Fig. 11.10

This figure is a near approach of a square wave form but not an exact square form. However, addition of more and more terms will give a resultant curve nearly approaching a square wave form.

ULTRASONICS

11.9. INTRODUCTION

The human ear is sensitive to sound waves in the frequency range from 20 to 20,000 Hz. This range is called audible range. Sound waves of frequency more than 20,000 Hz are called *ultrasonics*. These frequencies are beyond the audible limit.

These waves also travel with the speed of sound (330 ms^{-1}).

These waves exhibit the properties of audible sound waves and also show some new phenomena.

Their wavelengths are small.

Example 1. *What is the wavelength of ultrasonic wave of frequency 330 kHz at 0°C ?* [**Given :** Velocity of sound at 0°C = 330 ms^{-1}.]

$$\lambda = \frac{v}{n} = \frac{\quad}{(330 \times 10^3)}$$

11.10. PIEZOELECTRIC EFFECT

If one pair of opposite faces of a quartz crystal is subjected to pressure, the other pair of opposite faces develops equal and opposite electric charges on them (Fig. 11.11). The sign of the charges is reversed when the faces are subjected to tension instead of pressure. The electric charge developed is proportional to the amount of pressure or tension. This phenomenon is called *Piezoelectric effect.*

The effect is *reversible, i.e.*, if an electric field is applied across one pair of faces of the crystal, contraction or expansion occurs across the other pair.

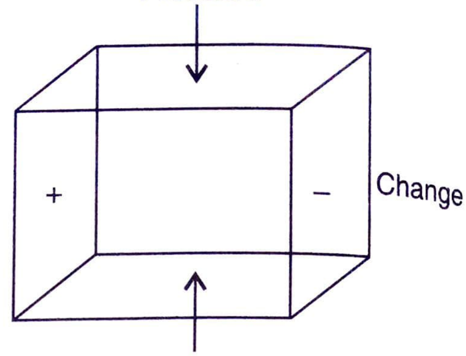

Fig. 11.11

When the two opposite faces of a quartz crystal, their faces being cut perpendicular to the optic axis, are subjected to alternating voltage, the other pair of opposite faces experiences stresses and strains. The quartz crystal will continuously contract and expand. Elastic vibrations are set up in the crystal.

When the frequency of the alternating voltage is equal to the natural frequency of vibration of the crystal or its simple higher multiples, the crystal is thrown into resonant vibrations. The amplitude is large. These vibrations are longitudinal in nature.

Consider a X-cut crystal plate of thickness t. The fundamental frequency of vibration is given by

$$n = \frac{1}{2t}\sqrt{\frac{E}{\rho}}.$$

E is the Young's modulus and ρ is the density of the material of the crystal plate.

Example 1. *A quartz crystal of thickness 0.001 m is vibrating at resonance. Calculate the fundamental frequency. Given E for quartz = 7.9 × 10^{10} Nm^{-2} and ρ for quartz* = 2650 *kg* m^{-3}.

Solution.

$$n = \frac{1}{2t}\sqrt{\frac{E}{\rho}} = \frac{1}{2 \times 0.001}\sqrt{\frac{(7.9 \times 10^{10})}{2650}} = \mathbf{2.73 \times 10^6\ Hz.}$$

Example 2. *A piezoelectric X-cut quartz plate has a thickness of 1.5 mm. If the velocity of propagation of longitudinal sound waves along the X direction is 5760 m/s, calculate the fundamental frequency of the crystal.*

Solution. For the fundamental mode of vibration,

$$\text{thickness} = \frac{\lambda}{2}$$

$$\therefore \quad \lambda = 2 \times \text{thickness} = 2 \times (1.5 \times 10^{-3})\ \text{m} = 3 \times 10^{-3}\text{m}$$

Frequency,

$$n = \frac{v}{\lambda} = \frac{5760}{(3 \times 10^{-3})} = \mathbf{1.92 \times 10^6\ Hz}$$

11.11. PRODUCTION OF ULTRASONIC WAVES — PIEZOELECTRIC CRYSTAL METHOD

Principle. This is based on the inverse piezoelectric effect. When a quartz crystal is subjected to an alternating potential difference along the electric axis, the crystal is set into elastic vibrations along its mechanical axis. If the frequency of the electric oscillations coincides with the natural frequency of the crystal, the vibrations will be of large amplitude. If the frequency of the electric field is in the ultrasonic frequency range, the crystal produces ultrasonic waves.

Construction. The circuit diagram is shown in Fig. 11.12.

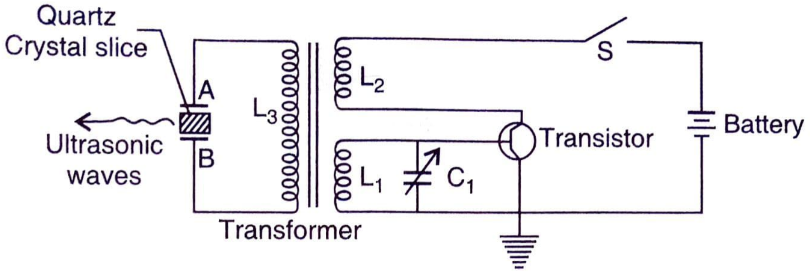

Fig. 11.12

It is a base tuned oscillator circuit. A slice of quartz crystal is placed between the metal plates A and B so as to form a parallel plate capacitor with the crystal as the dielectric. This is coupled to the electronic oscillator through primary coil L_3 of the transformer.

