APPLIED PHYSICS II – MODULE I

WAVE MOTION AND ITS APPLICATIONS

CO1: Calculate the characteristics of waves.

Periodic Motion:

The uniform circular motion where the motion is repeated after a certain interval of time, which is periodic. A particle that moves periodically about an equilibrium position is said to be oscillating or vibrating. In vibratory motion, bodies move to and fro or back and forth over the same path. They repeat over and over a fixed series of motions returning to each position at regular intervals of time. The pendulum of a clock executes to and fro motion about a mean position. The membranes in drums vibrate to and fro about their mean position.

Thus, a motion that repeats itself at regular intervals of time is called periodic motion. There are many examples for periodic motion such as,

a) Vibrations of strings of musical instruments.

b) The motion of the earth and other planets around the sun.

c) Vertical oscillations of loaded spring.

d) Oscillations of a simple pendulum.

e) Vibrations of atoms in a crystal.

If a body moves in a circular path, it is said to describe circular periodic motion and if the motion is repeated along a line it is said to describe a linear periodic motion. Periodic motion is also called harmonic motion.

Simple Harmonic Motion (SHM):

Simple harmonic motion is a particular case of periodic motion and is the most fundamental type of periodic motion. ***Simple harmonic motion can be defined as a motion in which the acceleration of the body is directly proportional to its displacement from a fixed point and is always directed towards the fixed point.*** The fixed point is called equilibrium position.

A body undergoing periodic motion has an equilibrium position inside its path. When the body is at this position no net external force acts on it. Therefore, if it is left there at rest it remains there forever. If the body is given a small displacement from the position, a force comes into play that tries to bring the body back to the equilibrium point giving rise to oscillations or vibrations. A ball placed in a bowl will be in equilibrium at the bottom. If displaced a little from the point, it will perform oscillations in the bowl.

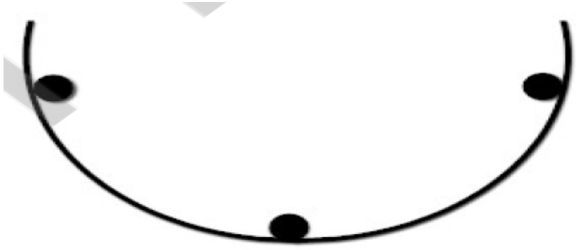


Fig. 1.1 Oscillation of a ball in a bowl

The properties of simple harmonic motion are:

a) The motion should be periodic.

b) When displaced from the mean position, a restoring force, directed towards the mean position and trying to bring it to the mean position must act on the body.

c) The restoring force should be directly proportional to the displacement of the body from its mean position.

Examples of Simple Harmonic Motion:

a) Swings that we see in the park.

b) The pendulum oscillates back and forth from the mean position.

c) The motion of vibrating mass attached to a spring.

d) When a tuning fork is made to vibrate, the prongs of the tuning fork perform to and fro motion. The to and fro motion of the prong is simple Harmonic.

e) The oscillations of Mercury contained in a U tube when the liquid column in one limb is depressed and released is simple Harmonic.

Conceptual Learning 1:

Have you done the simple pendulum experiment? If not, experiment in your laboratory and find the following.

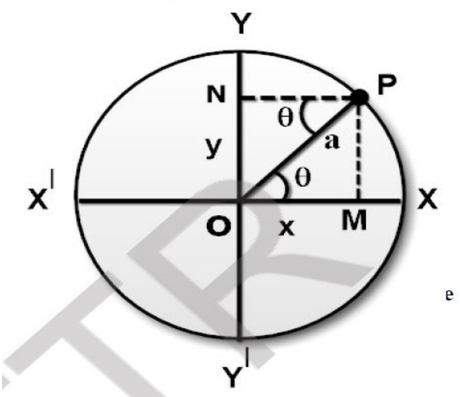
a) Find the dependent factors of the period of the simple pendulum.

b) Find the independent factors of the period of the simple pendulum.

c) Why pendulum clocks are not suitable for use in a spaceship?

d) Write some effects of friction on the oscillations of a body.

