CHAPTER : 14

WAVE PHENOMENA

You would have noticed that when a stone is dropped into still water in a pond, concentric rings of alternate elevations and depressions emerge out from the point of impact and spread out on the surface of water. If you put a straw piece on the surface of water, you will observe that it moves up and down at its place. Here the particles of water are moving up and down at their places. But still there is something which moves outwards. We call it a *wave.* Waves are of different types : Progressive and stationary, mechanical and electro-magnetic. These can also be classified as longitudinal and transverse depending on the direction of motion of the material particles with respect to the direction of propagation of wave in case of mechnical waves and electric and magnetic vectors in case of e.m. waves. Waves are so intimate to our existence.

Sound waves travelling through air make it possible for us to listen. Light waves, which can travel even through vacuum make us see things and radio waves carrying different signals at the speed of light connect us to our dear ones through differents forms of communication. In fact, wave phenomena is universal.

The working of our musical instruments, radio, T.V require us to understand wave phenomena. Can you imagine the quality of life without waves? In this lesson you will study the basics of waves and wave phenomena.

OBJECTIVES

After studying this lesson, you should be able to :

- *explain propagation of transverse and longitudinal waves and establish the relation* $\upsilon = v\lambda$ *;*
- *write Newton's formula for velocity of longitudinal waves in a gas and explain Laplace's correction;*

- *discuss the factors on which velocity of longitudional waves in a gas depends;*
- *explain formation of transverse waves on stretched strings;*
- *derive the equation of a simple harmonic wave;*
- *explain the phenomena of beats, interference and phase change of waves on the basis of principle of superposition*
- *explain formation of stationary waves and discuss harmonics of organ pipes and stretched strings;*
- *discuss Doppler effect and apply it to mechanical and optical systems;*
- *explain the properties of em waves, and*
- *state wavelength range of different parts of em spectrum and their applications.*

14.1 WAVE PROPAGATION

From the motion of a piece of straw, you may think that waves carry energy; these do not transport mass. A vivid demonstration of this aspect is seen in tidal waves. Do you recall the devastation caused by Tsunami waves which hit Indonesia, Thailand, Sri lanka and India caused by a deep sea quake waves of 20 m height were generated and were responsible for huge loss of life.

To understand how waves travel in a medium let us perform an activity.

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ACTIVITY 14.1

Take a long coiled spring, called slinky, and stretch it along a smooth floor or bench, keeping one end fixed and the other end free to be given movements . Hold the free end in your hand and give it a jerk side–ways.[Fig 14.1(a)]. You will observe that a kink is produced which travels towards the fixed end with definite speed . This kink is a wave of short duration. Keep moving the free end continuously left and right. You will observe a train of pulses ravelling towards the fixed end. This is a *transverse wave* moving through the spring [Fig. 14.1 (b)].

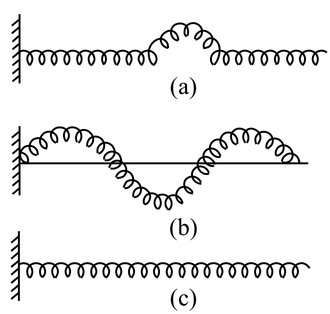

Fig. 14.1 : Wave motion on a slinky (a) pulse on a slinky, (b) transverse wave, and (c) longitudinal Wave

There is another type of wave that you can generate in the slinky . For this keep the slinky straight and give it a push along its length . A pulse of compression thus moves on the spring. By moving the hand backwards and forwards at a constant rate you can see ulternate compressions and rarefactions travelling along its length . These are called *longitudinal waves* [Fig. 14.1(c)].

14.1.1 Propagation of Transverse Waves

Refer to Fig 14.2. It shows a mechanical model for wave propapation. It comprises a row of spherical balls of equal masses, evenly spaced and connected together by identical springs. Let us imagine that by means of suitable device, ball-1, from left, is made to execute S.H.M. in a direction perpendicular to the row of balls with a period T. All the balls, owing to inertia of rest will not begin to oscillate at the same time. The motion is passed on from one ball to the next one by one. Let

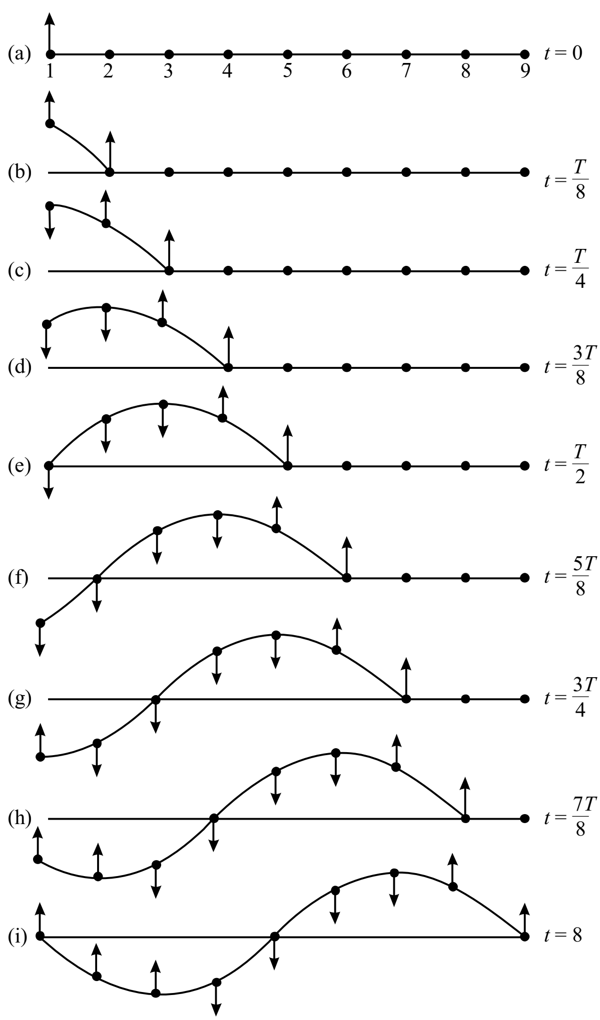

Fig. 14.2 : Instantaneous profiles at intervals of T/8 when a transverse wave is generated on a string.

us suppose that the time taken by the disturbance to travel from one ball to the next is $T/8$s. This means that in the interval $T/8$s, the disturbance propagates from the particle at mark 1 to the particale at mark 2. Similarly, in the next $T/8$ interval, the disturbance travels from the particle at mark 2 to the particle at mark 3 and so on. In parts (a)—(i) in Fig. 14.2 we have shown the instantaneous positions of particles at all nine marked positions at intervals of $T/8$. (The arrows indicate the directions of motion along which particles at various marks are about to move.) You will observe that

(i) At $t = 0$, all the particles are at their respective mean positions.

(ii) At $t = T$, the first, fifth and ninth particles are at their respective mean positions. The first and ninth particles are about to move upward whereas the fifth particle is about to move downward. The third and seventh particles are at position of maximum displacement but on opposite sides of the horizontal axis. The envelop joining the instantaneous positions of all the particles at marked positions in Fig. 14.2(a) are similar to those in Fig. 14.2(i) and represents a *transverse wave.* The positions of third and seventh particles denote a *trough and a crest*, respectively.

The important point to note here is that *while the wave moves along the string, all particles of the string are oscillating up and down about their respective equilibrium positions with the same period* (T) *and amplitude* (A). This wave remains *progressive* till it reaches the fixed end.

In a wave motion, the distance between the two nearest particles vibrating in the same phase is called a wavelength. *It is denoted by λ.*

It is evident that time taken by the wave to travel a distance λ is T. (See Fig. 14.2). Therefore, the velocity of the wave is

$$\upsilon = \frac{\text{Distance}}{\text{Time}} = \frac{\lambda}{T} \qquad (14.1)$$

But, $1/T = \nu$, the frequency of the wave. Therefore,

$$\upsilon = \nu\lambda \qquad (14.2)$$

Further, if two consecutive particles in same state of motion are separated by a distance λ, the phase difference between them is 2π. Therefore, the phase change per unit distance

$$k = \frac{2\pi}{\lambda} \qquad (14.3)$$

We call k the propagation constant. You may recall that ω denotes phase change per unit time. But the phase change in time T is 2π hence

$$\omega = \frac{2\pi}{T} = 2\pi\nu \qquad (14.4)$$

Dividing Eqn. (14.3) by Eqn. (14.4), we get an expression for the wave velocity:

$$\upsilon = \frac{\omega}{k} = \frac{2\pi v}{2\pi/\lambda}$$

or

$$\upsilon = v\lambda \tag{14.5}$$

Let us now explain how the logitudinal waves propagate.

14.1.2 Propagation of a Longitudinal Wave

In longitudinal waves, the displacement of particles is along the direction of wave propagation In Fig. 14.3, the hollow circles represent the mean positions of equidistant particles in a medium. The arrows show their (rather magnified) longitudinal displacements at a given time. You will observe that the arrows are neither equal in length nor in the same direction. This is clear from the position of solid circles, which describe instantaneous positions of the particles corresponding to the heads of the arrows. The displacements to the right are shown in the graph towards + y-axis and displacements to the left towards the $-y$-axis.

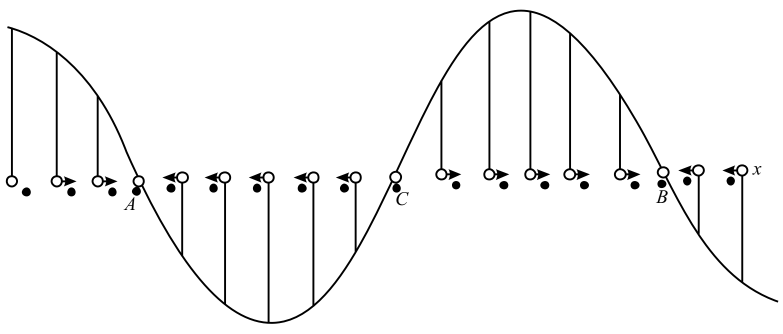

Fig. 14.3 : Graphical representation of a longtudinal wave.

For every arrow directed to the right, we draw a proportionate line upward. Similarly, for every arrow directed to the left, a proportionate line is drawn downward. On drawing a smooth curve through the heads of these lines, we find that the graph resembles the displacement-time curve for a transverse wave. If we look at the solid circles, we note that around the positions A and B, the particles have crowded together while around the position C, they have separated farther. These represent regions of *compression and rarefaction.* That is, there are alternate regions where density (pressure) are higher and lower than average.A sound wave propagating in air is very similar to the longitudinal waves that you can generate on your spring (Fig. 14.4).