Coils L_2 and L_1 of oscillator circuit are taken from the secondary of the transformer. The collector coil L_2 is inductively coupled to base coil L_1. The coil L_1 and variable capacitor C_1 form the tank circuit of the oscillator.

Working. When the battery is switched on, the oscillator produces high frequency oscillations. An oscillatory e.m.f. is induced in the coil L_3 due to transformer action. So the crystal is now under high frequency alternating voltage.

The capacitance of C_1 is varied so that the frequency of oscillations produced is in resonance with the natural frequency of the crystal. Now the crystal vibrates with large amplitude due to resonance. Thus high power ultrasonic waves are produced.

Advantages

1. Ultrasonic frequencies as high as 500 MHz can be generated.
2. The output power is very high. It is not affected by temperature and humidity.
3. It is more efficient than magnetostriction oscillator.
4. The breadth of the resonance curve is very small. So we can get a stable and constant frequency of ultrasonic waves.

Disadvantages

1. The cost of the quartz crystal is very high.
2. Cutting and shaping the crystal is very complex.

11.12. PRODUCTION OF ULTRASONIC WAVES — MAGNETOSTRICTION METHOD

Principle. When a rod of ferromagnetic material like nickel is magnetised longitudinally, it undergoes a very small change in length. This is called *magnetostriction effect.*

A nickel rod placed in a rapidly varying magnetic field alternately expands and contracts with twice the frequency of the applied magnetic field. By adjusting the frequency of the alternating magnetic field to be equal to the natural frequency of longitudinal vibration of the rod, resonance is produced. Due to resonance, vibrations of large amplitude are produced in the rod. Ultrasonic waves are emitted from the ends of the rod if the frequency of the alternating magnetic field is more than 20 kHz.

The frequency of vibrations of the rod is

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

Here, l = length of the rod,

E = Young's modulus of the material of the rod,

ρ = density of the material of the rod.

Construction. The circuit diagram of magnetostriction ultrasonic generator is shown in Fig. 11.13.

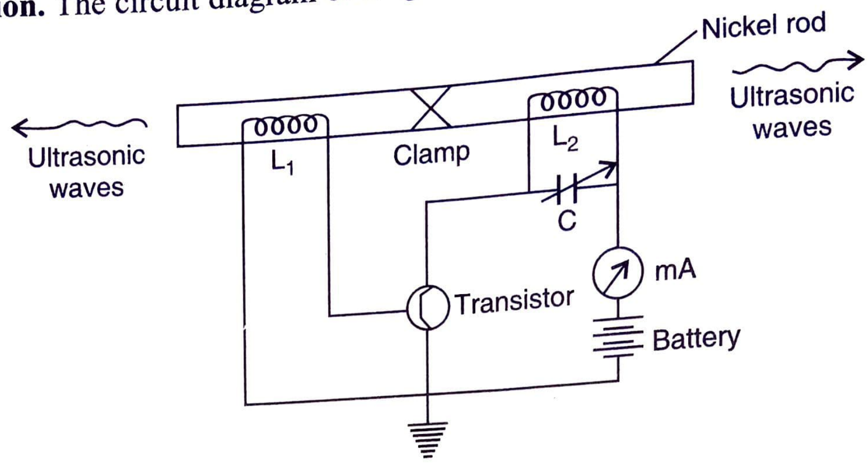

Fig. 11.13

A short permanently magnetised nickel rod is clamped in the middle between two knife edges. A coil L_2 is wound on the right hand portion of the rod. C is a variable capactior. L_2 and C form the resonant circuit of the collector tuned oscillator. Coil L_1 wound on the left hand portion of the rod is connected in the base circuit. The coil L_1 is used as a feedback loop.

Working. When the battery is switched on, the resonant circuit L_2C sets up an alternating current of frequency

$$f = \frac{1}{2\pi\sqrt{L_2C}}.$$

This current flowing round the coil L_2 produces an alternating magnetic field of frequency f along the length of the nickel rod. The rod starts vibrating due to magnetostrictive effect. The vibrations of the rod create ultrasonic waves.

The longitudinal expansion and contraction of the rod produces an e.m.f. in the coil L_1. This e.m.f. is applied to the base of the transistor. Hence the amplitude of high frequency oscillations in coil L_2 is increased due to positive feedback.

The developed alternating current frequency can be tuned with the natural frequency of the rod by adjusting the capacitor. The resonance condition is indicated by the rise in the collector current shown in the milliammeter.

Advantages

1. Magnetostriction oscillators are mechanically rugged.
2. The construction cost is low.
3. They are capable of producing large acoustical power with fairly good efficiency (*e.g.*, 60%).

Limitations

1. It can produce frequencies up to 3MHz only.
2. The frequency of oscillations depends greatly on temperature.
3. Breadth of the resonance curve is large. It is due to variations of elastic constants of ferromagnetic material with the degree of magnetisation. So we cannot get a constant single frequency.

θ is the angle of diffraction.

n is the order of spectrum.

λ is the wavelength of the monochromatic source of light.

