the speaker.
- Large polished wooden reflecting surfaces above the speakers are helpful.
- Use of good quality loudspeakers is essential.
- Low ceilings are helpful for better reflection of sound.
- The wall at speaker's end should be given a parabolic shape as shown in fig. 2.11. This ensures uniform sound intensity in every part of the hall.

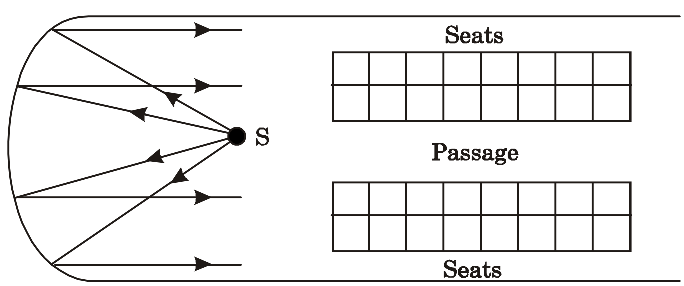


Fig. 2.11 Loudness - remedy

3. Focussing

Sound waves that reflect from the concave surfaces of a building get focussed to a point. The intensity of sound will be maximum at such points and zero at other places. This is called focussing effect.

As a result, sound cannot be heard with equal intensity through the entire area of the building.

In fig. 2.12, the listener at point O receives sound waves from the speaker S along the direct path SO. The listener also receives sound waves after reflection from the ceiling. Thus, the intensity of sound at point O is comparatively higher than in other positions.

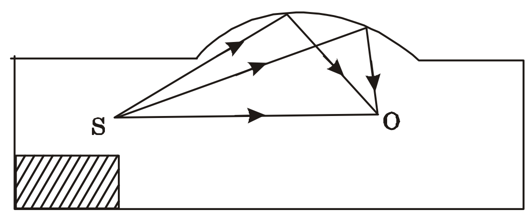


Fig. 2.12. Focussing effect

It may sometimes happen that direct and reflected waves are in opposite phase. This would result in minimum intensity of sound at O. Further more, direct and reflected waves may form a stationary wave form. This causes an uneven distribution of sound intensity.

Remedy

Uniform distribution of sound in the hall is achieved by the following ways.

- There should not be any curved surfaces in the hall. If such surfaces are present, they should be covered with suitable sound absorbing materials.
- Ceiling should be as low as possible.

4. Echoes

Sometimes, when a sound wave falls on a reflecting surface (more than 17 metres away), it is reflected as a distinct repetition of direct sound. This reflected sound is called an ***echo***.

Echoes occur due to the reflected sound waves. They reach the listener a little later than the direct sound, which causes confusion. This defect is common particularly when the reflecting surface is curved.

Remedy

- Providing low ceiling.
- Echoes can be avoided by covering walls and ceiling with suitable sound absorbing materials.

5. Echelon effect

Sound produced in front of regular structures like a set of railing or staircase or any regular spacing of reflecting surfaces, may produce sound note due to regular repetition of echoes of the original sound to the observer as shown in fig. 2.13. This effect is called as **echlelon effect**.

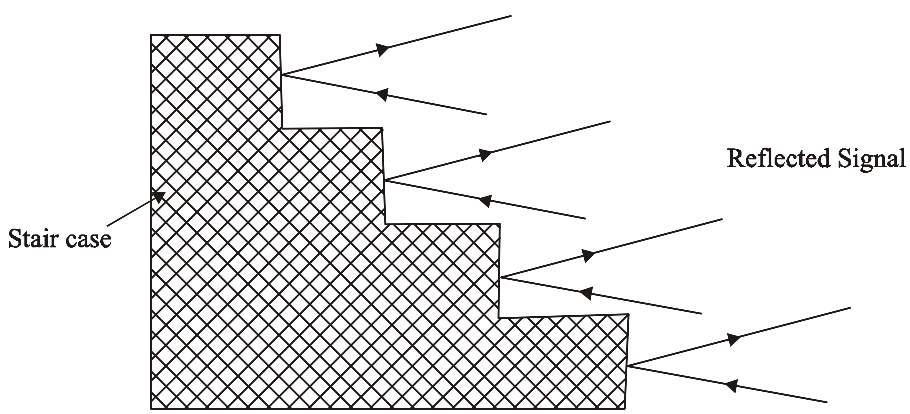


Fig. 2.13 Echelon Effect

Remedy

- Regular structure like a stair case or a set of railings in the hall should be avoided
- The stair cases may be covered with carpets to avoid reflection

6. Resonance

Sometimes window-panes, sections of wooden portions, and walls lacking rigidity (loosely fitted) are thrown into vibrations and they create other sounds.