Let us now derive equation of a simple harmonic wave.

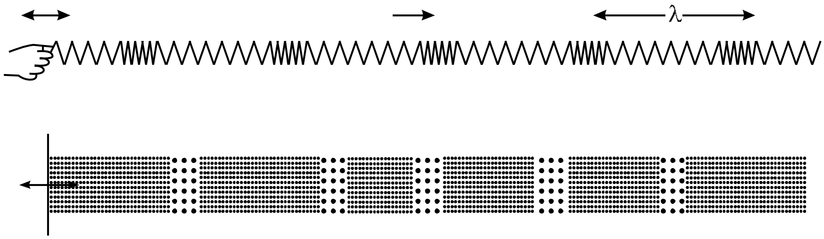

Fig. 14.4 : Longitudinal waves on a spring are analogous to sound waves.

14.1.3 Equation of a Simple Harmonic Wave in One Dimension

Let us consider a simple harmonic wave propagating along OX (Fig. 14.5). We assume that the wave is transverse and the vibrations of the particle are along YOY′. Let us represent the displacement at $t = 0$ by the equation

$$y = a \sin \omega t \qquad (14.6)$$

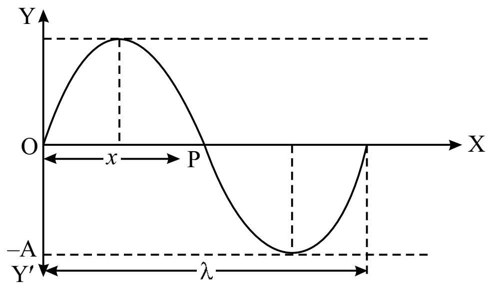

Fig. 14.5 : Simple harmonic wave travelling along x-direction

Then the phase of vibrations at that time at the point P lags behind by a phase, say ϕ. Then

$$y = a \sin (\omega t - \phi) \qquad (14.7)$$

Let us put OP = x. Since phase change per unit distance is k, we can write $\phi = kx$. Hence,

Eqn. (14.7) take the form $\quad y(x, t) = a \sin (\omega t - kx) \qquad (14.8)$

Further as $\omega = 2\pi/t$ and $k = 2\pi/\lambda$, we can rewrite Eqn (14.8) as

$$y\,(x,\, t) = a \sin 2\pi \left(\frac{t}{T} - \frac{x}{\lambda}\right) \qquad (14.9)$$

In terms of wave velocity ($\upsilon = \lambda/T$), this equation can be expressed as

$$y = a \sin \frac{2\pi}{\lambda} (\upsilon\, t - x) \qquad (14.10)$$

In deriving Eqn. (14.8) we have taken initial phase of the wave at O as zero. However, if the initial phase angle at O is ϕ_0, the equation of the wave would be

$$y(x,t) = a \sin [(\omega t - kx) + \phi_0] \qquad (14.11)$$

Phase difference between two points on a wave

Let us consider two simple harmonic waves travelling along OX and represented by the equations

$$y = a \sin (\omega t - kx) \qquad (14.11a)$$

and

$$y = a \sin [\omega t - k(x + \Delta x)] \qquad (14.12)$$

The phase difference between them is

$$\Delta\phi = k\Delta x = \frac{2\pi}{\lambda}\Delta x = -\frac{2\pi}{\lambda}(x_2 - x_1) \qquad (14.13)$$

where Δx is called the path difference between these two points. Here the negative sign indicates that a point positioned later will acquire the same phase at a later time.

Phase difference at the same position over a time interval Δt :

We consider two waves at the same position at a time interval Δt. For the first wave, phase ϕ, is given by

$$\phi_1 = \frac{2\pi}{T}t_1 - \frac{2\pi}{\lambda}x$$

and for the another wave phase

$$\phi_2 = \frac{2\pi}{T}t_2 - \frac{2\pi}{\pi}x.$$

The phase difference between them

$$\Delta\phi = \phi_2 - \phi_1 = \frac{2\pi}{T}(t_2 - t_1)$$

$$= 2\pi\nu(t_2 - t_1) \qquad [14.13(a)]$$

$$= 2\pi\nu(\Delta t)$$

Example 14.1 : A progressive harmonic wave is given by $y = 10^{-4} \sin (100\pi t - 0.1\pi x)$. Calculate its (i) frequency, (ii) wavelength and (iii) velocity y and x are in metre.

Solution: comparing with the standard equation of progressive wave

$$y = A \sin\left(\frac{2\pi t}{T} - \frac{2\pi x}{\lambda}\right)$$

we get (i) $2\pi\nu = 100\,\pi \Rightarrow \nu = 50$ Hz

(ii) $\frac{2\pi}{\lambda} = 0.1\,\pi \Rightarrow \lambda = 20$ m

(iii) $\upsilon = \nu\lambda = 1000$ ms^{-1}

14.1.4 Transverse and Longitudinal Waves

We now consider transverse and longitudinal waves and summerise the difference between them.

Transverse waves	Longitudinal waves
(i) Displacements of the particles are perpendicular to the direction of propagation of the wave.	(i) Displacements of the particles are along the direction of propagation of the wave.
(ii) Transverse waves look as crests and troughs propagating in the medium.	(ii) Longitudinal waves give the appearance of alternate compressions and rarefaction moving forward.
(iii) Transverse waves can only be transmitted in solids or on the surface of the liquids.	(iii) Longitudinal waves can travel in solids, liquids and gases.
(iv) In case of a transverse wave, the displacement - distance graph gives the actual picture of the wave itself.	(iv) In case of longitudinal waves, the graph only represents the displacement of the particles at different points at a given time.

Essential properties of the medium for propagation of longitudinal and transverse mechanical waves are: (i) the particles of the medium must possess mass, (ii) the medium must possess elasticity. Longitudinal waves for propagation in a medium require volume elasticity but transverse waves need modulus of rigidity. However, light waves and other electromagnetic waves, which are transverse, do not need any material medium for their propagation.

INTEXT QUESTIONS 14.1

1. State the differences between longitudinal and transverse waves?
2. Write the relation between phase difference and path difference.
3. Two simple harmonic waves are represented by equations $y_1 = a \sin(\omega t - kx)$ and $y_2 = a \sin[(\omega t - kx) + \phi]$. What is the phase difference between these two waves?

14.2 VELOCITY OF LONGITUDINAL AND TRANSVERSE WAVES IN AN ELASTIC MEDIUM

14.2.1 Newton's Formula for Velocity of Sound in a Gas

Newton to derive a relation for the velocity of sound in a gaseous medium, assumed that compression and rarefaction caused by the sound waves during their passage through the gas take place under isothermal condition. This means that the changes in volume and pressure take place at constant temperature. Under such conditions, Newton agreed that the velocity of sound wave in a gas is given by

$$\upsilon = \sqrt{\frac{P}{\rho}} \tag{14.15}$$

For air, at standard temperature and pressure $P = 1.01 \times 10^5$ Nm^{-2} and $\rho = 1.29$ kg m^{-3}. On substituting these values in Eqn.(14.15) we get

$$\upsilon = \sqrt{1.01 \times 10^5 / 1.29} = 280 \text{ ms}^{-1}$$

Clouds collide producing thunder and lightening, we hear sound of thunder after the lightening. This is because the velocity of light is very much greater than the velocity of sound in air. By measuring the time interval between observing the lightening and hearing the sound, the velocity of sound in air can be determined. Using an improved technique, the velocity of sound in air has been determined as 333 ms^{-1} at 0^0C. The percent error in the value predicted by Newton's formula and that determined experimentally is $\frac{333-280}{333} \times 100\% = 16\%$. This error is too high to be regarded as an experimental error. Obviously there is something wrong with Newton's assumption that during the passage of sound, the compression and the rarefaction of air take place isothermally.

14.2.2 Laplace's Correction

Laplace pointed out that the changes in pressure of air layers caused by passage of sound take place under adiabatic condition owing to the following reasons.

(i) Air is bad conductor of heat and

(ii) Compression and rarefactions caused by the sound are too rapid to permit heat to flow out during compression and flow in during rarefaction.

Under adiabatic conditions

$$E = \gamma P,$$

Where

$$\gamma = \frac{C_p}{C_v}$$

Hence, $$v = \sqrt{\frac{\gamma P}{\rho}} \qquad (14.16)$$

For air, $\gamma = 1.4$. Therefore, at STP, speed of sound is given by

$$v = \sqrt{1.4 \times 1.01 \times 10^5 / 1.29}$$

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

This value is very close to the experimentally observed value.

14.2.3 Factors affecting velocity of sound in a gas

(i) Effect of Temperature

From Laplace's formula

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

Since density is ratio of mass perumit volume, this expression takes the form

$$= \sqrt{\frac{\gamma PV}{M}}$$

Using the equation of state PV = nRT, where n is number of moles in mass m of the gas

$$v = \sqrt{\frac{\frac{\gamma RT}{M}}{n}}$$

$$= \sqrt{\frac{\gamma RT}{m}} \qquad (14.17\text{ a})$$

Where m denotes the gram molecular mass. This result shows that

$$v \; \alpha \; \sqrt{T}$$

$$\Rightarrow \qquad v = v\text{o} \left(1 + \frac{t}{2 \times 273}\right) + ...$$

$$\simeq 333 + \frac{333}{546} t$$

$$\simeq 333 + 0.61t \qquad (14.17\text{b})$$

Note that for small temperature variations, velocity of sound in air increases by 0.61 ms^{-1} with every degree celsius rise in temperature.

(*ii*) Effect of pressure

When we increase pressure on a gas, it gets compressed but its density increases in the same proportion as the pressure i.e. P/ρ remains constant. It means that, pressure has no effect on the velocity of sound in a gas.

(*iii*) Effect of density

If we consider two gases under identical conditions of temperature and pressure, then

$$\upsilon \;\alpha\; \frac{1}{\sqrt{\rho}}$$

If we, compare the velocities of sound in oxygen and hydrogen, we get

$$\frac{\upsilon_{\text{oxygen}}}{\upsilon_{\text{hydrogen}}} = \sqrt{\frac{\rho_{\text{hydrogen}}}{\rho_{\text{oxygen}}}} = \sqrt{\frac{M_{\text{hydrogen}}}{M_{\text{oxygen}}}} = \sqrt{\frac{2}{32}} = \frac{1}{4}$$

This shows that velocity of sound in hydrogen is 4 times the velocity of sound in oxygen under identical conditions of temperature and pressure. Is this result valid for liquids and solids as well. You will discover answer to this question in the next sub–section.

