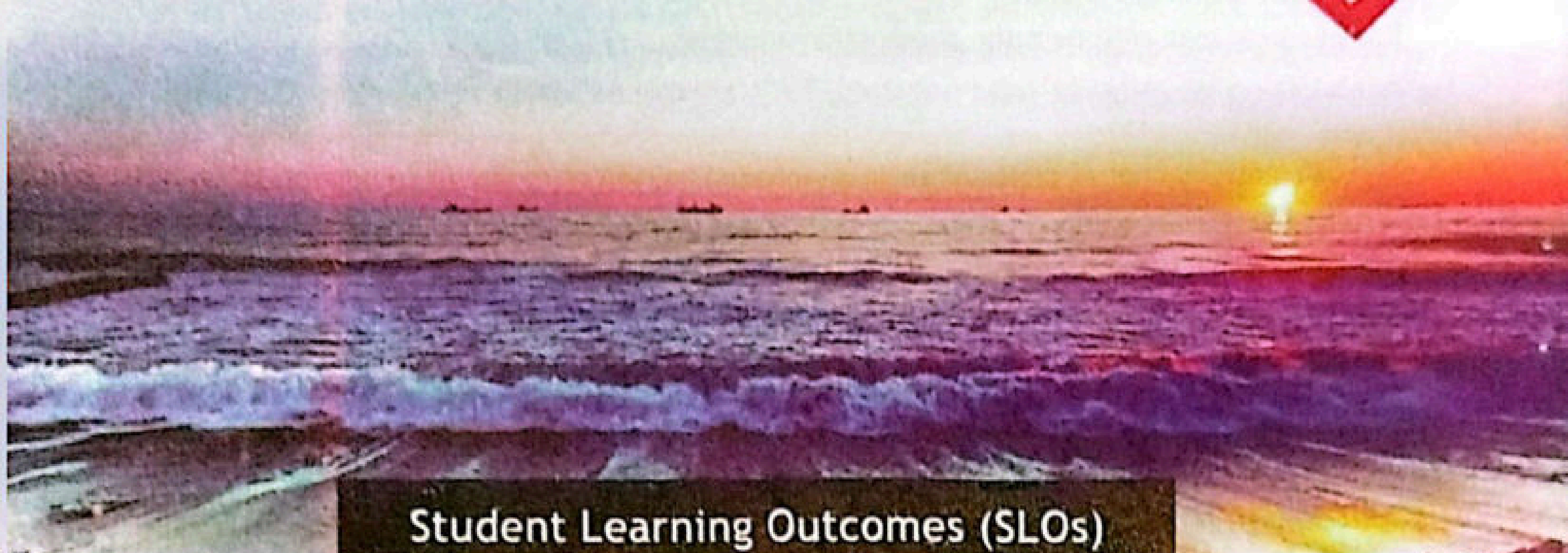
WAVES

UNIT 9



Student Learning Outcomes (SLOs)

The students will:

- Use intensity = power/area to solve problems. Use *intensity* $\propto$ *(amplitude)*^{2} for a progressive wave to solve problems.
- Explain that when a source of sound waves moves relative to a stationary observer, the observed frequency is different from the source frequency [describing of the Doppler effect for a stationary source and a moving observer is not required]
- Use the expression $f' = \frac{v}{v \pm v_s} f$ for the observed frequency when a source of sound waves moves relative to a stationary observer.
- Explain the applications of the Doppler effect [such as radar, sonar, astronomy. satellite, radar speed traps and studying cardiac problems in humans].
- Explain that polarization is a phenomenon associated with transverse waves.
- Define and apply Malus's law [$I = I_o \cos^2 \theta$ to calculate the intensity of a plane-polarized electromagnetic wave after transmission through a polarizing filter or a series of polarizing filters. (calculation of the effect of a polarizing filter on the intensity of an un-polarized wave is not required)].
- Use the principle of superposition of waves to solve problems.
- Differentiate between constructive and destructive interference.
- Apply the principle of superposition to explain the working of noise canceling headphones.
- Illustrate experiments that demonstrate stationary waves [using microwaves, stretched strings and air columns (it will be assumed that end corrections are negligible; knowledge of the concept of end corrections is not required)].
- Explain the formation of a stationary wave using graphical representation.
- Explain the formation of harmonics in stationary waves.
- Analyze experiments that demonstrate diffraction [including the qualitative effect of the gap width relative to the wavelength of the wave; for example, diffraction of water waves in a ripple tank].
- Explain the term coherence.
- Explain beats [as the pulsation caused by two waves of slightly different frequencies interfering with each other].
- Illustrate examples of how beats are generated in musical instruments.
- Explain the use of polaroids in sky photography and stress analysis of materials.
- Describe qualitatively gravitational waves [as waves of the intensity of gravity generated by the accelerated masses of an orbital binary system that propagate as waves outward from their source at the speed of light].
- State that as a gravitational wave passes a body with mass the distortion in space-time can cause the body to stretch and compress periodically.
- State that gravitational waves pass through the Earth due to far off celestial events, but they are very minute amplitude.
- Describe the use of interferometers in detecting gravitational waves [Interferometers are very sensitive detection devices that make use of the interference of laser beams (working and set up details are not required) and were used to first detect the existence of gravitational waves].

