Unit 8

WAVES

Major Concepts (27 PERIODS)

- Periodic waves
- Progressive waves
- Transverse and longitudinal waves
- Speed of sound in air
- Newton's formula and Laplace correction
- Superposition of waves
- Stationary waves
- Modes of vibration of strings
- Fundamental mode and harmonics
- Vibrating air columns and organ pipes
- Doppler effect and its applications
- Generation, detection and use of ultrasonic

Conceptual Linkage

This chapter is built on Sound Science VII & VIII Oscillation & Waves Physics IX

Students Learning Outcomes

After studying this unit, the students will be able to:

- Describe what is meant by wave motion as illustrated by vibrations in ropes, springs and ripple tank.
- Demonstrate that mechanical waves require a medium for their propagation while electromagnetic waves do not.
- Define and apply the following terms to the wave model; medium, displacement, amplitude, period, compression, rarefaction, crest, trough, wavelength, velocity.
- Solve problems using the equation: $v = f\lambda$.
- Describe that energy is transferred due to a progressive wave.
- Identify that sound waves are vibrations of particles in a medium.
- Compare transverse and longitudinal waves.
- Explain that speed of sound depends on the properties of medium in which it propagates and describe Newton's formula of speed of waves.
- Describe the Laplace correction in Newton's formula for speed of sound in air.
- Identify the factors on which speed of sound in air depends.
- Describe the principle of superposition of two waves from coherent sources.
- Describe the phenomenon of interference of sound waves.
- Describe the phenomenon of formation of beats due to interference of non coherent sources.
- Explain the formation of stationary waves using graphical method

- Define the terms, node and antinodes.
- Describe modes of vibration of strings.
- Describe formation of stationary waves in vibrating air columns.
- Explain the observed change in frequency of a mechanical wave coming from a moving object as it approaches and moves away (i.e. Doppler Effect).
- Explain that Doppler Effect is also applicable to electromagnetic waves.
- Explain the principle of the generation and detection of ultrasonic waves using piezoelectric transducers.
- Explain the main principles behind the use of ultrasound to obtain diagnostic information about internal structures.

INTRODUCTION

The phenomenon of a wave motion is a vast field in the study of physics. because we observe daily various kinds of waves and their propagation such as; sound waves, light waves, waves on the surface of water, waves in a string, seismic (earth quake) waves, radio waves, x-rays and so on. All these waves are disturbance produced by vibrating bodies.

The waves can travel from one place to another place through a medium or without medium. One of the most important properties of waves is that they transfer energy. This transfer of energy is initiated by a vibrational motion. It is the physical manifestation of the form of energy transfer from one place to another. On the other hand, a wave does not transmit matter it transfers only energy. For example, electromagnetic waves from sun carry energy in the form of light and heat, sound energy from musical instruments causes our ear drums to vibrate. The energy carried by seismic waves (earthquakes) can devastate vast areas causing land to move and building to collapse and also produce tsunami.

Certain types of waves can travel only through some material called medium. Those waves which require a medium for their propagation are known as mechanical waves. For example, water waves, sound waves, waves on a string and so on.

On the other hand, the waves which do not require any medium for their propagation are called electromagnetic waves. These waves are capable of traveling even through an empty space without the help of a medium. Such as radio waves, light waves, x-rays, γ-rays, infrared and ultraviolet radiations.

Now according to De-Broglie's hypothesis, the subatomic particles of matter such as electrons, protons, neutrons and other fundamental particles are moving in the form of wave. This kind of wave is termed as matter or De-Broglie wave which is usually studied in modern physics.

In this chapter we discuss not only the general properties of waves such as wavelength, frequency and speed of wave, but also study the behavior of transverse and longitudinal waves. In the later part of this chapter our main focus will be on the sound waves and its characteristics. We will also define the principle of superposition and explain the phenomenons of interference, beats and stationary waves. In the last we will study the apparent change in frequency due to relative motion of source and observer which is called Doppler Effect.

8.1 PROGRESSIVE WAVES

It is common observation that a disturbance is produced on the surface of still water in a pond, when a stone is dropped into it. This disturbance causes the waves which spread out across the surface of water as shown figure 8.1. If we place a leaf on these ripples, we can observe its up and down motion but the leaf does not move along the ripples. This example has confirmed that water waves do carry energy only but there is no movement of matter across the surface of water. Thus a wave which transfers energy from one point to another point by a periodic disturbance is called progressive wave or travelling wave. There are some characteristics of progressive waves which are summarized as;

Fig.8.1: Progressive waves spread out across the surface of water.

Crest

The peak of the portion of the wave above its equilibrium or mean level in a transverse wave is called crest as shown in Fig. 8.1.

Trough

The peak of the portion of the wave below its equilibrium position in a transverse wave is called a trough as shown in Fig. 8.1. The direction of a trough is opposite to that of a crest.

Amplitude

In progressive wave, the maximum displacement of a vibrating particle from the mean level to the peak point of crest or trough is known as amplitude as shown in Fig 8.1. The unit of amplitude is meter and its dimensional formula is $[M^oLT^o]$.

Wave Length

The distance between any two consecutive crests or two consecutive troughs is called wavelength. Wavelength is represented by 'λ' (lambda) and it is measured in metres.

Time period and frequency

The time in which one wave cycle of a wave is passed through a certain point is called time period. It is represented by T. The unit of time period is second.

The numbers of waves passing through a certain point in one second is called frequency. It is measured in Hertz (Hz) and its dimensional formula is $\left[M^{o}L^{o}T^{-1}\right]$. Frequency and time period are reciprocal to each other that is, $f=\frac{1}{T}$. A graph of progressive waves is shown in figure 8.2.

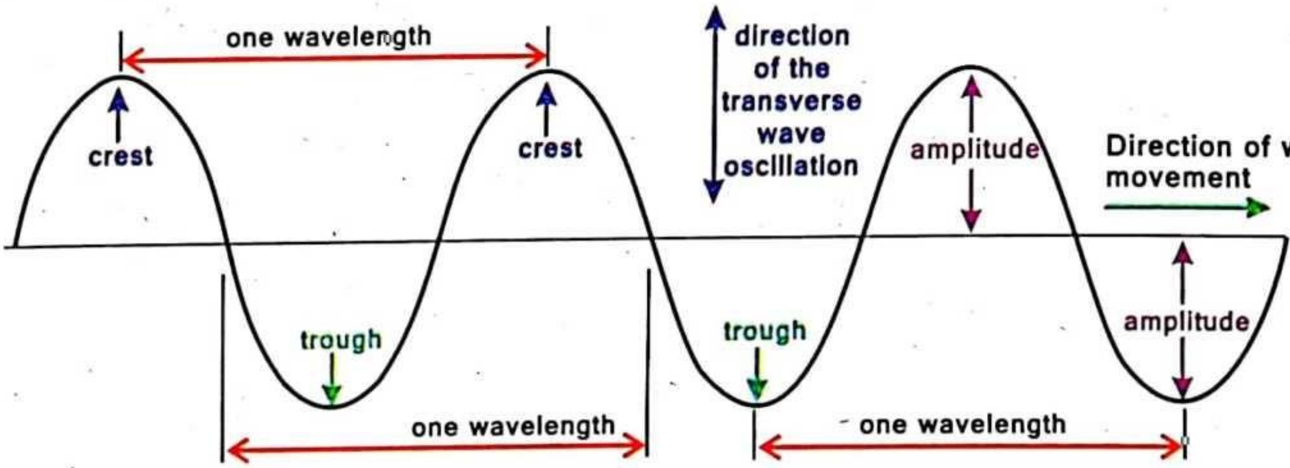


Fig.8.2: Propagation of progressive wave consists of crests and troughs with certain amplitude and wavelength.

8.1.1 Types of progressive waves

Every day, we come across a number of progressive waves. All these waves can be classified into two classes on the basis of their propagations (i) Transverse Waves (ii) Longitudinal Waves.

(i) Transverse Waves

The waves in which the particles of the medium vibrate perpendicular to the direction of propagation of waves are called transverse waves. The wave travelling along a stretched string is an example of a transverse wave which is explained as under;

Let one end of a string of length 'l' be connected to a rigid support and the other free end is moved up and down in a direction perpendicular to its length. A wave consisting of crests and troughs is set up in the string.

This wave is travelling along the length of the string with speed called wave speed. But the particles of the string are vibrating up and down perpendicular to the length of string as shown in figure 8.3.

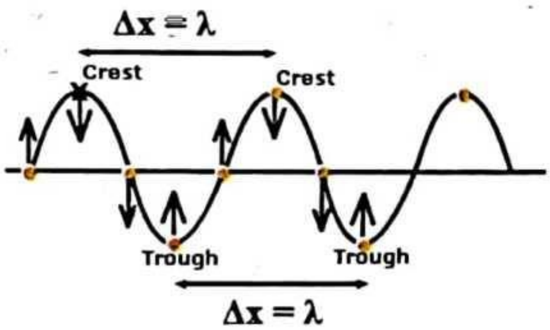


Fig.8.3: A transverse pulse traveling on a stretched string. The direction of disturbance is perpendicular to the direction of propagation.

Another result is also obtained from this example that the wave transfers only its waveform in the forward direction but the particles of the string remain at their own places which are vibrating up and down and they do not move forward.

The speed of transverse wave can be calculated by using the general relation of speed;

$$v = \frac{\Delta x}{\Delta t}$$

If $\Delta x = \lambda$ (Wavelength of the wave)

$\Delta t = T$ (Time period)

Then above equation becomes

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

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

$$v = f\lambda \quad ......(8.1)$$

This is the fundamental equation for speed of a wave and it is equally applicable to all kinds of wave.

Example 8.1

The radar waves with 3.4 cm wavelength are sent out from a transmitter. If these waves travel with speed is $3\times10^8 ms^{-1}$, what is their frequency?

Solution:

Wavelength $(\lambda) = 3.4$ cm. $= 0.034$ m

Speed of waves $(v) = 3\times10^8$ m s^{-1}

Frequency $(f) = ?$

According to equation 8.1

$$v = f\lambda$$

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

$$f = \frac{3\times10^8 ms^{-1}}{0.034 m}$$

$$f = 8.8\times10^9 Hz$$

$$f = 8.8 GHz$$

(ii) Longitudinal Waves

A wave in which the particles of the medium are vibrating along the direction of propagation of wave is called longitudinal wave. It is explained as under.

Consider two springs of equal lengths which are connected to a body such that the body remains between them. Now let a force is applied on either side to displace the body and then it is made to free. The body sets into oscillation. As a result, a longitudinal wave is produced which consists of compression and rarefaction travelling along the spring. On the other hand, each particle of the spring is also vibrating along the direction of wave in the spring, as shown in Fig.8.4. In longitudinal wave, the distance between the centres of two consecutive compressions or two rarefactions is called its wavelength.

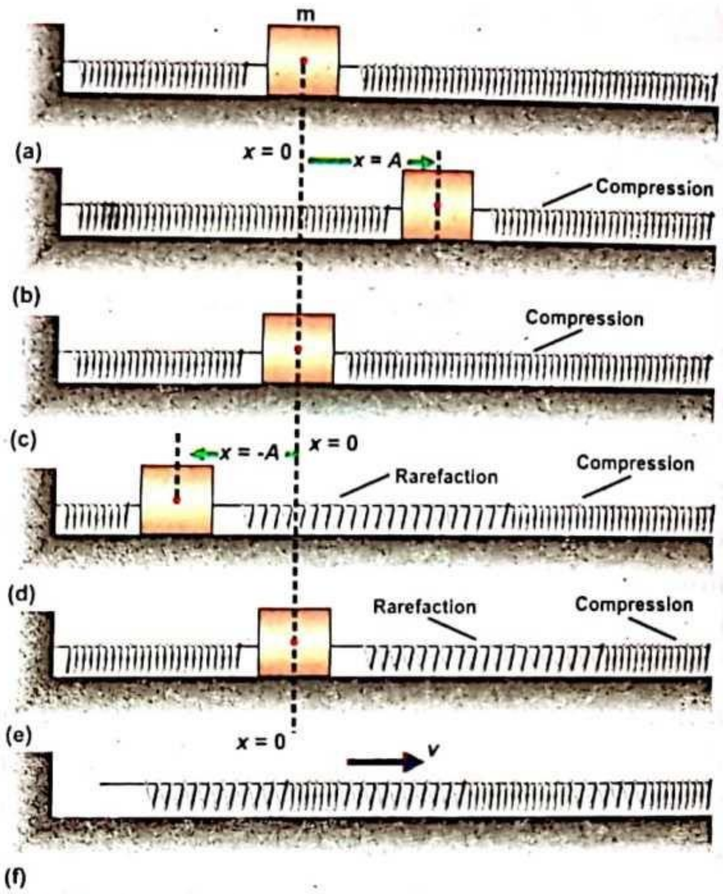


Fig.8.4: A longitudinal pulse along a stretched spring. The displacement of the coils is parallel to the direction of the propagation

8.2 PERIODIC WAVES

We have defined wave in terms of disturbance which is produced by a source and travels in a medium. If a steady vibrating source produces continuous, regular and rhythmic disturbance in a medium, then it is called periodic wave. A vibrating mass spring system as shown in Fig.8.5 is a good example of a periodic vibrator that produces a periodic wave.

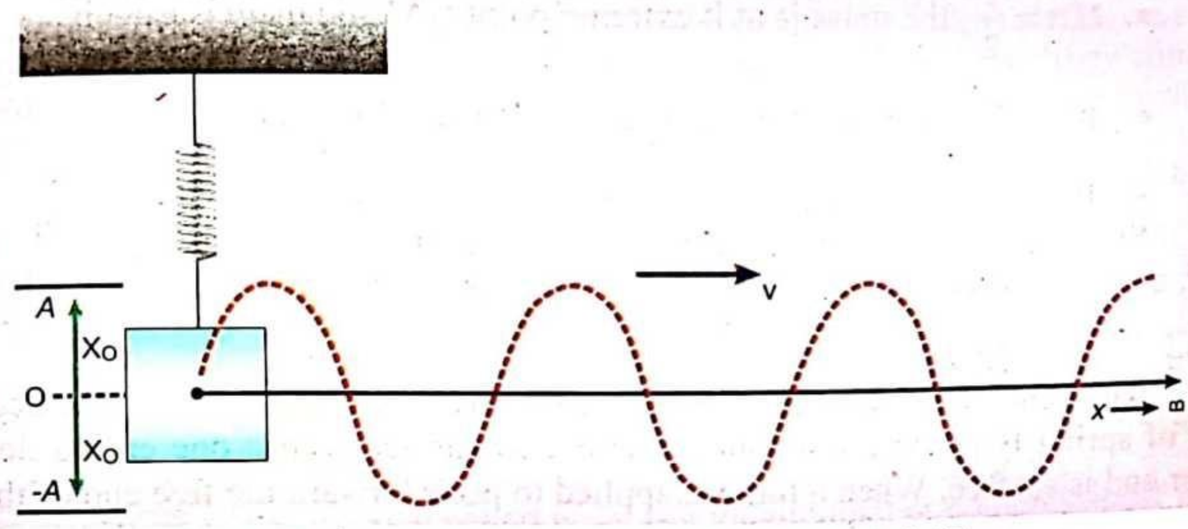


Fig.8.5: The experimental arrangement of Transverse Periodic Wave

8.2.1 Transverse periodic waves

A transverse periodic wave can be demonstrated by the mass-spring experimental setup which consists of a block of mass 'm' connected with a vertical hanging spring, as shown in Fig.8.5. A length of string in the horizontal direction is also connected with the mass. Now when a force is applied to displace the block upward from its mean position 'O' to its extreme position 'A' at a distance 'x_o' and it is made to free, then the block starts vibrating up and down. At the same time, a transverse periodic wave is produced in the string which travels along the length of string. Such waves consist of crests and troughs as shown in Fig.8.5.