For some note of audio frequency, the frequencies of new created sounds may be the same thus resulting in the resonance. Such vibrations are called ***resonant vibrations***.

Due to the interference between original sound and the created sound, the original sound is distorted. Hence, it leads to unpleasant effect. Such resonant vibrations should be suitably damped.

Remedy

Resonance is rectified by hanging large number of curtains in the hall.

7. Noise

Unwanted sound is called noise. There are three types of noises.

They are

(i) **Inside noise**

(ii) **Air - borne noise**

(iii) **Structure - borne noise**

Noises produce a disturbing and displeasing effect on the ear. Hence, noise should be avoided and controlled.

(i) Inside noise

Noise produced inside the room is known as inside noise.

Example of inside noise

- The sound created by moving of people, crying babies, movement of furniture.
- The sound produced from machines, typewriters, etc.

Remedy

- Machines and typewriters can be placed over sound absorbing materials.
- The walls, floors and ceilings can be covered with suitable sound absorbing materials
- The engines that create noise may be fitted on the floor with a layer of wood or felt between them.

(ii) Air-borne noises

Noises coming through open windows, doors and ventilators are known as air-borne noises.

These types of noises are common in a densely populated area.

Remedy

- The use of double doors and windows with separate frames and by placing sound absorbing material in between them.
- By allotting proper places for doors and windows.
- Using heavy glasses in doors, windows and ventilators.
- By making the hall air-conditioned.

(iii) Structure borne noise

Noises conveyed through the structures of a building are called structure-borne noises.

Example

The machinery operation, movement of furniture, foot steps etc. produce structural vibration giving rise to structure-borne noise.

Remedy

- Noises from water pipe can be controlled by using rubber couplings at junctions.
- Using double walls with an air space between them.
- Covering the floors and ceilings with suitable sound absorbing materials and anti-vibration mounts.

2.11 NOISE MEASUREMENT

Sound (Noise) Level

Sound and unwanted sound, called noise, is the result of fluctuations or oscillations in atmospheric pressure. These excite the ear mechanism and evoke the sensation of hearing.

The human ear responds to changes in sound pressure over a very wide range - the loudest sound pressure to which the human ear responds is ten million times greater than the softest. This large ratio is reduced to a more manageable size by the use of logarithms.

The logarithms scale provides a more convenient way of comparing the sound pressure of one sound with another. To avoid a scale which is too compressed, a factor of 10 is introduced, giving rise to the decibel unit.

It is a ratio, expressed in logarithmic scale relative to a reference sound pressure level.

1 decibel (dB) $= 10 \log_{10}$ (intensity measured / reference intensity)

The reference intensity used in the threshold of hearing which means sound which can be first heard at the sound pressure of 2×10^{-5} Newtons per sq. meter or sound intensity of 10^{-12} watts per sq. meter.

The level of sound pressure p is said to be L_p decibels greater than a reference sound pressure P_{ref} according to the following definition:

$$\text{Sound Pressure Level (Lp or SPL)} = 10 \log_{10} (P^2 / P^2_{ref}) \text{ dB}$$

$$= 20 \log_{10} P - 20 \log_{10} P_{ref} \text{ dB}$$

where P is the sound pressure fluctuation (above or below atmospheric pressure) and P_{ref} is 20 micropascals (2×10^{-5} Pa), which is approximately the threshold of hearing.

Noise meters

These are the instruments specially designed for noise measurement from low to high frequencies, characteristics of human ear capacity. Noise meters record the dB scale for routine measurement of general noise levels.

Refined noise meters have been developed to take care of peak noise levels, duration of noise exposure and quality of noise which are aspects of specified noise situation.

