Wave and Sound

Unit: 8.1

Wave Motion

Wave is a form of disturbance that travels through a medium due to the repeated periodic motion of the particles of the medium about their mean positions. In a wave, energy is transferred from one point to another point of the medium but not particles of the medium.

Types of waves:

(i) **Mechanical or elastic waves:** Any periodic disturbance which requires a material medium for its propagation is called mechanical wave. Mechanical waves are also called *elastic waves* because their propagation depends on the elastic properties of the material medium.

Examples: sound waves, water waves.

(ii) **Electromagnetic waves:** An electromagnetic wave is a periodic disturbance that does not require a material medium for its propagation. They can travel through vacuum with a speed of of light, i.e. 3×10^8 m/s.

Examples: light, radio waves, X-rays.

(iii) **Matter waves:** The wave associated with a moving material particle like electron, proton, neutron, etc. is called matter waves.

A mechanical wave may be classified into two categories:

(i) **Transverse waves:** A wave in which particles of the medium vibrate perpendicular to the direction of propagation of the wave is known as transverse waves.

Example: waves traveling along stretched string when one end is shaken.

(ii) **Longitudinal waves:** A wave in which particles of the medium vibrate along the direction of propagation of the wave is known as longitudinal waves. When a longitudinal wave travels, it produces compressions and rarefactions in the medium.

Example: sound waves.

Some terms associated with wave motion:

(i) **Wavelength (λ):** It is the distance travelled by a wave during which a particle of the medium completes one vibration.

Wavelength can also be defined *as the distance between two successive crests or troughs in transverse waves,* or *the distance between two successive compressions or rarefactions in longitudinal waves*.

(ii) **Amplitude (A):** The amplitude of a wave is defined as the maximum displacement of the particles of the medium from their equilibrium positions.

(iii) **Time period (T):** The time taken by a wave to travel a distance equal to its wavelength is called time period.

(iv) **Frequency (υ):** It is defined as the number of waves produced in one second. Frequency is the reciprocal of the time period, i.e. $\upsilon = 1/T$

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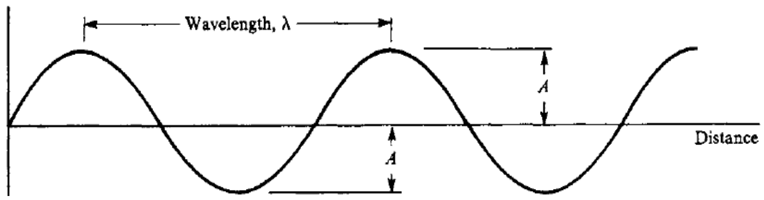

Fig. 8.1.1

Relation between velocity, frequency and wavelength of a wave:

The distance travelled by a wave in a medium in one second is called the velocity of propagation of the wave in that medium. If v represents the velocity of propagation of the wave, then

$$v = \lambda/T$$

=> $v = \upsilon\lambda$

Example 1 A tuning fork of frequency 528 Hz produces a sound which travels with velocity 330 ms^{-1}. Find the wavelength and time period of the wave.

Solution: Here, frequency (υ) = 528 Hz

speed of sound (v) = 330 ms^{-1}

∴ Time period, T $= \frac{1}{\upsilon} = \frac{1}{528} \approx 1.89 \times 10^{-3}$ s

& wavelength, $\lambda = \frac{v}{\upsilon} = \frac{330}{528} = 0.625$ m

Unit: 8.2

Newton's formula for the velocity of sound waves in air:

Newton assumed that sound propagates through air medium in such that temperature of the medium remains constant, i.e. the process is isothermal. He obtained the formula for velocity of sound in air as

$$v = \sqrt{\frac{P}{\rho}}$$

where P is the pressure of air and ρ is the density of air.

At normal temperature and pressure (NTP),

P = 76 cm of mercury

= $(0.76 \times 13.6 \times 10^3 \times 9.8)$ N m^{-2} [see unit 6.1]

ρ = 1.293 kg m^{-3}

Velocity of sound in air at NTP is

$$v = \sqrt{\frac{0.76 \times 13.6 \times 10^3 \times 9.8}{1.293}} \approx 280 \text{ m s}^{-1}$$

The experimental value for the velocity of sound in air is 332 m s^{-1}. But the velocity of sound calculated from Newton's formula is less than its experimental value. This contradiction could not be explained by Newton's formula.