If λ_u is the wavelength of ultrasonics, then we can write from fig.2.10 as $\lambda_u = 2d$ ......(2)

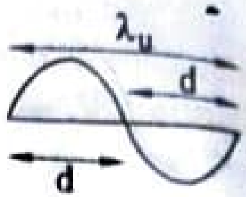

Fig. 2.10

$\therefore$ Equation (1) becomes $\lambda_u \sin\theta = n\lambda$

(or) Wavelength of ultrasonics $\boxed{\lambda_u = \dfrac{n\lambda}{\sin\theta}}$ ...(3)

We know,

$$\text{Velocity of ultrasonics} = \begin{pmatrix}\text{Frequency of}\\ \text{ultrasonics}\end{pmatrix} \times \begin{pmatrix}\text{Wavelength}\\ \text{of ultrasonics}\end{pmatrix}$$

Frequency of ultrasonics produced by piezo-electric oscillator will be the same as that of the frequency of the oscillatory circuit. So if ν_u is the frequency of the ultrasonics produced using piezo-electric oscillator then,

$$\boxed{\textbf{Velocity of Ultrasonics } (v) = \nu_u \lambda_u} \quad ...(4)$$

Substituting equation (3) in (4), we get

Velocity of ultrasonics $\boxed{v = \dfrac{\nu_u n\lambda}{\sin\theta}}$

Thus the velocity (or) wavelength of the ultrasonics can be determined using acoustical grating.

> ***NOTE :** Using this method we can determine the velocity of any liquids (or) gases, even at various temperatures.*

2.6 APPLICATIONS OF ULTRASONICS IN ENGINEERING FIELD

1) *Sound Signalling* : High frequency ultrasonics can be sent out in the form of beams, which spreads in all directions as spherical wavefronts and passes the signals from one place to another. Thus the signals can be used as an identification for landing the ships. In military field the method of sound signalling can used to identify our warships

2) Depth sounding : Echo sounding is the principle used to find the depth of the sea. A beam of ultrasonics is directed towards the bottom of the sea and the reflected signal is received as shown in Fig. 2.11.

The time interval between the transmitted and received signal is noted and let it be 't'. If 'v' is the velocity of the ultrasonics, then

$$\text{Velocity} = \frac{\text{Distance travelled}}{\text{Time taken}}$$

From Fig.2.11, we can write

$$v = \frac{PR + RQ}{t} = \frac{2RO \text{ (approx)}}{t}$$

$$\therefore \ RO = \text{Depth of sea} = \frac{vt}{2}$$

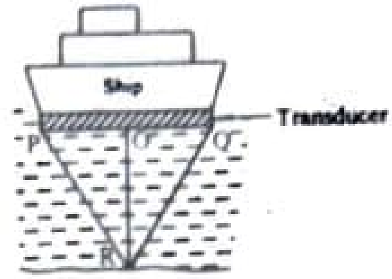

Fig. 2.11

The depth of the sea can be directly calibrated using the instrument called as Fathometer (or) Echometer.

3) Ultrasonic welding and soldering : Some materials cannot be welded at high temperature. In such cases the welding can be done at room temperature using ultrasonics and is called as cold welding. It is also used for soldering aluminium foil condensers, aluminium wires etc., without any flux.

4) Ultrasonic drilling and cutting : Ultrasonics are used for making holes in very hard materials such as glass, diamond etc., When ultrasonics are passed through these materials it creates air bubbles. This air bubbles collapses within a short span of time, thereby releasing a large amount of pressure and temperature which are used for cutting and drilling.

5) Ultrasonic cleaning and drying : Ultrasonics can also be employed in cleaning motors, aeroplanes, electronic assemblies etc., Here the cleaning tank is partially filled with detergent solutions. The article to be cleaned is placed in this tank. The ultrasonics are imparted to the solution, which accelerates the molecules in the liquid to move with high kinetic energy. This particles strikes the dirt particles and clean it. Further it can also be dried using acoustic drier.

6) Coagulation : They are used in coagulation (changing from liquid phase to a semi solid phase) and crystallisation, hence can be used in the manufacturing of paints, polishes etc.

7. They are used to increase the sensitivity of colour in photographs by dispersion of dye in the emulsion.

8. They are used to remove air bubbles in the liquid metals and convert them into fused metals.

9. Low frequency ultrasonics are used in sorting paper fibers from the paper pulp.

10. They are also used in sound navigation purpose (SONAR).

2.7 SONAR (SOund Navigation And Ranging)

Principle : *It is based on the principle of ECHO-SOUNDING. When ultrasonic waves are transmitted through water, it is reflected by the objects in the water and will produce an echo signal. The change in frequency of the echo signal, due to doppler effect helps us to determine the velocity and the direction of the object.*

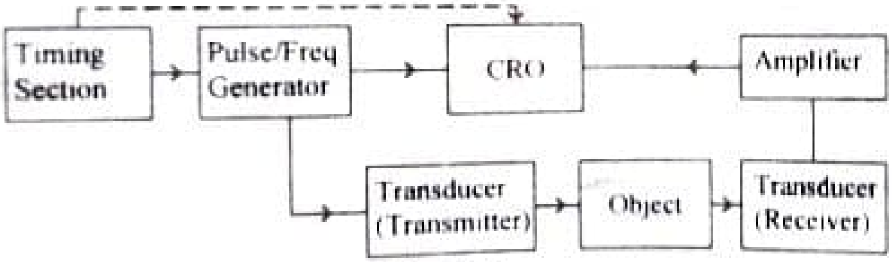

Fig 2.12

Description : It consists of a timing section which triggers the electric pulse from the pulse generator. This pulse generator is connected to the transducer (Transmitter and receiver) so that ultrasonics can be produced. The transducer is further connected with the CRO for display. The timing section is also connected to the CRO display for reference of the timing at which the pulse is transmitted as shown in block diagram Fig.2.12.