Decibel scale is shown in figure 2.14

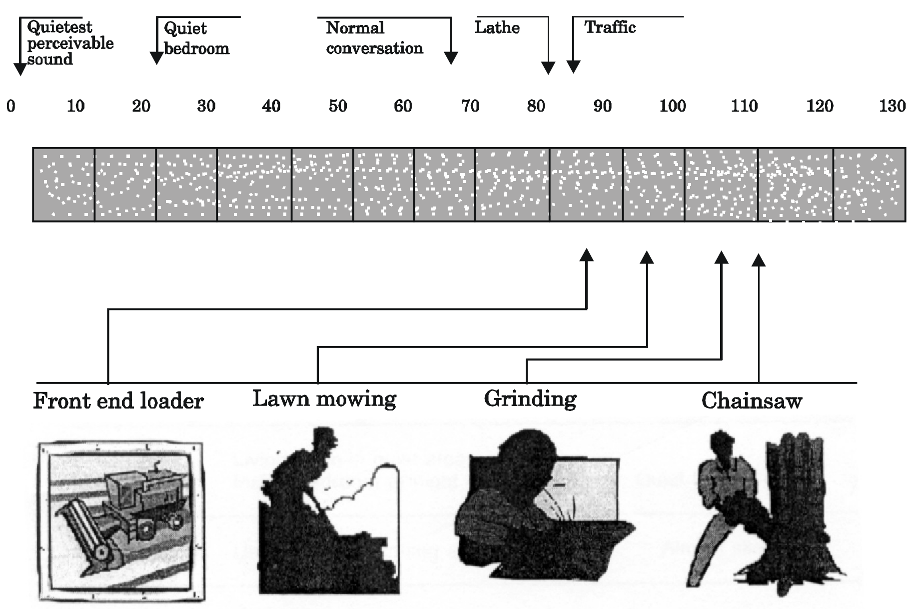


Fig. 2.14 Decibel Scale

TABLE 2.3

Sound Measurement (Intensities, Pressures and Decibels) in Air at Room Temperature and Sea Level Pressure

Intensity (W/m^2)	Pressure (Nm^2)	dB	Sound source
100	2,00,000	200	Rocket take off
1.0	20	120	Boiler shop
10^{-2}	2.0	100	Siren at 5 meters
10^{-4}	0.2	80	Heavy machinery
10^{-6}	0.02	60	Normal conversation at 1 meter
10^{-8}	0.002	40	Public library
10^{-12}	2×10^{-5}	0	Threshold of hearing

2.12 SOUND INSULATION AND ITS MEASUREMENT

The art of preventing the transmission of noise inside or outside the hall or rooms of a building is known as sound insulation.

It is also called sound proofing and it is a measure used to reduce the level of sound when it passes through the insulating building component. The basic principle of sound insulation is to suppress the noise.

Sound Insulation Measurement

Sound is transmitted through most walls and floors by setting the entire structure into vibration. This vibration generates new sound waves of reduced intensity on the other side.

The passage of sound into one room of a building from a source located in another room or outside the building is termed "sound transmission".

The sound reduction index is used to measure the level of sound insulation provided by a structure such as a wall, window, door, or ventilator.

Transmission loss or Sound Reduction Index R dB is a measure of the effectiveness of a wall, floor, door or other barrier in restricting the passage of sound. The transmission loss varies with frequency and the loss is usually greater at higher frequencies.

The unit of measure of sound transmission loss is the decibel (dB). The higher the transmission loss of a wall, the better it functions as a barrier to the passage of unwanted noise.

There are two types of sound insulation in buildings: airborne and impact. Airborne sound insulation is used when sound produced directly into the air is insulated and it is determined by the sound pressure level in the adjacent room below. (Fig. 2.15)

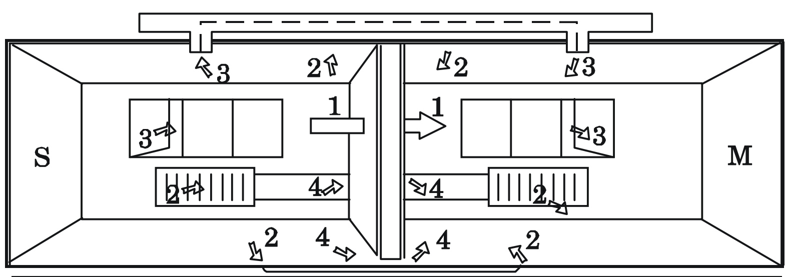


Fig. 2.15 Sound insulation and its measurement

1. **Direct sound transmission**

2. **Flanking transmission**

3. **Overhearing**

4. **Leakage**

Methods of sound insulation

The method of sound insulation will depend on the type of noise to be treated and the degree of sound insulation required. The methods of sound insulation can thus be classified into three main categories.

1. **When the source of noise is in the room itself**.
2. **When noise is air-borne**.
3. **When noise is structure-borne**.

1. When source of noise is in the room itself

Following are the methods of sound insulation which are commonly used when the source of noise is situated in the room to be treated for sound insulation.

(i) Improvement in working methods

(a) A working method creating less noise may be adopted. For instance, welding may be preferred to riveting.

(b) The machinery like type writers etc. should be placed on absorbent pads.

(c) The engine should be fitted on the floor with a layer of wood or felt between them.

(ii) Acoustical treatment

(a) The wall floors and ceilings should be provided with sound absorbing materials.

(b) The sound absorbing materials should be mounted on the surfaces near the source of noise.

(c) The acoustical treatment of the room considerably reduces the noise level in the room.

2. When noise is air-borne

Sound insulation for the reduction of air-borne noise can be achieved by the following methods.

