UNIT - 4

ACOUSTICS & ULTRASONICS
ACOUSTICS
ACOUSTICS

• Deals with the production, propagation and detection of sound waves

Classification of sound:

(i) **Infrasonic** $<20 \text{ Hz}$ (Inaudible)

(ii) **Audible** $20 \text{ to } 20,000\text{Hz}$ (Music and Noise)

(iii) **Ultrasonic** $>20,000\text{Hz}$ (Inaudible)
Characteristics of Musical sound:

(i) *Pitch or frequency*

*Pitch:* a degree of sensation depends on frequency

*Frequency:* number of vibrations of sound producing object/second

*High frequency* – *shrill sound* - voice of ladies, children, mosquito

*Low frequency* - *grave sound* - sound by lion
ii) Quality or Timbre

- Distinguish b/w any two or more musical sound having same pitch and frequency

- Smallest frequency is called *fundamental* and frequencies accompanying fundamental are called *overtones*.

(iii) Intensity or Loudness

*Intensity*: amount of sound energy flowing per sec per unit area

\[ I = \frac{Q}{A} \text{ watt/m}^2 \]

*Loudness*: degree of sensation varies from one observer from other
WEBER-FECHNER LAW

- Loudness is directly proportional to the logarithm of intensity

\[ L \propto \log I \]

\[ L = K \log I \]

where \( k \) is a constant.
**DECIBEL**

**Threshold of audibility or Standard Intensity:**
The low intensity of sound to which normal human ear can respond is $10^{-12}$ Wm$^{-2}$.

**Relative intensity or Intensity level:**
Ratio of intensity of a sound to the standard intensity

$$L = \log_{10} \frac{I_1}{I_2}$$

The intensity level ($L$) of sound is expressed in bel.

Comparatively bel is a large unit, so for convenience, one tenth of bel is called a decibel (db)

$$1 \text{ bel} = 10 \text{ decibel} = 10 \text{ db}$$

Intensity level

$$L = 10 \log_{10} \frac{I_1}{I_2}$$

Other units of loudness are Phon and Sone.
ACOUSTICS OF BUILDINGS

- Deals with design and construction of hall
- Halls or rooms are acoustically poor due to:
  - distribution of intensity is not uniform
  - different frequency of sound interfere at some point
    reduces the quality
To get good acoustical building, factors to be considered

- Reverberation time
- Focusing and interference
- Echoes and Echelon effect
- Resonance and
- Extraneous noise
Reverberation:

persistence or prolongation of sound in a hall even after
the sound source is stopped

Reverberation Time:

time taken by the sound wave to fall below the minimum
audibility level

i.e., to fall to one millionth of its initial intensity, after the
source is stopped

\[ I = \frac{1}{10^6} I_0 \]
If Reverberation Time is too low:

Sound disappear quickly and become inaudible.

If Reverberation Time is too high:

Sound exist for a long period of time - an overlapping of successive sounds - can not hear the information clearly

For the good audibility

Reverberation time should be kept at an optimum value.
Sabine’s Formula for Reverberation Time

• Professor Wallace C. Sabine (1868–1919)

• Derived from reverberation theory which explains the nature of growth and decay of sound energy.

Assumptions:

• The sound energy is uniformly distributed throughout the hall
• The absorption of sound by the air is neglected
• The source emits the sound energy constantly.
Steps involved:

- The rate of incident energy on the walls and the rate of absorption by the walls.
- The final steady value of $E$ in terms of rate of emission of power $P$ of the source.
- Rate of growth and decay of sound energy in a room.
- Obtain the reverberation time.
Consider a small shaded portion lying between circles having $\theta$ and $\theta + d\theta$ from normal

- If radial length $= dr$  \hspace{1cm} Arc length $= rd\theta$

  \[
  \text{Area of shaded portion} = rd\theta \ dr \hspace{1cm} \text{... (1)}
  \]

- If the whole figure is rotated about the normal through an angle $d\phi$, then area of shaded portion travel a distance of $dx$

  \[
  dx = r \sin\theta \ d\phi \hspace{1cm} \text{... (2)}
  \]

Volume traced by a shaded portion $dV = \text{area} \times \text{distance}$

\[
= r \ d\theta \ dr \ r\sin\theta \ d\phi
= r^2 \sin\theta.\ d\theta \ dr \ d\phi \hspace{1cm} \text{... (3)}
\]
$r \sin \theta \, d \phi$
Sound energy present in this volume = \( E \times dV \)

\[ = E r^2 \sin \theta \, d\theta \, dr \, d\phi \]

This sound energy travels in all the direction through this element.