The world is full of waves: sound waves, waves on a string, seismic waves, and electromagnetic waves, such as visible light, radio waves, television signals, and x-rays. All these waves have a source: a vibrating object. The importance of radio and television signals and other forms of electromagnetic waves cannot be ignored. Communication using these waves is the backbone of modern civilization.

Waves transfer energy from one location to another. In this chapter, we will study about different phenomenon of waves such as Doppler's effect, beats, interference, stationary waves and their applications.

9.1 INTENSITY OF WAVES

All waves carry energy and sometimes their energy can be directly observed. For example, earthquakes can shake whole cities, performing the work of thousands of wrecking balls. Loud sounds can damage nerve cells in the inner ear, causing permanent hearing loss. Ultrasound is used for deep-heat treatment of muscle strains. A laser beam can burn away a malignancy. Water waves abolish beaches.

Energy carried by a wave per unit area in unit time is called intensity.

The amount of intensity in a progressive wave is directly related to square of its amplitude, as shown in the following relation:

$$\textit{Intensity} \propto (\textit{amplitude})^2$$

So, an earthquake having large amplitude produce large ground displacements. The energy of a wave depends on time as well. For example, the longer deep-heat ultrasound is applied, the more energy it transfers. Waves can also be concentrated or spread out. For example, sunlight can be focused to burn wood. Earthquakes spread out, so they do less damage as farther they get from the source. All these pertinent factors are included in the definition of *intensity I* as power per unit area:

$$I = \frac{P}{A} \quad \text{———} \quad (9.1\ a)$$

where P is the power carried by the wave through area A. As, power is energy per unit time ($P = E/t$), equation (9.1 a) can be written as:

$$I = \frac{E}{A \times t} \quad \text{———} \quad (9.1\ b)$$

The definition of intensity is valid for any energy in transit, including that carried by progressive waves. The SI unit for intensity is watts per square meter ($W\ m^{-2}$).

EXAMPLE 9.1:

1) The average intensity of sunlight on Earth's surface is about 500 $W\ m^{-2}$. Calculate the amount of energy that falls on a solar collector with an area of 0.50 m^2 in 4.0 h.

Given: Intensity of sunlight on the Earth = I = 500 $W\ m^{-2}$
Area of solar collector = A = 0.5 m^2 Time = t = 4.0 h

To Find: Energy fall on solar collector = E = ?

Solution: Using equation:

$$I = \frac{E}{A \times t}$$

or $$E = I \times A \times t$$

Substitute the values into the equation, we get:

$$E = (500\ \text{W m}^{-2})(0.50\ \text{m}^2)(4.0 \times 3600\ \text{s})$$

$$E = 3.6 \times 10^6\ \text{J}$$

2) If amplitude of the wave is doubled then how much energy is increased?

Solution:

Energy depends on the intensity of the wave. Intensity is proportional to the square of the amplitude. i.e.,

$$\textit{Intensity} \propto (\textit{amplitude})^2$$

If amplitude is increased to double then energy will be increased to 4 times because 4 is the square of 2.

Assignment 9.1

To increase intensity of a wave by a factor of 50, by what factor should the amplitude of the wave be increased?

9.2 DOPPLER'S EFFECT

Possibly you have noticed how the sound of a vehicle's horn changes as the vehicle moves away from you. The frequency of the sound you hear appears higher as the vehicle approaches you and appears lower as it moves away from you. This phenomenon is known as Doppler's Effect, named after an Austrian physicist Christian Doppler (1803-1853), who described it in 1842.

The apparent change in the frequency of a wave due to the relative motion between the observer and the source is called Doppler's effect.