Laplace's correction:

The propagation of sound waves is accompanied by compressions and rarefactions of the medium. Laplace argued that compressions and rarefactions occur so quickly that they do not get enough time to equalize their temperature with the surroundings. The process is therefore adiabatic where temperature does not remain constant. Under adiabatic condition, the velocity of sound in air is obtained to be

$$v = \sqrt{\frac{\gamma P}{\rho}} \quad \text{[Laplace's corrected formula]}$$

where $\gamma = \frac{C_P}{C_V}$ is the ratio of heat capacities at constant pressure and at constant volume.

For air at NTP,

$\gamma = 1.41$, $\rho = 1.293$ kg m^{-3}

$$v = \sqrt{\frac{\gamma P}{\rho}} \approx 332.3 \text{ m s}^{-1}$$

This result is in agreement with the experimental value of 332 m s^{-1}.

Factors affecting velocity of sound in gases:

(i) **Pressure:**

At constant temperature, Boyle's law states that

PV = constant

=> $P\ m/\rho$ = constant

Since mass (m) is constant, so

P/ρ= constant

The Laplace formula for velocity is $v = \sqrt{\frac{\gamma P}{\rho}}$

Therefore, *the velocity of sound in a gas is independent of the change in pressure provided the temperature remains constant.*

(ii) **Temperature:**

For a gas,

$PV = RT \ \ => \ P/\rho = RT/m$

where m is the mass of the gas, T is the absolute temperature and R is the gas constant. Therefore

$$v = \sqrt{\frac{\gamma RT}{m}}$$

which shows that *the velocity of sound in a gas is directly proportional to the square root of its absolute temperature.*

(iii) **Density:**

We consider two different gases at same temperature and pressure with different densities.

The velocity of sound in two gases are given by

$$v_1 = \sqrt{\frac{\gamma_1 P}{\rho_1}} \text{ and } v_2 = \sqrt{\frac{\gamma_2 P}{\rho_1}}$$

$$\frac{v_1}{v_2} = \sqrt{\frac{\gamma_1 \rho_2}{\gamma_1 \rho_1}}$$

For gases having same value of γ,

$$\frac{v_1}{v_2} = \sqrt{\frac{\rho_2}{\rho_1}}$$

Hence, *the velocity of sound in a gas is inversely proportional to the square root of the density of the gas.*

(iv) **Moisture or humidity:**

The presence of moisture or water vapour decreases the density of air as the density of water vapour is less than that of dry air. Since velocity of sound is inversely proportional to the square root of density, the sound travels faster in moist air than in dry air. Thus, *sound travels faster on a rainy day than on a dry day*.

(v) **Wind:**

The velocity of sound in air is affected by wind. If the wind blows with the velocity w along the direction of sound, then the velocity of sound increases to $v + w$. If the wind blows in the opposite direction to the direction of sound, then the velocity of sound decreases to $v - w$.

Unit: 8.3

Audible range

The generally accepted standard range of audible frequencies is 20 Hz to 20 kHz.

Infrasonic sound:

Sounds of frequencies below 20 Hz are called infrasonic sound or infrasound. If we could hear infrasound, we would hear the vibrations of a pendulum just as we hear the vibrations of the wings of a bee. Rhinoceroses, elephants, whales etc can produce sound in the infrasonic range.

Ultrasonic sound:

Sounds having frequencies higher than 20 kHz are called ultrasonic sound or ultrasound. Ultrasounds can be produced by some animals, e.g. dolphins, bats etc. Bats can produce ultrasound of frequency in the range of 30 kHz to 50 kHz.

Application of ultrasonic sound to calculate the depth of ocean:

SONAR (Sound Navigation And Ranging) is a device that uses ultrasonic waves to measure the depth, direction and speed of underwater objects.

SONAR consists of a transmitter and a detector and is installed in a boat or a ship [Fig. 8.3.1]. The transmitter produces and transmits ultrasonic waves. These waves travel through water and after striking the object on the seabed, get reflected back and are sensed by the detector. The detector converts the ultrasonic waves into electrical signals which are appropriately interpreted. The distance of the object that reflected the sound wave can be calculated by knowing the speed of sound in water and the time interval between transmission and reception of the ultrasound. Let the time interval between transmission and reception of ultrasound signal be t and the speed of sound through seawater be v. The total distance ($2d$) travelled by the ultrasound is then $2d = v \times t$ where d is the depth of the sea bed.