Projection of a uniform circular motion along a diameter:



Consider a particle moving along a circle of radius ‘a’ with a constant speed v as shown in Fig. Let the particle be at a point P at any time t. Draw a perpendicular from point P on the vertical diameter $YY^{|}$ on the circle. Let N be the projection (foot of the perpendicular) of the point P. When the particle is at X, the projection is at O. When the particle moves from X to Y the projection moves from O to Y. When the particle reaches $X^{|}$ the projection comes back from Y to O. When the particle reaches $Y^{|}$ the projection also reaches $Y^{|}$ and when the particle comes to X, the projection comes back to O. As a particle moves along the circle, the projection moves along the diameter $YY^{|}$. Now if in the place of projection, we have a particle to move as the projection moves, under the influence of some force, the particle will be said to be performing a linear simple harmonic motion along $YY^{|}$.

Hence simple harmonic motion may be considered as the projection of a uniform circular motion on the diameter of the circle.

Expression for the displacement of a particle executing SHM:

Consider a particle moving along the circumference of a circle of radius ‘a’ (OP = a) with O as the center and with constant speed v in the anticlockwise direction as shown in Fig. above. Let ω be the angular velocity of the particle. Let the particle makes an angular displacement θ = ωt in moving to a point P in ‘t’ seconds. From point P, draw perpendiculars to both the diameters of the circle. The foot of the perpendiculars M and N are the projections of point P on the X-axis and Y-axis respectively. As P moves on the circle in the anticlockwise direction, M and N execute simple harmonic motion about the center O on X and Y axes respectively.

From fig. above,

$$OM = OP\, cos\theta = a\, cos\theta = a\, cos\omega t$$

and

$$ON = OP\, sin\theta = a\, sin\theta = a\, sin\omega t$$

OM and ON are displacements along X-axis and Y-axis respectively of the points M and N from the mean position O. Let OM =x and ON = y. Hence the displacements of a particle executing simple harmonic motion along X and Y axes are given by

$$x = a\ cos\omega t$$

$$y = a\ sin\omega t$$

Expressions for velocity and acceleration of a particle executing SHM:

The displacement of a particle executing simple harmonic motion is given by

$$y = a\ sin\omega t$$

The velocity of the particle executing SHM is

$$\frac{dy}{dt} = a\omega\ cos\omega t$$

The acceleration of the particle executing SHM is

$$\frac{d^2y}{dt^2} = -a\omega^2\ sin\omega t$$

$$\frac{d^2y}{dt^2} = -\omega^2\ y$$

This equation shows that the acceleration of the particle executing SHM is proportional to the displacement from its mean position and is always directed towards the center as indicated by as

$$\frac{d^2y}{dt^2} + \omega^2\ y = 0$$

This is the differential equation for SHM.

Period (T):

The time required to complete one vibration is known as period and denoted by T. If ω is the angular velocity and T is the period, then

$$\omega = \frac{2\pi}{T}$$

$$T = \frac{2\pi}{\omega}$$

Frequency (f):

The number of vibrations made by the body in one second is known as the frequency of the vibrating body and is denoted by the letter f. Frequency is the reciprocal of the period. If T is the period of the vibrating body and f its frequency, then

$$f = \frac{1}{T}$$

The SI unit of frequency is Hertz (Hz).

Waves:

When a stone is dropped on the surface of still water, waves are produced at the point where the stone strikes the water. When the stone falls on the surface of the water the water molecules are pressed. Due to the elasticity of the water, particles try to regain their original position. In doing so these particles acquire enough velocity. They not only come back to their original position but also move back in the direction opposite to their earlier motion does result in an elevation. Due to gravitational attraction, these water particles fall back from the elevated position and again rather than coming to the surface go down thus causing depression and so on. In this way, the particles which were disturbed by the stone begin to vibrate up and down about their mean position executing simple harmonic motion. This up and down motion of an individual particle affects the neighbouring particles and is gradually handed to all the neighbouring particles. As soon as the stone strikes the surface of water ripples are produced which travel outwards in the form of a widening circle from the point of disturbance as a center.

If we place corks near the center of the disturbance at certain distances, we find that when the ripple reaches cork, it will simply move the cock up and down and no movement of cork takes place in the direction of the propagation of disturbance. This shows that it is only the disturbance that travels out towards while the water particles keep on moving up and down and continue to impart motion to the neighbouring particles. It may be noted that each particle starts vibrating a little later than its predecessor. This type of motion is called wave motion.

The propagation of disturbance from one point to another without the translatory motion of the particles of the medium is called wave motion. Wave motion is a periodic motion in which the particles of the medium execute the simple harmonic motion.