The experiment shows that the mass-spring vibrator is executing simple harmonic motion. Its amplitude and time period are equal to the amplitude and time period of a transverse periodic wave. This transverse wave is travelling along the length of the string in the form of a sinusoidal wave.

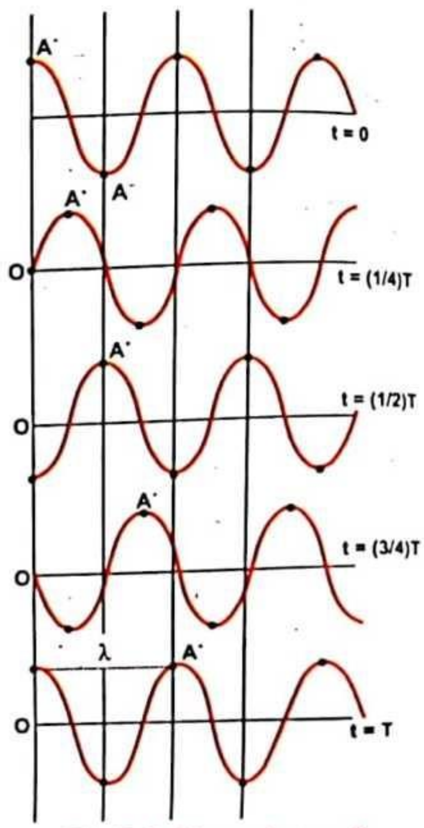


Fig.8.6: Wave shape of Transverse Periodic Wave

Fig.8.6 illustrates the wave shape of such periodic wave. This graph is between the time and displacement and it is explained as under.

- If $t = 0$, the block is at extreme point 'A' and there is crest of transverse periodic wave.
- If $t = \frac{T}{4}$, the mass is at it mean position 'O'.
- If $t = \frac{T}{2}$, the mass is at it extreme point '-A' and there is trough.
- If $t = \frac{3T}{2}$, then mass is again at its mean position 'O'.
- If $t = T$ the mass is again at extreme position and there is again the crest.

Similarly, for the next cycles of wave, the same process is repeated. In this way, a periodic transverse wave moves to the right as shown in Fig.8.6.

8.2.2 Longitudinal periodic waves

The generation of longitudinal periodic waves can also be demonstrated by a coil of spring lying on a horizontal frictionless surface whose one end is tied and other end is set free. When a force is applied to push forward the free end of the coil then a few turns of the spring are compressed. As a result, a compression portion is formed at the free end. This compression portion exerts a force on the next few turns of the spring so that another compression is formed which is transferred in the next section and so on. In this way a compression portion travels along the spring in forward direction.

Similarly, when a force is applied to pull backward the free end then a rarefaction portion is formed in the loops near the free end of the spring. This rarefaction is transferred to the next section and starts travelling along the spring.

Thus, when a regular and steady periodic force is applied to push forward and pull backward the spring at constant rate then a periodic longitudinal wave is set up in the spring, which travels along the spring. It consists of a series of compressions and rarefaction. Graphically, when this longitudinal wave is drawn on a graph then a sinusoidal wave (sine or cosine) is obtained as shown in Fig.8.7.

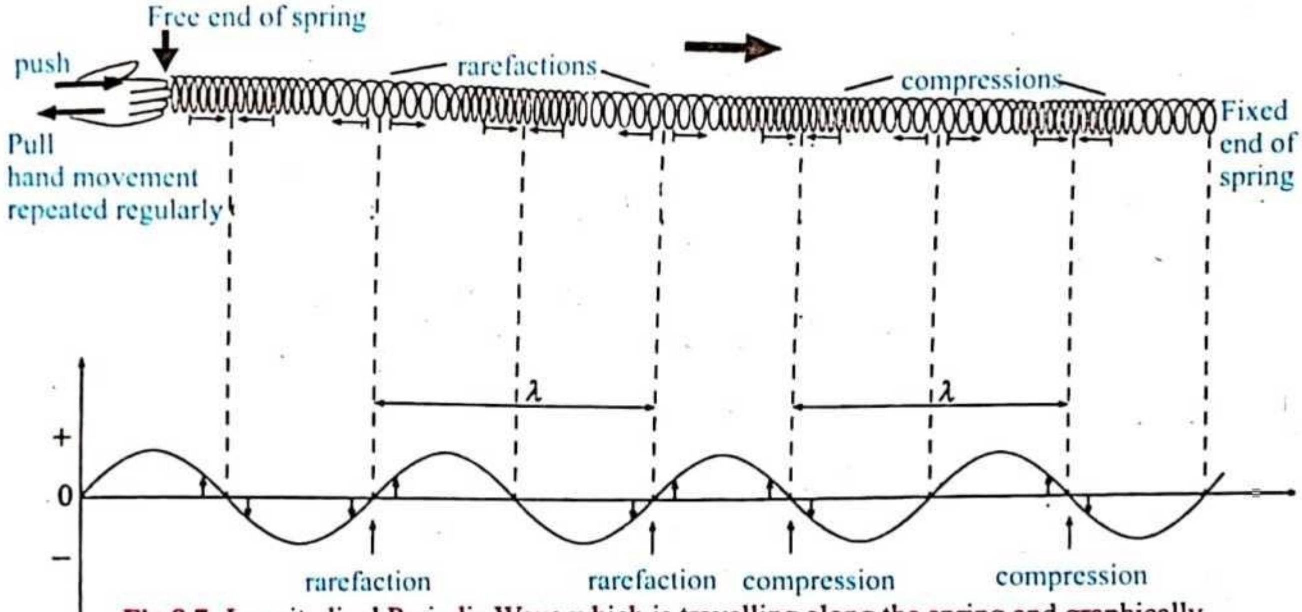


Fig.8.7: Longitudinal Periodic Wave which is travelling along the spring and graphically its wave form is a sinusoidal wave.

Sound wave is also a good example of longitudinal waves and it can be explained with the help of a tuning fork. When the tuning fork is struck on a rubber pad, its prongs start vibration. When the prongs move outward then they compress a small column of air and forms compressions. When the prongs move inward then rarefactions is formed in the air column. In this way, a sound wave, which consists of a series of compressions and rarefactions, travels in air as shown in Fig.8.8.

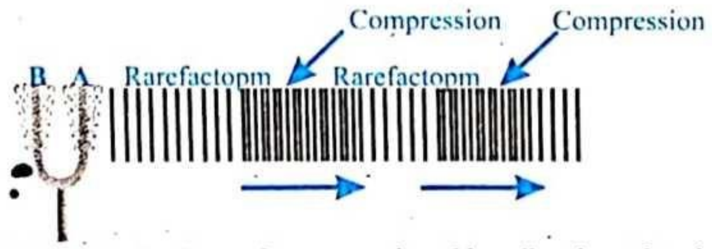


Fig.8.8: Longitudinal sound wave produced by vibration of tuning fork.

Thus, one can say that sound wave is a longitudinal or compressional wave.

8.3 SPEED OF SOUND IN AIR

Sound wave is a longitudinal or compressional wave, and it requires a medium for its propagation. This medium may be solid, liquid or gas. Experiments show that the speed of sound depends upon elasticity 'E' and density 'ρ' of the medium. Mathematically it can be expressed as;

$$v = \sqrt{\frac{E}{\rho}} \quad ......(8.2)$$

Stress = F/A
Strain = ΔV/V

But according to Hook's law

$$\text{Elasticity (E)} = \frac{\text{stress}}{\text{strain}}$$

$$E = \frac{\Delta P}{\frac{\Delta V}{V}} \quad ......(8.3)$$

Besides, elasticity and density of the medium, the speed of sound also depends upon the nature of the medium, for example the molecules of solids are much closer to one another than in liquids or gases. So a quick disturbance takes place in solid. Therefore the speed of sound is much higher in solids than in liquids or gases. The value of speed of sound in various solids, liquids and gases is given in the table 8.1.

Table 8.1: Speed of Sound in different substances in ms^{-1}

Gases (20°C)		Liquids (25°C)		Solids (20°C)	
Hydrogen	1284	Glycerin	1904	Iron	5960
Carbon Dioxide	259	Sea Water	1535	Pyrex Glass	5640
Oxygen	316	Water	1493	Aluminum	5100
Nitrogen	334	Mercury	1450	lead	2160
Air	344	Methyl Alcohol	1103	Rubber	1550

8.3.1 Newton's formula for the speed of sound in air

Sound is a longitudinal wave and it consists of a series of compressions and rarefactions. We know that the temperature of a gas increases on its compression and fall when allowed to expand. Newton assumed that when a sound travels through air or a gaseous medium, then the process of formation of compressions and rarefactions is very slow. So, the temperature in the regions of compression and rarefaction remains constant i.e. the temperature changes are extremely small and can be neglected. Thus, according to the assumption of Newton the propagation of sound through air or a gaseous medium is under isothermal process in which the temperature of the medium remains constant.

Consider a certain mass of air having volume 'V' and pressure 'P'. When sound is travelling through it, then the pressure of air during compression is increased from 'P' to $P + \Delta P$ and its volume is decreased from V to $V - \Delta V$ as shown in Fig.8.9. The propagation of sound waves through air under isothermal process follows Boyle's law i.e.;

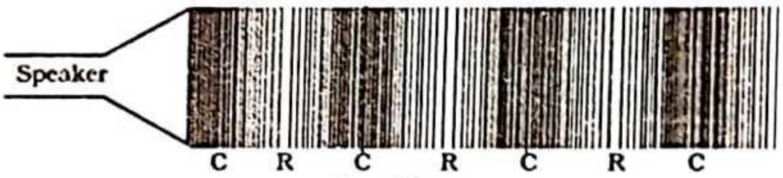


Fig.8.9: When sound wave propagates, a change in pressure and volume of the medium occurs due to the compression and refraction.

$$PV = (P + \Delta P)(V - \Delta V)$$

$$PV = PV - P\Delta V + V\Delta P - \Delta P\Delta V$$

The product of ΔP and ΔV is very small and it can be neglected.

$$0 = -P\Delta V + V\Delta P$$

$$P\Delta V = V\Delta P$$

$$P = \frac{\Delta P}{\left(\frac{\Delta V}{V}\right)}$$

> **CRITICAL THINKING**
> When explosions due to the fusion reactions occur on the surface of sun then why we cannot hear their sound?

$$P = \frac{\text{Stress}}{\text{Strain}} = E \quad \ldots\ldots(8.4)$$

Substitute the values P for E in equation (8.2), we get;

$$v = \sqrt{\frac{P}{\rho}} \quad \ldots\ldots(8.5)$$

Eq.(8.5) is referred as Newton's formula for speed of sound.

At S.T.P

Pressure $= 1.01\times10^{5}\ \text{N m}^{-2}$

And the density of air is $\rho = 1.293\ \text{kg m}^{-3}$

By putting these values in equation (8.5), we have

$$v = \sqrt{\frac{1.01\times10^{5}\ \text{N m}^{-2}}{1.29\ \text{kg m}^{-3}}}$$

$$v = 279\ \text{m s}^{-1}$$

This result differs from the experimental result of speed of sound i.e. $333\,ms^{-1}$. The theoretical value of speed of sound is about 16 percent less than the experimental value.

8.3.2 Laplace's correction

Laplace has pointed out that during compression, volume of air is decreased from V to V − ΔV and pressure is increased from P to P + ΔP but its temperature does not remain constant. Because compression and rarefaction are occurred very quickly such that air neither loses heat during compression nor gains during rarefaction. Thus the propagation of sound through air follows adiabatic process and we should apply adiabatic equation rather than of Boyle's law.

$$PV^{\gamma} = (P+\Delta P)(V-\Delta V)^{\gamma} \quad \ldots\ldots(8.6)$$

Where γ is adiabatic constant and its value can be calculated in terms of ratio.

$$\gamma = \frac{\text{Molar specific heat of gas at constant pressure}}{\text{Molar specific heat of gas at constant volume}}$$

Solving equation (8.6)

$$PV^{\gamma} = (P+\Delta P)V^{\gamma}\left(1-\frac{\Delta V}{V}\right)^{\gamma}$$

$$P = (P+\Delta P)\left(1-\frac{\Delta V}{V}\right)^{\gamma} \ldots(8.7)$$

FOR YOUR INFORMATION

Molar Specific Heat of Various Gases

Monoatomic	1.67
Diatomic	1.41
Polyatomic	1.31

Solving $\left(1-\frac{\Delta V}{V}\right)^{\gamma}$ by binomial theorem and neglecting the higher terms in $\left(\frac{\Delta V}{V}\right)$, we get

$$\left(1-\frac{\Delta V}{V}\right)^{\gamma} = 1-\gamma\frac{\Delta V}{V} + \text{neglected terms}$$

Eq. (8.4) becomes

$$P = (P+\Delta P)\left(1-\gamma\frac{\Delta V}{V}\right)$$

$$P = P-\gamma\frac{P\Delta V}{V}+\Delta P-\gamma\frac{\Delta P\Delta V}{V}$$

The product of ΔP and ΔV is again very small and it can be neglected.

$$-\gamma P\frac{\Delta V}{V}+\Delta P = 0$$

$$\Delta P = \gamma P\frac{\Delta V}{V}$$

FOR YOUR INFORMATION

Binomial series expansion

$$(a+x)^n = 1+nx+\frac{n(n-1)}{2i}x^2+\ldots$$

FOR YOUR INFORMATION

Because radio waves travel at speed $3 \times 10^8\ ms^{-1}$ and sound waves are slower, $3.4 \times 10^2\ ms^{-1}$, a broadcast voice can be heard sooner 1300 miles away then it can be heard at the back of the room in which it originated.

$$\gamma P = \frac{\Delta P}{\frac{\Delta V}{V}}$$

$$\gamma P = E$$

If we substitute this result in eq.(8.2), we get

$$v = \sqrt{\frac{\gamma P}{\rho}} \qquad ......(8.8)$$

This is the required Laplace formula for the speed of sound in gaseous medium.

$$\gamma = 1.4 \text{ for diatomic gas at STP}$$

$$v = \sqrt{\frac{1.4 \times 1.01 \times 10^5 \text{ Nm}^{-2}}{1.29 \text{ kg m}^{-3}}}$$

$$v = 333 \text{ ms}^{-1}$$

The above value of speed of sound in gaseous medium is in close agreement with the experimental value. Hence, Laplace formula for the velocity of sound in gases is correct and widely used.