1. By avoiding opening of pipes and ventilators.
2. By allotting proper places for doors and windows.
3. Using double doors and windows with separate frames and having insulating material in them.
4. Using heavy glass in doors, windows and ventilators.
5. By making arrangements for perfectly shutting the doors and windows.

3. When noise is structure-borne

Sound insulation for the reduction of structure-borne noise is done by the following ways.

1. Treatment of floors and ceilings with suitable sound absorbing material and antivibration mounts.
   - (i) By using floating floors and suspended ceilings.
   - (ii) Soft floor finish (carpet, cork, vinyl, rubber, etc.)
   - (iii) Resilient (anti vibrations) mounts help considerably in reducing structure-borne sound.
2. Using double walls with air space between them.
3. Insulation of machinery.

2.13 IMPACT OF NOISE IN MULTI-STOREYED BUILDINGS

It is defined as the structure whose usage levels are regular in distribution and which correspond roughly to the required for human habitation. There are four main actions which causes impact of noise in multistoreyed buildings.

1. Speech privacy (will not be there)

2. **Background noise (e.g fan, a.c, generator, printer)**
3. **Sound masking**
4. **Orientation of buildings**

(i) Speech privacy: It is an issue within office building, including individual work space, inside conference halls and between offices. It mainly affects the quality of work in the adjacent office.

(ii) Back ground noise: It can adversely affect the work space. Even a little background noise letting to hear what is going on in work space can have an impact.

(iii) Sound masking: It can blend the building systems noise levels and exterior noise levels within electronic noise systems in the middle. Traditional sound masking systems are located in loud speakers above the ceiling.

(iv) Orientation of building: The noise impact may also be great for rooms perpendicular to road ways because

(a) a noise pattern can be more annoying in perpendicular rooms.

(b) windows on perpendicular walls dont reduce noise as effectively as those on parallel walls because of the angle of sound.

Apartment dwellers are often annoyed by noise in their homes, especially when the building is not well designed.

In this case, internal building noise from plumbing, boilers, generators, air conditioners and fans can be audible and annoying.

Improperly insulated walls and ceilings can reveal the sound of amplified music, voices, and noisy activities from neighbouring units.

External noise from emergency vehicles, traffic, refuse collection and other city noises can be a problem for urban residents, especially when windows are open or insufficiently glazed.

Concluding Remark

Unless we study the basic concepts of the above topics, we cannot understand how a good auditorium or a cinema hall may be designed.

Even our classrooms or halls for indoor games are based on the principles stated above. The reverberation time is a key factor in designing a good acoustical structure. This knowledge is the backbone of civil engineering, structural and architectural engineering.

ANNA UNIVERSITY SOLVED PROBLEMS

Problem 2.5

Calculate the increase in the acoustic intensity level when the sound intensity is doubled. ***(A.U. Jan 2012)***

Given data

$$\text{Sound intensity ratio, } \frac{I_2}{I_1} = 2$$

Solution

$$\text{Sound intensity level } \beta = 10 \log_{10}\left[\frac{I_2}{I_1}\right]$$

$$= 10 \log_{10}(2) = 3.01 \text{ dB}$$

Hence, increase in sound intensity level $= 3.01$ dB

Problem 2.6

Calculate the intensity level in decibel of a sound of intensity 10^{-9} Wm^{-2} ***(A.U. Jan 2011)***

Given data

Intensity of sound $I = 10^{-9}$ Wm^{-2}

Standard intensity $I_o = 10^{-12}$ Wm^{-2}

Solution

We know that sound intensity level (β) $= 10 \log_{10}\left(\frac{I}{I_o}\right)$

Substituting the given values, we have $= 10 \log_{10}\left(\frac{10^{-9}}{10^{-12}}\right)$

$$= 10 \log_{10} 10^{3} = 10 \times 3 = 30 \text{ dB}$$

Problem 2.7

The intensity of sound is 4.0×10^{-3} W/m^2 Calculate sound intensity level in decibel. ***(A.U. Dec 2013)***

Given data

Intensity of sound, $I = 4.0 \times 10^{-3}$ Wm^{-2}

Standard intensity of sound $I_o = 10^{-12}$ Wm^{-2}

Solution

We know that

$$\text{Sound intensity level } (\beta) = 10 \log_{10}\left(\frac{I}{I_o}\right)$$

Substituting the given values, we have

$$(\beta) = 10 \log_{10}\left(\frac{4 \times 10^{-3}}{10^{-12}}\right)$$

$$= 10 \log_{10} (4 \times 10^{9}) = 96.0206 \text{ dB}$$

Problem 2.8

Calculate the intensity level of a turbine whose sound intensity is 100 Wm^{-2} when it is in operation. Given that the standard intensity level is 10^{-12} Wm^{-2}.