Working : The transducer is mounted on the ship's hull without any air gap between them as shown in fig.2.13. The timing at which the pulse generated is recorded at the CRO for reference and this electrical pulse triggers the transducer which is kept in the hull of the ship to produce ultrasonic waves due to the principle of inverse piezo electric effect.

These ultrasonic waves are transmitted through the water in the sea. On stricking the object the ultrasonic waves (echo pulses) are reflected in all directions.

5. **Sterilization.** Ultrasonic waves can kill bacteria. Therefore, they are used for sterilising milk.

6. **Blood flow meters.** Ultrasonic Doppler blood flow meters are used to study the blood flow velocities in blood vessels of our body.

ACOUSTICS OF BUILDINGS

11.17. REVERBERATION

When a source produces sound waves inside a closed building, the waves are generally reflected repeatedly by walls, ceiling and other materials present in the room. The intensity of the sound wave decreases at every reflection and finally the sound becomes inaudible. So the listener receives (*i*) direct waves and (*ii*) reflected waves due to multiple reflections, at the various surfaces. There is also a time gap between the direct wave received by the listener and the waves received by successive reflection. Due to this, the sound persists for some time even after the source has stopped. This persistence of sound is called *reverberation*.

Definition of Reverberation. *Reverberation is the persistence of sound in an enclosure due to multiple reflections of sound at the walls after the source has ceased to emit sound.*

Definition of Reverberation time. *The interval of time taken by sustained or continuous sound to fall in intensity to one millionth of its original value is called reverberation time* (T).

It is the time taken for the sound to fall below the minimum audibility after the source stopped sounding.

The reverberation time will depend on the size of the room or the auditorium, the nature of the reflecting material on the wall and the ceiling and the area of the reflecting surfaces.

Sabine's method of determining reverberation time

An organ pipe of frequency 512 Hz is sounded. At the same time, a stop watch is started. The time for the sound to become inaudible is measured. This gives the reverberation time.

11.18. DERIVATION OF SABINE'S FORMULA FOR REVERBERATION TIME

The main assumptions are :

(1) The average energy per unit volume is uniform. It is represented as σ.

(2) The energy is not lost in the auditorium. The energy lost is only due to the absorption of the material of the walls and ceiling and also due to the escape through the windows and ventilators. Both these factors are included in the term '**absorption**' of energy.

Suppose a source is producing sound continuously. This sound energy is propagated in all directions. Let σ be the energy contained in a unit volume, *i.e.*, energy density.

Energy contained in a solid angle $d\phi = \dfrac{\sigma . d\phi}{4\pi}$

Let this energy be incident on a unit surface area of the wall at an angle θ (Fig. 11.17).

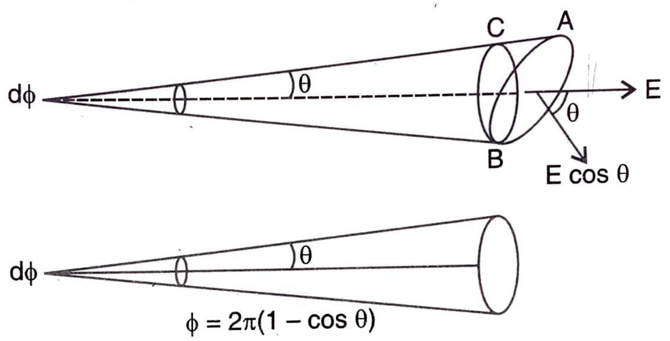

Fig. 11.17

Let v = Velocity of sound

Total energy falling per second on a unit surface area of the wall

$$= \left(\frac{\sigma . d\phi}{4\pi}\right)(\cos\theta).v$$

The total energy falling per second within a hemisphere

$$= \frac{\sigma v}{4\pi} . \int \cos\theta . d\phi \qquad ...(1)$$

But $\phi = 2\pi(1 - \cos\theta)$

or $d\phi = 2\pi \sin\theta . d\theta$

Substitute this value of $d\phi$ in Eq. (1).

The total energy falling per second within a hemisphere

$$= \frac{\sigma v}{4\pi} . \int_0^{\pi/2} 2\pi \sin\theta . \cos\theta . d\theta$$

$$= \frac{\sigma v}{2\pi}\left[-\frac{\cos^2\theta}{2}\right]_0^{\pi/2}$$

$$= \frac{\sigma v}{4}$$

Let α = absorption coefficient of the walls.

The amount of energy absorbed per second per unit area $= \frac{\alpha \sigma v}{4}$.

Let A = area of the walls and the other absorbing materials including ceiling, windows and ventilators etc.

