UNIT-IV

ACOUSTICS OF BUILDINGS

3.1 Introduction:

The branch of physics that deals with the process of generation, propagation and hearing (reception) of sound in a room, be it a small room or an auditorium is called acoustics. Architectural acoustics, also called acoustics of buildings, deals with the behavior of sound waves in a closed space. It deals with the design and construction of acoustically good buildings, music halls, recording rooms and movie theatres, where the audience receives the best sound quality.

3.2 Reverberation and time of Reverberation:

A sound produced inside a hall will propagate in all directions. Sound waves incident on the surfaces of walls, floor, ceiling and furniture inside a hall, will be multiply reflected. As the source of sound is turned off, the listener hears the sound with gradually reducing intensity for some time due to the persistence of sound by multiple reflections at different places in the room.

A listener inside the hall will receive the sound waves directly from the source, as well as the reflected waves. *The persistence of audible sound even after the source of sound is turned off is called Reverberation. The time taken by the sound intensity to fall to one millionth* $\left(\frac{1}{10^6}\right)$ *of its Initial intensity i.e., the intensity just before the source of sound is turned off is called Reverberation time.*

3.3 Sabine's formula for reverberation time:

According to Sabine's law, the reverberation time T is seconds is expressed as,

$$T = \frac{0.165V}{\sum aS}$$

Where, V is the volume of the hall in m^3 and $\sum aS$ is given by,

$$\sum aS = a_1S_1 + a_2S_2 + \ldots\ldots + a_nS_n$$

Here, a_1, a_2 ……………a_n are the absorption coefficients of the materials in the hall whose surface areas exposed to sound are S_1, S_2……………….S_n respectively, measured in m^2.

The average value of absorption coefficient $\bar{a}$ is given by,

$$\bar{a}=\frac{a_1S_1+a_2S_2+\cdots a_nS_n}{S_1+S_2+\cdots S_n}=\sum\frac{aS}{S}$$

$$\text{or } \sum aS=\bar{a}S$$

From the Sabine's formula for reverberation time, the reverberation time, T is,

i. Directly proportional to the volume of the auditorium.
ii. Inversely proportional to the areas of sound absorbing surfaces such as ceiling, walls, floor and other materials present inside the hall and
iii. Inversely proportional to the total absorption.

3.4 Basic requirements of acoustically good hall

The basic requirements of an acoustically good hall are,

1) **The volume of the auditorium** is decided by the type of programme to be conducted there and also the number of seats to be accommodated. A musical hall requires a large volume where as a lecture hall requires a smaller volume. In deciding the volume of the hall, its height plays an imp role than its length and breadth. The ratio between the ceiling height and breadth should be 2:3. In deciding the volume of the hall, the following guidelines may be followed.
   i) 3.74-4.2 m^3 per seat in cinema theatres.
   ii) 2.8-3.7m^3 per seat in lecture halls.
   iii) 4.2-5.6m^3 per seat in musical halls.
2) **The shape of the wall and ceiling** should be so as to provide uniform distribution of sound throughout the hall. The design of a hall requires smooth decay and growth of sound. To insure these factors, the hall should have scattering objects, walls should have irregular surface and walls must be fixed with absorptive materials.
3) **The reverberation of sound** in an auditorium is mainly due to multiple reflections at various surfaces inside. The reverberation should be optimum i.e., neither too large nor too small. The reverberation time should be 1-2 seconds for music and 0.5-1 sec for speech. To control the reverberation, the sound absorbing materials are to be chosen carefully.
4) **The sound heard** must be sufficiently loud in every part of the hall and no echoes should be present.
5) **The total quality of the speech and music** must be unchanged i.e., the relative intensities of the several components of a complex sound must be maintained.

6) For the sake of **clarity,** the successive syllables spoken must be clear and distinct i.e., there must be no confusion due to overlapping of syllables.

7) There should be no **concentration of sound** in any part of the hall.

8) The boundaries should be sufficiently **sound proof** to avoid noise from outside.

9) There should be no **echelon effect**.

10) There should be no **resonance** within the building.