(A.U. May 2013)

Given data

Intensity of sound $I = 100 \text{ W m}^{-2}$

Standard Intensity of sound $I_o = 10^{-12} \text{ Wm}^{-2}$

Solution

We know that intensity level $(\beta) = 10 \log_{10}\left[\frac{I}{I_o}\right]$

Substituting the given values, we have

$$= 10 \log_{10}\left[\frac{100}{10^{-12}}\right]$$

$$= 10 \log_{10} 10^{14} = 14 \times 10$$

$$= 140 \text{ dB}$$

Problem 2.9

A hall of volume 1000 m^3 has a sound - absorbing surface of area 400 m^2. If the average absorption co-efficient of the hall is 0.2, what is the reverberation time of the hall? ***(A.U. May 2014)***

Given data

Volume of the hall V = 1000 m^3

Surface area of the hall s = 400 m^2

Average absorption coefficient $\bar{a}$ = 0.2

Solution

We know that

$$\text{Reverberation time } T = \frac{0.167\,V}{\bar{a}s}$$

substituting the given values, we have

$$\text{Reverberation time } T = \frac{0.167 \times 1000}{0.2 \times 400}$$

$$= 2.09 \text{ second}$$

Problem 2.10

A hall has a volume of 1200 m 3. Its total absorption is equivalent to 480 m^2 of open window. What will be the effect on the reverberation time if audience fills the hall and thereby increases the absorption by another 480 m2 of open window. ***(A.U. Jan 2012)***

Given data:

Volume of hall (V) = 1200 m^3

Total absorption (Σas) = 480 O.W.U. m^2

Solution:

$$\text{Reverberation time} \quad T_1 = \frac{0.167\,V}{\Sigma\,as}$$

$$T_1 = \frac{0.167 \times 1200}{480}$$

$$T_1 = 0.418 \text{ second} \quad \text{(for empty hall)}$$

Now, absorption increases by another 480 m^2 of open window, due to audience. Then

$$\text{Reverberation time } T_2 = \frac{0.167 \times 1200}{480 + 480}$$

$$T_2 = 0.209 \text{ second}$$

Problem 2.11

A hall has a volume of 1,20,000 m^3. It has a reverberation time of 1.5 second. What is the average absorbing power of the surface if the total absorbing surface area is 25,000 m^2. ***(A.U. April 2011)***

Given data

Volume of hall $V = 1{,}20{,}000 \text{ m}^3$

Reverberation time $T = 1.5$ second

Total absorbing surface area $= 25{,}000 \text{ m}^2$

Solution

$$T = \frac{0.167 \text{ V}}{\Sigma \text{ a s}}$$

$$\text{Total sound absorption, } \Sigma as = \frac{0.167\text{V}}{\text{T}}$$

$$= \frac{0.167 \times 1{,}20{,}000}{1.5}$$

$$\Sigma as = 13{,}360 \text{ O.W.U. m}^2$$

$$\text{Average absorbing power of the surface } \bar{a} = \frac{\Sigma a s}{\Sigma s}$$

$$= \frac{13{,}360}{25{,}000}$$

$$\bar{a} = 0.534 \text{ sabine / m}^2.$$

Problem 2.12

A hall has a volume of 5000 m^3. It is required to have reverberation time of 1.5 second. What should be the total absorption in the hall? ***(A.U. May 2010)***

Given data

Volume of hall V $= 5{,}000\ m^3$

Reverberation time T $= 1.5$ second

Solution

We know that $T = \dfrac{0.167\,V}{\Sigma\, as}$

$\therefore$ Total absorption in the hall $\Sigma\, as = \dfrac{0.167V}{T}$

Substituting the given values, we have

$$= \frac{0.167 \times 5000}{1.5}$$

$$\Sigma\, as = 556.66\ \text{O.W.U. m}^2 \text{ or sabine}$$

Problem 2.13

A hall has a volume of 12500 m^3 and reverberation time of 1.5 second. If 200 cushioned chairs are additionally placed in the hall, what will be the new reverberation time of hall. The absorption of each chair is 1 O.W.U. m^2. ***(A.U. Dec. 2009)***

Given data

Volume of the hall V $= 12500\ m^3$

Reverberation time $T_1 = 1.5$ second

Solution

Initial reverberation time, $T_1 = \dfrac{0.167\ V}{\Sigma\, as}$

$$\Sigma\, as = \frac{0.167\ V}{T_1} = \frac{0.167 \times 12500}{1.5}$$

$$= 1392\ \text{O.W.U. m}^2 \text{ or sabine}$$

Reverberation time after addition of 200 cushioned chairs,

$$T_2 = \frac{0.167\ V}{\Sigma\, as + a_1 s_1}$$

$$= \frac{0.167 \times 12500}{1392 + 200} \qquad [\because\ a_1 s_1 = 200\ \text{O.W.U.m}^2]$$

$$= \frac{2087.5}{1592}$$

$$T_2 = 1.31 \text{ second}$$

ANNA UNIVERSITY Part - A '2' Marks Q & A

1. Enumerate the ways in which sound is classified

(A.U. Jan 2014)