The Doppler's effect is most often associated with sound, however it's common to all waves, including water and light. In deriving the Doppler's effect, we assume the air is stationary and all speed measurements are made relative to this stationary medium.

Motion of a source of sound toward an observer increases the rate at which he or she receives the vibrations. The velocity of each vibration is the speed of sound whether the source is moving or not. Each vibration from an approaching source has a shorter distance to travel. The wavelength is shortened when the source is moving towards the observer and is lengthened when it is moving away from the observer. The vibrations are therefore received at a higher frequency than they are sent. Similarly, sound waves from a receding source are received at a lower frequency than they are sent.

Consider a source of sound S emitting sound wave having magnitude of velocity v, frequency f and wavelength λ. When source S and listener L are at rest then listener will receive f number of waves per second, according to relation:

$$v = f\lambda$$

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

Following are the possible situations regarding source of sound and the listener:

(1) The Source is at Rest and Listener is Moving

(a) Listener Moves Towards Stationary Source: If the listener L is moves with speed v_L towards the stationary sounding source S, as shown in Fig. 9.1 (a). The speed of sound relative to listener increases to $(v + v_L)$ and wavelength remains unchanged.

The apparent frequency f' is:

$$f' = \frac{(v + v_L)}{\lambda}$$

Putting $\lambda = \frac{v}{f}$, we get:

$$f' = \frac{v + v_L}{v} f \quad \text{\_\_\_\_\_\_ (9.2)}$$

As $\frac{v + v_L}{v} > 1$

So, $f' > f$

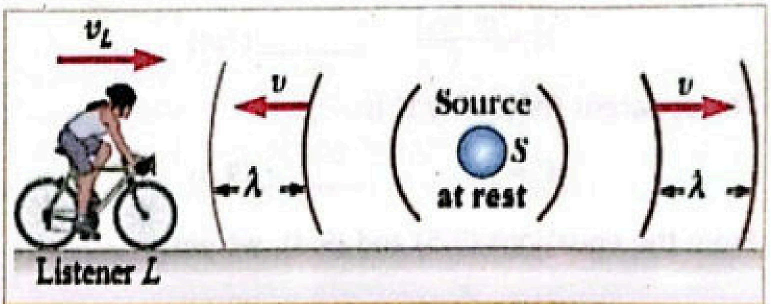


Figure 9.1 (a): The listener is moving toward the stationary source.

Hence, the frequency of sound increases, as a result its pitch also increases.

(b) Listener Moves Away from the Stationary Source: If the listener L is moves away from the stationary sounding source S with speed v_L, as shown in Fig. 9.1 (b), then speed of sound relative to the listener decreases to $(v - v_L)$ and wavelength remains unchanged.

The apparent frequency f' is:

$$f' = \frac{v - v_L}{\lambda}$$

Putting $\lambda = \frac{v}{f}$, we get

$$f' = \frac{v - v_L}{v} f \quad \text{\_\_\_\_\_\_ (9.3)}$$

As $\frac{v - v_L}{v} < 1$

So, $f' < f$

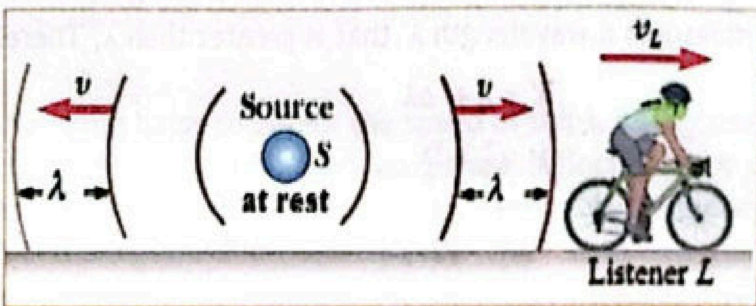


Figure 9.1 (b): Listener moves away from the stationary source.

Hence, the frequency of sound decreases, as a result its pitch also decreases.