11) The hall must be full of **audience**.

3.5 Absorption Co-efficient:

- The co-efficient of absorption of a material is defined as the ratio of the sound energy absorbed by the surface to that of the total sound energy incident on the surface i.e., Absorption co-efficient, a=$\frac{sound\ energy\ absorbed\ by\ the\ surface}{total\ sound\ energy\ incident\ on\ the\ surface}$
- An open window is considered as an ideal absorber of sound. The unit of sound absorption is open window unit or Sabine. A $1m^2$ Sabine is equal to the amount of sound energy that is absorbed or passed through one square meter area of open window.
- Absorption co-efficient of a surface is also defined as the reciprocal of its area which absorbs the same sound energy, as absorbed by unit area of open window.

3.5.1 Determination of Absorption Co-efficient

Method-1

The first method is based on the determination of standard times of reverberation in the room, without and with the sample of the material inside the room.

If T_1 is the reverberation time without the sample inside the room, then applying Sabine's formula,

$$\frac{1}{T_1} = \frac{A}{0.165V} = \frac{\sum aS}{0.165V}$$

Time T_2 is measured with the sample inside the room.

$$\frac{1}{T_2} = \frac{\sum aS + a_1 S_1}{0.165V}$$

Where, a_1 is the absorption coefficient of the area S_1

$$\text{Now, } \left(\frac{1}{T_2} - \frac{1}{T_1}\right) = \frac{a_1 S_1}{0.165V}$$

$$a_1 = \left(\frac{0.165V}{S_1}\right)\left(\frac{1}{T_2} - \frac{1}{T_1}\right) \qquad \rightarrow (1)$$

Hence, knowing the terms on the right hand side of the equation (1), the absorption coefficient a_1 of the given material can be calculated.

Method-2

This method consists of finding times of decay of the steady energy density, to the bear audibility for two sources of power outputs P_1 and P_2 respectively. From the equation of the decay of energy density,

$$E = E_m e^{-\propto t}$$

$$\text{Where, } E_m = \frac{4P}{\upsilon A} \text{ and } \propto = \frac{\upsilon A}{4V}$$

υ - Velocity of sound

A - $\sum$ ads, the total absorption of all the surfaces on which sound falls.

E – Energy density in the room, t seconds after the source is cut off.

Let t_1 and t_2 be the respective times of decay of energy density to the base audible limit E_0 for sources of power outputs P_1 and P_2 respectively. Then,

$$E_0 = \frac{4P_1}{\upsilon A} e^{-\alpha t_1} \text{ and } E_0 = \frac{4P_2}{\upsilon A} e^{-\alpha t_2}$$

Dividing the two equations,

$$\frac{P_1}{P_2} = e^{\alpha(t_1 - t_2)}$$

$$log_e\left(\frac{P_1}{P_2}\right) = \alpha(t_1 - t_2)$$

$$log_e\left(\frac{P_1}{P_2}\right) = \frac{\upsilon A}{4v}(t_1 - t_2)$$

$$\Rightarrow A = \frac{4V\,log_e\left(\frac{P_1}{P_2}\right)}{\upsilon(t_1 - t_2)}$$

$$\text{(or) } aS = \frac{4V\,log_e\left(\frac{P_1}{P_2}\right)}{\upsilon(t_1 - t_2)}$$

Where, 'a' is the average coefficient of absorption,

$$\boxed{a = \frac{4V\,log_e\left(\frac{P_1}{P_2}\right)}{\upsilon S(t_1 - t_2)}}$$

'a' can be calculated knowing the quantities on the right hand side of the equation.

3.6 Factors affecting the Architectural acoustics and their remedies

Following factors affect the architectural acoustics.

1) Reverberation

- In a hall, when reverberation is large, there is overlapping of successive sounds which results in loss of clarity in hearing. On the other hand, if the reverberation is very small, the loudness is inadequate. Thus, the reverberation time for a hall should neither to be too large nor too small. *The preferred value of reverberation time is called the Optimum reverberation time.*
- Experimentally it is observed that the time of reverberation depends upon the size of the hall, loudness of sound and on the kind of the music for which the hall is used.
- For a frequency of 512 Hz, the best time of reverberation lies between 1 and 1.5 sec for small halls and for large ones, it is up to 2-3 seconds.