Sound is classified on the basis of frequency

(i) Infrasonics (frequency less than 20 Hz)

(ii) Audible sound (frequency in between 20 Hz and 20,000 Hz)

(iii) Ultrasonics (frequency greater than 20 kHz)

2. Define intensity of sound. What is its unit ?

(A.U. April 2015)

It is the amount of sound energy flowing per second per unit area held normally at the point to the direction of propagation. The unit of intensity is watt metre^{-2} or Wm^{-2}

3. What is loudness? ***(A.U. Jan 2013)***

It is the degree of sensation produced on the ear and varies from one person to another person. Loudness is different from intensity of sound.

4. State Weber - Fechner law in sound. (or) How is loudness of sound related to intensity of the sound wave? ***(A.U. Dec 2014, Jan 2016)***

It states that loudness of sound (L) is directly proportional to logarithm of intensity.

$$L \propto \log_{10} I$$

$$\boxed{L = k \log_{10} I}$$

where k is a constant which depends on the quality of the sound, sensitivity of the ear and other factors.

5. Distinguish between loudness and intensity of sound. ***(A.U. Dec 2015)***

S.No.	Loudness	Intensity
(i)	It is the degree of sensation produced on the ear and hence it depends upon the listener.	It is the amount of sound energy flowing per unit area per second. Hence, it depends on the source of sound and does not depend upon the listener.
(ii)	It is not a pure physical quantity. It is subjective in nature.	It is a pure physical quantity.
(iii)	Loudness can not be measured directly.	Intensity is directly measured in watt metre^{-2}

6. Define sound intensity level and write its unit. ***(A.U. Jan 2012, May 2013)***

Sound intensity level is obtained by comparing the intensity of the sound I with standard zero level sound intensity I_o.

I_o is taken to be 10^{-12} watt m^{-2} at 1000 Hz.

Unit for sound intensity level is decibel.

$$\text{Sound intensity level in decibel} = 10 \log_{10}\left(\frac{I}{I_o}\right)$$

7. What is a decibel? ***(A.U. Jan 2011)***

A decibel (dB) is the unit of sound intensity level of a sound. Sound intensity level is measured in decibel scale (or) logarithmic scale because the response of human ear to sound is found to vary in a logarithmic way with intensity of sound.

$$\text{Sound intensity level in decibel} = 10 \log_{10}\left(\frac{I}{I_o}\right)$$

where I_o – threshold of audibility (10^{-12} watt m^{-2})

I – intensity of sound

8. Show that a 26% change in intensity alters the sound intensity level by 1 decibel. ***(A.U. Dec. 2013)***

$$\text{Sound intensity level, } \beta = 10 \log_{10}\left(\frac{I}{I_o}\right) \text{ decibel}$$

If β is 1 decibel.

$$1 = 10 \log_{10}\left(\frac{I}{I_o}\right)$$

$$\log_{10}\frac{I}{I_o} = \frac{1}{10}$$

$$\therefore \frac{I}{I_o} = \text{antilog}\left(\frac{1}{10}\right)$$

$$\therefore \boxed{\frac{I}{I_o} = 1.26}$$

$\therefore$ 26% change in intensity alters sound intensity level by 1 dB.

9. What is reverberation? ***(A.U. Dec 2012)***

The prolongation or persistence of sound inside a room or hall even after the source of sound has stopped producing the sound is called reverberation.

This is due to multiple reflections from the walls, ceiling, floor and other reflecting surfaces of the room.

10. Define reverberation time of an auditorium.
(A.U. Dec 2011, Jan 2013)

(or)

What is reverberation time? ***(A.U. May 2010)***

The time duration for which the sound persists even after the source of sound has stopped producing the sound is known as reverberation time.

11. What is standard reverberation time? (or) What is Sabine's law? ***(A.U. Dec 2013)***

Sabine's law states that the standard reverberation time is the time taken by the intensity of sound to fall to one-millionth (10^{-6}) of its initial intensity after the source of sound is cut off.