Total amount of energy absorbed per second $= \frac{A\alpha\sigma v}{4}$.

Let V be the volume of the auditorium.

Total sound energy present at any instant $= V\sigma$

The rate of increase of energy $= \frac{d}{dt}(V\sigma) = v\frac{d\sigma}{dt}$ ...(2)

Suppose, the source supplies energy at the rate of Q units per second.

Rate of increase of energy $= Q - \frac{A\alpha\sigma v}{4}$ ...(3)

Equating (2) and (3), we get

$$V.\frac{d\sigma}{dt} = Q - \frac{A\alpha\sigma v}{4} \quad ...(4)$$

Put $\frac{A\alpha v}{4} = K, \frac{K}{V} = \beta$ and $B = \frac{Q}{K} = \frac{4Q}{A\alpha v}$.

Eq. (4) becomes

$$V.\frac{d\sigma}{dt} = Q - K\sigma$$

$$\frac{d\sigma}{dt} = \frac{Q}{V} - \frac{K}{V}.\sigma \quad ...(5)$$

The general solution of this equation is

$$\sigma = B + be^{-\beta t}$$

When $t = 0, \sigma = 0.$

$$0 = B + b$$

or $b = -B$

$\therefore$ $\sigma = B - Be^{-\beta t}$

$$\sigma = B\,[1 - e^{-\beta t}]$$

Substituting the values of B and β,

$$\sigma = \frac{4Q}{A\alpha v}\left[1 - e^{-\left(\frac{A\alpha v}{4V}\right)t}\right] \quad ...(6)$$

Eq. (6) represents the rise of average sound energy per unit time from the time the source commences to produce sound.

The maximum value of average energy per unit volume

$$\sigma_{max} = \frac{4Q}{A\alpha v} \quad ...(7)$$

Similarly, after the source ceases to emit sound, the decay of the average energy per unit volume is given by

$$\sigma = \frac{4Q}{A\alpha v}e^{-\left(\frac{A\alpha v}{4V}\right)t} \quad ...(8)$$

$$\sigma = \sigma_{max}\, e^{-\left(\frac{A\alpha v}{4V}\right)t} \quad ...(9)$$

Fig. 11.18 shows the decay of the energy density with time.

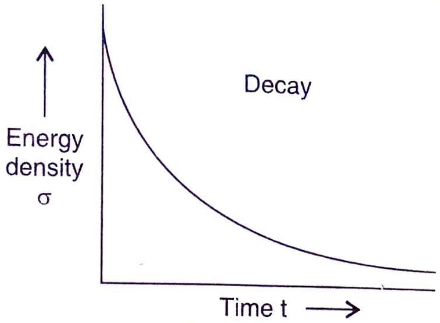

Fig. 11.18

Reverberation Time (*T*)

Reverberation time is defined as the time taken for the energy density to fall to one-millionth of its value before the cut-off.

Hence, substituting $\sigma = \frac{\sigma_{max}}{10^6}$ and $t = T$ in Eq. (9),

$$\frac{\sigma_{max}}{10^6} = \sigma_{max}\, e^{-\left(\frac{A\alpha v}{4V}\right)T}$$

$$10^{-6} = e^{-\left(\frac{A\alpha v}{4V}\right)T}$$

$$e^{\left(\frac{A\alpha v}{4V}\right)T} = 10^6$$

Taking logarithms,

$$\left(\frac{A\alpha v}{4V}\right)T = \log_e 10^6 = 6 \log_e 10 = 6 \times 2.3026$$

Take velocity of sound (v) approximately at room temperature as 350 ms^{-1}.

$$T = \frac{6 \times 2.3026 \times 4V}{A\alpha v} = \frac{6 \times 2.3026 \times 4}{350} \times \left(\frac{V}{A\alpha}\right)$$

$$T = \frac{0.158V}{A\alpha}$$

In general,

$$T = \frac{0.158V}{\Sigma A\alpha} \quad ...(10)$$

Here, V and A are in metres.

Eq. (10) represents the Sabine's reverberation time formula.

Explanation of Sabine's formula

Sabine's formula for reverberation time is

$$T = \frac{0.158V}{\Sigma A\alpha} \quad ...(1)$$

According to Eq.(1), the reverberation time is

(*i*) directly proportional to the volume of the auditorium,

(*ii*) inversely proportional to the area of the ceilings, area of the walls etc.; and

(*iii*) inversely proportional to the total absorption plus transmission through open surfaces.

Importance of Sabine's Formula

If the reverberation time is too small, the sound dies away almost instantaneously and gives the hall a '*dead*' effect. If the reverberation time is too long, each syllable continues to be heard even after the next syllable has been uttered. This makes the sound unintelligible. Therefore, the value of reverberation time is maintained at an *optimum value*. Rooms of different dimensions were used by Sabine to find the optimum reverberation time. For speech, the reverberation time should be about 1 to 2 seconds. For music, it is between 2 and 2.5 seconds.

11.19. JAEGER'S METHOD FOR DERIVATION OF SABINE'S FORMULA

Let a_1, a_2, a_3 .... a_n be the absorption coefficients of the surfaces of areas $S_1, S_2, S_3, ... S_n$ respectively.