Remedy: The reverberation can be controlled by the following factors.

i. By providing windows and ventilators which can be opened and closed to make the value of time of reverberation, optimum
ii. Decorating the walls by pictures and maps.
iii. Using heavy curtains with folds.
iv. By lining the walls with absorbent materials such as felt, fiber board etc.
v. Having full capacity of audience.
vi. By covering the floor with carpets.
vii. By providing acoustic tiles.

2) Loudness

With large absorption, the time of reverberation will be smaller and the intensity of sound may go below the level of hearing. Sufficient loudness at every point in the hall is an important factor for satisfactory hearing.

Remedy: The loudness may be increased by,

i. Using large sounding boards behind the speakers and facing the audience.
ii. Low ceilings are of great help to reflect the sound energy towards the audience.

iii. Providing additional sound energy with the help of equipments like loud speakers. For uniform distribution of intensity throughout the hall, the loudspeakers should be polished carefully.

3) Focusing

If there are focusing surfaces such as concave, spherical, cylindrical or parabolic ones on the walls or ceiling of the hall, they produce concentration of sound in particular regions, while in some other parts, no sound reaches at all. In this way, there will be regions of silence.

Remedy: For uniform distribution of sound energy in the hall,

i. There should be no curved surfaces. If such surfaces are present, they should be covered with absorbent material.

ii. Ceiling should be low.

iii. A paraboloidal reflected surface, with the speaker at the focus is also helpful in sending a uniform reflected beam of sound in the hall.

4) Echoes

An echo is heard when direct sound waves coming from the source, and it's reflected wave, reach the listener with a time internal of about 1/7 second. The reflected sound arriving earlier helps in raising the loudness while those arriving later produce echoes and confusion.

Remedy: Echoes may be avoided by covering the long distant walls and high ceiling with absorbent material.

5) Echelon effect

A musical note produced due to the combination of echoes, having regular phase difference is known as Echelon effect. The reflected sound waves from regularly spaced reflecting surfaces such as equally spaced stair cases or a set of railings produce musical note due to the regular succession of echoes of the original sound to the listener. This makes the original sound confused or unintelligible.

Remedy: Echelon effect can be avoided by forming the staircases with unusual spacing between them and covering them with sound absorbing materials like carpet.

6) Resonance

Sometimes, window panes loosely fitted wooden portions, wall separators and hollows, start vibrating by absorbing the sound produced in the hall. These may create sound. Certain tones of the original music and the created sound combine to produce interference such that the original sound gets disturbed.

Remedy: Resonance can be suppressed by hanging a large number of curtains in the hall.

7) Noise

Generally, there are three types of noise. They are (a) Air-borne noise (b) Structure borne noise (c) Inside noise.

(a) Air-borne noise: The noise that enters the hall from outside through open windows, doors and ventilators is known as air-borne noise.

Remedy:

i. By using heavy glass doors, windows or ventilators.
ii. By using double wall-doors and windows with insulating material in between them.
iii. Forming double wall construction.
iv. By fixing doors and windows at proper places.
v. Air conditioning the hall and sealing the openings perfectly.

(b) Structure-borne noise: The noise that reaches through the Structures of buildings is known as Structural noise. The activity around the building may cause a structural vibration of the building. Ex: footsteps, operating machinery, street traffic etc;

Remedy:

i. By using double walls with air space in between them.
ii. By using anti-vibration mounts.
iii. By properly insulating the equipments such as refrigerators, lifts, fans etc.,
iv. By using carpets on the floor.

(c) Inside noise: The noise produced inside big halls or offices due to equipment such as air conditioners, type writers and fans is called inside noise. This noise may be minimized as follows.

Remedy:

i. Placing the machinery on sound absorbent pads.
ii. Using noise-free air conditioners.
iii. Covering the floor with carpets, walls, ceilings with sound absorbing materials.