Example 8.2

Helium is a mono-atomic gas that has a density of 0.179 kg m^{-3} at STP and a temperature of $0^{\circ}C$. Find the speed of sound in helium at this temperature and pressure.

Solution:

$\rho = 0.179 \text{ kg m}^{-3}$, $P = 1.01 \times 10^5 \text{ N m}^{-2}$

$T = 0^{\circ}C = 273 \text{ K}$

As helium is monatomic so $\gamma = 1.67$.

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

$$v = \sqrt{\frac{1.67 \times 1.01 \times 10^5 \text{ Nm}^{-2}}{0.179 \text{ kg m}^{-3}}}$$

$$v = \sqrt{9.42 \times 10^5} \text{ ms}^{-1}$$

$$v = 970.7 \text{ ms}^{-1}$$

FOR YOUR INFORMATION

Vibrating vocal cords produce the human voice.

The ear can detect very tiny pressure variations.

8.3.3 Effect of various factors on speed of sound in air

Sound waves cannot propagate without any medium. Therefore the speed of sound is affected by a number of parameters which are related to a medium and these are summarized as;

(1) Effect of pressure

According to Laplace, the speed of sound through air is given as;

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

But pressure is directly proportional to the density that is;

$P \propto \rho$ or $\frac{P}{\rho}$ = constant and 'γ' is also constant

Therefore, v = constant

This shows that the speed of sound is not affected by the variation in pressure of the gas (air).

(2) Effect of density

Again the velocity of sound in a gas is given by

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

The Laplace relation shows that at the same temperature and pressure, the speed of sound in a gas is inversely proportional to the square root of its density. Now, let us consider two gases which are at the same pressure and the same value of γ. If ρ_1 and ρ_2 be their densities, then velocity of sound in the two gases are

$$v_1 = \sqrt{\frac{\gamma P}{\rho_1}} \text{ and } v_2 = \sqrt{\frac{\gamma P}{\rho_2}}$$

$$\therefore \frac{v_1}{v_2} = \frac{\sqrt{\frac{\gamma P}{\rho_1}}}{\sqrt{\frac{\gamma P}{\rho_2}}}$$

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

FOR YOUR INFORMATION

The V-shaped bow wave of a boat is formed because the boat speed is greater than the speed of the waves it generates. A bow wave is analogous to a shock wave formed by an airplane.

If the speed of a body in air exceeds the speed of sound, then it is called supersonic. Such a body leaves behind it a conical region of disturbance which spread continuously. Such a disturbance is called 'shock waves'. These waves may make cracks in window panels.

We know that the density of oxygen is 16 times that of Hydrogen therefore, from equation (8.7), we have

$$\frac{v_H}{v_O} = \sqrt{\frac{\rho_O}{\rho_H}} = \sqrt{\frac{16\rho_H}{\rho_H}} = \sqrt{16} = 4$$

or $$v_H = 4v_O$$

Thus, the speed of sound in hydrogen is greater than (about four times) that in oxygen.

(3) Effect of temperature

The experiments show that at constant pressure, the volume of gas is increased by increasing temperature, hence its density is decreased and speed of sound will be affected. Mathematically it is explained as;

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

As $$\rho = \frac{m}{V}$$

$$v = \sqrt{\frac{\gamma P}{\frac{m}{V}}}$$

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

FOR YOUR INFORMATION

- Sound is produced by vibrating objects.
- Sound waves are longitudinal waves.
- Sound has properties of all other waves: reflection, refraction, interference, diffraction.

According to ideal gas equation $PV = nRT$ and for one mole of gas $PV = RT$

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

FOR YOUR INFORMATION

- The speed of sound is higher in liquids and solids than it is in gas.
- The speed of sound in air increases 0.6 ms^{-1} for each °C increase.

The factor $\sqrt{\frac{\gamma R}{m}}$ is constant

So $$v = \text{constant}\sqrt{T}$$

$$v \propto \sqrt{T}$$

Now the speed of sound at $0°C$ (273K) is v_o and at $t°C = (t + 273)$ K is v_t then

$$\frac{v_t}{v_o} = \sqrt{\frac{T_2}{T_1}}$$

$$\frac{v_t}{v_o} = \sqrt{\frac{t+273}{273}}$$

$$\frac{v_t}{v_o} = \left(1 + \frac{t}{273}\right)^{\frac{1}{2}}$$

Using Binomial theorem and expanding $\left(1+\frac{t}{273}\right)^{\frac{1}{2}}$ and neglecting higher power terms, we have $1+\frac{1}{2}\left(\frac{t}{273}\right)+.... = 1+\frac{1}{546}t$

$$\frac{v_t}{v_o} = 1+\frac{1}{546}t$$

$$v_t = v_o\left(1+\frac{t}{546}\right)$$

$$v_t = v_o + \frac{v_o t}{546}$$

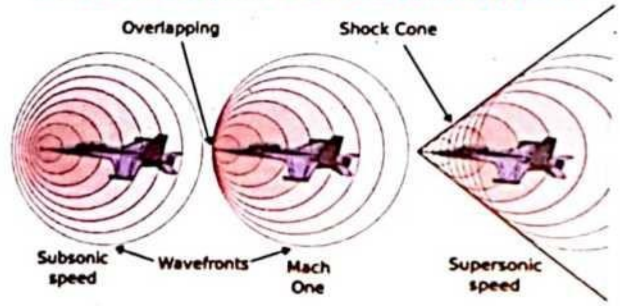
As for air $\quad v_o = 332\,m/s$

$$v_t = v_o + \frac{332\,t}{546}$$

$$v_t = v_o + 0.61\,t \quad ......(8.9)$$

It has been proved experimentally that the speed of sound is increased by $0.61\,ms^{-1}$ for each 1^oC temperature rise of the air.

INTERESTING INFORMATION



Example 8.3

Find the temperature at which the velocity of sound in air will become double of its value at 27^oC.

Solution:

Let v_t be the velocity of sound in air at t^oC and v_0 be the velocity at 27^oC.

$T_1 = 27^oC + 273 = 300\ K$

$T_2 = ?$

$$v_t = 2\,v$$

or $$\frac{v_t}{v} = 2$$

We know that, $$\frac{v_t}{v_o} = \sqrt{\frac{T_2}{T_1}}$$

$$\frac{v_t}{v} = \sqrt{\frac{T_2}{300}} = 2$$

or $$\sqrt{\frac{T_2}{300}} = 2$$

Squaring both sides, we get,

CHECK YOUR CONCEPT

The speed of sound in air is a function of

(a) wavelength
(b) frequency
(c) temperature
(d) amplitude.

$$\frac{T_2}{300} = 4$$

$$T_2 = 4 \times 300 = 1200\,K$$

$$T_2 = 1200\,K - 273 = 927^\circ C$$

Example 8.4

A normal person can hear sound waves ranging in frequency from 20 Hz to 20 kHz. Determine the wavelengths of sounds at these limits. Take the speed of sound in air as $340\ m\ s^{-1}$.

Solution:

Frequency = f_1 = 20 Hz

Frequency = f_2 = 20 kHz = 20×10^3 Hz

$\lambda_1 = ?$

$\lambda_2 = ?$

Speed of sound = v = $340\ ms^{-1}$

As $v = f\lambda$

$$\lambda_1 = \frac{v}{f_1} = \frac{340}{20}$$

$$\lambda_1 = 17\ m$$

$$\lambda_2 = \frac{v}{f_2} = \frac{340}{20 \times 10^3}$$

$$\lambda_2 = 17 \times 10^{-3}\ m$$

$$\lambda_2 = 17\ mm \text{ or } 1.7\ cm$$

> **CHECK YOUR CONCEPT**
> The sounds are carried by electro-magnetic waves in space. Why our ears cannot hear it?

8.4 PRINCIPLE OF SUPERPOSITION

The principle of superposition was first observed experimentally by Thomas Young in 1801. It is related to the study of combined effect of two or more waves and it is stated as, **"When two or more waves meet at a point in the same medium, the resultant amplitude at that point is the algebric sum of the amplitudes of the individual waves"**.

For example, when a man talks to us while we are listening music, we receive a complex sound but we can still distinguish the sound of speech and the sound of the music from each other. It happens like that because the total sound waves reaching our ears is the algebric sum of the waves produced by a man voice and the waves produced by music. Superposition principle is applicable to all types of waves including the electro-magnetic wave such as light.

Let we consider two waves of amplitudes Y_1 and Y_2 which are in phase. When they are superimposed at the point in the same medium as shown in Fig.8.10(a) then their resultant amplitude 'Y' at that point is given as;

$$Y = Y_1 + Y_2$$

Similarly, the two waves which are in opposite phase or out of phase and they are superimposed at point in the same medium then we get the result which is shown in Fig.8.10(b). The amplitude of their resultant wave is given as;

$$Y = Y_1 - Y_2$$

If $\quad Y_1 = Y_2$

then $\quad Y = 0$

In general, if there are 'n' number of waves passing through the same medium then the amplitude of their resultant wave is given as;

$$Y = Y_1 + Y_2 + Y_3 + \ldots + Y_n \quad \ldots\ldots(8.10)$$

This is the mathematical form of principle of superposition.

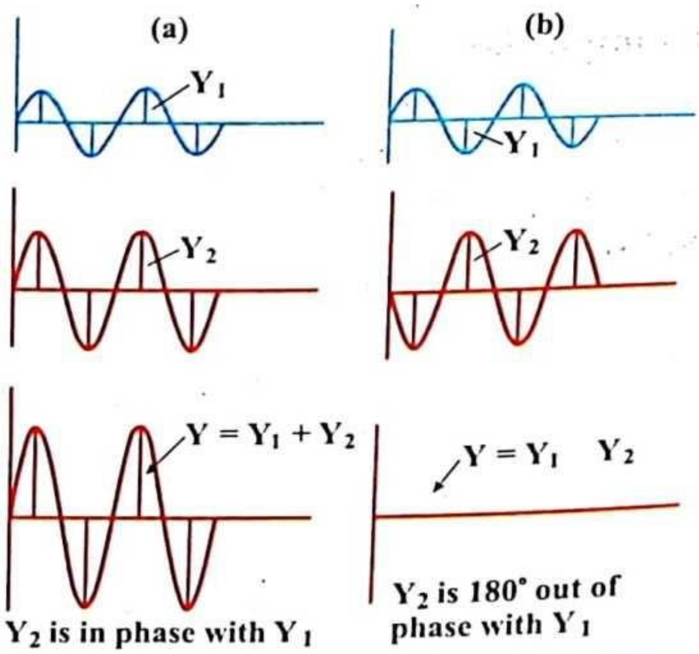


Fig.8.10: Superposition of two waves of same frequency (a) The two waves which are at the same phase and their resultant is increased (b) The two waves which are at the out of phase and their result is decreased (zero).

The superposition of two waves give rise to the following three important phenomena:

1. When two waves of same frequency (or wavelength) moving with same speeds in the same direction in a medium superpose on each other, they give rise to an effect called **interference of waves**.
2. When two waves of slightly different frequency (or wavelength) moving with same speeds in the same direction in a medium superpose on each other, they give rise to **beats**.
3. When two waves of same frequency or wavelength moving with same speeds in opposite direction in a medium superpose on each other, they give rise to **stationary waves**.

8.5 INTERFERENCE

When two or more waves having the same frequency travel through the same medium and in the same direction are combined, then this results in a phenomenon called interference. The amplitude of the resultant wave is greater or smaller than the amplitude of combining individual waves and depends upon the relative phase of individual waves.

Now when two coherent waves (the wave having same frequency), which are exactly in phase, are allowed to superimpose such that the crests of one wave coincide with crests of the other wave and troughs with trough then the amplitude of the resultant wave will be increased as shown in Fig.8.11. This is called constructive interference.

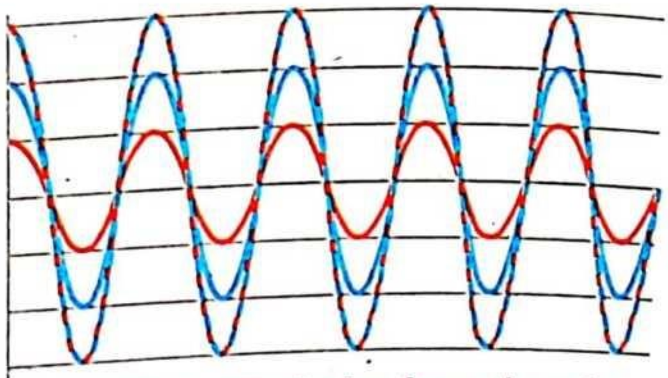


Fig.8.11: Constructive Interference due to the superposition of coherent waves in the same phase

Similarly, when two coherent waves, which are exactly in opposite phase, are allowed to superimpose such that crest of one wave coincide with the trough of second wave then the amplitude of the resultant wave is decreased, as shown in Fig.8.12 and it is called destructive interference.

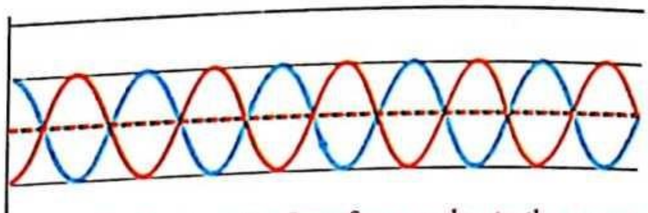


Fig.8.12: Destructive Interference due to the super position of coherent waves, in the opposite phase.

Conditions of Interference

To demonstrate interference phenomenon, considering two identical sources of sound S_1 and S_2 (loud speakers) are placed at some distance. These sources generate continuously spherical waves of same frequency and of same phase which are called coherence waves. These coherent waves are propagated in the outward direction such that they are superimposed at different points as shown in Fig.8.13. Thus, we have both constructive and destructive interferences at different points. In figure, the thick lines represent crests while the thin lines represent troughs.