(2) The Source is Moving and Listener is at Rest

(a) When the Source Moves Toward a Stationary Listener: If the source is moving with speed v_S toward the stationary listener A, as shown in Fig. 9.1 (c), then each new wave is emitted from a position to the right of the origin of the previous wave. As a result, the wave fronts heard by the listener A are closer together as compared to when the source is stationary. As a result, the wavelength λ' measured by listener A is shorter than the wavelength λ of the source. During each vibration, which lasts for a time interval T (the period), the source moves a distance $v_S T = v_S/f = \Delta\lambda$ causing the wavelength to be shortened by this amount. Therefore, the apparent wavelength λ' is:

$$\lambda' = \lambda - \Delta\lambda$$

$$\lambda' = \frac{v}{f} - \frac{v_S}{f}$$

$$\lambda' = \frac{(v - v_S)}{f} \quad \text{\_\_\_\_\_\_ (9.4)}$$

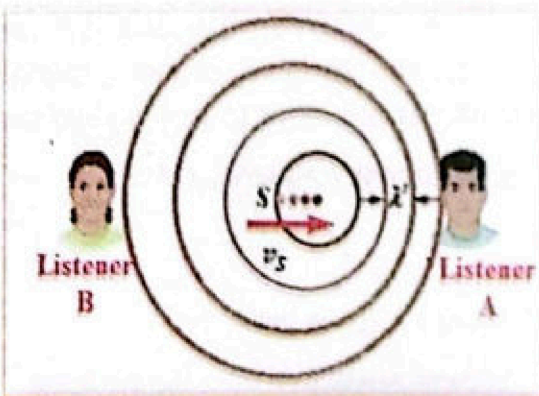


Figure 9.1 (c): The source is moving and listener is at rest.

The apparent frequency f′ is:

$$f' = \frac{v}{\lambda'} \quad \text{\_\_\_\_\_\_ (9.5)}$$

From the equations (9.5) and (9.4), we get:

$$f' = \frac{v}{v - v_S} f \quad \text{\_\_\_\_\_\_ (9.6)}$$

As $\frac{v}{v - v_S} > 1$

So, $f' > f$

Thus, when the source moves toward stationary listener, the frequency of sound increases, as a result its pitch also increases.

(b) When the Source Moves Away from a Stationary Listener: In this case, the observer measures a wavelength λ' that is greater than λ, Therefore, the apparent wavelength λ' is:

$$\lambda' = \lambda + \Delta\lambda$$

$$\lambda' = \frac{v}{f} + \frac{v_S}{f}$$

$$\lambda' = \frac{(v + v_S)}{f} \quad \text{\_\_\_\_\_\_ (9.7)}$$

The apparent frequency f′ is:

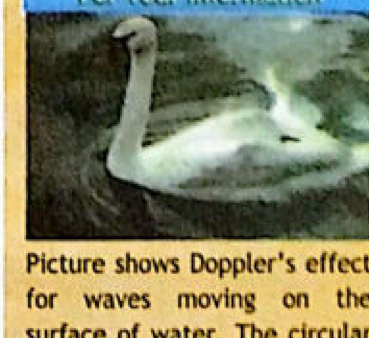
$$f' = \frac{v}{\lambda'} \quad \text{\_\_\_\_\_\_ (9.8)}$$

From the equation (9.7) and (9.8), we get:

$$f' = \frac{v}{v + v_S} f \quad \text{\_\_\_\_\_\_ (9.9)}$$

As $\frac{v}{v + v_S} < 1$

For Your Information



Picture shows Doppler's effect for waves moving on the surface of water. The circular wave crests are closer together in front of a swimming duck, than those behind it and reach a receiver more frequently.

So, $f' < f$

Hence, when the source moves away from a stationary listener, the frequency of sound decreases, as a result its pitch also decreases.

Example 9.2: A sound source is receding from a stationary observer at 22 m s^{-1} and have frequency 354 Hz. If the speed of sound is 332 m s^{-1}, then what frequency does the observer hear?

Given: Frequency of sound wave = f = 354 Hz Speed of sound source = v_S = 22 m s^{-1}

Speed of sound = v = 332 m s^{-1}

To Find: Apparent frequency = f' = ?

Solution: When a source is receding from a stationary observer, then the apparent frequency is:

$$f' = \frac{v}{v + v_S} f$$

$$f' = \frac{332}{332 + 22}(354) = 332 \text{ Hz}$$

Assignment 9.2

A bus is moving at 20 m s^{-1} along a straight road with its 500 Hz horn sounding. You are standing at the road side. What frequency do you hear as the bus is:

a) Approaching you? b) Receding from you? (Take the speed of sound = 340 m s^{-1})

Activity: 9.1

Take a tub full of water and sweep an object such as glass, on the surface of water. What do you observe? Share your experience with your class fellows.