Chapter-4 ULTRASONICS

4.1 Introduction:

Ultrasonic has important uses in recent years. The audible frequency range of a healthy human ear is 20 Hz to 20,000 Hz (20 kHz). The sound waves which have a frequency less than 20 Hz are called infrasonic. The sound waves which have frequency more than 20 kHz are called ultrasonic. The frequency of ultrasonic may go up to megahertz. The properties are similar to that of sound waves. Ultrasonic has a large number of applications in engineering and medical fields.

4.2. Generation of ultrasonic waves:

Ultrasonic sound cannot be produced using a loudspeaker. It is because the diaphragm of the loudspeaker cannot vibrate with such high frequency. The following methods can be used to produce ultrasonic waves.

4.2.1. Magnetostriction method:

Principle of magnetostriction:

When a magnetic field is applied along the length of the ferromagnetic rod (such as iron or nickel), a small elongation occurs in its length. This phenomenon is called magnetostriction.

The increase in length depends on the intensity of applied magnetic field and nature of ferromagnetic material used. When a ferromagnetic rod is placed in a solenoid carrying alternating current, the length of the rod increases and contracts at a frequency twice that of the frequency of alternating current. The amplitude of these vibrations is small. When resonance occurs between the natural frequency of the rod and alternating current, the amplitude of the vibration increases. The natural frequency of the rod is given by;

$$f = \frac{1}{2l}\sqrt{\frac{\gamma}{\rho}} \qquad \text{.............} (1)$$

Where, γ is Young's modulus, ρ is the density of the material of the rod and l is length of the rod.

Construction:

An oscillator designed with NPN transistor is used to generate alternating current. The experimental arrangement is shown in figure 4.1. The LC circuit is connected to the collector of the transistor, the coil L_S is connected to the base of the transistor and the emitter is grounded. When the switch 'S' is on, the collector

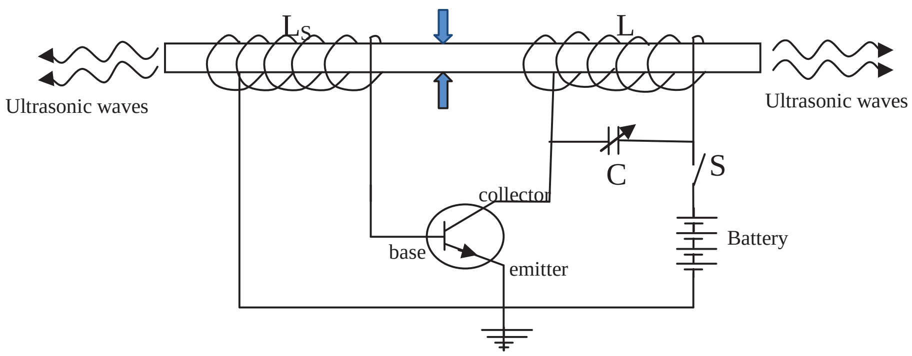

Figure 4.1. Magnetostriction oscillator

current starts increasing and oscillations start in LC circuit due to mutual inductance between L and L_S. The frequency of oscillations is given by;

$$f = \frac{1}{2\pi\sqrt{LC}} \qquad \text{.............. (2)}$$

By varying C, the frequency can be changed and can be made equal to the natural frequency of the ferromagnetic rod. Under this resonance condition, ultrasonic waves are produced by the rod. By changing the length of the rod and the capacitance of the capacitor C, various high frequency oscillations can be obtained.

Merits:

1. Magnetostrictive material is easily available and low cost.
2. The oscillator circuit is easy to construct.
3. Required high frequency can be generated.

Demerits:

1. Frequencies beyond 300kHz cannot be produced.
2. As elastic constant changes with magnetization frequency of oscillations also change
3. Eddy current losses may occur due to a single rod of ferromagnetic material.