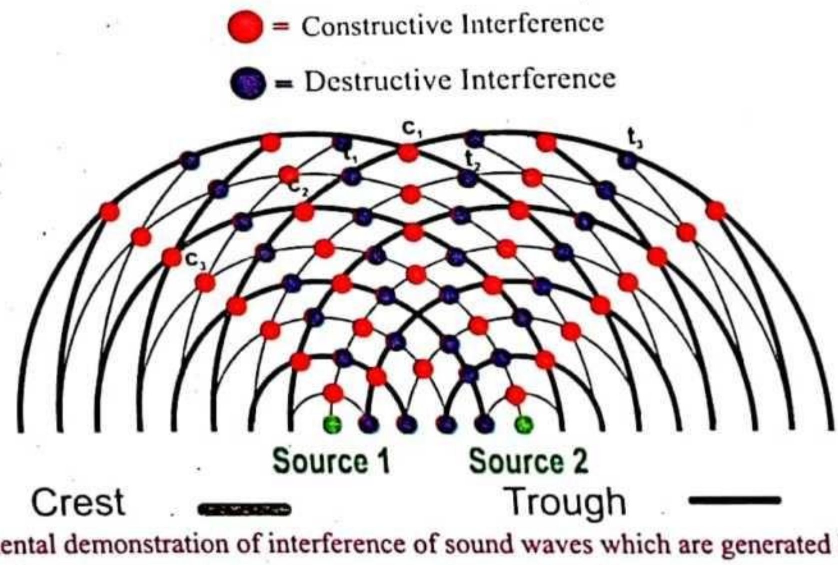


Fig.8.13: Experimental demonstration of interference of sound waves which are generated by two coherent sources

The points where crests coincide with crests and troughs with troughs, a constructive interference is obtained. These are represented by red dots as C_1, C_2, C_3 $\ldots C_n$. On the other hand, the points where crests coincide with troughs, a destructive interference is obtained. These are represented by blue dots as $t_1, t_2, t_3, t_4, t_5, \ldots t_n$ crest.

Now mathematical condition of constructive interference can be developed as;

Path difference between two waves at point $C_1 = \Delta S = S_2C_1 - S_1C_1$

$$\Delta S = 4\lambda - 4\,\lambda = 0\,\lambda$$

Path difference between two waves at point $C_2 = \Delta S = S_2C_2 - S_1C_2$

$$\Delta S = 4\lambda - 3\,\lambda = 1\lambda$$

Path difference between two waves at point $C_3 = \Delta S = S_2C_3 - S_1C_3$

$$\Delta S = 4\frac{1}{2}\lambda - 2\frac{1}{2}\lambda = 2\lambda$$

In general, the path difference between two waves for constructive interference is given as:

$$\text{Path difference} = 0, \pm\lambda, \pm 2\lambda, \pm 3\lambda, \pm 4\lambda \ldots. m\lambda$$

$$\text{Path difference} = \Delta S = m\lambda \qquad \ldots\ldots(8.11)$$

where $\qquad m = 0, \pm 1, \pm 2, \pm 3, \pm 4 \ldots$

This is a condition for constructive interference and it shows that for constructive interference, the path difference is a whole number of wavelength or the path difference is integral multiple of wavelength.

Similarly, mathematical condition of destructive interference can be developed as;

Path difference between two waves at point $t_1 = \Delta S = S_2t_1 - S_1t_1$

$$\Delta S = 4\lambda - 3\frac{1}{2}\lambda = \frac{1}{2}\lambda$$

Path difference between two waves at point $t_2 = \Delta S = S_2t_2 - S_1t_2$

$$\Delta S = 3\frac{1}{2}\lambda - 4\lambda = -\frac{1}{2}\lambda$$

Path difference between two waves at point $t_3 = \Delta S = S_2t_3 - S_1t_3$

$$\Delta S = 4\lambda - 5\frac{1}{2}\lambda = \frac{3\lambda}{2}$$

In general, the path difference between two waves for destructive interference is given as;

$$\text{Path difference} = \pm\frac{\lambda}{2}, \pm\frac{3\lambda}{2}, \pm\frac{5\lambda}{2}, \pm\frac{7\lambda}{2} \ldots$$

$$\text{Path difference} = \left(m + \frac{1}{2}\right)\lambda \qquad \ldots\ldots(8.12)$$

or Path difference $= (2m+1)\frac{\lambda}{2}$

Where $m = 0, \pm 1, \pm 2, \pm 3, \pm 4, \ldots$

This is the condition for destructive interference and it shows that the path difference between two waves for destructive interference is an odd integral multiple of half-wavelengths.

8.6 BEATS

In interference, we have studied the superposition of two waves having the same frequency. But what will be the effect of the superposition of two waves when they have a slight difference in their frequencies? It can be studied in beats phenomenon. When two sound waves of same amplitude but slightly differing in frequencies are travelling through a medium in the same direction and they are allowed to superimpose at a point then a periodic variation in the intensity of resultant wave is observed at that point. This variation in the intensity of resulting wave is in the form of series of loud sound followed by faint sound. This phenomenon is called beats. It is further explained by an example.

Consider two tuning forks A and B of frequencies 100 Hz and 102 Hz. It means that tuning fork 'A' will produce 100 complete waves in one second and tuning 'B' will produce 102 complete waves in one second when each of them is struck against rubber pad. When both tuning forks are sounded together then phenomenon of beats takes place. Let us study the variation in the intensity of resulting sound over a span of one second.

After $\frac{1}{4}$ second, the number of waves produced by A are 25 and distance covered is 25λ and the number of waves produced by B are $25\frac{1}{2}$ and distance $25\frac{1}{2}\lambda$ respectively. The path difference between them is $\frac{\lambda}{2}$. This is the condition of destructive interference. At this point two waves cancel to each other and no sound or faint sound is heard.

Similarly, after $\frac{1}{2}$ second, the number of waves produced by A and B are 50 and 51 and corresponding distances covered are 50λ and 51λ respectively. The path difference between them is '1λ'. This is the condition of constructive interference. At this point two waves reinforce each other and loudness is increased.

After $\frac{3}{4}$ second the number of waves produced by A and B are 75 and $76\frac{1}{2}$ and corresponding distances covered are 75λ and $76\frac{1}{2}\lambda$. The path difference between them is $\frac{3\lambda}{2}$ which is again the condition of destructive interference. Hence, no sound or a faint sound is observed because two waves cancel each other.

After one second, the number of waves produced by A and B are 100 and 102 and corresponding distances covered are 100λ and 102λ. The path difference between them is '2λ' which is the condition of constructive interference. Hence we observe a loud sound because two waves reinforce each other.

This example clearly shows that when the two waves of nearly same frequency are superimposed then there is increase and decrease in loudness at regular interval of time. As a result we have a beats phenomenon. Graphically, it is shown in Fig.8.14.

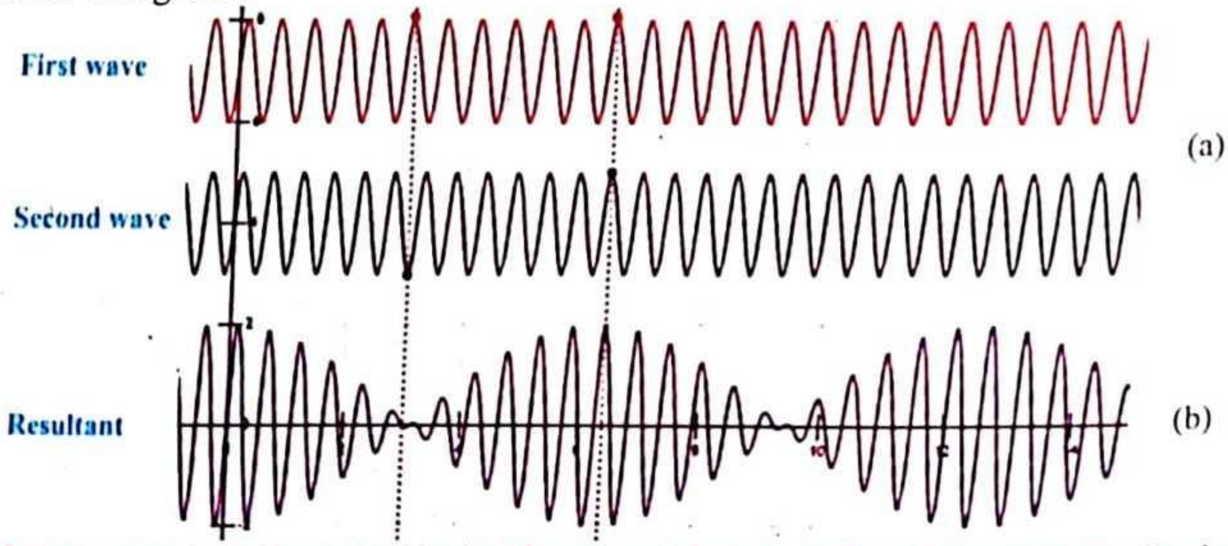


Fig.8.14: Beats are formed by the combination of two waves of slightly different frequencies travelling in the same direction; (a) The two individual waves (b) The combined resultant wave has amplitude that oscillates with time

It may be noted from figure 8.14(b) that rise and fall in the intensity of resulting sound (increase and decrease in loudness) takes place twice in one second and difference in frequency of the two sources is also two. In other words two beats are produced in one second.

Thus it is concluded that, **"the difference in frequency of the two sources is equal to the number of beats produced per unit time is called beat frequency"**. If f_A and f_B be the frequencies of sound waves of two sources then;

INTERESTING INFORMATION

Musicians use beats phenomenon to tune their string instruments like guitar, violin and piano, by beating a note against a note of known frequency. The strings are then adjusted to the desired frequency by tightening or loosening it until no beats are heard.

$$f_B - f_A = \frac{\text{number of beats}}{\text{time}} \quad \text{.... (8.13)}$$

It is important to note that beats cannot be observed if the difference in frequency is more than 10 Hz.

Uses of beats

The phenomenon of beats can be used in the following cases.

1. To determine the frequency of a note
2. Beats are used to tune musical instruments
3. To detect the hidden metals by using metal detectors.
4. To detect the harmful gases in mines.
5. Beats are used for radio wave reception.

> **DO YOU KNOW**
> Metal detector is working under the principle of beats phenomenon.

8.7 REFLECTION OF WAVES

A mechanical wave requires a medium for its propagation and its velocity depends upon the nature of the medium. When the wave comes across the boundary of two media then all or a part of this travelling wave is reflected back. This reflected wave has the same wavelength and frequency but its phase may change depending upon the nature of the boundary.

The reflection of a wave at the boundary of the media can be studied by an example of a stretched string under two different cases.

When one end of the stretched string is connected with a rigid support and the other free end in the hand is shaken up and down then a pulse of transverse wave is produced which travels along the string towards the rigid support with velocity v_i.

When the pulse arrives at the end, it exerts a force on a rigid support. In reaction, the rigid support which acts as a

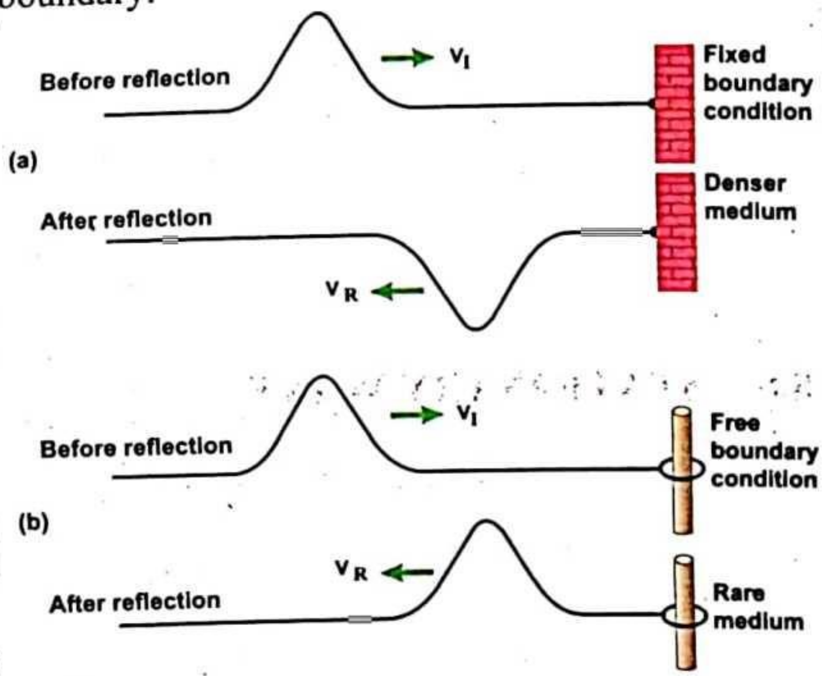


Fig.8.15: A pulse of a wave along a string reflected from
(a) Denser medium (rigid support)
(b) Rare medium (ring & rod)

dense medium also exerts an opposite force on the string. As a result, a reflected inverted pulse starts travelling along the string in the reverse direction with velocity v_R as shown in Fig.8.15 (a).

The incident wave and reflected wave are out of phase a change of 180° in phase and the change in path difference between them is $\frac{\lambda}{2}$.

If one end of the string is connected with a light ring which can move freely up and down. This light ring act as a rare medium and it exerts no force on the string.

FOR YOUR INFORMATION

Type of wave	Boundary of	After reflection	Change of phase
Longitudinal	Denser	Compression as rarefaction Rarefaction as compression	$\pi = 180^\circ$
	Rare	Compression as compression Rarefaction as rarefaction	0
Transverse	Denser	Crest as trough Trough as crest	$\pi = 180^\circ$
	Rare	Crest as crest Trough as trough	0

When the pulse of transverse wave arrives at light ring then it reflects in the reverse direction without any phase change in the reflected wave as shown in Fig.8.15(b).

From the above discussion, it is concluded that a transverse wave which is reflected from a denser medium with phase change of 180° and path difference of $\frac{\lambda}{2}$. But when the transverse wave is reflected from a rare medium, no phase change takes place in the reflected wave.

8.8 STATIONARY WAVE

In interference and beats phenomenons, we have studied the superposition of two waves which are travelling along the same direction. If two waves of same frequency and amplitude move along a straight line in opposite directions and are allowed to superimpose then the new resultant wave is called stationary or standing wave. The formation of standing waves is shown in Fig.8.16.

It can be explained by an example of a string whose one end is connected with a support and the free end in hand is oscillated up and down continuously. Then a transverse waves is produced which travel along the string and reflected from the support. Due to the superposition of the incident waves with the reflected waves, a pattern of the stationary waves is obtained in the string as shown in Fig.8.16. The points in stationary waves which are permanently at rest with zero amplitudes are called nodes (N).

The point between two successive nodes where the particles oscillate with maximum displacement is called as anti-node (A).

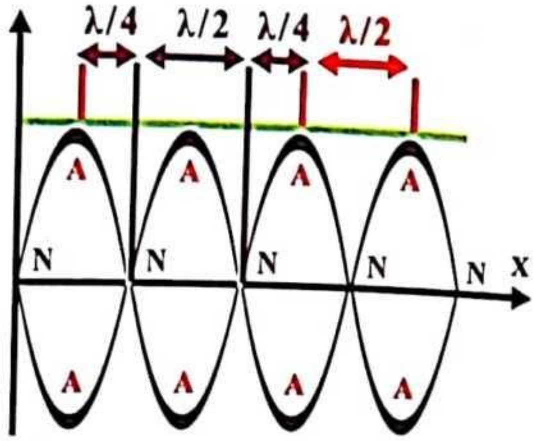


Fig.8.16: The formation of stationary wave due to the superposition of two waves moving in opposite direction. The displacement is marked as node 'N' and anti node 'A'.