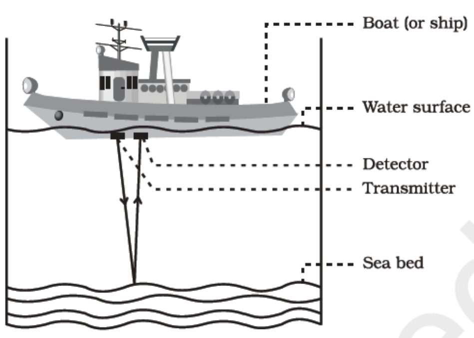

Fig. 8.3.1

Unit: 8.4

Reflection of sound:

Let us take two metal tubes A and B and place one end of each tube on a metal plate as shown in the Fig. 8.3.1. We place a clock at the open end of the tube A and interpose a cardboard between A and B. It is observed that at a particular inclination of the tube B with the cardboard, ticking of the clock is clearly heard. The angle of reflection made by the tube B with the cardboard is equal to the angle of incidence made by the tube A with the cardboard.

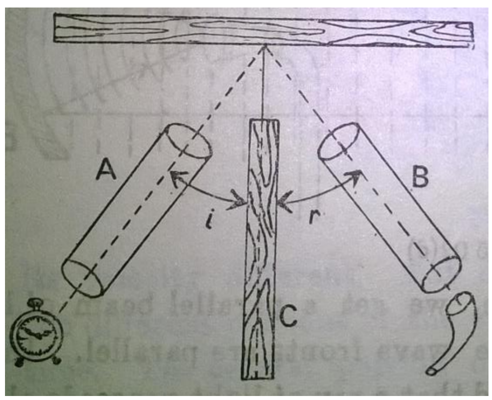

Fig. 8.3.1

Applications of reflection of sound waves:

(i) **Whispering gallery:** The whispering gallery at St. Paul's Cathedral is a circular shaped chamber designed in such a way that the walls of it repeatedly reflect sound waves round the gallery. So, when a person talking quietly at one end can be heard distinctly at the other end.

(ii) **Stethoscope:** Stethoscope is an instrument used by medical doctors to listen to the sounds produced by various organs of the body. It consists of a long tube made of rubber or metal. When sound pulses pass through one end of the tube, the pulses get concentrated to the other end due to several reflections on the inner surface of the tube. Using this doctors hear the patients' heart beat as concentrated rays.

(iii) **Echo:** Echo is a phenomenon observed due to reflection of sound waves from a certain distance. Due to persistence of hearing, we keep hearing a sound for 1/10th of a second even after the sounding source has stopped vibrating. Assuming the velocity of sound to be 340 ms^{-1}, the total distance covered by the sound is 34 m if the sound reaches the obstacle and returns after 0.1 second. No echo is heard if the reflecting obstacle is less than 17 m away from the source.

Reverberation: A man in a hall continues to receive successive reflections of sound (with corresponding decrease in intensity) from the walls, ceiling, floor of the hall even after the source of sound is cut off. This prolongation of sound before its intensity falls off to zero is known as reverberation.

Unit: 8.5

Musical sound and Noise

Sounds are classified into two categories, viz. (i) musical sound and (ii) noise

Musical sound:

A musical sound is one which consists of a series of harmonic waves following each other rapidly at regular interval of time without a sudden change in amplitude. It can produce pleasing effect on the ear of the listener.

Noise:

The sound that produces displeasing effect on the ear is called a noise. The noise succeeds at irregular intervals and there is sudden change in loudness. e.g. sounds produced by a plate falling on the ground.

Characteristics of musical sound:

(i) **Loudness:** It is closely related to the intensity of the sound. Intensity can be defined as the power transferred through a unit area perpendicular to the direction of propagation. The unit of intensity is $watt/m^2$.

Threshold of hearing: It is defined as the lowest intensity of sound that can be perceived by the human ear.

The loudness is said to be 1 bel if the intensity of sound is 10 times the threshold of hearing.

The unit *bel* of loudness is very large, hence one-tenth of a *bel* known as *decibel* (*dB*) is used frequently.

$1 \text{ dB} = \frac{1}{10} \text{ bel}$

(ii) **Pitch:** The pitch is that characteristic of sound sensation that helps us to distinguish a note as high note or low note. *Pitch increases with increasing frequency*.

(iii) **Quality or timbre:** Quality or timbre is that characteristic of musical sound which enables us to distinguish two sounds having same intensity and frequency. Notes of the same pitch and intensity sounded on two different musical instruments differ in quality from each other owing to the difference in number of overtones.

Doppler effect:

The change in the observed frequency of a wave when the source and the observer moves relative to the medium is known as Doppler effect. For sound, the observed frequency ν in terms of the source frequency ν_o is given by

$$\nu = \nu_0 \left(\frac{v + v_o}{v - v_S}\right)$$

where v is the velocity of sound through the medium, v_o is the velocity of observer relative to the medium (*considered positive for motion toward the source and negative for motion away from the source*) and v_s is the source velocity relative to the medium (*considered positive for motion toward the observer and negative for motion away from the observer*) .