Sound energy present in this volume \( dV/\text{unit solid angle} \) is

\[ \frac{E r^2 \sin \theta \, d\theta \, dr \, d\phi}{4\pi} \]

Solid angle subtended by the area \( dS \) at this element of volume \( dV \) is

\[ \frac{dS \cos \theta}{r^2} \]
Solid angle

Consider a sphere of radius ‘r’

Solid angle subtended by sphere at its centre

\[ \omega = \frac{\text{surface area}}{\text{radius}^2} = \frac{4\pi r^2}{r^2} = 4\pi \]

Consider a surface AB of area \( dS \) and P be at a distance of ‘r’

Solid angle subtended by AB at its centre P

\[ \omega = \frac{\text{area of } AB}{\text{radius}^2} \]

Solid angle subtended by BC at its centre P

\[ \omega = \frac{\text{area of } BC}{\text{radius}^2} = \frac{\text{area of } AB \cdot \cos \theta}{\text{radius}^2} = \frac{dS \cdot \cos \theta}{r^2} \]
Sound energy travelling towards \( dS \) from \( dV \) is

\[
= \text{Sound energy present in } dV \times \text{Solid angle subtended}
\]

\[
= \frac{E \ r^2 \sin \theta \ d\theta \ dr \ d\phi}{4\pi} \cdot \frac{dS \ \cos \theta}{r^2}
\]

\[
= \frac{E \ \sin \theta \ \cos \theta \ d\theta \ dr \ dS \ d\phi}{4\pi}
\]

To find the total energy by \( dS \) in one sec,

Integrate the eqn. (4) for whole volume lying within a distance of \( C \) of \( dS \)

\[
\Phi = 0 \text{ to } 2\pi
\]

\[
\theta = 0 \text{ to } \pi/2
\]

\[
r = 0 \text{ to } C
\]
Integrating w.r.t. ‘ϕ’

\[
\int E \sin\theta \cos\theta \, d\theta \, dr \, dS \int_0^{2\pi} \, d\phi \\
= \frac{E \sin\theta \cos\theta \, d\theta \, dr \, dS}{4\pi} \int_0^{2\pi} \, d\phi \\
= \frac{E \sin\theta \cos\theta \, d\theta \, dr \, dS}{4\pi} 2\pi \\
= \frac{E \sin\theta \cos\theta \, d\theta \, dr \, dS}{2}
\]
Integrating w.r.t. \( \theta \)

\[
E \frac{dr \, dS}{2} \int_0^{\pi/2} \sin \theta \cos \theta \, d\theta
\]

\( X \) by 2 and divide by 2

\[
= \frac{E}{4} \frac{dr \, dS}{2} \int_0^{\pi/2} 2 \sin \theta \cos \theta \, d\theta
\]

\[
= \frac{E}{4} \frac{dr \, dS}{2} \int_0^{\pi/2} \sin 2\theta \, d\theta
\]

\[
= \frac{E}{4} \frac{dr \, dS}{2}
\]
Integrating w.r.t. ‘r’

\[ = \frac{E}{4} dS \int_0^c \, dr \]

\[ = \frac{EC}{4} dS \quad \ldots \quad (5) \]

Let ‘a’ be the absorption coefficient of wall.