It is clear that the distance between two consecutive nodes or consecutive antinodes is $\frac{\lambda}{2}$ and the distance between a node and an adjacent antinode is $\frac{\lambda}{4}$.

Graphically, standing waves can be illustrated by considering two waves 'a' and 'b' having same frequency and amplitude which are travelling along the string in opposite directions as shown in Fig.8.17. The resultant standing wave "c" at instants $0, \frac{T}{4}, \frac{T}{2}, \frac{3T}{4}$ and T is obtained using the principle of superposition (Fig.8.17)

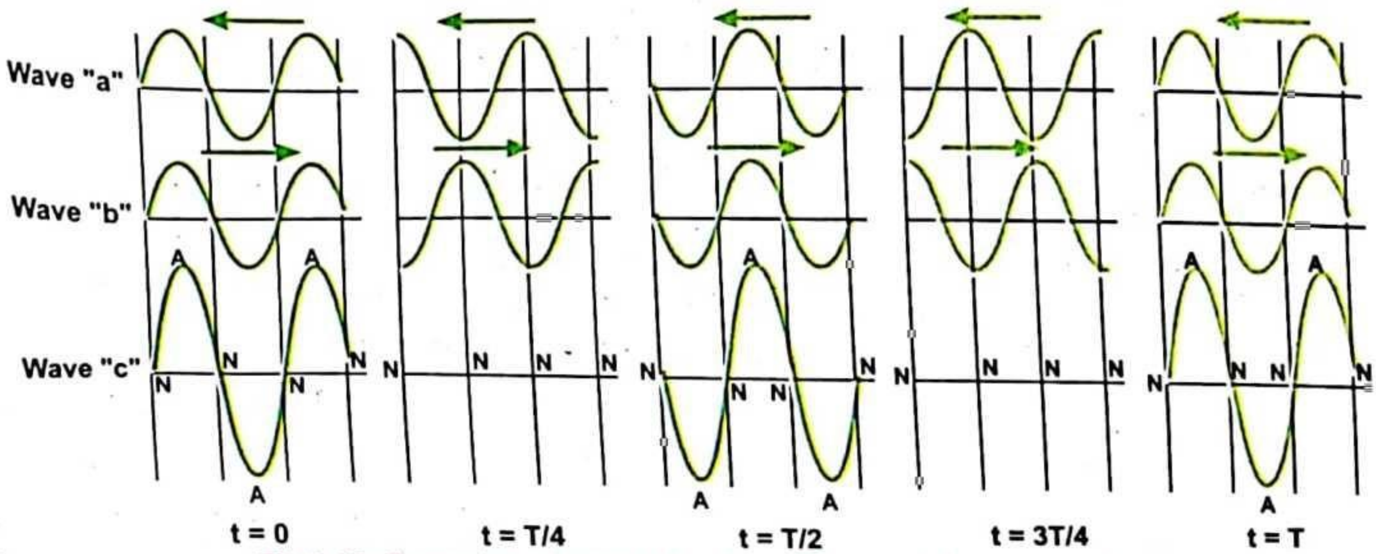


Fig.8.17: Formation of stationary waves. The set of figures show the state of resultant displacement at four different times.

(i) At $t = 0$, both waves "a" and "b" are in phase. After superposition, they produce resultant wave "c" where the amplitude of its nodes is zero and the amplitude of its antinodes is maximum, i.e. equal to the sum of amplitudes of individual waves.

(ii) At $t=\frac{T}{4}$, then wave "a" has travelled a distance $\frac{\lambda}{4}$ to the right and wave "b" has travelled distance $\frac{\lambda}{4}$ to the left. Therefore, both waves are out of phase. This is the condition of destructive interference and the amplitude of the resultant wave "c" is zero at each point.

(iii) At $t=\frac{T}{2}$, wave "a" has travelled a distance $\frac{\lambda}{2}$ to the right and wave "b" has travelled a distance $\frac{\lambda}{2}$ to the left. Both waves are in phase where the amplitude of the nodes of the resultant wave "c" are zero and the amplitudes of anti nodes are maximum.

Similarly, after $t=\frac{3T}{4}$ and $t=T$ the results are same as for $t=\frac{T}{4}$ and $t=0$ or $\frac{T}{2}$ respectively i.e. out of phase and in phase and are shown in Fig.8.17.

The pattern of the resultant wave "c" is known as stationary waves, because neither the patterns move nor the location of nodes and anti nodes changes.

Notice that stationary waves do not travel to left or right. Therefore, they cannot transfer energy because the energy is confined in antinodes. That's why stationary waves are also called standing wave.

POINT TO PONDER
What will happen when a longitudinal wave is reflected from a denser medium and from a rare medium?

Some features of stationary wave are given below:

1. The disturbance produced is confined to the region where it is produced i.e. it does not move forward or backward.
2. Different particles move with different amplitudes.
3. The particles at nodes always remain at rest.
4. All the particles cross their mean positions together.
5. All the particles between two successive nodes are in phase.
6. The energy of one region is always confined in that region.

8.8.1 Stationary waves in a stretched string

Consider a string of length 'L' which is stretched between two rigid supports such that a tension 'T' is developed in the string. When the string is plucked from its centre, two waves, in the form of transverse waves, originate from this point. One of them moves toward the right end and the other toward the left end of the string. When these two waves reach to the two rigid supports, they are reflected back and superimpose to each other. The resulting stationary wave is in the form of a single loop. It has two nodes and one anti node as shown in Fig.8.18.

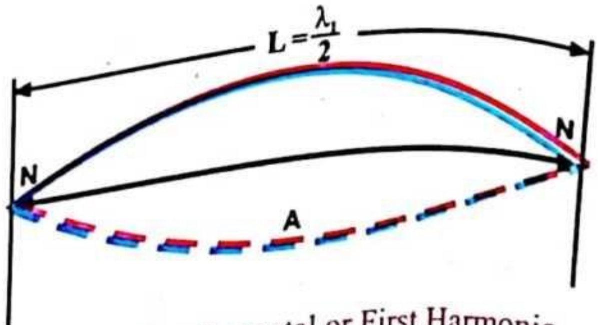


Fig.8.18: Fundamental or First Harmonic with single loop has two nodes and one anti-node.

This single loop stationary wave is called fundamental mode of vibration. Let f_1 be its frequency and 'λ_1' be its wavelength, then these parameters are related to the length of the string 'L' as,

$$L = \frac{\lambda_1}{2}$$

$$\lambda_1 = 2L \quad ......(8.14)$$

The wave travels through the string its speed (v) depends upon tension 'T' and mass per unit length or linear mass density $\left(\mu = \frac{m}{L}\right)$ of the string.

The dependence of speed of wave on tension (T) and mass per unit length (μ) of the string is given by,

$$v = \sqrt{\frac{T}{\mu}} \quad ......(8.15)$$

As $\quad v = f_1 \lambda_1$

$$f_1 = \frac{v}{\lambda_1}$$

$$f_1 = \frac{v}{2L} \quad ......(8.16)$$

$$\therefore f_1 = \frac{1}{2L}\sqrt{\frac{T}{\mu}} \quad ......(8.17)$$

This is called the *fundamental frequency or first harmonic* of the string. It is the minimum frequency that can be produced as standing waves in a string.

Second mode of vibration

When the same string is plucked from one-fourth, three-fourth of its length, a stationary wave with two loops is set up in the string. It has three nodes and two anti nodes as shown in Fig.8.19.

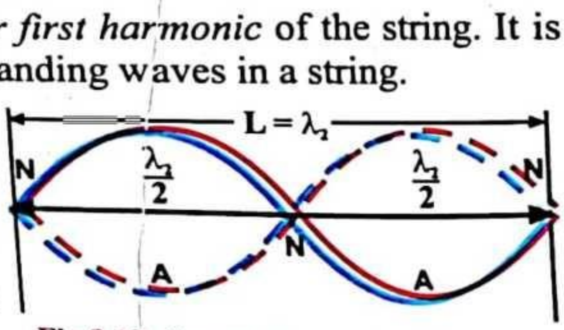


Fig.8.19: Second Harmonic with two loops have three nodes and two anti-nodes.

These two loops of stationary waves are called second mode of vibration. Let f_2 be its frequency and λ_2 be its wavelength which is related with the length of the string.

$$L = \lambda_2$$

As $$v = f_2\lambda_2$$

$$v = f_2 L$$

$$f_2 = \frac{v}{L} \quad ......(8.18)$$

$$f_2 = 2\left(\frac{v}{2L}\right)$$

But $\frac{v}{2L} = f_1$ (from eq. 8.16)

$$f_2 = 2f_1$$

DO YOU KNOW

The speed of a wave along a stretched ideal string depends only on the tension and linear density of the string and not on the frequency of the wave.

This frequency is called second harmonic or first overtone. It is clear from above equation that if the string vibrates in two loops then the frequency of second harmonic is twice the frequency of first harmonic.

Third mode of vibration

Similarly, if the same string is plucked from one sixth $\left(\frac{5}{6}\right)$th of its length, then the string vibrates in three loops, having four nodes and three antinodes as shown in Fig.8.20. It is called third mode of vibration. Let f_3 be its frequency and λ_3 be its wavelength then;

$$L = \frac{3\lambda_3}{2}$$

$$\lambda_3 = \frac{2}{3}L$$

As $$v = f_3\lambda_3$$

$$f_3 = \frac{v}{\lambda_3}$$

$$f_3 = \frac{v}{\left(\frac{2}{3}L\right)}$$

$$f_3 = 3\left(\frac{v}{2L}\right)$$

$$f_3 = 3f_1$$

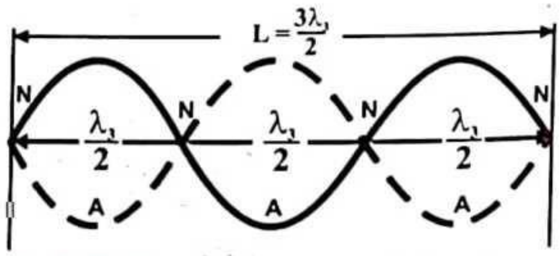


Fig.8.19: Third Harmonic with three loops have four nodes and three anti-nodes.

In general, if the string vibrates in 'n' number of loops then it has 'n + 1' number of nodes and 'n' antinodes. The frequency 'f_n' of such stationary wave setup in the string is expressed as;

$$f_n = nf_1 \text{ where } n = 1, 2, 3...$$

This is known as quantization of frequencies i.e. the frequencies of the various (or overtones) are whole number (positive integar > 0) multiple of first harmonic (the fundamental frequency).

Example 8.4

A steel wire hangs vertically from a fixed point, supporting a weight of 80 N at its lower end. The diameter of the wire is 0.50 mm and its length from the fixed point to the weight is 1.5 m. Calculate the fundamental frequency emitted by the wire it is plucked? (Density of the steel wire = 7.8×10^3 kg m^{-3})

Solution:

Weight = Tension = T = 80 N

Diameter of wire = d = 0.5 mm = 0.5×10^{-3} m

Length = ℓ = 1.5 m

Density of steel wire = 7.8×10^3 kg m^{-3}

By definition of density $= \rho = \frac{\text{mass}}{\text{volume}}$

$$\text{Mass} = \rho \times \text{volume}$$

$$\text{Mass} = \rho \times \text{Area} \times \text{length}$$

$$\text{Mass} = \rho \times \pi r^2 \times \ell$$

$$\text{Mass} = \rho \times \pi \left(\frac{d}{2}\right)^2 \times \ell$$

$$\text{Mass} = \rho \times \pi \frac{d^2}{4} \times \ell$$

$$\text{Mass} = (7.8 \times 10^3 \text{ kg m}^{-3})(3.14)\frac{(0.5 \times 10^{-3}\text{ m})^2}{4} \times 1.5 \text{ m}$$

$$\text{Mass} = 2.30 \times 10^{-3} \text{ kg}$$

Now linear mass density or mass per unit length is given as;

$$\mu = \frac{\text{mass of wire}}{\text{length of wire}} = \frac{2.30 \times 10^{-3} \text{ kg}}{1.5 \text{m}}$$

$$= 1.53 \times 10^{-3} \text{ kg m}^{-1}$$

FOR YOUR INFORMATION

The energy emitted from sound produced by a crowd of 60,000 at a football match is enough to warm a cup of tea.

GEOPHYSICS

Waves through a solid can be either transverse or longitudinal. An earthquake produces both transverse and longitudinal waves that travel through earth. Geologist studying the waves with seismograph found that longitudinal wave could pass through Earth's core, transverse waves could not. From this evidence, they concluded that Earth's core is liquid. From its density, it is most likely molten iron.

The fundamental frequency

$$f_1 = \frac{1}{2L}\sqrt{\frac{T}{\mu}}$$

$$f_1 = \frac{1}{2\times 1.5\,\text{m}}\sqrt{\frac{80\ \text{N}}{1.53\times 10^{-3}\,\text{kg m}^{-1}}}$$

$$f_1 = 76\ \text{Hz}$$

8.8.2 Stationary waves in air column

We have observed stationary waves along a vibrating stretched string, but these waves can also be set up in other media. For example, the vibrating air column of a closed or open organ pipes. Similarly, when air is blown at the mouth of a bottle, sound is produced due to vibrations of air column inside the bottle. Now consider a sound wave from a tuning fork which is allowed to vibrate the air at the one end of the pipe. This wave will travel along the pipe and will be reflected from the far end of the pipe. Thus there are two waves in the pipe i.e. incident wave and reflected wave. The superposition of incident and reflected waves produces a stationary wave in the vibrating air column of organ pipe. The relation between incident wave and reflected wave depends upon the closed and open ends of organ pipe. The open end of the pipe behaves as anti node due to free motion of molecules of air whereas the node is formed at the closed end because the movement of molecules is restricted. Stationary waves in the air column can be studied under the following two cases.

I. When one end of the Pipe is closed

Let us consider a pipe of length 'L' such that its one end is closed and its other end is open. In this case all the sound energy is reflected from the closed end and it causes a stationary wave in the pipe. Node is formed at the closed end and antinode at the open end.