The average value of absorption coefficient,

$$a = \frac{a_1S_1 + a_2S_2 + ... + a_nS_n}{S_1 + S_2 + S_3 + ... + S_n} = \frac{\Sigma a_i S_i}{S}$$

Here, S is the total area of the surfaces.

By statistical method, Jaeger showed that the sound travels an average distance $\frac{4V}{S}$ between two successive reflections.

Here, V is the volume of the hall.

Time between two successive reflections $= \frac{4V}{Sv}$.

Here, v is the velocity of sound.

Number of reflections in one second $= \frac{Sv}{4V}$.

The average number of reflections in time $t = \frac{Svt}{4V}$.

Let a be the fraction of sound absorbed at a single reflection.

Fraction of sound reflected = $(1 - a)$.

After two reflections, the fraction of sound reflected = $(1 - a)^2$.

After $\frac{Svt}{4V}$ reflections, the fraction of sound reflected = $(1 - a)^{Svt/4V}$

Let I_0 be the initial intensity of sound and I_t, the intensity after time t.

$$I_t = I_0 (1 - a)^{Svt/4V} \quad ...(1)$$

Reverberation time is the time taken by sound to fall to one millionth of the intensity just before the source is cut off.

When $t = T, \quad I_T/I_0 = 10^{-6}$

Substituting these values in Eq.(1), we get

$$\frac{I_T}{I_0} = 10^{-6} = (1 - a)^{Svt/4V} \quad ...(2)$$

Taking natural logarithms of both sides of Eq.(2),

$$\log_e 10^{-6} = \frac{SvT}{4V} \log_e (1 - a)$$

$$T = \log_e 10^{-6} \times \frac{4V}{Sv \log_e (1 - a)}$$

$$T = 2.3026 \times \log_{10} 10^{-6} \times \frac{4V}{Sv \log_e (1 - a)}$$

Put

$$v = 350\text{ms}^{-1}$$

$$T = \frac{2.3026 \times (-6) \times 4V}{S \times 350 \times \log_e(1-a)}$$

$$= 0.158 \frac{V}{-S\log_e(1-a)}$$

$$\log_e(1-a) = -a$$

$$T = \frac{0.158V}{Sa}$$

$$\therefore \quad T = \frac{0.158V}{\Sigma a_i S_i}$$

This is Sabine's formula for the reverberation time. It shows that the reverberation time depends on volume and total absorbing power of the hall.

Example 1. *A hall of volume 5500 metre³ is found to have a reverberation time of 2.3s. The sound absorbing surface of the hall has an area of 750m². Calculate the average absorption coefficient.*

Solution. Here, $V = 5500$ m³, $T = 2.3$s, $A = 750$ m².

Reverberation time, $T = \dfrac{0.158V}{A\alpha}$ (*Sabine's formula* for reverberation time)

$$\alpha = \frac{0.158V}{AT} = \frac{0.158 \times 5500}{750 \times 2.3} = \mathbf{0.504}$$

Example 2: *The volume of a room is 600 m³. The wall area of the room is 220 m², the floor area is 120 m² and the ceiling area is 120 m². The average sound absorption coefficient, (i) for the walls is 0.03 ; (ii) for the floor is 0.06 and (iii) for the ceiling is 0.80. Calculate the average sound absorption coefficient and the reverberation time.*

Solution. Average absorption coefficient,

$$\alpha = \frac{\Sigma\alpha A}{\Sigma A} = \frac{\alpha_1 A_1 + \alpha_2 A_2 + \alpha_3 A_3}{A_1 + A_2 + A_3} = \frac{0.03 \times 220 + 0.06 \times 120 + 0.8 \times 120}{220 + 120 + 120} = 0.2387$$

Total sound absorption of the room = $\alpha\Sigma A = 0.2387 \times 460 = 109.8$ metric sabine

Reverberation time, $T = \dfrac{0.158V}{\alpha\Sigma A} = \dfrac{0.158 \times 600}{109.8} = \mathbf{0.8634s}$

11.20. ABSORPTION COEFFICIENT

First Definition. *The sound absorption coefficient (α) of a material is defined as the ratio of sound energy absorbed by it to the total energy incident on it.*

Absorption coefficient (α) = $\dfrac{\text{Sound energy absorbed by the surface}}{\text{Total sound energy incident on the surface}}$

Sabine chose 1 square metre of an open window as a standard unit of absorption since all sound waves falling on it pass through and can be said to be completely absorbed. This unit is called *sabine*. It is also called open window unit (O.W.U.).

Second Definition. *The absorption coefficient of a material is defined as the ratio of sound energy absorbed by it to that absorbed by an equal area of an open window.*

According to Sabine's formula,

$$T_1 = \frac{0.158V}{\Sigma \alpha A} \quad ...(1)$$

Here $(\Sigma \alpha A)$ is the absorption in the hall without the material.

V = Volume of the hall.

(*ii*) The absorbing material is put inside the room.

Let α_1 be the absorption coefficient of the material and s its surface area.

Now the reverberation time T_2 is measured.

$$T_2 = \frac{0.158V}{\Sigma \alpha A + \alpha_1 s} \quad ...(2)$$

$$\frac{1}{T_2} - \frac{1}{T_1} = \frac{\alpha_1 s}{0.158V}$$

$$\therefore \quad \alpha_1 = \frac{0.158V}{s}\left(\frac{1}{T_2} - \frac{1}{T_1}\right) \quad ...(3)$$

Knowing the values of V, s, T_1 and T_2, the absorption coefficient of the absorbing material α_1 is calculated.