(*iv*) Effect of humidity on velocity of sound in air

As humidity in air increases (keeping conditions of temperature and pressure constant), its density decreases and hence velocity of sound in air increases.

Example 14.2 : At what temperature is the speed of sound in air double of its value at S.T.P.

Solution : We know that $\frac{\upsilon}{\upsilon_0} = \sqrt{\frac{T}{m}} = 2 = \sqrt{\frac{T}{273}}$

On squaring both sides and rearranging terms, we get

$\therefore$ $$T = 273 \times 4 = 1092\text{k}$$

14.2.4 Velocity of Waves in Stretched Strings

The velocity of a transverse wave in a stretched string is given by

$$\upsilon = \sqrt{\frac{F}{m}} \qquad (14.18\text{ a})$$

Where F is tension in the string and *m* is mass per unit length of the wire. The velocity of longtudinal waves in an elastic medium is given by

$$\upsilon = \sqrt{E/\rho} \qquad (14.18\text{b})$$

where E is elasticity. It may be pointed out here that since the value of elasticity is more in solids, the velocity of longitudinal waves in solids is greater than that in gases and liquids. In fact, $\upsilon_g < \upsilon_\ell < \upsilon_s$.

INTEXT QUESTIONS 14.2

1. What was the assumption made by Newton in deriving his formula?
2. What was wrong with Newton's formula?
3. Show that for every 1^0C rise in temperature, the velocity of sound in air increases by 0.61 ms^{-1}.
4. Calculate the temperature at which the velocity in air is (3/2) times the velocity of sound at 7^0C?
5. Write the formula for the velocity of a wave on stretched string?
6. Let λ be the wavelength of a wave on a stretched string of mass per unit length *m* and *n* be its frequency. Write the relation between *n*, λ, *F* and *m*? Further if $\lambda = 2\ell$, what would be the relation between *n*, *l*, *F* and *m*?

14.3 SUPERPOSITION OF WAVES

Suppose two wave pulses travel in opposite directions on a slinky. What happens when they meet? Do they knock each other out? To answer these questions, let us perform an activity.

ACTIVITY 14.2

Produce two wave crests of different amptitudes on a stretched slinky, as shown in Fig. 14.6 and watch carefully. The crests are moving in the opposite directions. They meet and overlap at the point midway between them [Fig. 14.6(b)] and then separate out. Thereafter, they continue to move in the same direction in which they were moving before crossing each other. Moreover, their shape also does not change [Fig. 14.6(c)].

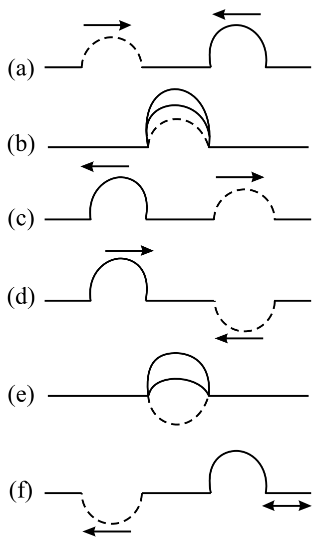

Fig. 14.6 : Illustrating principle of superpositionof waves

Now produce one crest and one trough on the slinky as shown in Fig. 14.6(d). The two are moving in the opposite direction. They meet [Fig. 14.6(e)], overlap and then separate out. Each one moves in the same direction in which it was moving before crossing and each one has the same shape as it was having before crossing. Repeat the experiment again and observe carefully what happens at the spot of overlapping of the two pulses [(Fig. 14.6(b) and (e)].

You will note that when crests overlap, the resultant is more and when crest overlaps the through, the resultant is on the side of crest but smaller size.We may summarize this result as : *At the points where the two pulses overlap, the resultant displacement is the vector sum of the displacements due to each of the two wave pulses.* ***This is called the principle of superposition.***

This activity demonstrates not only the principle of superposition but also shows that two or more waves can traverse the same space independent of each other. Each one travels as if the other were not present. This important property of the waves enable us to tune to a particular radio station even though the waves broadcast by a number of radio stations exist in space at the same time. We make use of this principle to explain the phenomena of *interference of waves, formation of beats and stationary or standing waves.*

14.3.1 Reflection and Transmission of Waves

We shall confine our discussion in respect of mechanical waves produced on strings and springs. What happens and why does it happen when a transverse wave crest propagates towards the fixed end of a string? Let us perform the following activity to understand it.

ACTIVITY 14.3

Fasten one end of a slinky to a fixed support as shown in (Fig. 14.7 (a). Keeping the slinky horizontal, give a jerk to its free end so as to produce a transverse wave pulse which travells towards the fixed end of the slinky (Fig. 14.7(a)). You will observe that the pulse bounces back from the fixed end. As it bounces back, the crest becomes a trough travels back in the opposite direction. Do you know the reason? As the pulse meets the fixed end, it exerts a force on the support. The equal and opposite reaction not only reverses the direction of propagation of the wave pulse but also reverses the direction of the displacement of the wave pulse (Fig. 14.7(b)). The support being much heavier than the slinky, it can be regarded as a denser medium. The wave pulse moving in the opposite direction is called the reflected wave pulse. So, we can say that ***when reflection takes place from a denser medium, the wave undergoes a phase change of π, that is, it suffers a phase reversal.***

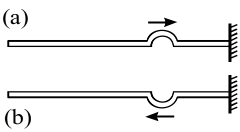

Fig. 14.7 : Reflection from a denser medium : a phase reversal.

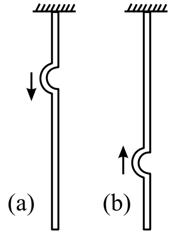

Fig.14.8(a) : A pulse travelling down towards the free end, (b) on reflection from the free end direction of its displacement remains unchanged

Let us now see what happens on reflection from a rarer medium. For this we perform another activity.

ACTIVITY 14.4

Suspend a fixed rubber tube from a rigid support (Fig. 14.8 a). Then generate a wave pulse travelling down the tube. On reflection from the free end, the wave pulse travels upward but without any change in the direction of its displacements i.e. crest returns as crest. Why? As the wave pulse reaches the free end of the tube, it gets reflected from a rarer boundary. (Note that air is rarer than the rubber tube.) Hence there is no change in the direction of displacement of the wave pulse. ***Thus on reflection from a rarer medium, no phase change takes place.***

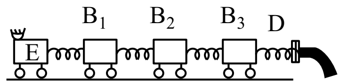

Fig. 14.9 : Longitudinal waves are reflected from a denser medium without change of type but with change of sign

You may now raise the question : Do longitudinal waves also behave similarly? Refer to Fig. 14.9, which shows a row of bogies. Now suppose that the engine E moves a bit towards the right. The buffer spring between the engine E and the first bogie gets compressed and pushes bogie B_1 towards the right. It then tries to go back to its original shape. As this compressed spring expands, the spring between the 1st and the 2nd bogie gets compressed. As the second compressed spring expands, it moves a bit towards the 3rd bogie. In this manner the compression arrives at the last buffer spring in contact with the fixed stand D. As the spring between the fixed stand and the last bogie expands, only the last bogie moves towards the left. As a result of this, the buffer spring between the next two bogies on left is compressed. This process continues, till the compression reaches between the engine and the first bogie on its right. Thus, a compression returns as a compression. But the bogies then move towards the left. In this mechanical model, the buffer spring and the bogies form a medium. The bogies are the particles of the medium and the spring between them shows the forces of elasticity.

Thus, when reflection takes place from a denser medium, the longitudinal waves are reflected without change of type but with change in sign. And on reflection from a rare medium, a longitudinal wave is reflected back without change of sign but with change of type. By 'change of type' we mean that rarefaction is reflected back as compression and a compression is reflected back as rarefaction.

INTEXT QUESTIONS 14.3

1. What happens when two waves travelling in the opposite directions meet?
2. What happens when two marbles each of the same mass travelling with the same velocity along the same line meet?

3. Two similar wave pulses travelling in the opposite directions on a string meet. What happens (i) when the waves are in the same phase? (ii) the waves are in the opposite phases?

4. What happens when a transverse wave pulse travelling along a string meets the fixed end of the string?

5. What happens when a wave pulse travelling along a string meets the free end of the string?

6. What happens when a wave of compression is reflected from (i) a rarer medium (ii) a denser medium?

14.4 SUPERPOSITION OF WAVES TRAVELLING IN THE SAME DIRECTION

Superposition of waves travelling in the same direction gives rise to two different phenomena (i) interference and (ii) beats depending on their phases and frequencies. Let us discuss these phenomena now.

14.4.1 Interference of waves

Let us compute the ratio of maximum and minimum intensities in an interference pattern obtained due to superposition of waves. Consider two simple harmonic waves of amplitudes a_1 and a_2 each of angular frequency ω, both propagating along $x-axis$, with the same velocity $\upsilon = \omega/k$ but differing in phase by a constant phase angle ϕ. These waves are represented by the equations

$$y_1 = a_1 \sin(\omega t - kx)$$

and

$$y_2 = a_2 \sin[(\omega t - kx) + \phi]$$

where $\omega = 2\pi/T$ is angular frequency and $k = \frac{2\pi}{\lambda}$ is wave number.