Waves are patterns of disturbances that transport energy and information. Waves help us to transmit signals of communication. When a sound wave is propagated through a medium, the particles of the medium execute the simple harmonic motion. Various forms of energy such as light, heat, sound, X-ray radiation extra are transmitted by wave motion. A wave motion takes place even without a medium. Such waves are called electromagnetic waves. light waves, X - rays, γ - rays, etc. are electromagnetic waves. There are two types of wave motions namely transverse and longitudinal.

Transverse waves:

Consider the waves produced on the surface of the water. The particles on the surface of the water which were originally at rest start vibrating up and down whereas the waves travel along the water surface. Here the vibration of the particles is at right angles to the direction of wave propagation. Such waves are called transverse waves.

If the particles of a medium vibrate about their mean positions, in a direction perpendicular to the direction of propagation of the disturbance, the wave motion is called transverse wave motion.

In a transverse wave, the points of maximum elevation are called crests and the points of maximum depression are called troughs. Examples of transverse waves: Water waves, heat waves, light waves are transverse waves.

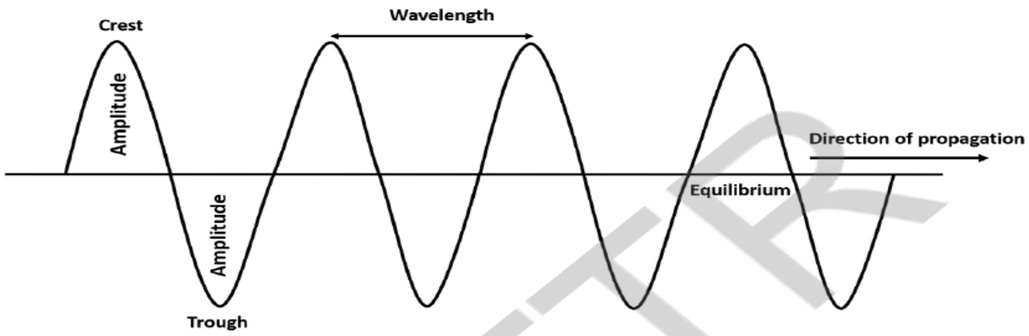


Fig. 1.5 Transverse wave propagating in positive X- direction

Another simple way of demonstrating transverse waves is as follows. Take a long string, tie one end of the string to a hook fixed in a wall and hold the other end of the string in your hand. After stretching the string till it becomes horizontal move your hand up and down many times. Several humps will be seen moving from the hand to the hook. All the particles of the string vibrate in a direction at right angles to the direction of propagation of the wave.

Longitudinal waves:

If the particles of a medium vibrate about their mean positions in a direction parallel to the direction of propagation of the disturbance, the wave motion is called longitudinal. Sound waves in a gas are longitudinal. When sound waves propagate through a gas, the particles of the medium vibrate to and fro parallel to the direction of propagation of the wave. For example, let a tuning fork be set into vibrations when the prong moves out, it compresses the air medium just in front of it. This region of increased pressure is called compression. This pulse of compression moves outwards. When the prong moves in the reverse direction, a region of low pressure called rarefaction is produced. This pulse of rarefaction also moves out towards. Hence in longitudinal wave motion, condensations and rarefactions are alternatively formed.

Example: sound waves.

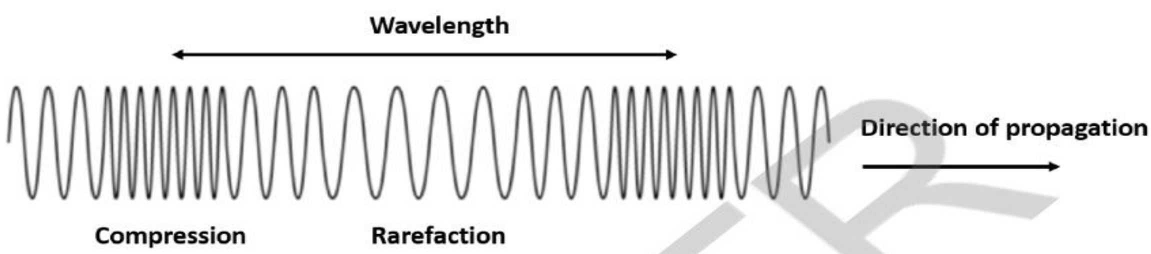


Fig. 1.6Longitudinal wave propagating in positive X- direction

Table 1.1 Differences between transverse and longitudinal waves

1. The vibration of the particles of the medium is at right angles to the direction of propagation of the wave.	1. The vibration of the particles of the medium is along or parallel to the direction of propagation of the wave.
2. A transverse wave consists of a series of crusts and troughs.	2. A longitudinal wave consists of a series of compressions and rarefactions.
3. It is possible only in solids and at the surface of a liquid.	3. It is possible in all types of media that is solids liquids and gases.
4. There is no pressure variation	4. There is pressure variation be maximum at compression and minimum at rarefaction.