4.2.2. Piezoelectric method:

Principle of piezoelectric effect:

When one pair of opposite faces of piezoelectric material (such as quartz, Rochelle salt, Ammonium Dihydrogen Phosphate ADP) undergoes pressure electric charges are developed on the other pair of opposite faces. Instead of applying pressure on opposite faces, if tension is created in the opposite direction to the pressure (to pull the surfaces away) the charges get reversed on to the opposite faces. The converse of this effect, that is "if an alternating voltage is applied to one set of opposite faces, the length along the other set of opposite faces either increase or decrease depending on the direction of applied potential. The frequency of oscillations of the crystal depends on number of AC cycles. The natural frequency of the crystal is given by,

$$f = \frac{1}{2l}\sqrt{\frac{\gamma}{\rho}} = \frac{\upsilon}{2l} \quad \text{.............. (3)}$$

Where, γ = Elastic modulus of material of the crystal

ρ = Density of material of the crystal

l = Length of material of the crystal between oscillating surfaces

υ = Velocity of longitudinal waves

Construction:

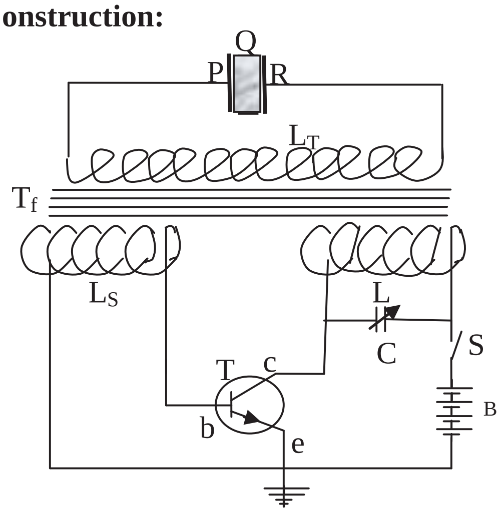

Figure 4.2. Piezoelectric oscillator

Q = Quartz crystal
P, R = Metal connectors
L, L_S, L_T = Coupled induction coils
C = Variable capacitor
S = Switch
T = Transistor
T_f = Transformer
B = Battery
c = Collector
b = Base
e Emitter

The above circuit is used to produce ultrasonic waves by the piezoelectric effect. A piezoelectric quartz crystal 'Q' is placed between two metal connectors, P and R which are connected to coupled induction coil L_T.

Working:

When the supply is switched on, the collector current increases and LC circuit connected to collector produces oscillations. The changes of current in L are fed back to base-emitter circuit by mutual inductance between L and L_S. The frequency of oscillations is given by

$$f = \frac{1}{2\pi\sqrt{LC}}$$

The frequency of oscillations can be varied by varying the capacity of the capacitor C. Due to mutual in the transformer T_f, an alternating emf is produced in the coil L_T. This alternating emf fed to electrodes P and R. The quartz crystal Q kept between electrodes P and R, experience oscillating electric force. Due to the inverse piezoelectric effect, the other pair of opposite faces in the crystal Q will oscillate with high frequency and thus ultrasonic waves are produced in quartz crystal. The capacity of the capacitor can be varied and made equal to the natural frequency of the quartz crystal so that resonance occurs and high frequency is generated. The frequency of the oscillation is given by;

$$f = \frac{1}{2l}\sqrt{\frac{\gamma}{\rho}} = \frac{\upsilon}{2l}$$

Merits:

1. Frequencies up to 500 MHz can be produced.
2. The oscillator circuit is easy to construct.
3. Required high frequency range can be generated.

Demerits:

1. Piezoelectric crystals are expensive.
2. Cutting piezoelectric crystal is difficult.

4.3. Properties of ultrasonic waves:

1. The human ear cannot hear ultrasound.
2. These are acoustic waves with a frequency greater than 20 kHz.
3. The wavelength of ultrasonic waves is small.
4. The diffraction of the wave is very less.
5. They can travel long distances. Hence they are used in SONAR.

6. These waves can also produce acoustic grating.
7. As frequency is very high, these waves are more energetic since E = hν.
8. When these waves are absorbed any medium through which they pass, it gets heated.