Since, the two waves are travelling in the same direction with the same velocity along the same line, they overlap. According to the principle of superposition, the resultant displacement at the given location at the given time is

$$y = y_1 + y_2 = a_1 \sin(\omega t - kx) + a_2 \sin[(\omega t - kx) + \phi]$$

If we put $(\omega t - kx) = \theta$, then

$$y = a_1 \sin\theta + a_2 \sin(\theta + \phi)$$

$$= a_1 \sin\theta + a_2 \sin\theta \cos\phi + a_2 \sin\phi \cos\theta$$

Let us put $\quad a_2 \sin\phi = A \sin\alpha$

and $\quad a_1 + a_2 \cos\phi = A \cos\alpha$

Then

$$y = A\cos\alpha \sin\theta + A \sin\alpha\cos\theta$$
$$= A \sin(\theta + \alpha)$$

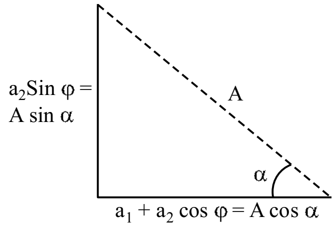

Fig. 14.10 : Calculating resultant amplitude A

Substituting for θ we get

$$y = A \sin [(\omega t - kx) + \alpha]$$

Thus, the resultant wave is of angular frequency ω and has an amplitude A given by

$$A^2 = (a_1 + a_2 \cos\phi)^2 + (a_2 \sin\phi)^2$$

$$= a_1^2 + a_2^2 \cos^2\phi + 2a_1a_2 \cos\phi + a_2^2 \sin^2\phi$$

$$A^2 = a_1^2 + a_2^2 + 2\, a_1a_2\cos\phi \qquad (14.18)$$

In Eqn. (14.18), ϕ is the phase difference between the two superposed waves. If path difference, between the two waves corresponds to phase difference ϕ, then

$\phi = \dfrac{2\pi p}{\lambda}$, where $\dfrac{2\pi}{\lambda}$ is the phase change per unit distance.

When the path difference is an even multiple of $\dfrac{\lambda}{2}$, *i.e.*, $p = 2m\dfrac{\lambda}{2}$, then phase difference is given by $\phi = (2\pi/\lambda) \times (2m\,\lambda/2) = 2m\pi$. Since $\cos 2\pi = +1$, from Eqn. (14.18) we get

$$A^2 = a_1^2 + a_2^2 + 2a_1a_2 = (a_1 + a_2)^2$$

That is, when the collinear waves travelling in the same directions are in phase, the amplitude of the resultant wave on superposition is equal to sum of individual amplitudes.

As intensity of wave at a given position is directly proportional to the square of its amplitude, we have

$$I_{max} \propto (a_1 + a_2)^2$$

When $p = (2m + 1)\,\lambda/2$, then $\phi = (2m + 1)\,\pi$ and $\cos\phi = -1$. Then from Eqn. (14.18),

we get
$$A^2 = a_1^2 + a_2^2 - 2a_1a_2 = (a_1 - a_2)^2$$

This shows that when phases of two collinear waves travelling in the same direction differ by an odd integral multiple of π, the amplitude of resultant wave generated by their superposition is equal to the difference of their individual amplitudes.

Then $I_{min} \propto (a_1 - a_2)^2$

Thus $$\frac{I_{max}}{I_{min}} = \frac{(a_1 + a_2)^2}{(a_1 - a_2)^2} \quad (14.19)$$

If $a_1 = a_2$, the intensity of resultant wave is zero. These results show that interference is essentially redistribution of energy in space due to superposition of waves.

14.4.2 Beats

We have seen that superposition of waves of same frequency propagating in the same direction produces interference. Let us now investigate what would be the outcome of superposition of waves of nearly the same frequency. First let us perform an activity.

ACTIVITY 14.5

Take two tuning forks of same frequency 512 Hz. Let us name them as A and B. Load the prong of the tuning fork B with a little wax. Now sound them together by a rubber hammer. Press their stems against a table top and note what you observe. You will observe that the intensity of sound alternately becomes maximum and minimum. These alternations of maxima and minima of intensity are called beats. One alternation of a maximum and a minimum is one beat. On loading the prong of B with a little more wax, you will find that no. of beats increase. On further loading the prongs of B, no beats may be heard. The reason is that our ear is unable to hear two sounds as separate produced in an interval less than one tenths of a second. Let us now explain how beats are produced.

(a) Production of beats : Suppose we have two tuning forks A and B of frequencies N and N + n respectively; n is smaller than 10. In one second, A completes N vibrations but B completes N + n vibrations. That is, B completes n more vibrations in one second than the tuning fork A. In other words, B gains n vibrations over A in 1s and hence it gains 1 vib. in (1/n) s. and half vibration over A in (1/2n) s. Suppose at $t = 0$, i.e. initially, both the tuning forks were vibrating in the same phase. Then after (1/2n)s, B will gain half vibration over A. Thus after $\frac{1}{2n}s$ it will vibrate in oposite phase. If A sends a wave of compression then B sends a wave of rarefaction to the observer. And, the resultant intensity received by the ear would be zero. After (1/n)s, B would gain one complete vibration. If now A sends a wave of compression, B too would send a wave of compression to the observer. The intensity observed would become maximum. After (3/2n)s, the two forks again vibrate in the opposite phase and hence the intensity would again become minimum. This process would continue. The observer would hear 1 beat in (1/n)s, and hence n beats in one second. Thus, the *number of beats heard in* *one second equals the difference in the frequencies of the two tuning forks.* If more than 10 beats are produced in one second, the beats are not heard as separate. The beat frequency is n and beat period is $1/n$.

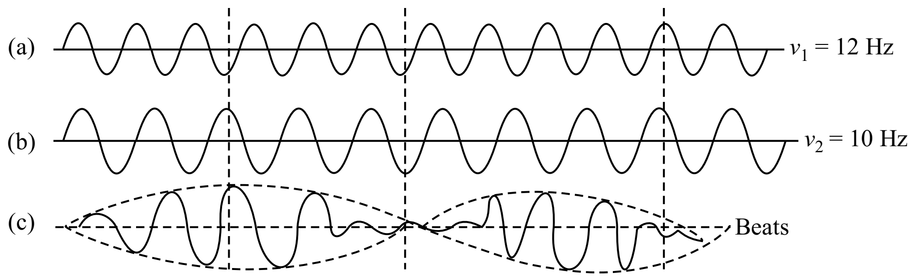

Fig.14.11 : (**a**) Displacement time graph of frequency 12 Hz. (**b**) displacement time graph of frequency 10 Hz. Superposition of the two waves produces 2 beats per second.

(b) Graphic method : Draw a 12 cm long line. Divide it into 12 equal parts of 1 cm. On this line draw 12 wavelengths each 1 cm long and height 0.5 cm. This represents a wave of frequency 12 Hz. On the line (b) draw 10 wavelengths each of length 1.2 cm and height 0.5 cm. This represents a wave of frequency 10Hz. (c) represents the resultant wave. Fig, 14.11 is not actual waves but the displacement time graphs. Thus, the resultant intensity alternately becomes maximum and minimum. The number of beats produced in one second is Δv. Hence, the beat frequency equals the difference between the frequencies of the waves superposed.

Example 14.3 : A tuning fork of unknown frequency gives 5 beats per second with another tuning of 500 Hz. Determine frequency of the unknown fork.

Solution : $v' = v \pm n = 500 \pm 5$

$\Rightarrow$ The frequency of unknown tuning fork is either 495 Hz or 505 Hz.

Example 14.4 : In an interference pattern, the ratio of maximum and minimum intensities is 9. What is the amplitude ratio of the superposing waves?

Solution : $\frac{I_{max}}{I_{min}} = \left(\frac{a_1 + a_2}{a_1 - a_2}\right)^2 \Rightarrow 9 = \left(\frac{1+r}{1-r}\right)^2$, where $r = \frac{a_2}{a_1}$.

Hence, are can write

$$\frac{1+r}{1-r} = 3$$

You can easily solve it to get $r = \frac{1}{2}$, i.e., amplitude of one wave is twice that of the other.

INTEXT QUESTIONS 14.4

1. If the intensity ratio of two waves is 1:16, and they produce interference, calculate the ratio I_{max}/I_{min}?
2. Waves of frequencies v and $v + 4$ emanating from two sources of sound are superposed. What will you observe?
3. Two waves of frequencies v and $v + \Delta v$ are supperposed, what would be the frequency of beats?
4. Two tuning forks A and B produce 5 beats per second. On loading one prong of A with a small ring, again 5 beats per second are produced. What was the frequency of A before loading if that of B is 512 Hz. Give reason for your answer.

14.5 SUPERPOSITION OF WAVES OF SAME FREQUENCY TRAVELLING IN THE OPPOSITE DIRECTIONS

So far we have discussed superposition of collinear waves travelling in the same direction. In such waves, crests, and troughs or rarefactions and compressions in a medium travel forward with a velocity depending upon the properties of the medium. Superposition of progressive waves of same wavelength and same amplitude travelling with the same speed along the same line in a medium in opposite direction gives rise to stationary or standing waves. In these waves crests and troughs or compressions and rarefactions remain stationary relative to the observer.

14.5.1 Formation of Stationary (Standing) Waves

To understand the formation of stationary waves, refer to Fig. 14.12 where we have shown the positions of the incident, reflected and resultant waves, each after T/4s, that is, after quarter of a period of vibration.

(i) Initially, at $t = 0$, [Fig. 14.12(i)], the incident wave, shown by dotted curve, and the reflected wave, shown by dashed curve, are in the opposite phases. Hence the resultant displacement at each point is zero. All the particles are in their respective mean positions.

(ii) At $t = T/4$s [Fig. 14.12(ii)], the incident wave has advanced to the right by $\lambda/4$, as shown by the shift of the point P and the reflected wave has advanced to the left by $\lambda/4$ as shown by the shift of the point P′. The resultant wave form has been shown by the thick continuous curve. It can be seen that the resultant displacement at each point is maximum. Hence the particle velocity at each point is zero and the strain is maximum

(iii) At t = T/2s [Fig. 14.12(iii)], the incident wave advances a distance λ/2 to the right as shown by the shift of the point P and the reflected wave advances a distance λ/2 to the left as shown by the shift of the point P′. At each point, the displacements being in the opposite directions, have a zero resultant shown by a thick line.

(iv) At t = 3T/4s [Fig. 14.12(iv)], the two waves are again in the same phase. The resultant displacement at each point is maximum. The particle velocity is zero but the strain is maximum possible.