12. Write down Sabine's formula for reverberation time.
(A.U. Jan 2016)

$$\text{Reverberation time } T = \frac{0.167\,V}{\Sigma\, as} \text{ second}$$

where V – Volume of the hall in $\mathbf{m^3}$

a – Absorption coefficients of surface areas of different materials in **O.W.U.**

s – Surface areas of the different materials in $\mathbf{m^2}$

$\Sigma\, as$ – Total absorption of sound in **O.W.U.** $\mathbf{m^2}$

13. Define absorption co-efficient of a material. What is its unit? ***(A.U. Dec 2013)***

The absorption co-efficient of a material is defined as the ratio of sound energy absorbed by it's surface to that of the total sound energy incident on the surface.

The unit of absorption co-efficient is open window unit (O.W.U).

14. What are the acoustical factors to be considered while we construct any buildings ? ***(A.U. Jan 2013)***

- Reverberation time
- Loudness
- Focussing
- Echoes
- Echelon effect
- Resonance
- Noises

15. Mention any four sound absorbing materials.

(A.U. May 2012)

Carpets, glass, wool, hair, furniture also wood, foam materials, audience.

16. How can we control reverberation time?

(A.U. Jan 2017)

- By providing many windows and ventilators.
- Using heavy curtains with folds.
- Covering the walls with sound absorbing materials such as felt, glass wool, etc,
- By covering the floor with carpets.
- Having a good size of audience.

17. How will you ensure adequate loudness in a hall?

(A.U. May 2010)

- Using large sound boards behind the speaker.
- By providing low ceiling for the reflection of energy towards the audience
- By providing additional energy with the help of equipments like loudspeakers.

18. What is focussing ? ***(A.U. Dec 2012)***

The sound waves falling on concave surfaces of buildings after reflection get focussed to a point. Hence, the intensity of sound is maximum at such points and zero at other places. This is called focussing effect.

19. What is echelon effect? ***(A.U. May 2013)***

Sound produced in front of regular structures like a set of railings or staircase may produce a musical note due to regular repetition echoes of the original sound to the listener.

This makes original sound to appear confused or unintelligible. Such an effect is called echelon effect.

20. What are the requirements for good acoustics?

(A.U. Jan 2002)

- The hall should have optimum reverberation time of about 1.1 to 1.5 second.
- The loudness of the sound should be uniform throughout the hall.
- Echoes should not be present.
- Resonance effect should be avoided.
- There should be no echelon effect.
- Noise should be reduced.

ADDITIONAL Q & A

1. What are the characteristics of musical sound?

(i) Pitch or frequency (ii) quality or timbre (iii) Intensity or loudness.

2. What is optimum reverberation time?

The reverberation time for a hall should not be too large or short. It should be a satisfactory value and this preferred value of the time of reverberation is called optimum reverberation time.

3. How will you ensure uniform distribution of sound energy in the hall?

- By taking care that there are no curved surfaces. If such surfaces are present, they should be covered with sound absorbing materials.
- By having low ceiling.

4. What are echoes? How are they avoided?

When a reflecting surface is far away from the source (more than 17 metres) then the sound is reflected back as a distinct repetition of direct sound. The reflected sound is called an **echo**.

Remedy

- Providing low ceiling
- Echoes can also be avoided by covering walls and ceiling with suitable sound absorbing material.

5. What is resonance? How is it corrected?

Sometimes the window-panes, sections of the wooden portions, and walls lacking in rigidity (loosely fitted) are thrown into vibrations and they create other sounds. Such vibrations are called resonant vibrations.

These resonant vibrations should be suitably damped.

Remedy

This defect can be rectified by hanging a large number of curtains in the hall.

6. What is noise? How is it classified?

Unwanted sound reaching our ears is called the noise

There are three types of noises

- Inside noise
- Airborne noise
- Structure borne noise

7. What is inside noise? Give the remedy to avoid such noise.

The noises produced inside the same room are known as inside noises.

Remedy

- The machineries and any sound producing equipments may be placed over the sound absorbing materials or pad.
- This type of noises can also be reduced by covering the walls, floors and ceilings with suitable sound absorbing materials.

8. What is air borne noise? Mention the ways to avoid such noise.

Noise from outside through open windows, doors, ventilators is known as air-borne noise.

Remedy

- By allotting proper places for doors and windows.
- By making perfect arrangement for shutting the doors and windows.
- Using heavy glasses in doors, windows and ventilators.
- By making the hall air conditioned, this noise may be eliminated.

9. What is structure borne noise?

The noise through the structure of the building is called structure borne noise.

10. What are sound absorbing material?

The special materials used to increase the absorption of sound waves or to reduce the reflection of sound waves in a room or hall are known as sound absorbing materials.

11. What are the requirement of a good acoustical material.

- It should be durable and should not be liable to be attacked by insects, termites, etc.
- It should be easily available at a reasonable cost.
- It should be efficient over a wide range of frequencies.
- It should be fire resistant.
- It should give pleasing appearance after fixing.
- It should have high coefficient of absorption.
- It should have sufficient structural strength.