4.4. Applications of ultrasonic waves:

4.4.1. Engineering applications:

SONAR:

SONAR stands for "**SO**und **N**avigation **A**nd **R**anging". Sonar is used to detect submerged objects underwater such as submarines, sinked boats inside the sea or depth of the sea. It is similar to RADAR in the air.

Let the depth of the sea or any forgin object in the sea be x . Let υ be the velocity of ultrasonic wave, t be the time interval between emitted ultrasonic signal and received echo signal after reflection from the base then,

$$x = \frac{\upsilon \times t}{2}$$

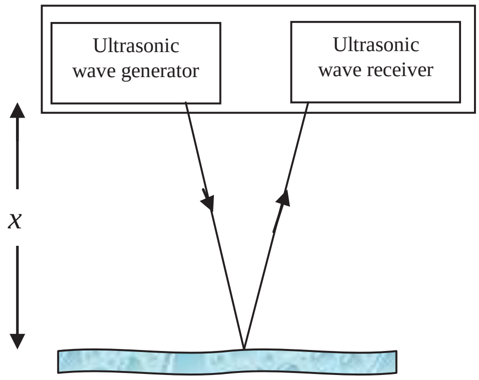

Figure 4.3. Measuring depth of sea using SONAR

Drilling, cutting and soldering of metals:

Ultrasonic waves can be used for drilling, cutting and soldering in metals at room temperature.

Cleaning:

Ultrasonic waves can also be used as a cleaning agent to clean clothes, utensils, removing dust and soot from chemney.

Chemical reactions:

These waves act as a catalyst to start and increase the rate of reaction.

Signaling systems:

Ultrasonic waves are more energetic and have less diffracting property, so they travel long distances in air and water even sea water. Hence, they can be used in signaling systems in air and sea water.

Non-destructive testing (NDT):

Widely used testing method is non-destructive testing. High frequency sound waves are used to test dimensional measurements, meterial characterization, flow detection and evaluation.

4.4.2. Medical applications:

Ultrasonic waves are used in various diagnostic and therapeutic applications.

Estimation of velocity of blood flow in veins and arteries:

The Doppler shift in higher ultrasound frequencies is used to estimate the velocity of blood flow in veins and arteries.

Ultrasonic scanning for heart, prostate enlargement detection and sonogram (echogram) of pregnant woman:

Low energy ultrasound from the transducer is used to study the movement of the heart, prostate enlargement in ultrasound scanning.

A sonogram (or echogram) of a pregnant woman can also be obtained using ultrasound scanning, which shows the fetal growth and study of the bodily organs in the womb.

Diagnostic use of ultrasound:

Ultrasonic waves are used in detectecting tumers or any other defects in the body.

Rheumatic and neuralgic pains:

When the ultrasonic waves are exposed on the part where the rheumatic or neuralgic pains occur, the massage action of the waves relieves the pain.

Sterilization:

Ultrasonic waves sterilize water and milk.

4.4.3. Other applications ultrasonic waves:

Ultrasonic wet-milling and grinding

Ultrasonics is an efficient means for the wet-milling and micro-grinding of particles. In particular for the manufacturing of superfine-size slurries, ultrasound has many advantages, when compared with common size reduction equipment, such as: colloid mills (e.g. ball mills, bead mills), disc mills or jet mills.

Ultrasonic cell extraction

Ultrasonics is used in the extraction of enzymes and proteins stored in cells and subcellular particles. The extraction of organic compounds contained within the body of plants and seeds by a solvent can be done using ultrasound.

Ultrasonic degassing of liquids

In this case the ultrasound removes small suspended gas-bubbles from the liquid and reduces the level of dissolved gas below the natural equilibrium level.

Ultrasonic leak detection of bottles and cans:

Ultrasound is being used in bottling and filling machines to check cans and bottles for leakage.

Ultrasonic wire, cable and strip cleaning:

Ultrasonic cleaning is an environmentally friendly. The cleaning of continuous materials, such as wire and cable, tape or tubes can be done with ultrasonic cleaning process. The ultrasonic power removes lubrication residues like oil or grease, soaps, stearates or dust.