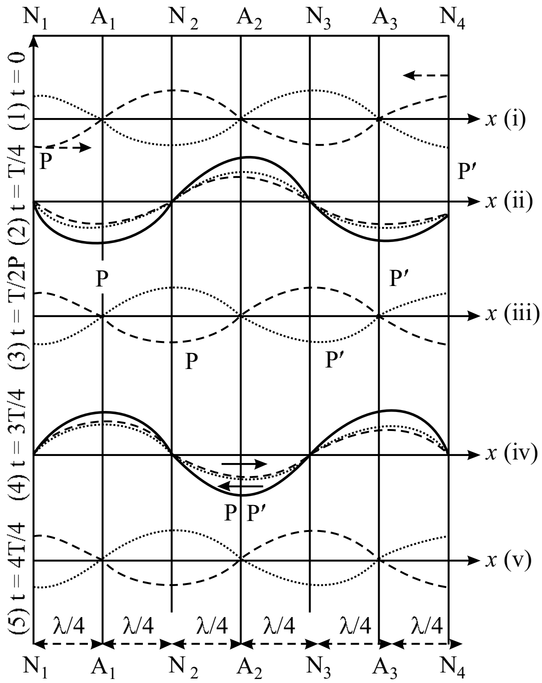

Fig. 14.12 : Showing formation of stationary waves due to superposition of two waves of same wave length, same amplitude travelling in opposite direction along the same line.

(v) At t = 4T/4s [Fig. 14.12(v)], the incident and reflected waves at each point are in the opposite phases. The resultant is a straight line (shown by an unbroken thick line). The strain $\Delta y/\Delta x$ at each point is zero.

Note that

- at points N_1, N_2, N_3 and N_4, the amplitude is zero but the strain is maximum. Such points are called **nodes;**
- at points A_1, A_2 and A_3, the amplitude is maximum but the strain is minimum. These points are called **antinodes;**
- the distance between two successive nodes or between two, successive antinode is λ/2;
- the distance between a node and next antinode is λ/4;
- the time period of oscillation of a stationary wave equals the time period of the two travelling waves whose superposition has resulted in the formation of the stationary wave; and
- the energy alternately surges back and forth about a point but on an average, the energy flow past a point is zero.

Superposition of two identical collinear waves travelling with the same speed in opposite directions leads to formation of stationary waves. They are called stationary waves, because the wave form does not move forward, but alternately shrinks and dilates. The energy merely surges back and forth and on an average, there is no net flow of energy past a point.

14.5.2 Equation of Stationary Wave

The equation of a simple harmonic wave travelling with velocity $\upsilon = \omega/k$ in a medium is

$$y_1 = -\, a \sin(\omega t - kx)$$

On reflection from a denser medium, suppose the wave travels along the same line along X–axis in the opposite direction with phase change of π. The equation of the reflected wave is therefore,

$$y_2 = a \sin(\omega t - kx)$$

Thus, owing to the superposition of the two waves, the resultant displacement at a given point and time is

$$\begin{aligned} y &= y_1 + y_2 \\ &= a \sin(\omega t - kx) - a \sin(\omega t - kx) \end{aligned}$$

Using the trigonometric identity. sin A – sin B = 2 Sin (A – B)/2, cos (A + B)/2, above expression simplifies to

$$y = -2a \sin kx \cos \omega t \qquad (14.20)$$

Let us put $-2a \sin kx = \text{A}$. Then we can write

$$y = \text{A} \cos \omega t$$

Eqn. (14.20) represents a resultant wave of angular frequency ω and amplitude $2a \sin kx$ This is the equation of stationary wave. The amplitude of the resultant wave, oscillates in space with an angular frequency ω, which is the phase change per metre. At such points where $kx = m\,\pi = m\lambda/2$, $\sin kx = \sin m\pi = 0$. Hence $\text{A} = 0$,

The points where the amplitude is zero are referred to as **nodes.** At these points $\Delta y/\Delta x$ = maximum, that is strain is maximum. Obviously, the spacing between two nearest points is $\lambda/2$.

At those points where

$$kx = (2m + 1)\,\pi/2 \text{ or } x = (2m + 1)\,\lambda/2 \times \lambda/2\pi = (2m + 1)\,\lambda/4$$

$$\text{Sin } kx = \sin(2m + 1)\,\pi/2 = \pm 1.$$

Hence, A is maximum. At these points the strain $\Delta y/\Delta x$ is zero. Obviously the spacing between two such neighbouring points is $\lambda/2$. These points where the amplitude is maximum but strain is zero are referred to as **antinodes.**

It may be pointed out here that at nodes, the particle velocity is zero and at antinodes, particle velocity $\Delta y/\Delta t$ is maximum. Therefore, it follows that the average flow of energy across any point is zero. The energy merely surges back and forth. That is why, these waves have been named stationary or standing waves.

14.5.3 Distinction between Travelling and Standing Waves

Let us summarise the main differences between travelling and standing waves.

Travelling Waves	Standing Waves
1. Particular conditions of the medium namely crests and troughs or compressions and rarefactions appear to travel with a definite spped depending on density and elasticity (or tension) of the medium.	Segments of the medium between two points called nodes appear to contract and dialate. Each particule or element of the medium vibrates to and fro like a pendulum.
2. The amplitude of vibration of all the particles is the same.	At nodes the amplitude is zero but at antinodes the amplitude is maximum.
3. All the particles pass through their mean positions with maximum velocity one after the other.	At nodes the particle velocity is zero and at antinodes it is maximum.
4. Energy is transferred from particle to particle with a definite speed.	The energy surges back and forth in a segment but does not move past a point.
5. In a travelling wave the particles attain their maximum velocity one after the other.	In a stationary wave the maximum velocity is different at different points. It is zero at nodes but maximum at antinodes. But all the particles attain their respective maximum velocity simultaneously.
6. In a travelling wave each region is subjected to equal strains one after the other.	In case of standing waves strain is maximum at nodes and zero at antinodes.
7. There is no point where there is no change of density.	Antinodes are points of no change of density but at nodes there is maximum change of density.

INTEXT QUESTIONS 14.5

1. Does energy flow across a point in case of stationary waves? Justify your answer.

2. What is the distance between two successive nodes, and between a node and next antinode?

3. Pressure nodes are displacement antinodes and pressure antinodes are displacement nodes. Explain.

4. Stationary waves of frequency 170Hz are formed in air. If the velocity of the waves is 340 ms^{-1}, what is the shortest distance between (i) two nearest nodes (ii) two nearest antinode (iii) nearest node and antinode?

14.6 CHARACTERISTICS OF MUSICAL SOUND

The characteristics of musical sounds help us to distinguish one musical sound from another.

These are pitch, londness and quality. We will now discuss these briefly.

14.6.1 Pitch

The term pitch is the characteristic of musical notes that enables us to classify a note as 'high' or 'low'. It is a subjective quantity which cannot be measured by an instrument. It depends on frequency. However, there does not exist any one-to-one correspondence between the two. A shrill, sharp or acute sound is said to be of high pitch. But a dull, grave and flat note is said to be of low pitch. Roaring of lion, though of high intensity, is of low pitch. On the other hand, the buzzing of mosquito, though of low intensity, is of high pitch.

14.6.2 Loudness

The loudness of sound is a subjective effect of intensity of sound received by listeners ear. The *intensity of waves is the average amount of energy transported by the wave per unit area per second normally across a surface at a given point.* There is a large range of intensities over which the ear is sensitive. As such, logarithmic scale rather than arithmetic intensity scale is more convenient.

Threshold of hearing and Intensity of Sound

The intensity level β of a sound wave is defined by the equation.

$$\beta = 10 \log I/I_0 \qquad (14.21)$$

where I_0 is arbitrarily chosen reference intensity, taken as 10^{-12} Wm^{-2}. This value corresponds to the faintest sound that can be heard. Intensity level is expressed in decibels, abbreviated *db*. If the intensity of a sound wave equals I_0 or 10^{-12} Wm^{-2}, its intensity level is then $I_0 = 0$ *db*. Within the range of audibility, sensitivity of human ear varies with frequency. ***The threshold audibility at any frequency is the minimum intensity of sound at that frequency, which can be detected.***

The standard of perceived loudness is the ***sone.*** A sone is the loudness experienced by a listener with normal hearing when 1kilo hertz tone of intensity 40db is presented to both ears.

The range of frequencies and intensities to which ear is sensitive have been represented in a diagram in Fig. 14.13, which is in fact a graph between frequency in hertz versus intensity level 1 in decibels. This is a graph of auditory area of good hearing. The following points may be noted.

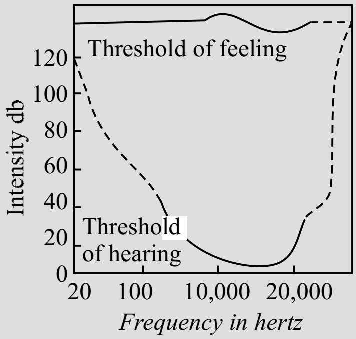

Fig. 14.13 : Auditory area between threshold of hearing and threshold of feeling

- The lower part of the curve shows that the ear is most sensitive for frequencies between 2000 Hz to 3000 Hz, where the threshold of hearing is about 5db. Threshold of hearing in general, is zero decibel.
- At intensities above those corresponding to the upper part of the curve, the sensation changes from one of hearing to discomfort and even pain. This curve represents the threshold of feeling.
- Loudness increases with intensity, but there is no definite relation between the two.
- Pure tones of same intensity but different frequencies do not necessarily produce equal loudness.
- The height of the upper curve is constant at a level of 120 db for all frequencies.

The intensity of sound waves depends on the following factors :

- ***Amplitude of vibration :*** *I* α a^2 *where a* is amplitude of the wave.
- ***Distance between the observer and the Source :*** I α $1/r^2$ where *r* is the distance of the observer from the source (provided it is a point source).
- ***Intensity is directly proportional to the square of frequency of the wave*** (I α v^2).
- ***Intensity is directly proportional to the density of the medium*** (I α ρ).

14.6.3 Quality

It is the *characteristic of sound waves which enables us to distinguish between two notes of the same pitch and intensity but sounded by two different instruments.* No instrument, except a tuning fork, can emit a pure note; a note of one particular frequency. In general, when a note of frequency *n* is sounded, in addition to it, notes of higher frequencies $2n$, $3n$, $4n$ ... may also be produced. These notes, have different amplitudes and phase relations. The resultant wave form of the emitted waves determines the quality of the note emitted. Quality, like loudness and pitch is a subjective quantity. It depend on the resultant wave form.