12. What are the types of sound absorbing material?

(a) Porous absorbents

(b) Cavity resonators

(c) Resonant absorbing or panel absorbers

(d) Composite types of absorbents.

13. How are noises measured?

Noise meters

These are the instruments specially designed for noise measurement from low to high frequencies, characteristics of human ear capacity. Noise meters record the dB scale for routine measurement of general noise levels.

Refined noise meters have been developed to take care of peak noise levels, duration of noise exposure and quality of noise which are aspects of specified noise situation.

14. What is sound insulation and how is it measured?

The art of preventing the transmission of noise inside or outside the hall or rooms of a building is known as sound insulation.

It is also called sound proofing and it is a measure used to reduce the level of sound when it passes through the insulating building component. The basic principle of sound insulation is to suppress the noise.

The sound reduction index is used to measure the level of **sound insulation** provided by a structure such as a wall, window, door, or ventilator.

15. What are the main actions which causes impact of noise in multistoreyed buildings?

1. Speech privacy (will not be there)
2. Background noise (e.g fan, a.c, generator, printer)
3. Sound masking
4. Orientation of buildings

ANNA UNIVERSITY Part - B (16 Marks) Questions

1. State and explain Sabine's formula for reverberation time of a hall. Derive Sabine's formula for reverberation time. ***[A.U. May 2014, 2015]***
2. Derive an expression for the reverberation period of an auditorium and explain how this can be used for determining the absorbing power of surfaces involved. ***[A.U. Dec 2016]***
3. Define absorption co-efficient in sound. Describe a method of measuring the absorption coefficient of a material ***[A.U. April 2013]***
4. Write an essay on the factors affecting architectural acoustics. Give remedies. ***[A.U. Dec 2014]***

4. Discuss the factors reverberation, resonance, echelon effect, and focussing that affect the acoustics in a hall. Give remedies. ***[A.U. Jan. 2014]***

5. Write in detail about the factors affecting architectural acoustics and their remedies. ***[A.U. May 2015]***

6. Discuss the factors, reverberation, resonance, echelon effect, focussing and reflection that affect the acoustics in hall and the remedies for them.

7. What is reverberation time? Using Sabine's formula explain how the sound absorption coefficient of a material is determined. ***[A.U. May 2013]***

8. Derive expressions for growth and decay of sound energy. ***[A.U. Jan. 2015]***

9. (i) Define reverberation time and absorption coefficient.

   (ii) Derive Sabine's formula for the reverberation time of a hall. ***[A.U June 2016]***

10. Derive expressions for growth and decay of energy density inside a hall and hence deduce Sabine's formula for the reverberation time of the hall. ***[A.U. Jan. 2013]***

11. Explain the different types of sound absorbing materials.

12. Describe the methods of sound absorption.

13. Explain sound insulation measurement.

14. Write a note on noise measurement and the impact of noise in multi storeyed building.

ASSIGNMENT PROBLEMS

1. Calculate sound intensity level of a jet plane taking off producing sound intensity of about 100 Wm^{-2}. ***(Ans: 140 dB)***

2. A sample sound has an intensity of $5 \times 10^{-8} \text{ Wm}^{-2}$. Express sound intensity level in decibel. ***(Ans: 46.99 dB)***

3. The intensity of sound produced by the roaring of a lion at a distance of 5 m is $0.01\ \mathrm{Wm}^{-2}$. Calculate the intensity level in decibel. ***(Ans: 100 dB)***
4. Calculate the increase in the acoustic intensity level, when sound intensity is tripled. ***(Ans: 4.7712 dB)***
5. The intensity of sound in a busy street is $8 \times 10^{-5}\ \mathrm{Wm}^{-2}$. Calculate the intensity level in dB. ***(Ans: 79.031 dB)***
6. A hall has a volume of $1.3 \times 10^{5}\ \mathrm{m}^{3}$. It has a reverberation time of 1.4 second. What is the average absorption coefficient of the surface if total absorbing surface is 25,000 m^2. ***(Ans: 0.620 sabine / $\mathbf{m^2}$)***
7. Calculate the reverberation time for an auditorium in which sound decays by absorption through 40 dB in 1.2 second. ***(Ans: 1.8 second)***

[Hint: Reverberation time is the time required for the level of sound in the room to decay by 60 dB.]

8. A hall has a volume of 2265 m^3. Its total absorption is equivalent to 92.9 m^2 of open window. What will be the effect on reverberation time if audience fills the hall and thereby increases the absorption by another 92.9 m^2.

[Ans: Initial reverberation time $T_1 = 4.07$ s
Final reverberation time $T_2 = 2.04$ s]