9.2.1 Applications of Doppler's Effect

Doppler's effect has many interesting applications. It is applied in weather observation to characterize cloud movement and weather patterns, and has other applications in aviation and radiology. We will discuss some of the most significant applications of the Doppler's effect in the following:

- **SONAR (Sound Navigation and Ranging)** helps to detect the speed of ships, aeroplanes and submarines using the Doppler's effect. When sound waves are reflected from a moving body such as submarine, their frequency changes. This change in frequency allows us to calculate the speed and direction of the submarine.
- The velocity of **Earth's satellites** is determined from the Doppler shift in frequency of the radio waves they transmit.
- Doppler's Effect can be used in **radar system** to find the speed and direction of aeroplanes. Radar systems send out radio waves. If the frequency of the reflected radio waves from an aeroplane decreases, then the aeroplane is moving away from the radar. If the frequency of the reflected radio waves from an aeroplane increased, then the aeroplane is moving toward the radar.

- The Doppler's effect is of great interest to astronomers, who use shift in the frequency of electromagnetic waves produced by moving stars in our galaxy and beyond in order to gather information about those stars and galaxies. In 1929, Edwin Hubble observed that all galaxies appeared to be red-shifted (i.e. moving away from us and each other), leading him to propose that the universe is expanding. Specific information about stars within galaxies can be determined by using the Doppler's effect.

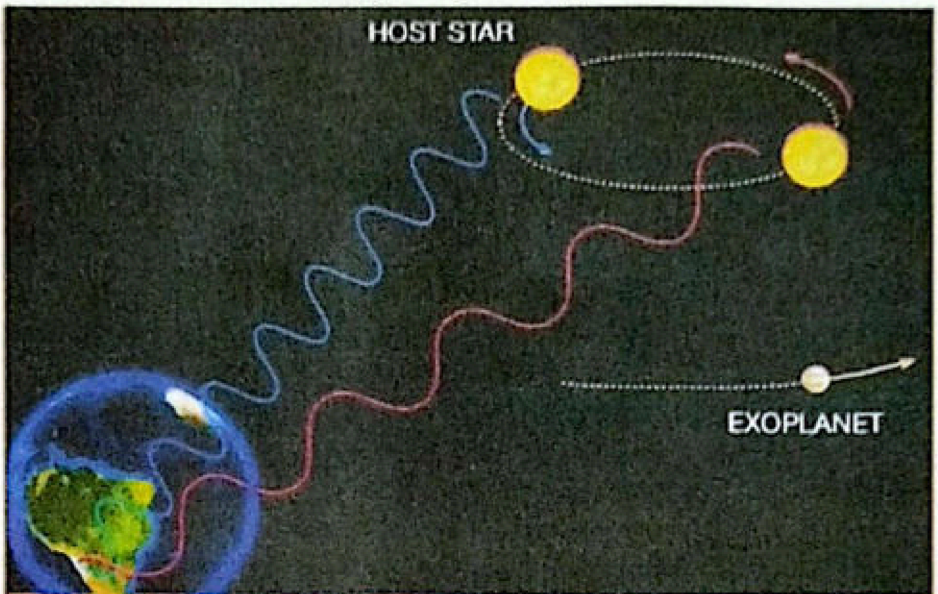
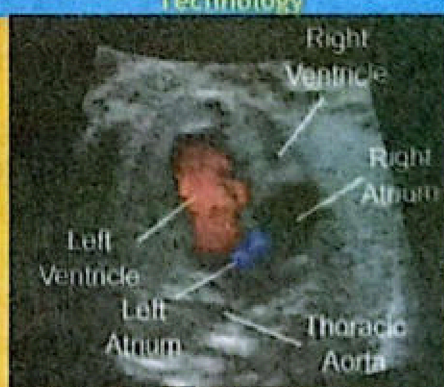


Figure 9.2: Blue shift and red shift.

Fig. 9.2 shows electromagnetic radiation emitted by stars in a distant galaxy would appear to be shifted to lower in frequencies (a red shift) if the star is moving away from the Earth. On the other hand, there is an upward shift in frequency (a blue shift) of such observed radiation if the star is moving towards the Earth.