14.6.4 Organ Pipes

It is the simplest form of a wind instrument. A wooden or metal pipe producing musical sound is known as organ pipe. Flute is an example of organ pipe. If both the ends of the pipe are open, we call it an ***open pipe.*** However, if one end is closed, we call it a ***closed pipe.*** When we blow in gently, almost a pure tone is heard. This pure tone is called a ***fundamental note***. But, when we blow hard, we also hear notes of frequencies which are integral multiple of the frequency of the fundamental note. You can differentiate between the sounds produced by water from a tap into a bucket. These frequencies are called **overtones.**

Note that:

- At the closed end of a pipe, there can be no motion of the air particles and the closed end must be node.
- At the open end of the pipe, the change in density must be zero since this end is in communication with atmosphere. Further, since the strain is zero, hence this end must be an antinode.

(a) Open pipe : The simplest mode of vibrations of the air column called fundamental mode is shown in Fig.14.14 (a). At each end, there is an antinode and between two antinodes, there is a node. Since the distance between a node and next antinode is $\lambda/4$, the length l of the pipe is

$$l = (\lambda/4) + (\lambda/4) = \lambda/2 \text{ or } \lambda = 2l.$$

The frequency of the note produced is

$$n_1 = \upsilon/\lambda = \upsilon/2l$$

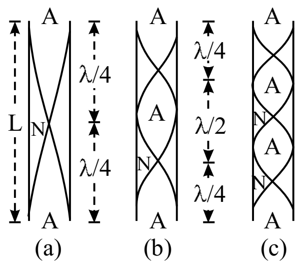

Fig. 14.14 : Harmoniscs of an open Organ pipe. The curves represent the wave of the longitudinal standing waves

The next mode of vibration of the air column is shown in Fig.14.14 (b). One more node and one more antinode has been produced. In this case

$$\lambda = (\lambda/4) + (\lambda/4) + (\lambda/4) + (\lambda/4) = l$$

The frequency of the note is

$$n_2 = \upsilon/\lambda = \upsilon/l = 2\upsilon/2l$$

$$n_2 = 2\upsilon/2l$$

That is $n_2 = 2n_1$

The note produced is called second harmonic or 1st ***overtone***. To get the second harmonic you have to blow harder. But if you blow still harder one more node and one more antinode is produced [Fig.14.14{c)]. Thus, in this case

$$l = \frac{\lambda}{2} + \frac{\lambda}{4} + \frac{\lambda}{2} + \frac{\lambda}{4}$$

$$\lambda = \frac{2l}{3}$$

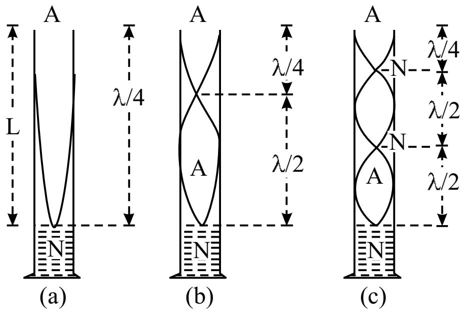

Fig. 14.15 : Harmonics of a closed organ pipe. The curves represented wave form of the longitudinal standing waves.

Therefore, the frequency of the note emitted is

$$n_3 = \frac{\upsilon}{\lambda} = \frac{3\upsilon}{2l} = 3n_1$$

The note produced is called the 3rd harmonic or 2nd overtone.

(b) Closed pipe : The simplest manner in which the air column can vibrate in a closed pipe is shown in Fig. 14.15(a). There is an antinode at the open end and a node at the closed end. The wave length of the wave produced is given by

$$l = \lambda/4 \text{ or } \lambda = 4l$$

Therefore, the frequency of the note emitted is

$$n_1 = \upsilon/\lambda = \upsilon/41$$

The note produced is called *fundamental* note. On blowing harder one more node and antinode will be produced (Fig. 14.15(b)). The wavelength of the note produced is given by

$$l = \frac{\lambda}{2} + \frac{\lambda}{4} = \frac{3\lambda}{4} \text{ or } \lambda = \frac{4l}{3}$$

The frequency of the note emitted will be

$$n_3 = \frac{\upsilon}{\lambda} = \frac{3\upsilon}{4l} = 3n_1$$

The note produced is called the first overtone or the 3rd harmonic of the fundamental, blowing still harder one more node and one more antinode will be produced Fig. 14.15(C). The wavelength of the note produced is then given by

$$l = \frac{\lambda}{2} + \frac{\lambda}{2} + \frac{\lambda}{4} + \frac{5\lambda}{4} \quad \text{or } \lambda = \frac{4l}{5}$$

The frequency of the note emitted then will be

$$n_3 = \frac{\upsilon}{\lambda} = \frac{5\upsilon}{4l} = 5n_1$$

The note produced is called the second overtone or the 5th harmonic of the fundamental. On comparison with the notes emitted by the open and closed pipe, you will find that the open pipe is richer in overtones. In closed pipe, the even order harmonics are missing.

Example 14.5 : Two organ pipes – one open and the other closed – are of the same length. Calculate the ratio of their fundamental frequencies.

Solution : $\frac{\text{Frequency of open pipe}}{\text{Frequency of closed pipe}} = \frac{\upsilon/2\ell}{\upsilon/4\ell} = 2$

∴ Frequency of note produced by open pipe = 2 × frequency of fundamental note produced by closed pipe.

INTEXT QUESTIONS 14.6

1. How pitch is related to frequency?
2. What is that characteristic of musical sounds which enables you distinguis between two notes of the same frequency, and same intensity but sounded by two different instruments?
3. Name the characteristic of sound which helps you identify the voice of your friend.
4. Out of open and closed organ pipes, which one is richer in overtones?
5. What is the ratio of the frequencies of the notes emitted (1) by an open pipe and (ii) by a closed pipe of the same length.
6. What will be the effect of temperature, if any, on the frequency of the fundamental note of an open pipe?

Noise Pollution

When the sensation of sound changes from one of hearing to discomfort, it causes noise pollution and if it persits for a long time, it has harmful effects on certain organ of human beings. Noise is also one of the by-products of industrialisation and misuse of modern amentities provided by science to human beings. We summarise here under the sources or description of noises and their effects as perceived by the human beings.

Table 14.1 : Sources of Noise and their Effects

Source	Intensity Level in decibels	Perceived Effect by human being
Threshold of hearing	0 (=10^{-12} Wm^{-2})	Just audible
Rustle of leaves	10	Quiet
Average whisper	20	Quiet
Radio at low volume	40	Quiet
Quiet automobile	50	moderately loud
Ordinary conversation	65	do
Busy street traffic	70 to 80	loud
Motor bike and heavy vehicles	90	very loud
Jet engine about 35m away	105	Uncomfortable
Lightening	120 (=1 Wm^{-2})	do
Jet plane at take off	150	Painful sound

(a) Effect of Noise Pollution

1. It causes impairment of hearing. Prolonged exposure of noise at 85 or more than 85db causes severe damage to the inner part of the ear.
2. It increases the rate of heart beat and causes dilation of the pupil of eye.
3. It causes emotional disturbance, anxiety and nervousness.
4. It causes severe headache leading to vomiting.

(b) Methods of Reducing Noise Pollution

1. Shifting of old industries and setting new ones away from the dwellings.
2. Better maintenance of machinery, regular oiling and lubrication of moving parts.
3. Better design of engines and machines.

4. Restriction on use of loudspeakers and amplifiers.
5. Restricting the use of fire crackers, bands and loud speakers during religious, political and marriage processions.
6. Planting trees on roads for intercepting the path of sound.
7. Intercepting the path of sound by sound absorbing materials.
8. Using muffs and cotton plugs.

Shock Waves

When a source of waves is travelling faster than the sound waves, shock waves are produced. The familiar example is the explosive sound heared by an observer when a supersonic plane flies past over the head of the observer. It may be pointed out that the object which moves with a speed greater than the speed of sound is itself a source of sound.

14.7 ELECTROMAGNETIC WAVES

You know that light is an e.m. wave. It has wavelength in the range 4000ºA to 7500ºA. A brief description of em waves is given below.

14.7.1 Properties of e.m. waves

The following properties of e.m. waves may be carefully noted.

(*i*) e.m. waves are transverse in nature

(*ii*) They consist of electric (**E**) and magnetic fields (**B**) oscillating at right angles to each other and perpendicular to the direction of propagation (*k*). Also **E** = *c***B**. [see figures 14.16]

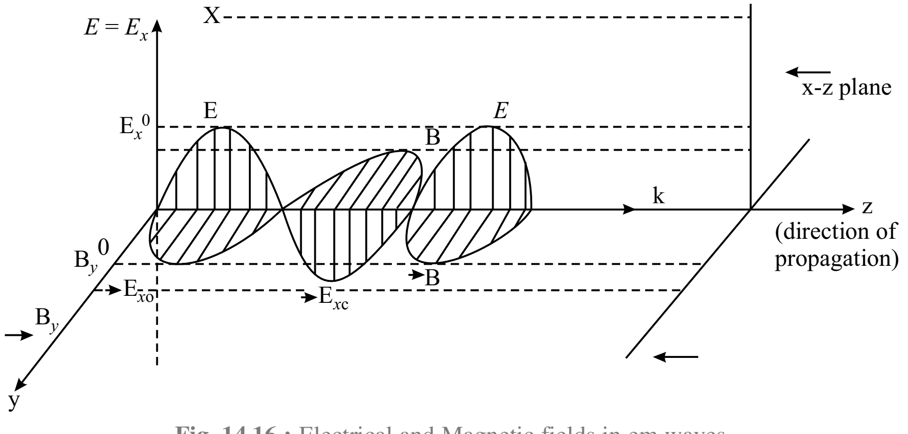

Fig. 14.16 : Electrical and Magnetic fields in em waves

(iii) They propagate through free space (in vacuum) with a uniform velocity = $\frac{1}{\sqrt{\mu_0 \varepsilon_0}} = 3 \times 10^8 \text{ ms}^{-1} = c$ (velocity of light). For a medium of permeability μ (= $\mu_0 . \mu_r$) and permittivity ε (= $\varepsilon_0 . \varepsilon_r$) the velocity becomes

$$v = \frac{1}{\sqrt{\mu\varepsilon}} = \frac{1}{\sqrt{\mu_0\varepsilon_0}\ \sqrt{\mu_r\varepsilon_r}} = \frac{c}{\sqrt{\mu_r\varepsilon_r}} < c$$

(iv) The nature and action of these waves depends on their frequency (or wavelength). Maxwell's theory placed no restriction on possible wavelengths for e.m. waves and hence e.m. waves of wavelengths ranging from 6×10^{-13} m have been successfully produced. There is no limit to very long wavelengths which correspond to radio broadcast waves. The whole range of e.m. waves from very long to very short wavelengths constitutes the *electromagnetic spectrum.*

James Clark Maxwell
(1831 – 1879)

Scottish Mathematician and physicist Maxwell is famous for his theories of electromagnetic fields. Through his equations of electromagnetic principles he showed that they implicitly indicated the existence of em waves which travelled with the speed of light, thus relating light and electromagnetism.