11.21. ACOUSTICS OF BUILDINGS

The branch of Physics which deals with the design and construction of buildings with good acoustic properties is called "Acoustics of buildings." It deals basically with (*i*) reverberation control, (*ii*) noise insulation and reduction and (*iii*) sound distribution and absorption.

The following are the requirements of a *good auditorium*:

1. The sound should be sufficiently loud and intelligible in every part of the hall.
2. Sound of each syllable should soon decay so that the succeeding syllable may be heard distinctly. There must be no confusion due to overlapping of syllables. This means that the auditorium must be free from excessive reverberation.
3. No echoes should be present.
4. There should not be *undesirable focussing* of sound in any part of the hall. There should not be any *zones of silence* or regions of poor audibility anywhere in the hall.
5. Interference, reflection and resonance effects should be avoided.
6. All extraneous noises must be shut out as far as possible. The boundaries should be sufficiently soundproof to exclude extraneous noise.
7. There should be no Echelon effect.
8. The quality of sound must be unaltered, *i.e.*, the relative intensity of the components of the complex sound must be preserved.

Fig. 11.19 shows the usual design of the hall.

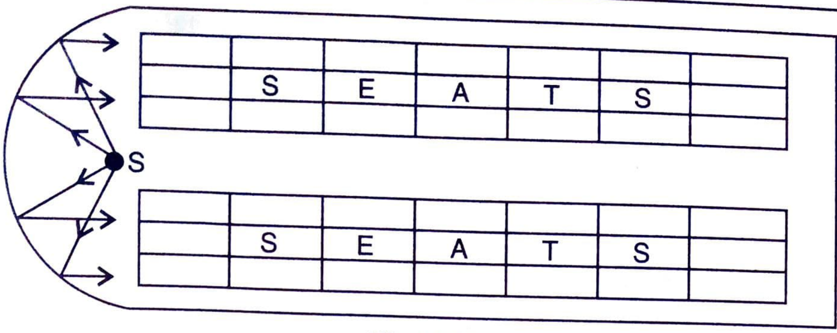

Fig. 11.19

It has a parabolic shape at the speaker's end *S*. As the speaker speaks, sound is reflected from the back almost as a parallel beam. So there is uniform distribution of sound intensity throughout the hall.

11.22. FACTORS AFFECTING THE ACOUSTICS OF BUILDINGS

The factors affecting the acoustics of a hall are :

(*i*) Reverberation time

(*ii*) Presence of echoes

(*iii*) Adequate loudness

(*iv*) Focussing and interference effects

(*v*) Resonances within the building

(*vi*) Echelon effect

(*vii*) Extraneous noises

(*viii*) Inside noise.

(*i*) Reverberation. Reverberation is one of the important single factors that affect the acoustics of a room or a hall.

The reverberation of sound in an auditorium is due to multiple reflections taking place at various surfaces present within the auditorium.

If the reverberation time is too small, the sound dies away almost instantaneously and gives the hall a '*dead*' effect. If the reverberation time is too long, each syllable continues to be heard even after the next syllable has been uttered. This makes the sound unintelligible. Therefore, the value of reverberation time is maintained at an *optimum value*. Rooms of different dimensions were used by Sabine to find the optimum reverberation time. For speech, the reverberation time should be about 1 to 2 seconds. For music, it is between 2 and 2.5 seconds.

To adjust the reverberation time to the best optimum value, the absorption of sound in the hall is increased in the following ways :

(*a*) providing windows and openings,

(*b*) covering ceiling and walls with sound absorbing materials like felt, fibre board, celotex, asbestos etc.,

(*c*) using heavy curtains with folds,

(*d*) covering the floor with carpets,

(*e*) by upholstering the seats so that the absorption is approximately the same with or without the audience,

(*f*) by having a good audience because one listener is equivalent to about 0.5 m^2 area of an open window, and

(*g*) by decorating the walls with pictures, maps etc.

(*a*) using large sounding boards behind the speaker and facing the audience,

(*b*) by providing low ceiling for the reflection of sound towards the audience, and

(*c*) by providing additional energy with the help of equipments like loud speakers.

***(iv)* Focussing :** If there is any concave surface in the hall, sound is concentrated at its focus region. There may be dead space at some other regions. Hence such surfaces must be avoided. If curved surfaces are present, they should be covered with absorbent materials.

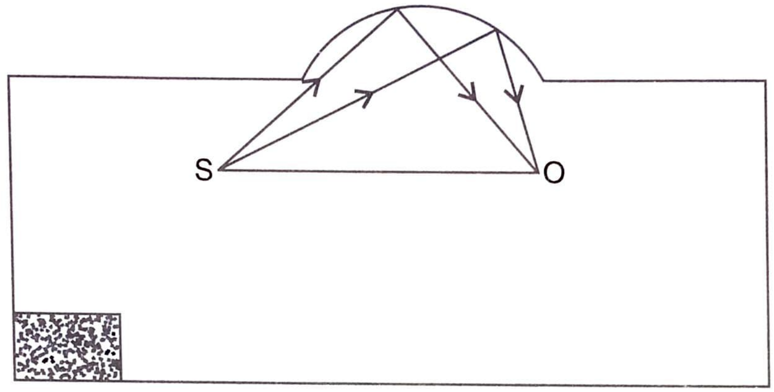

Fig. 11.20

In Fig. 11.20, the observer at *O* receives sound from the speaker along the direct path *SO*. The observer also receives the sound waves after reflection from the ceiling. Thus the intensity of sound at *O* is comparatively higher than at other positions in the auditorium. There should be no interference of direct and reflected waves. Good absorbing materials avoid this defect.