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Characteristics of a wave:

a) Amplitude (a): The amplitude of a wave is the maximum displacement of any particle of the medium in the path of the wave.

b) Phase (φ): It represents the state of vibration of the particle of a medium with respect to its mean position.

c) Period (T): The time taken by a vibrating particle to complete one vibration is called the period.

d) Frequency (f): The frequency of a wave is the number of vibrations made by any particle of the medium in one second. If T is the period of vibrations of the particles of the medium, the frequency is given by

$$f = \frac{1}{T}$$

e) Wavelength (λ): It is the distance travelled by the wave in the time in which the particle of the medium completes one vibration or it is the linear distance between any two nearest particles of the medium which are in the same state of vibration. In the case of a transverse wave, the distance between two adjacent crests or troughs is equal to the wavelength. In the case of a longitudinal wave, the distance between two successive compressions or rarefactions is equal to the wavelength.

f) Wave velocity (v): The distance travelled by a wave in one second is called the velocity.

Relation between wave velocity, frequency, and wavelength:

The velocity of the wave is the distance travelled by the wave in one second.

i.e., wave velocity $= \frac{distance}{time}$

Wavelength λ is the distance travelled in T seconds, then wave velocity is given by

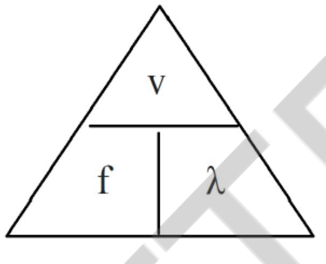
$$v = \frac{\lambda}{T}$$

The relation between frequency and period is

$$f = \frac{1}{T}$$

$$\therefore v = f\lambda$$

i.e. wave velocity is the product of frequency and wavelength.



Example 1.1

Calculate the wavelength of the waves generated by a tuning fork of frequency 500Hz. The velocity of sound in air is 340m/s.

Solution: f = 500Hz

v = 340m/s

λ = ?

v = f λ

λ = v / f = 340/500 = 0.68m

Example 1.2

A tuning fork makes one complete vibration in 1/200 second. If the velocity of sound in air is 340m/s, find the wavelength of the sound waves produced by the tuning fork.

Solution: Time period, T = 1/200 s

f = 1/T = 200 Hz

v = 340m/s

λ =?

v = f λ

λ = v / f = 340 / 200 = 1.7m

Example 1.3

Determine the frequency of light of wavelength 600nm.Velocity of light is 3 x 10^8 m/s.

Solution:

$\lambda = 600 \times 10^{-9}$ m

$v = 3 \times 10^{8}$ m/s

$f = ?$

$v = f\lambda$

$f = v / \lambda$

$= 3 \times 10^{8} / 600 \times 10^{-9} \quad = 5 \times 10^{14}$ Hz

Sound waves:

Sound is produced by a vibrating body. If a bell is struck with the hammer sound is produced due to the vibrations set up in the bell. As the vibrations die down the intensity of sound diminishes. If the ringing bell is touched with fingers, the sound ceases because the vibrations are stopped by the fingers. Sound waves are longitudinal. When a body vibrates, it produces compressions and rarefactions in the surrounding medium that travels forward as sound waves. When the sound waves reach our ear, the eardrum is set into vibrations, producing the sensation of hearing. The sound waves, whether they travel through solids, liquids or gases are longitudinal.

The following points may be noted about the sound waves.

a) Sound waves are longitudinal.

b) Material medium is necessary for the transmission of sound from one place to another.

c) The velocity of sound is greater in solids and liquids than in gases.