Sound energy absorbed by dS in one sec

\[ = \frac{ECA}{4} dS \]

Total energy absorbed at any time

\[ = \frac{1}{4} EC \Sigma a dS \]

\[ = \frac{1}{4} ECA \quad \ldots \quad (6) \]
If ‘P’ is the rate of emission of sound energy, then,

\[ P = \frac{1}{4} E_{\text{max}} CA \]

\[ E_{\text{max}} = \frac{4P}{CA} \]

... (7)

**Rate of Growth and Decay**

**Total rate of energy increase in medium:**

Energy density \( = E \)
Total volume of the Hall \( = V \)
Total sound energy \( = EV \)

Rate of growth of sound energy : \[ \frac{d}{dt} (EV) = V \frac{dE}{dt} \]
W.K.T,
Rate of emission of sound energy = Rate of growth of sound energy + Rate of absorption of sound energy

\[ P = V \frac{dE}{dt} + \frac{1}{4} ECA \]

\[ \frac{P}{V} = \frac{dE}{dt} + \frac{CA}{4V} E \]

Let, \( \frac{CA}{4V} = \alpha \) or \( \frac{CA}{4\alpha} = V \)

\[ \frac{dE}{dt} + \alpha E = \frac{4P}{CA} \alpha \]
Multiply $e^{\alpha t}$ on both the sides,

$$\frac{dE}{dt}e^{\alpha t} + e^{\alpha t}\alpha E = \frac{4P}{CA}\alpha e^{\alpha t}$$

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

Integrating the above eqn. we get,

$$Ee^{\alpha t} = \frac{4P}{CA}e^{\alpha t} + K$$  \[\ldots (8)\]
Growth of Energy

During Growth, when \( t = 0 \), \( E = 0 \)

From eqn. (8),

\[
K = -\frac{4P}{CA}
\]

Then eqn(8) becomes,

\[
Ee^{\alpha t} = \frac{4P}{CA} e^{\alpha t} - \frac{4P}{CA}
\]

\[
Ee^{\alpha t} = \frac{4P}{CA} (e^{\alpha t} - 1)
\]

\[
E = E_{max}(1 - e^{-\alpha t})
\]

E increases until \( E = E_{max} \) and \( t = \infty \)
Decay of Energy

If sound energy is cut off,

rate of emission \( P = 0 \)
\( t = 0 \)
\( E = E_{\text{max}} \)

From eqn. (8), \( K = E_{\text{max}} \) then,

\[
E e^{\alpha t} = \frac{4P}{CA} e^{\alpha t} + E_{\text{max}}
\]

Since \( P = 0 \)

\[
E e^{\alpha t} = E_{\text{max}}
\]

\[
E = E_{\text{max}} e^{-\alpha t}
\]

evend though source is cut off, energy decreases exponentially
Reverberation time

By definition, \[ E = \frac{E_{\text{max}}}{10^6} \]

From equation of decay
\[ E = E_{\text{max}} e^{-\alpha t} \]

Comparing these two eqns.
\[ E_{\text{max}} e^{-\alpha t} = \frac{E_{\text{max}}}{10^6} \]
\[ e^{-\alpha t} = 10^{-6} \]

Taking log on both the sides.
\[ -\alpha t = -6 \times 2.303 \log_{10} 10 \]
\[ \alpha = \frac{CA}{4V} \quad \text{and} \quad t = T \]

Then,

\[ \frac{CA}{4V} T = 6 \times 2.303 \log_{10} 10 \]

\[ T = \frac{4V}{CA} \times 6 \times 2.303 \]

\[ T = \frac{4V}{330 \times A} \times 6 \times 2.303 \]

\[ T = \frac{0.167 V}{A} \]

\[ T = \frac{0.167 V}{\sum as} \]
Absorption Coefficient
- inverse of the area of the sound absorbing materials which absorbs the same amount of sound as that of 1m² of an open window.

- unit: OWU or Sabine.

Determination of Absorption Coefficient

without sound absorbing material

\[ T_1 = \frac{0.167V}{\Sigma as} \]

with sound absorbing material

\[ T_2 = \frac{0.167V}{\Sigma as + a_m s_m} \]

from \( T_2 - T_1 \), Absorption Coefficient

\[ a_m = \frac{0.167V}{s_m} \cdot \frac{T_1 - T_2}{T_1 T_2} \]
## Materials and their Absorption coefficient