With clausius he developed the kinetic theory of gases. He developed a statistical theory of heat. A man of varied interests, he derived the theorem of equipartition of energy, showed that viscosity varies directly with temperature and tried to explain the rings of saturn.

14.7.2 Electromagnetic Spectrum

Maxwell gave the idea of e.m. waves while Hertz, J.C. Bose, Marconi and others successfully produced such waves of different wavelengths experimentally. However, in all the methods, *the source of e.m. waves is the accelerated charge.*

Electromagnetic waves are classified according to the method of their generation and are named accordingly. Overlapping in certain parts of the spectrum by different classes of e.m waves is also observed. This tells that the e.m. waves of wavelenths in the overlapping region can be produced by two different methods. It is ***important to remember that the physical properties of e.m. waves are determined by the frequencies or wavelengths and not by the method of their generation.*** A suitable classification of e.m. waves is called the electromagnetic spectrum.

There is no sharp dividing point between one class of e.m. waves and the next. The different parts are as follows :

(i) **The low frequency radiations** $\left\{\begin{matrix} \nu = 60\text{Hz to }50\text{Hz} \\ \lambda = 5\times10^{6}\, m \text{ } to \text{ } 6\times10^{6}\, m \end{matrix}\right\}$: generated from a.c. circuits are classified as power frequencies or power waves or electric power utility e.m. waves. These *weaves have the lowest* frequency.

(ii) **Radio Waves** $\left\{\begin{matrix} \lambda = 0.3\text{m to }10^{6}\text{ m} \\ \nu = 10^{9}\text{Hz } to \text{ } 300\text{Hz} \end{matrix}\right\}$: Radio waves are generated when charges are accelerated through conducting wires. They are generated in such electronic devices as LC oscillators and are *used extensively in radio and television communications.*

(iii) **Microwaves** $\left\{\begin{matrix} \lambda = 10^{-3}\text{m to }0.3\text{m} \\ \nu = 10^{11}\text{Hz } to \text{ } 10^{9}\text{Hz} \end{matrix}\right\}$: These are generated by oscillating currents in special vacuum tubes. Because of their short wavelengths, they are well suited for the radar system used in aircraft navigation, T.V. communication and for studying the atomic and molecular properties of matter. Microwave ovens use these radiations as heat waves. It is suggested that solar energy could be harnessed by beaming microwaves to Earth from a solar collector in space.

(iv) **Infra-red waves** $\left\{\begin{matrix} \lambda = 7\times10^{-7}\text{ m to }10^{-3}\text{ m} \\ \nu = 4.3\times10^{14}\text{Hz to }3\times10^{11}\text{Hz} \end{matrix}\right\}$: Infra-red waves, also called heat waves, are produced by hot bodies and molecules. These are readily absorbed by most materials. The temperature of the body, which absorbs these radiations, rises. Infrared radiations have many practical and scientific applications including physical therapy infrared photography etc. These are detected by a thermopile.

(v) **Visible light** $\left\{\begin{matrix} \lambda = 4\times10^{-7}\text{ m to }7\times10^{-7}\text{ m} \\ \nu = 7.5\times10^{14}\text{Hz to }4.3\times10^{14}\text{Hz} \end{matrix}\right\}$: These are the e.m. waves that human eye can detect or to which the human retina is sensitive. It forms a very small portion of the whole electromagnetic spectrum. These waves are produced by the rearrangement of electrons in atoms and molecules. When an electron-jumps from outer orbit to inner orbit of lower energy, the balance of energy is radiated in the form of visible radiation. The various wavelengths of visible lights are classified with colours, ranging from violet ($\lambda = 4 \times 10^{-7}$m) to red ($\lambda = 7 \times 10^{-7}$). Human eye is most sensitive to yellow-green light ($\lambda = 5 \times 10^{-7}$m). Light is the basis of our communitation with the world around us.

(vi) **Ultraviolet** $\begin{Bmatrix} \lambda = 3\times10^{-9}\text{ m to }4\times10^{-7}\text{ m} \\ v = 10^{-17}\text{ Hz to }7.5\times10^{14}\text{ Hz} \end{Bmatrix}$: Sun is the important source of ultraviolet radiations, which is the main cause of suntans. Most of the ultraviolet light from Sun is absorbed by atoms in the upper atmosphere i.e. stratosphere, which contains ozone gas. This ozone layer then radiates out the absorbed energy as heat radiations. Thus, the lethal (harmful to living beings) radiations get converted into useful heat radiations by the ozone gas, which warms the stratosphere. These ultraviolet rays are used in killing the bacteria in drinking water, in sterilisation of operation theatres and also in checking the forgery of documents.

(vii) **X-rays** $\begin{Bmatrix} \lambda = 4\times10^{-13}\text{ m to }4\times10^{-8}\text{ m} \\ v = 7.5\times10^{20}\text{ Hz to }7.5\times10^{15}\text{ Hz} \end{Bmatrix}$: These are produced when high energy electrons bombard a metal target (with high melting point) such as tungsten. X-rays find their important applications in medical diagnostics and as a treatment for certain forms of cancer. Because, they destroy living tissues, care must be taken to avoid over-exposure of body parts. X-rays are also used in study of crystal-structure. They are detected by photographic plates.

(viii) **Gamma rays** $\begin{Bmatrix} \lambda = 6\times10^{-17}\text{ m to }10^{-10}\text{ m} \\ v = 5\times10^{24}\text{ Hz to }3\times10^{18}\text{ Hz} \end{Bmatrix}$: These are emitted by radioactive nuclei such as cobalt (60) and ceasium (137) and also during certain nuclear reactions in nuclear reactors. These are highly penetrating and cause serious damage when absorbed by living tissues. Thick sheets of lead are used to shield the objects from the lethal effects of gamma rays.

The energy (E) of e.m. waves is directly proportional to their frequency v $\left(E = hv = \frac{hc}{\lambda}\right)$ and inversely proportional to their wave-length (λ). Thus gamma rays are the most energetic and penetrating e.m. waves, while the power frequencies, and the A.M. radio waves are the weakest radiations. Gamma rays are used to detect metal flaws in metal castings. They are detected by Geiger tube or scintillation counter.

Depending on the medium, various types of radiations in the spectrum will show different characteristic behaviours. For example, while whole of the human body is opaque to visible light, human tissues are transparent to X-rays but the bones are relatively opaque. Similarly Earth's atmosphere behaves differently for different types of radiations.

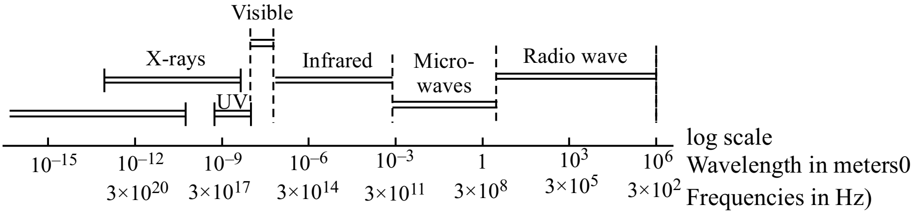

Fig. 14.17: Electromagnetic spectrum

INTEXT QUESTIONS 14.7

1. Fill in the blanks:

   (i) ....are generated by oscillating currents in special vacuum tubes.

   (ii) Human eye is most sensitive to.....................................color light.

   (iii) ....is the important source of ultraviolet radiation.

   (iv) ....are used as the diagnostic tool in medical,

   (v) Infrared radiations can be detected by a....................................

2. Which of the e.m. waves are more energetic?

   (i) Ultraviolet or infrared.

   (ii) x-rays or γ-rays

3. Which of the e.m. waves are used in aircraft navigation by radar?

4. Which gas in the atmosphere absorbs ultraviolet radiations from the Sun before reaching the earth's surface?

5. How are the electric field and magnetic field oriented with respect to each other in an e.m. wave?

14.8 DOPPLER EFFECT

While waiting on a railway platform for the arrival of a train, you might have observed that the pitch of the whistle when the engine approaches you and when the engine moves away from you are different. You will note that the pitch is higher when the engine approaches but is lower when the engine moves away from you. Similarly, the pitch of the horn of a bus going up a hill changes constantly.

Apparent change of frequency observed due to the relative motion of the observer and the source is known as Doppler effect.

Let υ be velocity of the sound waves relative to the medium, (air), υ_s velocity of the source; and υ_o velocity of the observer.

Christian Doppler

(1803 – 1853)

C.J. Doppler, an Austrian physicist and mathematician, was born on Nov., 29, 1803 in a family of stone mesons. A pale and frail person, he was not considered good enough for his family business. So on recommendation of the professor of mathematics at Salzburg Lycousin, he was sent to Vienna Polytechnic from where he graduated in 1825.

A struggler through out his life, Doppler had to work for 18 months as a book-keeper at a cotton spinning factory. He could think of marrying in 1836 only when he got a permanent post at the technical secondary school at prague. He was once reprimanded for setting too harsh papers in maths for polytechnique students. But he pushed his way through all odds and finally got succes in getting the position of the first director of the new Institute of Physics at Vienna University.

The Doppler effect discovered by him made him famous overnight, because the effect had far reaching impact on acoustics and optics. The RADAR, the SONAR, the idea of expanding universe there are so many developments in science and technology which owe a lot to Doppler effect. He died on March 17, 1853 in Venice, Italy.