Light waves:

Light is an agent which makes it possible for us to see things. When light falls on an object, it gets scattered. This scattered light enters the eye and forms an image of the object on the retina of the eye. This is how we see things. Light is a form of energy that travels in a straight line. It travels at the speed of 3×10^{8} m/s in air or vacuum. Light waves are electromagnetic waves that do not require a medium for their propagation. Visible light is having wavelengths in the range of 400 – 700 nano metres. Light waves are transverse.

Principle of superposition of waves:

Suppose two persons are holding a string at the two ends and move their hands to produce two wave pulses. One wave pulse is travelling from left to right and the other from right to left. Let the two wave pulses A and B be of equal amplitude propagating in opposite directions as shown in fig.1.7 (a). The two pulses travel towards each other and mix each other into a single wave pulse as shown in fig.1.7 (b). It is clear from the figure that the resultant wave pulse has a displacement equal to twice the magnitude of either pulse. This kind of superposition is said to be constructive. After some time, the two wave pulses A and B travel retaining their original shape and direction as shown in fig.1.7 (c).

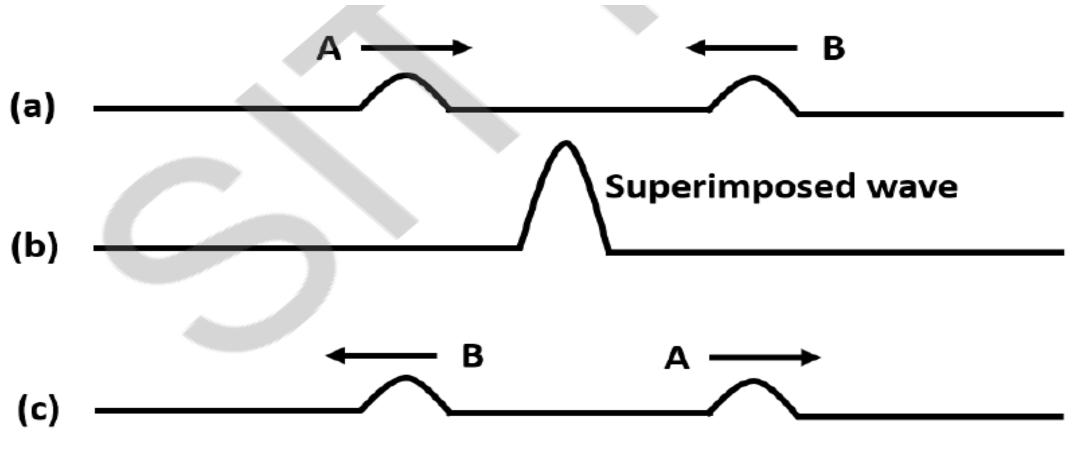


Fig 1.7 Constructive superposition of two wave pulses

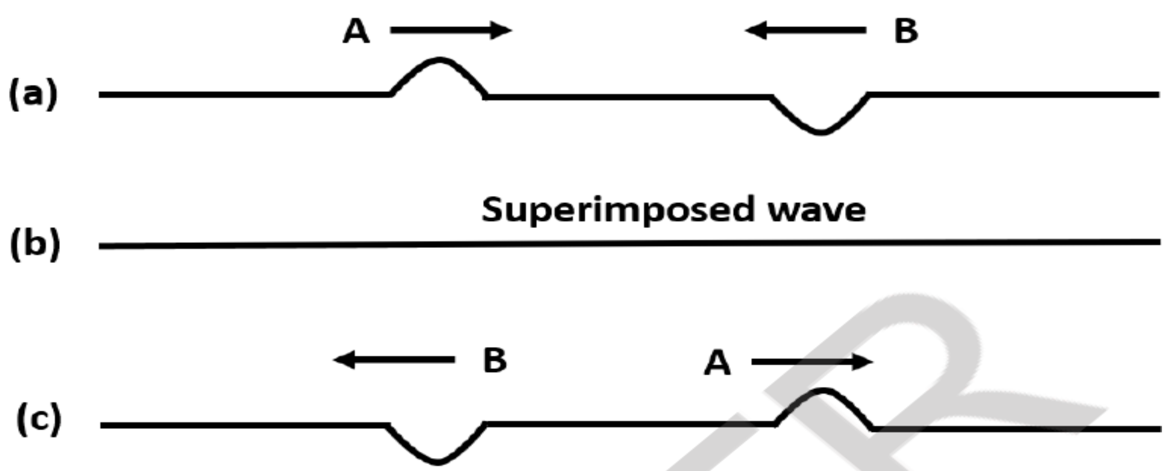


Fig 1.8Destructive superposition of two wave

Now suppose that the second wave pulse is inverted with respect to the first wave pulse, but still travelling in the opposite direction as shown in fig. 1.8 (a). These two wave pulses superpose with each other and the resultant wave pulse has zero displacements as shown in fig. 1.8 (b). After crossing each other, they continue to move forward retaining their original shapes as in fig. 1.8 (c). Thus, it is seen that the resultant waveform is the algebraic sum of individual waves. This rule of the addition of individual waveforms to determine the resultant waveform is called the superposition principle.