First Harmonic

When the stationary wave is formed in pipe vibrating with a half loop which consists of one node and an anti-node as shown in Fig.8.21 then it is called 1st harmonic. Let f_1 be its frequency and λ_1 be its wavelength which is related with the length of the pipe that is;

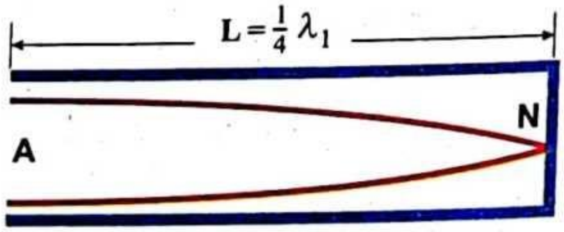


Fig.8.21: Fundamental or First Harmonic stationary wave with a half loop has one node and one anti-node.

$$L = \frac{\lambda_1}{4}$$

$$\lambda_1 = 4L$$

As
$$v = f_1 \lambda_1$$
$$f_1 = \frac{v}{\lambda_1}$$
$$f_1 = \frac{v}{4L} \quad \ldots\ldots(8.19)$$

Second Harmonic

The stationary wave which is vibrating, in one and half loops and contains two nodes and two anti-nodes is called 2nd harmonic as shown in Fig.8.22. Let f_2 be its frequency and λ_2 be its wavelength which is related with the length of the pipe as;

$$L = \frac{3\lambda_2}{4}$$
$$\lambda = \frac{4}{3}L$$
As
$$v = f_2\lambda_2$$
$$f_2 = \frac{v}{\lambda_2}$$
$$f_2 = \frac{v}{\frac{4}{3}L} = 3\left(\frac{v}{4L}\right)$$
$$f_2 = 3f_1$$

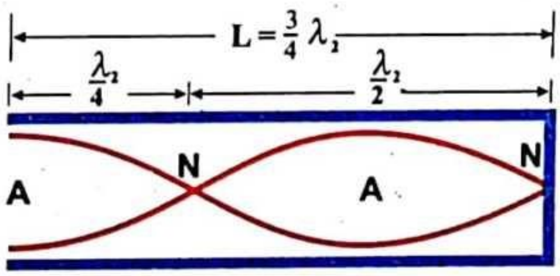


Fig.8.22: Second Harmonic stationary wave with one and half loops have two nodes and two anti-nodes.

Third Harmonic

In third harmonic, the stationary waves are vibrating with two and half loops and contain three nodes and three anti-nodes as shown in Fig.8.23. Let f_3 be its frequency and λ_3 be it wave length which is related with the length of the pipe as;

$$L = \frac{5\lambda_3}{4}$$
$$\lambda_3 = \frac{4}{3}L$$
As
$$v = f_3\lambda_3$$
$$f_3 = \frac{v}{\lambda_3}$$
$$f_3 = \frac{v}{\frac{4}{5}L}$$

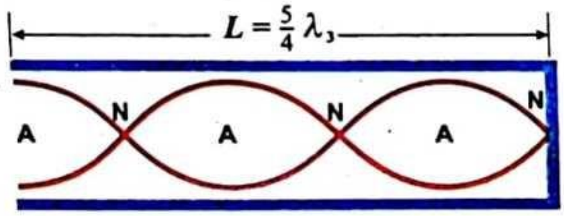


Fig.8.23: Third Harmonic stationary wave with two and half loops have three nodes and three anti-node.

CRITICAL THINKING

Under what principle a sound is produced in a flute?

$$f_3 = 5\left(\frac{v}{4L}\right)$$

$$f_3 = 5f_1$$

A closed pipe resonates when its length is an odd number of quarter wavelengths.

In general, if 'n' represents the numbers of half loops in the above stated pipe then its quantization frequency 'f_n' of stationary wave as;

$$f_n = nf_1$$

where $n = 1, 3, 5, 7, ...$

II. Open Organ Pipe

Consider a pipe of length 'L' whose both ends are open. The most of sound energy is passed outside but some of them is reflected and it causes stationary waves in the open ended pipe.

First Harmonic

The first or fundamental harmonic stationary wave consists of two antinodes and one node as shown in Fig.8.24. Let f_1 be its frequency and λ_1 be its wavelength. The wavelength is related with the length of pipe as;

Then $$L = \frac{\lambda_1}{4} + \frac{\lambda_1}{4} = \frac{\lambda_1}{2}$$

$$\lambda_1 = 2L$$

As $$v = f_1\lambda_1$$

$$f_1 = \frac{v}{\lambda_1}$$

$$f_1 = \frac{v}{2L} \quad ......(8.20)$$

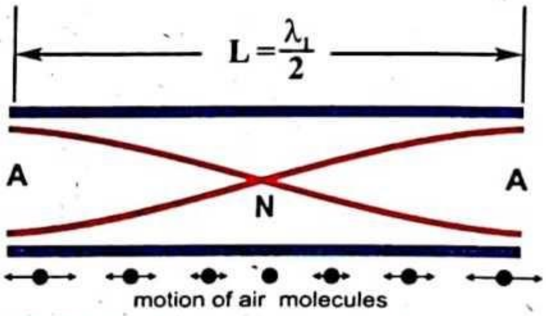


Fig.8.24: Fundamental or first Harmonic stationary wave have one node and two anti-nodes.

Second Harmonic

The second harmonic of stationary wave in open ended pipe consists of three antinodes and two nodes as shown in Fig.8.25. Let f_2 and λ_2 be its frequency and wavelength respectively of the second harmonic stationary wave. The wavelength is related with the length of pipe as;

$$L = \frac{\lambda}{4} + \frac{\lambda}{4} + \frac{\lambda}{4} + \frac{\lambda}{4}$$

i.e. $$L = \frac{4\lambda_2}{4}$$

$$\lambda_2 = L$$

$$v = f_2\lambda_2$$

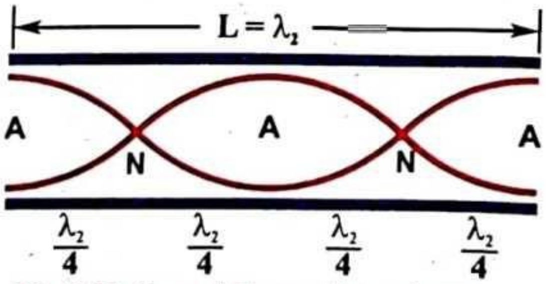


Fig.8.25: Second Harmonic stationary wave have two nodes and three anti-nodes.

$$f_2 = \frac{v}{\lambda_2} = \frac{v}{L}$$

$$f_2 = 2\left(\frac{v}{2L}\right)$$

$$f_2 = 2 f_1$$

Third Harmonic

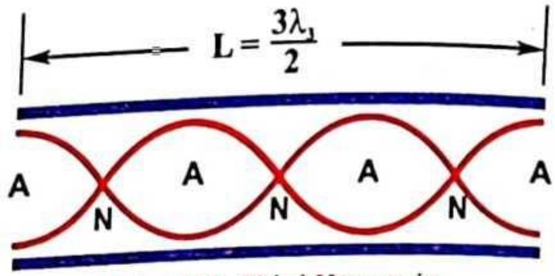


Fig.8.26: Third Harmonic

The third harmonic stationary wave in open ended pipe consists of three antinodes and two nodes as shown in Fig.8.26. Let f_3 be the frequency and λ_3 be the wave of third harmonic stationary wave in the pipe. The wavelength is related with the length of the pipe as;

$$L = 6\frac{\lambda_3}{4} = \frac{3\lambda_3}{2}$$

$$\lambda_3 = \frac{2}{3}L$$

$$v = f_3\lambda_3$$

$$f_3 = \frac{v}{\lambda_3} = \frac{v}{\frac{2}{3}L}$$

$$f_3 = 3\left(\frac{v}{2L}\right)$$

$$f_3 = 3 f_1$$

In general, for nth harmonic the quantization frequency of the stationary wave in open ended pipe is given as;

$$f_n = n\left(\frac{v}{2L}\right)$$

$$f_n = nf_1$$

Where $n = 1, 2, 3, 4, \ldots$

> An open pipe resonates when its length is an even number of quarter wavelengths

Example 8.5

What will be the frequencies of fundamental and first three overtones for a 75 cm long organ pipe? (a) If it's both ends are open (b) If its one end is closed. The speed of sound in air is 340 ms^{-1}.

Solution:

Length of organ pipe = L = 75 cm = 0.75 m

Speed of sound = v = 340 ms^{-1}

(a) For an open pipe, the quantized frequency is

$$f_n = n\left(\frac{340\,ms^{-1}}{2\times 0.75\,m}\right) = n(226.7)\,Hz$$

$$n=1,\ f_1 = (1)(226.7)\,Hz$$

This the fundamental frequency of the given open pipe.

$$n=2,\ f_2 = 2(226.7)\,Hz = 453.4\,Hz = 453\,Hz$$

$$n=3,\ f_3 = 3(226.7)\,Hz = 680.1\,Hz = 680\,Hz$$

$$n=4,\ f_4 = 4(226.7)\,Hz = 906.8\,Hz = 907\,Hz$$

The frequencies of first three overtones are 453 Hz, 680 Hz and 907 Hz respectively.

(b) For a closed pipe, the quantized frequency is given by

$$f_n = n\left(\frac{v}{2L}\right) \text{ where } n = 1,3,5,7,\ldots\ldots$$

$$f_n = n\,(113.3s^{-1}) = n\,(113.3)\,Hz$$

$$f_1 = 1\times(113.3)\,Hz = 113.3\,Hz$$

$$f_3 = 3\times(113.3)\,Hz = 339.9\,Hz = 340\,Hz$$

$$f_5 = 5\times(113.3)\,Hz = 566.5\,Hz = 566\,Hz$$

$$f_7 = 7\times(113.3)\,Hz = 793.1\,Hz = 793\,Hz$$

The fundamental frequency of given closed pipe is 113.3 Hz. The frequencies of the first three overtones are 340 Hz, 566 Hz and 793 Hz respectively.

8.9 DOPPLER EFFECT

It is a common observation that when the source of sound and the observer both are at rest; the observer receives the frequency of sound in its actual form as the frequency originated from the source. However, the frequency of the sound appears to change if there is relative motion between the source and observer (listener). The frequency appears to increase as the moving source approaches the stationary observer and appears to decrease as the source moves away from the stationary

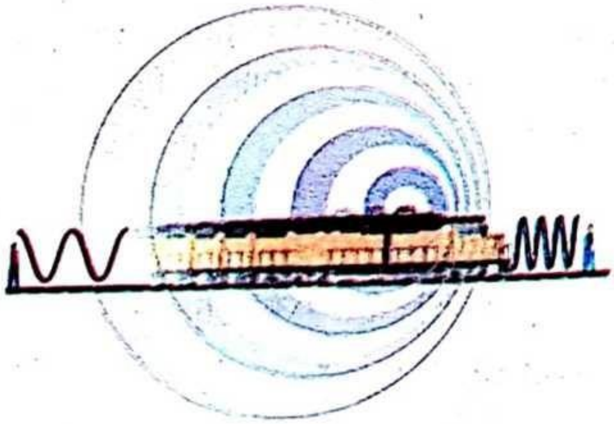


Fig.8.27: The pitch of sound of the train increases when it is moving toward the observer and decreases when it is moving away from the observer

observer. For example, let an observer who is standing at a railway platform. The pitch of the whistle by train increases when the train is approaching toward the observer and the pitch of the sound decreases when the train is moving away from the observers as shown in Fig.8.27. This apparent change in frequency is called Doppler effect and it is stated as; **"there is an apparent change in the frequency of sound due to relative motion between the source of sound wave and the listener".**

The Doppler effect is named after the Austrian physicist and mathematician Christian Johann Doppler (1803–1853), who did experiments with both moving sources and moving observers. The Doppler effect holds not only for sound waves but also for electromagnetic waves, including microwaves, radio waves, and visible light. However, here we will discuss only the Doppler effect for sound waves. The Doppler effect can be studied under the following four cases.

Consider a source of sound which generates a sound waves of frequency 'f' and wavelength 'λ' in all directions. Let v be the velocity of sound, v_o be the velocity of the observer and v_s is the velocity of source. We assume that the medium (air) between source and observer is stationary.

Case I: Observer is moving towards a stationary source.

In this case the observer is moving towards the stationary source with a velocity v_o as shown in Fig.8.28. If the relative velocity of sound is 'v' then net velocity between observer and source is $v + v_o$. Thus, the number of waves received in one second f_1 is given as;

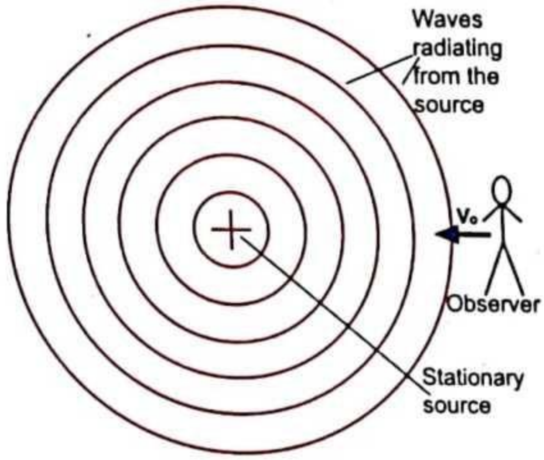


Fig.8.28: Observer is moving towards a stationary source.

$$f_1 = \frac{v + v_o}{\lambda}$$

As $$\lambda = \frac{v}{f}$$

$$f_1 = \frac{v + v_o}{\left(\frac{v}{f}\right)}$$

$$f_1 = \left(\frac{v + v_o}{v}\right) f \quad \text{......(8.21)}$$

This shows that $f_1 > f$, the apparent frequency of sound increases.

Case II: Observer is moving away from a stationary source

Now the observer is moving away from the stationary source with velocity v_o as shown in Fig.8.29. The relative velocity between observer and source is $v - v_o$ and the numbers of waves received in one second f_2 is given as;

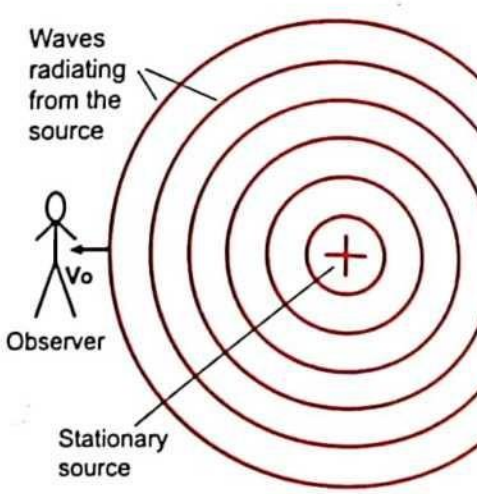


Fig.8.29: Observer is moving away from a stationary source.

$$f_2 = \frac{v - v_o}{\lambda}$$

$$f_2 = \frac{v - v_o}{\frac{v}{f}}$$

$$f_2 = \left(\frac{v - v_o}{v}\right) f \quad ......(8.22)$$

This shows that $f_2 < f$ therefore apparent frequency of sound decreases when the observer is at rest and source is in motion.