It is important to note that the wave originated at a moving source does not affect the speed of the sound. The speed υ is the property of the medium. The wave forgets the source as it leaves the source. Let us suppose that the source, the observer and the sound waves travel from left to right. Let us first consider the ***effect of motion of the source.*** A particular note which leaves the sources at a given time after one second arrives at the point A such that SA = υ. In this time, the source moves a distance υ_s. Hence all the n waves that the source had emitted in one second are contained in the space $x = \upsilon - \upsilon_s$. Thus length of each wave decreased to

$$\lambda' = \frac{\upsilon - \upsilon_s}{n} \qquad ...(14.22)$$

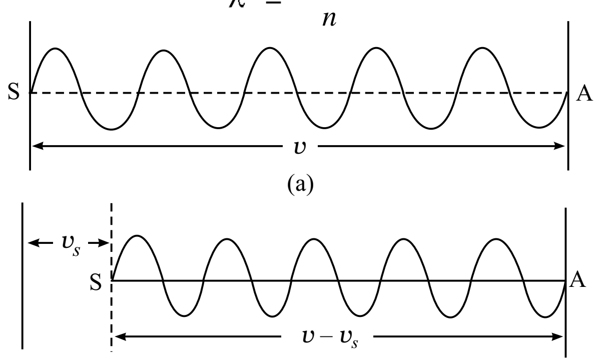

Fig. 14.18 : Crowding of waves when source is moving

Now let us consider the ***effect of motion of the observer.*** A particular wave which arrives at O at a particular time after one second will be at B such that OB = υ. But in the mean time, the observer moves from O to O′. Hence only the waves contained in the space O′B have passed across the observer in one second. The number of the waves passing across the observer in one second is therefore,

$$n' = (\upsilon - \upsilon_0)/\lambda' \qquad (14.23)$$

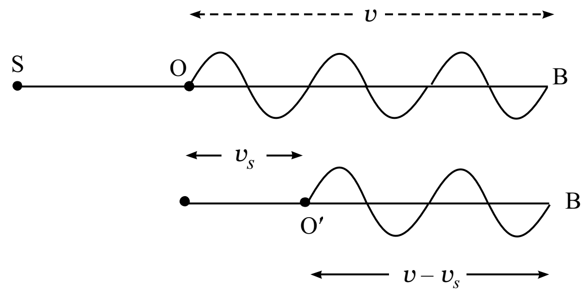

Fig. 14.19 : Waves received by a moving listner

Substituting for λ' from Eqn. (14.22) we get

$$n' = \frac{\upsilon - \upsilon_0}{\upsilon - \upsilon_s} n \qquad (14.24)$$

where n' is the observed frequency when both observer and source are moving in the direction from the source to the observer.

In using Eqn.(14.24) ***the velocity of sound is taken positive in the direction from the source to the observer. Similarly ,*** υ_0 and υ_s are taken positive if these are in the direction of υ and vice versa.

The utility of Doppler's effect arises from the fact that it is applicable to light waves as much as to sound waves. In particular, it led us to the concept of expansion of the universe.

The following examples will help you to understand this application of Doppler's effect.

Example 14.6 : The light from a star, on spectroscopic analysis, shows a shift towards the red end of the spectrum of a spectral line. If this shift, called the red shift, is 0.032%, calculate the velocity of recession of the star.

Solution : In this case, the source of waves is the star. The observer is at rest on the Earth. We have shown that in such a case

$$\lambda' = \frac{\upsilon - \upsilon_s}{n}$$

But $n = \upsilon/\lambda$ Therefore, $\lambda' = \dfrac{\upsilon - \upsilon_s}{\upsilon/\lambda}$

$$= \lambda \frac{(\upsilon - \upsilon_s)}{\upsilon}$$

$$= \lambda \left(1 - \frac{\upsilon_s}{\upsilon}\right)$$

On rearranging terms, we can write

$$\frac{\lambda' - \lambda}{\lambda} = -\frac{\upsilon_s}{\upsilon}$$

or

$$\frac{\Delta\lambda}{\lambda} = \frac{\upsilon_s}{\upsilon}$$

we are told that $\frac{\Delta\lambda}{\lambda}$ = 0.032/100. And since $\upsilon = c = 3 \times 10^8$ ms^{-1}, we get

$$\upsilon_s = \upsilon \frac{\Delta\lambda}{\lambda} = -(3 \times 10^8 \text{ ms}^{-1} \times 0.032/100) = -9.6 \times 10^4 \text{ ms}^{-1}.$$

The negative sign shows that the star is receding away. This made the astrophysists to conclude that the world is in a state of expansion

INTEXT QUESTIONS 14.8

1. A SONAR system fixed in a submarine operates at frequency 40.0kHz. An enemy submarine moves towards it with a speed of 100ms^{-1}. Calculate the frequency of the sound reflected by the sonar. Take the speed of sound in water to be 1450 ms^{-1}.
2. An engine, blowing a whistle of frequency 200Hz moves with a velocity 16ms^{-1} towards a hill from which a well defined echo is heard. Calculate the frequency of the echo as heard by the driver. Velocity of sound in air is 340ms^{-1}.

Constancy of Speed of Light

Aristotle, believed that light travels with infinite velocity. It was for the first time in September, 1876 that the Danish astronomer, Roemer, indicated in a meeting of Paris Academy of Sciences that the anomalous behaviour of the eclipse, times of Jupiter's inner satellite, Io, may be due to the finite speed of light. Feazeu, Focult, Michelson and many other scientists carried out experiments to determine the speed of light in air with more and more precision.

Albert Einstein, in his 1905 paper, on special theory of relativity, based his arguments on two postulates. One of the postulates was the constancy of speed of light in vacuum, irrespective of the wavelength of light, the velocity of the source or the observer. In 1983, the velocity of light in vacuum, was declared a universal constant with a value 299792458 ms^{-1}.

However, the Autralian researcher Barry Setterfield and Trevn Norwah have studied, the data of 16 different experiments on the speed of light in vacuum, carried out over the last 300 years, by different scientists at different places. According to them, the speed of light in vacuum is decreasing with time. If this hypothesis is sustained and coroborated by experiements, it will bring in thorough change in our world view. Major areas in which this change will be enormous are : Maxwell's laws, atomic structure, radioactive decay, gravitation, concepts of space, time and mass etc.

WHAT YOU HAVE LEARNT

- The distance between two nearest points in a wave motion which are in the same phase is called wavelength.
- The equation of a simple harmonic wave propagating along x–axis is $y = a \sin(\upsilon t - kx)$.
- The energy transmitted per second across a unit area normal to it is called intensity..
- If the vibrations of medium particle are perpendicular to the direction of propagation, the wave is said to be transverse but when the vibrations are along the direction of propagation the wave is said to be longitudinal. Velocities of transverse wave and longitudinal waves is given by $\upsilon = \sqrt{T/m}$ and $\upsilon = \sqrt{E/\rho}$ respectively.
- On reflection from a denser medium, phase is reversed by π. But there is no phase reversal on reflection from a rarer medium.
- When two waves are superposed, the resultant displacement at any point is vector sum of individual displacements at that point. Superposition of two colliner waves of same frequency but differing phases, when moving in the same direction results in redistribution of energy giving rise to interference pattern.
- Superposition of two collinear waves of the same frequency and same amplitude travelling in the opposite directions with the same speed results in the formation of stationary waves. In such waves, waveform does not move.
- In a stationary wave, the distance between two successive nodes or successive antinodes is $\lambda/2$. It is, therefore, obvious that between two nodes, there is an antinode and between two antinodes there is a node.

- The displacement is maximum at antinodes and minimum at nodes.
- Intensity level is defined by the equation $\beta = 10\log(I/I_0)$, where I_0 is an arbitrarily chosen reference intensity of 10^{-12} W m^{-2}. Intensity level is expressed in decibels (Symbol. db)
- Quality of a note is the characteristic of musical sounds which enable us to distinguish two notes of the same pitch and same loudness but sounded by two different instruments.
- Electromagnetic waves are transverse in nature, and do not require any medium for their propagation.
- Light is an e.m. wave with wavelength in the range 4000 Å – 7500 Å.
- The frequency of e.m. waves does not change with the change in the medium.
- e.m. waves are used for wireless radio communication, TV transmission, satellite communication etc.

ANSWERS TO INTEXT QUESTIONS

14.1

1. See section 14.1.4.
2. If p be the path difference, then the phase difference is $\theta = \frac{2\pi}{\lambda} p$.
3. ϕ

14.2

1. Newton assumed that compression and rarefaction caused by sound waves takes place under isothermal condition.
3. Newton assumed that isothermal conditions instead of adiabatic conditions for sound propagation.
4. 357^0C.

5. $v = \sqrt{\frac{T}{m}}$

6. Therefore, $n = \frac{1}{\lambda}\sqrt{\frac{T}{m}}$

Further, for the simplest mode of vibration, at the two ends of the string, there are nodes and in between the two nodes is an antinode. Therefore, $l = l/2$ or $\lambda = 2l$, hence $n = \lambda/2l \sqrt{\frac{T}{m}}$. If the string vibrates in p segments, the $\lambda = p\ l/2$ or $\lambda = 2l/p$. Then $n = (p/2l)\sqrt{\frac{T}{m}}$.

14.3

For answers to all questions see text.

14.4

1. 25/9.
2. Beats with frequency 4Hz are produced.
3. Frequency of beat is Δv.
4. 517, on loading the frequency of A decreases from 517 to 507.

14.5

1. No energy swings back and forth in a segment.
2. Distance between two successive nodes is $\lambda/2$, and between a node and antinode is $\lambda/4$.
4. (i) 1m, (ii) 1m, (iii) 1/4m.

14.6

1. Pitch increases with increase in frequency.
2. Timbre
3. Timbre
4. Open pipe
5. For a closed pipe in case of fundamental note $l = \lambda/4$ or $\lambda = 4l$, therefore $n = \upsilon/\lambda = \upsilon/4l$.

For an open pipe $\ell = \lambda/2$. Therefore $n' = \upsilon/2l$.

Comparing (i) and (ii) we find that $n' = 2n$

6. $n = \frac{\upsilon}{2\ell}$. As υ increases with increase in temperature n also increases.

14.7

(*i*) microwaves.

(*ii*) yellow–green ($\lambda = 5 \times 10^{-7}$ m)

(*iii*) Sun.

(*iv*) X – rays.

(*v*) thermopile.

2. (*i*) ultra voilet

(ii) r – rays.

3. Microwaves

4. Ozone.

5. Perpendicular to each other.

14.8

1. $n' = n \frac{c - \upsilon_0}{c}$

$$= 40 \times 10^3 \times \frac{1450 - 100}{1450}$$

$$= 40 \times \frac{135}{145} \times 10 = 37.2 \text{ KHz.}$$

2. $n' = 200 \times \frac{340 + 16}{340 - 16}$

$$= 200 \times \frac{356}{224} = 220 \text{ Hz.}$$