The principle of superposition of waves states that if two or more waves travel in a medium, each wave produces its own displacement and the resultant displacement of a particle at any point is the vector sum of the displacements due to each wave. The superposition principle can be applied to the phenomenon of beats.

Beats

When two sound waves of equal amplitudes and slightly different frequencies travelling in the same direction arrive simultaneously at a point, the intensity of sound caused by the superposition of two waves fluctuates.

The periodic variations in the intensity of sound due to the superposition of two sound waves of slightly different frequencies are called beats.

When the intensity rises to the maximum, we use the term waxing of sound and when it falls to the minimum, we use the term weaving of a sound. *One waxing and one waning constitute one beat. The number of beats produced per second is called beat frequency.*

When sound travels through air, condensations and rarefactions are produced. If two condensations due to two notes reach the ear simultaneously, the sound heard will be the maximum. The same is the case with two rarefactions also. These correspond to the waxing of sound intensity. But if the condensation due to one note and the rarefaction due to the other reach the ear simultaneously, the sound heard will be a minimum. It corresponds to a waning of sound intensity. This explains the production of beats.

Applications of beats are:

a) Beats are used in tuning musical instruments.

b) Beats can be used to find the frequency of the given tuning fork.

c) Beats can be used in the detection of harmful gases in mines.

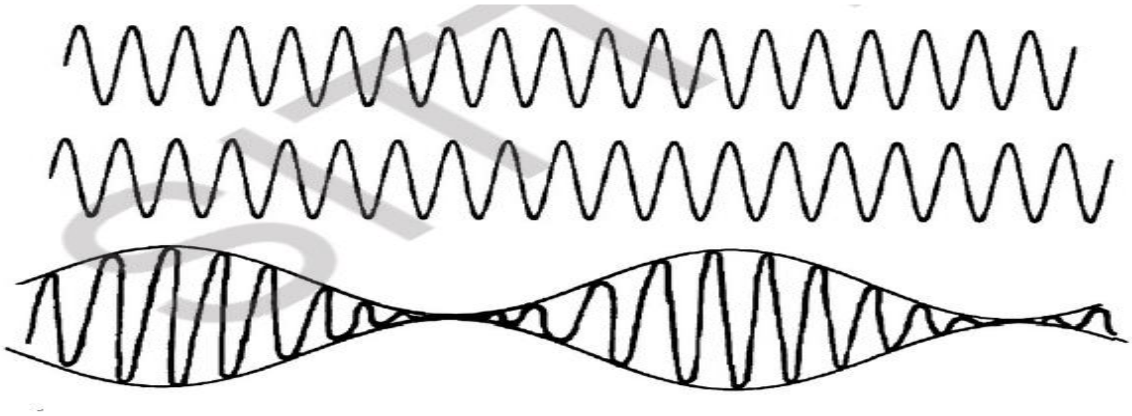


Fig 1.9Formation of beats by the superposition of two sound waves of equal amplitude and slightly different frequencies

Ultrasonic waves:

The frequency of sound between 20 Hz and 20 kHz is called audible frequency. Sounds of frequency below 20 Hz are called infrasonics. ***Sound waves having a frequency above 20 kHz are called ultrasonic waves.*** Due to high frequency, human ears cannot detect ultrasonic waves. Bats can produce and detect ultrasonic waves. Ultrasonic waves produced by the bats, get reflected by some objects in their way. When the reflected waves are received by the bats, they get an idea of the distance of the obstacle in their path. This is how bats can fly in the darkness.