Case III: When the source is moving towards the stationary observer

When the source is moving with velocity v_s towards a stationary observer as shown in Fig.8.30. The net velocity is $v - v_s$. In this case, the wavelength λ_3 measured by observer at rest is shorter than the wavelength λ of the source. The waves are compressed and its frequency 'f' remains same, this compression in wavelength is called Doppler shift. It is represented by $\Delta\lambda$.

$$\Delta\lambda = \frac{v_s}{f}$$

Now decrease in wavelength during compression of waves is given as;

$$\Delta\lambda = \lambda - \lambda_3$$

$$\lambda_3 = \lambda - \Delta\lambda$$

$$\lambda_3 = \frac{v}{f} - \frac{v_s}{f}$$

$$\lambda_3 = \frac{v - v_s}{f}$$

As $$v = f_3\lambda_3$$

$$f_3 = \frac{v}{\lambda_3}$$

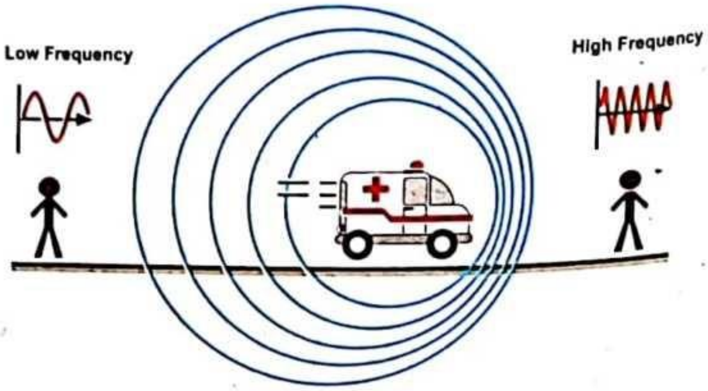


Fig.8.30: Source is in moving towards and moving away from a stationary observer.

$$f_3 = \frac{v}{\frac{v - v_s}{f}}$$

$$f_3 = \left(\frac{v}{v - v_s}\right)f \quad ......(8.23)$$

This shows that $f_3 > f$ thus apparent frequency of sound increases.

Case IV: When the source is moving away from the stationary observer

Similarly, when the sources is moving away from the stationary observer with velocity v_s then the wavelength λ_4 of sound waves increases but its number of waves in one second remains same. In this case the observer measures a wavelength λ_4 that is greater than λ and hears a decreased frequency.
Thus the increase in wavelength is given as;

$$\Delta\lambda = \lambda_4 - \lambda$$

$$\lambda_4 = \Delta\lambda + \lambda$$

$$\lambda_4 = \frac{v_s}{f} + \frac{v}{f} = \frac{v_s + v}{f}$$

$$v = f_4\lambda_4$$

$$f_4 = \frac{v}{\lambda_4}$$

$$f_4 = \frac{v}{\frac{v_s + v}{f}}$$

$$f_4 = \left(\frac{v}{v_s + v}\right)f \quad ......(8.24)$$

BIOPHYSICS

Physicians can detect the speed of the moving heart wall in a fetus by means of Doppler Effect in ultrasound.

POINT TO PONDER

Can you apply Doppler Effect for light wave and source of light?

This shows that $f_4 < f$ therefore, the apparent frequency of the observer increases.

Example 8.6

A train is approaching a station at 108 km h^{-1} sounding a whistle of frequency 1100 Hz. What will be the apparent frequency of the whistle as heard by an observer standing on the platform? What will be the apparent frequency heard by the same observer if the train moves away from the station with the same speed? Speed of sound is taken as 340 ms^{-1}.

Solution:

Speed of sound = v = 340 m s^{-1}

Speed of the train = V_s = 108 km h^{-1} = 30 m s^{-1}

Frequency of the source = f = 1100 Hz

Apparent frequency of the whistle when the train is approaching towards observer = f =?

$$f = \left(\frac{v}{v - v_s}\right) f$$

$$f = \left(\frac{340\,\mathrm{m\,s^{-1}}}{340\,\mathrm{m\,s^{-1}} - 30\,\mathrm{m\,s^{-1}}}\right) 1100\,\mathrm{Hz}$$

$$f = \left(\frac{340\,\mathrm{m\,s^{-1}}}{310\,\mathrm{m\,s^{-1}}}\right) 1100\,\mathrm{Hz}$$

$$f = 1206\,\mathrm{Hz}$$

Apparent frequency of the whistle when the train is moving away from the observer = f =?

$$f = \left(\frac{v}{v + v_s}\right) f$$

$$f = \left(\frac{340\,\mathrm{ms^{-1}}}{340\,\mathrm{ms^{-1}} + 30\,\mathrm{ms^{-1}}}\right) 1100\,\mathrm{Hz}$$

$$f = \left(\frac{340\,\mathrm{ms^{-1}}}{370\,\mathrm{ms^{-1}}}\right) 1100\,\mathrm{Hz}$$

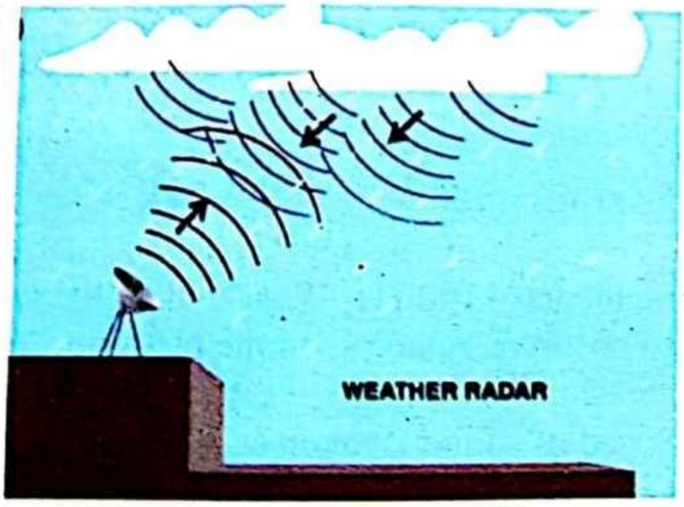
$$f = 1011\,\mathrm{Hz}$$

Applications of the Doppler effect

In addition to sound waves, Doppler effect is also applicable to electromagnetic waves and its some application are summarized as:

(i) The Doppler effect provides a method for tracking a satellite.

Suppose the satellite is emitting a radio signal (i.e., an electromagnetic wave) of constant frequency f_s. The frequency f_L of the signal received on the Earth decreases as the satellite is passing.



The received signal is combined with a constant signal generated in the receiver to produce beat. The beat frequency produces an audible note whose pitch changes as the satellite passes overhead.

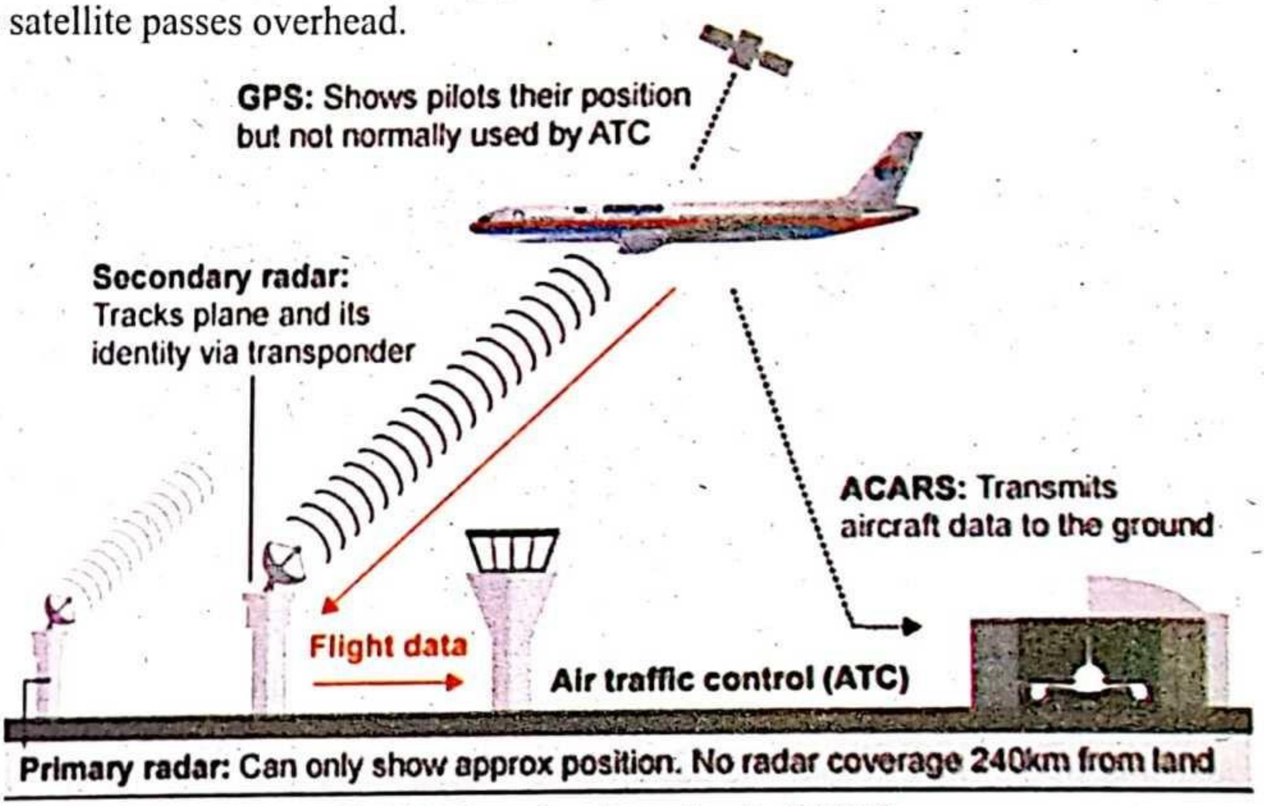


Fig.8.31: Detection of aeroplane by RADAR

Similarly, the radar system uses radio waves to determine the elevation and speed of an aeroplane. Radar is a device, which transmits and receives radio waves. If an aeroplane approaches towards the radar, then the wavelength reflected from aeroplane would be shorter and if it moves away, then the wavelength would be larger as shown in Fig.8.31.

(ii) Sonar is an acronym derived from "sound navigation and ranging". Sonar is the name of the technique for detecting the presence of objects under water by acoustical echo.

In Sonar, "Doppler detection" relies upon the relative speed of the target and the detector to provide an indication of the target speed. It employs the Doppler effect in which an apparent change in frequency occurs when the source and the observer are in relative motion to one another. It is known military applications include the detection and location of submarines, control of antisubmarine weapons, mine hunting and depth measurement of sea.

(iii) Astronomers use the Doppler effect to calculate the speeds of distant stars and galaxies. By comparing the line spectrum of light from the stars with light from a laboratory source, the Doppler shift of the star's light can be measured. Then the speed of the star can be calculated.

(iv) Stars moving towards the Earth show a blue shift. This is because the wavelength of light emitted by the star is shorter than if the star had been at rest. So, the spectrum is shifted towards shorter wavelength, i.e., the blue end of the spectrum as shown in Fig.8.32.

Stars moving away from earth show a red shift. The emitted waves have a longer wavelength than if the star had been at rest. So, the spectrum is shifted towards longer wavelength, i.e., towards the red end of the spectrum as shown in Fig.8.32. Astronomers have also discovered that all the distant galaxies are moving away from us and by measuring their red shifts, they have estimated their speeds.

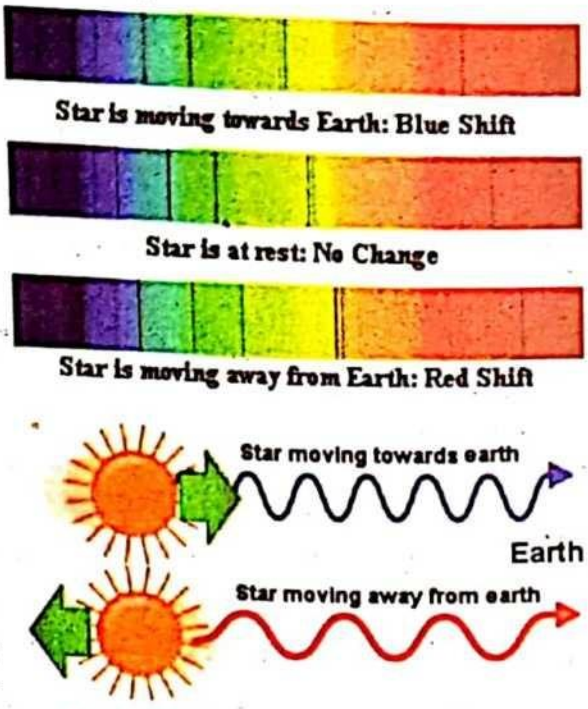


Fig.8.32: Doppler Blue and Red Shift

(v) The Doppler effect is used in measuring the speed of automobile by traffic police. A radar gun is fixed on police car. An electromagnetic signal is emitted by the radar gun in the direction of the automobile whose speed is to be checked. The wave is reflected from the moving automobile and received back.

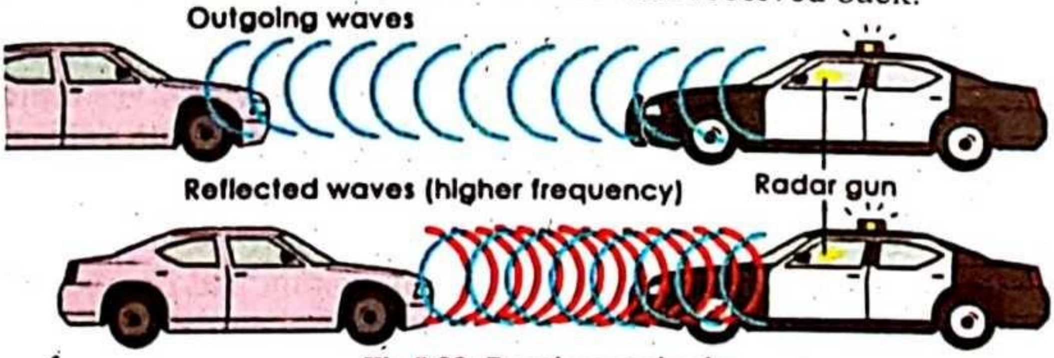


Fig.8.33: Doppler speed radar

The reflected wave is then mixed with the locally generated original signal and beats are produced. The frequency shift is measured using beats and hence the speed of the automobile is determined.