<table>
<thead>
<tr>
<th>Material</th>
<th>Absorption Coefficient</th>
</tr>
</thead>
<tbody>
<tr>
<td>Brick wall</td>
<td>0.02</td>
</tr>
<tr>
<td>Wooden floor</td>
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</tr>
<tr>
<td>Chair</td>
<td>0.25</td>
</tr>
<tr>
<td>Glass</td>
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<tr>
<td>Carpet</td>
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<td>Cushion</td>
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<tr>
<td>Rubber floor</td>
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</tr>
<tr>
<td>Human</td>
<td>0.4</td>
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</table>
Factors Affecting Acoustics of Building and their Remedies

i. Reverberation and reverberation time

ii. Loudness

iii. Focussing and interference effects

iv. Echo

v. Echelon Effect

vi. Resonance, and

vii. Noise
Reverberation

*The persistence or prolongation of sound in a hall even though the sound source is stopped*

Reverberation Time

*The time taken by the sound wave to fall below the minimum audibility level after the source is stopped*
If Reverberation Time is too low:

sound disappear quickly and become inaudible.

If Reverberation Time is too high:

sound exist for a long period of time - an overlapping of successive sounds - can not hear the information clearly

For the good audibility

the reverberation time should be kept at an optimum value.
Remedies

- reduced by installing sound absorbing materials like
  - windows and openings
  - arranging full capacity of audience
  - completely covering the floor with carpets
  - False ceilings
  - heavy curtains with folds and
  - decorating the walls with drawing boards, picture boards
Loudness

- measures the magnitude of sensation produced in the ear.

- uniform distribution of loudness must be maintained throughout the hall

- high absorption or low reflecting surfaces near the sound source lead to this defect.
Remedies

If loudness is low:

• the speakers may be placed at regular distances

• Properly focused sound boards behind speakers

• lowering the ceiling and placing reflecting surfaces at necessary places.

If loudness is high:

• sound absorbents can be placed at noisy places.
Echo

Sound get scattered by wall, instead of reflection

If the time interval between the direct sound and the reflected sound is less than $1/15$ of a second, the reflected sound reaches the audience later than the direct sound.

Remedies

properly covering the long distance walls, high ceilings with suitable sound absorbing materials.
Echelon Effect

- new sound produced by *repetitive echoes*

- regular reflecting surface like stair case may create this effect.

Remedies

Cover such regular reflecting surfaces properly.
Focusing and Interference Effect

Focusing

reflected sound by the ceiling and wall must be distributed evenly throughout the hall rather it should not be focused at a particular area of the hall.

Plane surface : reflect and distribute the sound evenly.

curved surface : focuses the sound in the front portion only.

Remedies

radius of curvature of concave ceiling should be two times the height of the building.

cover the curved surfaces with proper sound absorbing materials.
Interference Effect

Caused by interference of direct and reflected wave

constructive interference : maximum sound intensity occurs

destructive interference : minimum sound intensity occurs

Remedies

By the usage of uniform painting and absorbent it may be avoided.
Resonance

If window panels or any other wooden sections are not covered properly, the original sound may vibrate with the natural frequency of them.

Remedies

• Vibrating materials should be mounted on non-vibrating and sound absorbing materials.

• Panels must be fitted properly.

• eliminated through proper ventilation or by Air-Conditioning
Noise

Unwanted sound produced externally/internally gives an irritating experience to the ears.

Different types of noises are:

(i) Air-borne noise,

(ii) Structure-borne noise and

(iii) Inside noise
Air-Borne Noise

- outside noise which reaches the audience through window, door, and ventilator.

Remedies

(i) The hall should be away from thickly populated area, factories and railway tracks.

(ii) With sound insulating materials, by air conditioning and by double door system it can be reduced.
**Structure-Borne Noise**

-noise reaches the audience through the structural defect of the building

-It is due to the movement of furniture, footsteps and the operation of heavy machinery like generators. is created.

**Remedies**

Use double walled doors, anti-vibration mounts, carpets etc.,
Inside Noise

- noise produced inside the hall like crying kids, the sound generated by type writers, fan, A/C, Refrigerators, etc.,

Remedies

• equipments must be serviced properly

• equipment should be placed on sound absorbing mount.

• Floor, wall and ceiling must be covered with suitable sound absorbing materials.