Suppose the direct and the reflected waves are in opposite phase at *O*. This results in minimum intensity of sound at *O*. Further, the direct and the reflected waves may form a stationary wave pattern. This causes uneven distribution of sound intensity.

***(v)* Resonance Effects :** Window panels, sections of wooden portions which are loosely fitted start vibrating, creating extra sounds. If there is resonance for any audio frequency note, the intensity of the note will be entirely different from the intensity desired. Such resonant vibrations should be damped.

***(vi)* Echelon effect :** Suppose there is regular structure similar to a flight of stairs in the hall. The sound produced in front of such a structure may produce a *musical note* due to regular successive echoes of sound reaching the observer. Such an effect is called *echelon effect*. If the frequency of this note is within the audible range, the listener will hear only this note prominently.

The remedy is to cover such surfaces with absorbing materials like carpets.

***(vii)* Extraneous noises :** They are classified as *air-borne* and *structure- borne* noises.

(*a*) Air-borne noise : The noise which reaches the hall from outside through open windows, doors and ventilators is called *Air borne noise*. It is reduced by the following methods:

1. Using double doors and windows with separate frames and having insulating materials between them.

2. Making the hall as an air-conditioned hall where the hall is completely closed.

(*b*) Structure-borne noise : The noise which is conveyed through the structure of the building is called *Structure borne noise*. This noise can be minimised by using double walls with air space between them.

***(viii)* Inside noise :** The noise which is produced inside the hall is called *inside noise*. It is produced by machinery like air-conditioners, typewriters, etc., in the hall. This noise is minimised by the following methods:

1. Covering the floor with carpet.
2. Walls, floor and ceiling should be provided with sound absorbing materials.
3 Placing the working machineries like air-cooler or air-conditioning machine on sound absorbent pads.
4. The rotating or impacting machines must be fixed using a fixed bed.

11.23. SOUND DISTRIBUTION IN AN AUDITORIUM

Sound distribution describes how the sound pressure level varies with position in an enclosure. The design of an auditorium requires smooth decay and growth of sound. In an auditorium, the sound must be distributed or diffused over the whole area. To ensure these factors, acoustic treatment is given, *viz.*, scattering effect of objects, irregularities on the wall surfaces, fixing absorptive material on the walls etc. Model analysis with light rays, ultrasonic waves or ordinary audio frequency sound is used to study sound distribution. Graphical construction of first reflection of the sound waves at various cross-sections can also be used as in Fig. 11.21. It is clear from the figure that the reflected sound is distributed evenly in the whole auditorium, viz., the main floor and the balcony. This design enables an even distribution of sound intensity.

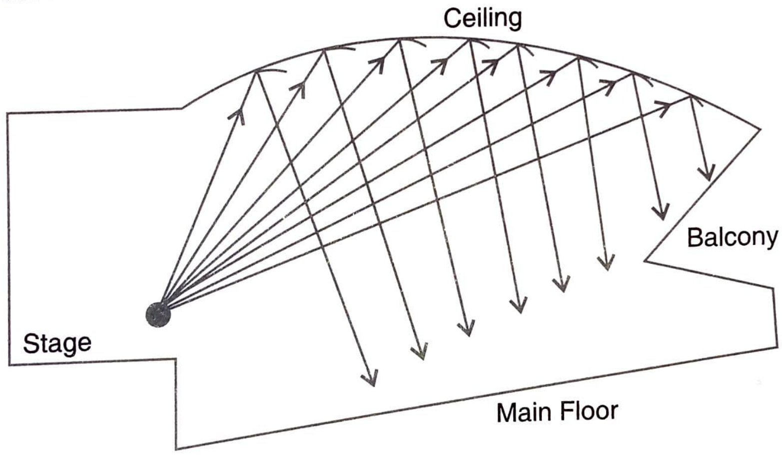

Fig. 11.21

EXERCISE XI

SECTION – A

1. Explain : Free vibrations, forced vibrations and resonance. Illustrate your answer by giving an example of each.
2. What are free, damped and forced vibrations ?
3. State the Fourier theorem and obtain expressions for Fourier coefficients.
4. What are ultrasonic waves ?
5. What is piezoelectric effect ? How is inverse piezoelectric effect used to produce ultrasonic wave ?
6. Explain the principle of magnetostriction method of producing ultrasonics.
7. What are the usual methods employed to detect ultrasonics ?
8. Mention the properties of ultrasonics.
9. Give important applications of ultrasonics.
10. What is meant by 'reverberation' and 'reverberation time'? Explain clearly what causes reverberation in a hall and how it can be minimised.

... Sabine's formula for Reverberation Time of a hall.