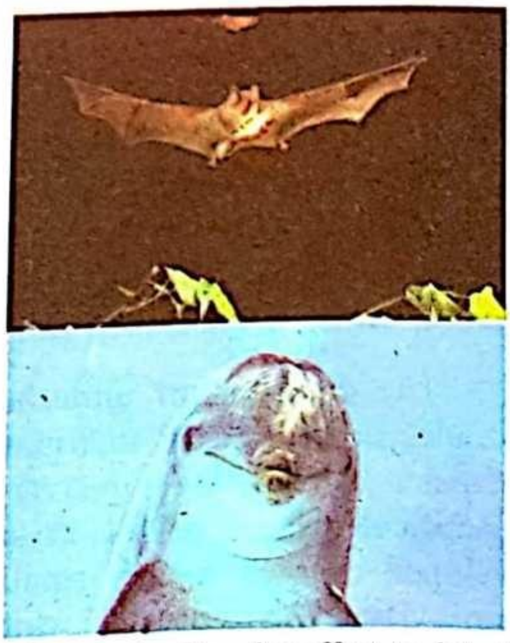
8.10 ULTRASONIC WAVES

Sound waves can be classified into three classes on the basis of their frequencies. That is, the sound which frequency less then 20Hz are called infrasonic waves and it cannot be heard by human ears. Similarly, the waves whose frequency range lie between 20Hz and 20 kHz are known as sonic or audible waves. These waves stimulate the human ear. The sound waves of frequency greater than the upper limit (20 kHz) are called ultrasonic or supersonic. These waves have high frequencies, shortest wavelength and carry much energy. Ultrasonic waves cannot stimulate our ear, but some animals like bats and dogs show response to them. Ultrasonic waves deserve special attention because of its multifarious application in metallurgy, medicines, biology and so many other fields.

There are several methods of generation of ultrasonic vibrations such as, mechanical and thermal but we discuss the electrical method which is named as piezoelectric generator. It was introduced by J and P. Curie in 1880; it is defined as electricity produced by pressure. Now the Piezoelectric method can be explained as; A slice of quartz crystal having regular faces is mounted between the two polished metal plates serving as electrodes. When two opposite faces of a crystal are subjected to pressure (compression or expansion) by the applied forces as shown in Fig.8.34, then there will be equal and opposite charges developed on the two opposite faces of the crystal. The amount of the developed charges is proportional to the subjected pressure. In this way, a potential difference will be developed across these faces. This process is called piezoelectric effect as shown in Fig.8.34.

Conversely, when the two faces of the crystal are subjected to an alternating potential difference as shown in the schematic diagram 8.35, then the crystal set into vibration due to its periodic contraction and expression. The frequency of the vibration is within the ultrasonic range (250Hz – 100000 kHz). This process is called inverse piezoelectric effect.

BIOPHYISCS



Bats use the Doppler effect to detect and catch flying insects. When an insect is flying faster than a bat, the reflected frequency is lower, but when the bat is catching up to the insect, as shown in figure, the reflected frequency is higher this is known as echolocation. This phenomenon is also using by the dolphins and whales to communicate each other and to locate prey. Scientists continue to studying the amazing behavior of dolphins and bats and to use sound waves.

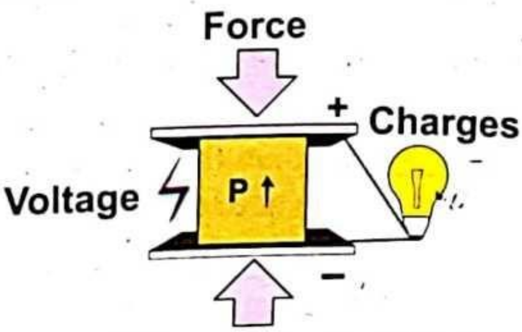


Fig.8.34: A schematic diagram of Piezoelectric effect

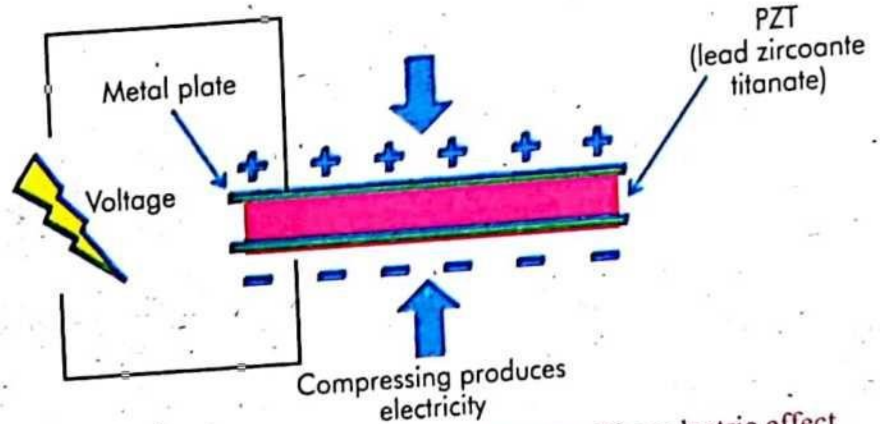


Fig.8.35: A schematic diagram of inverse Piezoelectric effect

The detection of ultrasonic waves can be detected by using the method piezoelectric transducer, that is when the ultrasonic waves fall on the two faces of the quartz crystal, then the varying electric charges are produced on the other perpendicular faces of the crystal as shown in Fig.8.36. The amount of these developed charges is very small but it can be amplified with the help of some means. Thus, this is the way which is being used to detect the ultrasonic waves.

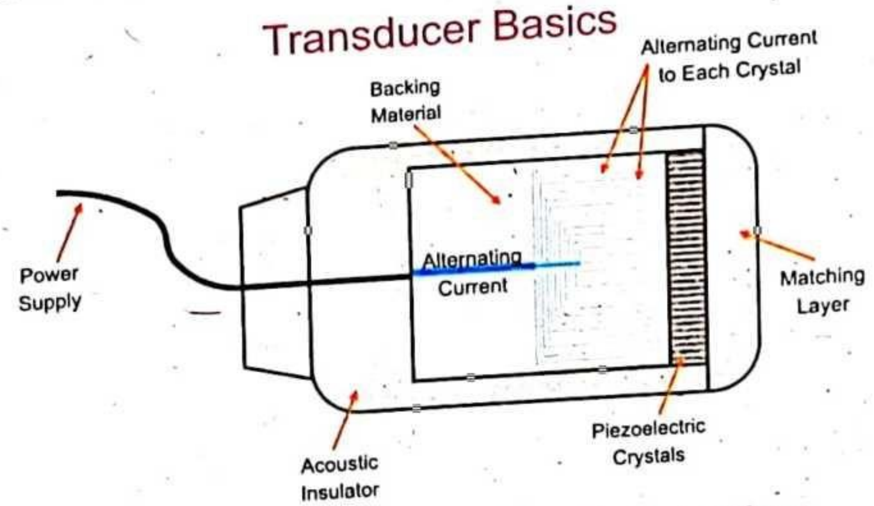


Fig.8.36: A schematic diagram of Piezoelectric transducer

SUMMARY

- **Wave:** A disturbance of medium by a vibrating body which transfers energy from one place to another place is known as wave.
- **Kinds of waves:** There are three kinds of waves, such as mechanical wave, electromagnetic wave and matter wave.
- **Transverse wave**: A wave in which the particles of the medium are vibrating perpendicular to the direction of propagation of wave is called transverse wave such waves consist of crest and trough.

- **longitudinal wave**: A wave in which the particle s of the medium are vibrating parallel to the direction of propagation of wave is called longitudinal wave - such waves consist of compression and rarefaction.
- **Speed of sound**: Speed of sound in air at 0°C is 332 ms^{-1} and it depends upon elasticity, density and temperature of the medium.
- **Principle of superposition:** When two or more waves are travelling in the same medium, their resultant amplitude is equal to the vector sum of all the individual amplitudes. This is called principle of superposition.
- **Interference:** If two or more waves of same frequency travelling in the same direction are superimposed then the amplitude of their resultant wave increases or decreases. This phenomenon is known as interference.
- **Beats:** When two or more waves differing slightly in their frequencies, travelling in the same direction, are superimposed then at regular interval of time the loudness of resulting wave increases or decreases. This phenomenon is known as beats.
- **Stationary waves:** Superposition of two waves of same amplitudes and same frequencies but travelling in the opposite direction are said to form a stationary wave.
- **Doppler's Effect:** The change in the pitch of sound due to the relative motion of the source of sound or the listener is called Doppler's effect.
- **Ultraviolet waves:** The waves with frequency greater than 20kHz are known as ultrasonic waves. These waves cannot be detected by human ears and these can be detected by piezoelectric method.
- **Piezoelectric generator:** A method in which electricity is produced by applying pressure is called piezoelectric and the process of piezoelectric transducer is being used to detect the ultrasonic waves.

EXERCISE

Multiple choice questions.

1. Wave is a mechanism which transmits;
(a) Wavelength (b) Amplitude
(c) Mass (d) Energy

2. The wave which requires a medium for its propagation is known as;
(a) Mechanical waves (b) Electromagnetic waves
(c) Radio waves (d) Light waves

3. Longitudinal wave consists of;
(a) Crests and troughs (b) Compression and rarefactions
(c) Crests and compressions (d) Troughs and rarefactions

4. Transverse wave is different from longitudinal wave, because it possesses a property of
(a) Reflection (b) Interference
(c) Diffraction (d) Polarization

5. Due to high elasticity, the speed of sound is maximum in
(a) Solids (b) Liquids (c) Gases (d) Plazma

6. The speed of sound does not depend upon;
(a) Density (b) Elasticity (c) Temperature (d) Pressure

7. Which of the following phenomenon is based on superposition principle
(a) Interference (b) Standing waves (c) Beats (d) All of these

8. When two waves of same frequency and travelling in the same direction are superimposed than we have
(a) Interference (b) Beats
(c) Standing wave (d) Stationary wave

9. Which one of the following change can be observed in the resultant interference wave?
(a) Amplitude (b) Time period (c) Wavelength (d) Frequency

10. How many beats can be observed when the difference in frequencies of two waves is two;
(a) 1 (b) 2 (c) 3 (d) 4

11. The length between node and antinodes is;
(a) $\frac{\lambda}{4}$ (b) $\frac{\lambda}{2}$ (c) λ (d) 2λ

12. Which one of the following wave does not transmit energy
(a) Mechanical wave (b) Standing wave
(c) Matter wave (d) Electromagnetic wave

13. The ratio of the fundamental frequency of an open ended pipe to a pipe whose one end is closed is;
(a) 1:1 (b) 1:2 (c) 2:1 (d) 1:4

14. The number of quantization frequency of stationary wave in pipe when its one end is closed is;
(a) The whole number (b) Natural number
(c) Even number (d) Odd number

15. When wave is reflected from denser medium to rare medium then there is phase change of;

(a) $\frac{\pi}{4}$ (b) $\frac{\pi}{2}$ (c) π (d) 2π

16. The sound which stimulates our ear is known as;
(a) Sonic (b) Infrasonic (c) Ultrasonic (d) Tidal

17. Which one of the following parameter of a wave does not change when it transmits through two different media
(a) Amplitude (b) Velocity (c) Frequency (d) Wavelength

18. Piezoelectric effect means to produce the electricity by;
(a) Thermal (b) Mechanical (c) Pressure (d) Tidal

SHORT QUESTIONS

1. Distinguish between transverse and longitudinal waves.
2. How can the wavelength of compression wave be measured?
3. Why transverse wave can travel in a liquid?
4. Why does sound travel faster in solids than the gases?
5. How did Laplace correct the formula for the speed of sound in air?
6. What are the mathematical conditions of constructive and destructive interferences?
7. By what factor would you have to multiply the tension in the string to double the wave velocity?
8. Why standing wave cannot transfer energy?
9. What happens to the wavelength of a wave that passes from a spring into another material with (a) Higher linear density (b) Lower linear density?
10. Does interference of two waves involve a loss of energy? Explain.
11. How many numbers of nodes and antinodes are there in a stationary wave vibrating with 'n' number of loops?
12. What do you know about the Doppler shift in wavelength?
13. Why the ear does not stimulate by sound which is produced by a vibrating simple pendulum?

COMPREHENSIVE QUESTIONS

1. Define wave with all its characteristics such as; crest trough, amplitude, wavelength, time period and frequency.
2. Compare transverse and longitudinal periodic waves.
3. What do you know about the speed of sound? Calculate the Newton's formula for the speed of sound.

4. Discuss that how the Newton's formula for speed of sound was corrected by Laplace.
5. Explain the effect of various parameters, pressure, density and temperature on the speed of sound.
6. What is principle of superposition of waves.
7. State and explain interference of sound waves with its two forms such as; constructive interference and destructive interference.
8. What are beats and how they can be produced? Write done the uses of beats.
9. State and explain the reflection of waves from rare and dense media.
10. Explain stationary waves and their formation.
11. Discuss the stationary waves in a stretched string and in a air column.
12. State and explain Doppler effect under various cases and discuss the applications of Doppler effect.

NUMERICAL PROBLEMS

1. A pulse of a transverse wave on a string moves a distance of 15 m in 0.075 s. If the wavelength of transverse wave is 0.8m then; (a) what is the velocity of the pulse? (b) What is the frequency of a periodic wave on the same frequency?
   ($200\ ms^{-1}$, 250 Hz)
2. What is the wavelength of electromagnetic wave when its frequency is 600 kHz and its speed is $3 \times 10^8\ ms^{-1}$? **(500 m)**
3. A steel wire 80 cm long has mass of 8 g. If the wire is under a tension of 110 N, what is the speed of transverse wave in the string? **($105\ ms^{-1}$)**
4. What is the speed of sound in a diatomic ideal gas that has density of 3.50 kg m^{-3} and pressure of 215 K Pa.? The value of 'γ' for diatomic gas is 1.40.
   ($293\ ms^{-1}$)
5. An 80 m long stretched string has a mass per unit length of 9×10^{-3} kg/m with tension of 20 N. When the string is plucked, a stationary wave is set up in the string. Calculate the fundamental frequency and the next three frequencies?
   (0.295 Hz, 0.59 Hz, 0.885 Hz, 1.18 Hz)
6. The fundamental frequency of an open organ pipe 100 cm long is 180 Hz. What is the speed of sound in the pipe? What is the frequency of the second possible overtone of that open pipe? **($360\ ms^{-1}$, 360 Hz)**
7. Calculate the length of a pipe that will resonate in air to a sound source of a fundamental frequency 240 Hz, if the pipe is (a) closed at one end and (b) open at both ends. Take the speed of sound in air to be $340\ ms^{-1}$.
   (35.7 cm, 70.8 cm)

8. Two tuning forks A and B produce 14 beats in 2 seconds. The frequency of the fork 'A' is 512 Hz. When a little wax is attached to the prongs of the fork 'B' the beats disappear. Determine the frequency of fork 'B'. **(519 Hz)**

9. A car travelling at 90 km h^{-1} sounds its horn which has a frequency 800 Hz. What frequency is heard by a stationary distant listener as the car approaches? What frequency is heard after the car has passed? Speed of sound in air is taken as 340 ms^{-1}. **(863.5 Hz, 745 Hz)**

10. Two cars P and Q are travelling along a straight road in the same direction, the leading car P travels at a steady speed of 12 ms^{-1}. The other car Q travelling at steady speed of 20 ms^{-1} sounds its horn to emit a steady note which is estimated by P's driver as a frequency of 830 Hz. What frequency does Q's own driver hear? Speed of sound in air is taken as 340 ms^{-1}. **(810 Hz)**