Ultrasonic waves have a large number of practical applications. Some applications of ultrasonics waves are listed below:

a) Echo depth sounding: Ultrasonic waves are used for detecting submarines and other underwater obstructions. Ultrasonic sound is also used for gauging the depth of seawater. A beam of ultrasonic sound is directed towards the bottom of the sea and the total time for the wave to go to the bottom and come back is measured. Knowing the velocity of the ultrasonic waves, the depth of the sea can be calculated.

b) SONAR: SONAR is the abbreviation of Sound Navigation and Ranging. It is a technique used for detecting and determining the distance and direction of underwater objects. In the military field, SONAR is used to detect, identify, and locate submarines. Nonmilitary uses of sonar include fish finding, mapping of the sea bottom, etc.

c) Detection of flaws in metals: Ultrasonic waves can be used to detect cracks or cavities in metal castings.

d) Soldering and metal cutting: Ultrasonic waves can be used for drilling and cutting processes in metals.

e) Scanning: An ultrasound scan uses high-frequency sound waves to make an image of a person's internal body structures. Doctors commonly use ultrasound to study a developing foetus.

The acoustics of buildings:

The branch of science which deals with the planning of a building or a hall intending to provide the best audible sound to the audience is called acoustics of the building.

The intensity of sound heard by the audience must be sufficiently loud and uniform throughout. The successive sounds in speech or music should not overlap for clear hearing. When a speaker speaks or music is played in a hall, sound waves are produced which spread out until they strike the walls, ceiling, or floor of the hall. Here the sound waves are partially reflected and partially absorbed. The amount of reflection and absorption depends upon the character of the surface. A hard and smooth surface reflects most of the sound and absorbs little of it. A porous surface absorbs most of the sound and reflects little of it. The greater the absorption of sound in a hall the lesser the reflection of sound and hence more is the clarity.

Reverberation

When sound is produced in an open space, it is heard by the listener once, as the wave travels across him. When sound is produced in a room or hall, sound persists even after the original sound has ceased. This is due to the repeated reflections of sound from walls, floor, ceiling, etc. This reduces the clarity of the sound.

The prolongation of audible sound in a room or hall after the sound has ceased to emit sound is called reverberation.

Reverberation time:

It is the time for which the sound persists in a room or hall after the original sound is cut off. This time is measured from the instant the source stops the emitting sound. To produce the best sound effects, the reverberation time should be as small as possible. The reverberation time can be decreased by increasing sound absorption in it. When sound falls on the walls, seats, or audience, it is either reflected or absorbed. If a greater part of it is absorbed, then the reverberation will be small. On the other hand, if most of the sound is reflected by the walls, floor, or audience, the sound will continue for some time after the source has been discontinued. In such a case, the reverberation will be large. The optimum reverberation time should be 0.5 seconds for speech and 1.0 to 1.5 seconds for music. The reverberation time of a room depends upon the total volume of the room and the absorbing power of the walls and does not depend upon the positions of the source and listener.

Methods to control reverberation time

The reverberation time of a room or hall can be decreased by increasing the absorption of sound in it. This can be done by the following methods:

a) By providing a few open windows.

b) By covering the walls with absorbent materials such as perforated cardboards, heavy curtains, carpet on the floor, etc.

c) By providing rough and decorative materials on the walls and ceilings.

d) Cushioned seats. Such seats not only provide greater comfort but also act as good absorbers of sound.

e) No large concave, spherical or cylindrical surfaces on the walls or ceiling of the hall or auditorium. This will avoid excessive reflections of sound.

Echo:

If the time interval between the instance of hearing the original sound and the reflected sound from the reflecting surface is greater than 1 / 10th of a second, the original sound and the reflected sound can be separately heard. Such a reflection of sound is called echo. Echoes are generally heard in halls whose ceilings are sufficiently high. To avoid Echoes, the ceilings should be covered with suitable sound absorbents. The roof and walls of the auditorium or cinema hall are generally covered with sound-absorbent materials like draperies or compressed fibreboard to reduce reverberation. These materials reduce the formation of echoes by absorbing sound waves.

Noise:

Any undesired sound is known as noise*. Noise entering a hall or auditorium may be airborne or structure-borne. The airborne noise originates in the air and travels through the air to the boundaries of the hall or auditorium.* External noise can mix up with the sound of speech or music in the hall and can create confusion for the audience. This includes noise travelling through the air, noise due to vibration of structures, etc. The external noises can be reduced by making the hall soundproof and constructing small soundproof cabins for the machinery.

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