- Doppler effect is used to measure speed in RADAR sensors. This is known as **radar speed traps.** When a fixed-frequency radio wave sent by the sender continuously strikes an object moving towards or away from the sender, the frequency of the reflected radio wave will be changed due to the object's motion. Thus, analyzing the frequency of the reflected wave one can find the speed of moving object.
- Doppler effect is used in the **diagnosis of cardiac diseases.** Doppler ultrasound (or Doppler echocardiography) is a test in which very high frequency sound waves are bounced off the heart and blood vessels. The returning sound waves are picked up and turned into pictures showing blood flow through the arteries or the heart. Doppler ultrasound

Doppler Effect and Medical Technology



Doppler ultrasound is used to assess blood flow through the coronary arteries (the blood vessels supplying the heart), the carotid artery (the main artery in the neck), the major arteries in the arms and legs, or in the heart itself (echocardiography).

testing allows doctors to clearly see flow of blood through the heart and blood vessels. It also allows them to see and measure obstructions in arteries and measure the degree of narrowing or leakage of heart valves.

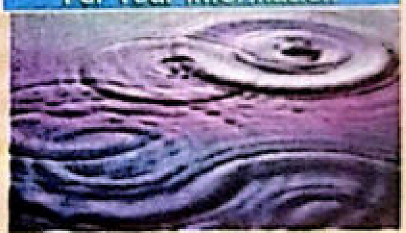
9.3 SUPERPOSITION OF WAVES

Various wave phenomena in nature require two or more waves passing through the same region of space at the same time. Two travelling waves can meet and pass through each other without being vanished or even altered.

When two waves of same nature pass through the same medium, their interaction may cause to the formation of a new wave. In the region of overlap, the resultant wave is found by adding the displacements of the individual waves. For such analysis, the superposition principle applies. According to this principle:

When two or more waves are passing through the same region at the same time, the total displacement at the point where they interact is equal to the vector sum of the individual displacements due to each pulse at that point.

For Your Information



When two pebbles are thrown into a pond, the expanding circular waves don't cancel each other. In fact, the ripples pass through each other.

If a particle of medium is simultaneously acted upon by n number of waves, such that its displacement due to each of the individual n waves is y_1, y_2, y_3, ..., y_n, then resultant displacement y of the particle is:

$$y = y_1 + y_2 + y_3 + ... + y_n$$

In Fig. 9.3, you can see two waves (X and Y) superposing to form the resultant wave (Z). The diagram shows only three points where it displays how the displacement of the resultant wave is calculated.

For example, when time t = 0, the displacement of the Y wave is -0.9 (signs must be taken into account as displacement is a vector quantity) and the displacement of the X wave was -2.1. As a result, the displacement of the resultant wave will be the vector sum of those, (-0.9) + (-2.1) = -3. This is simply the principle of superposition.

The superposition of waves can lead to the following three effects:

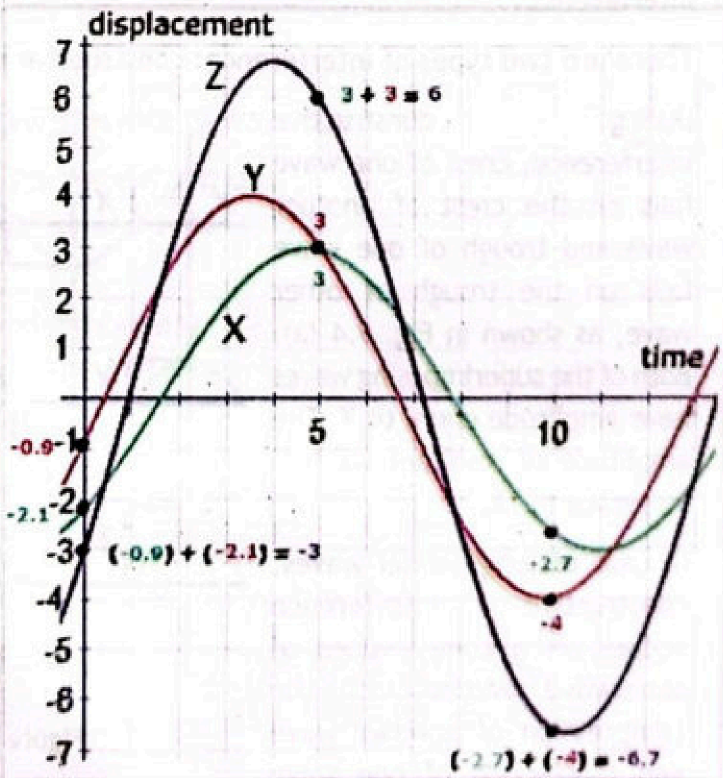


Figure 9.3: Two waves (X and Y) superposing to form the resultant wave (Z).

1. When two waves having the same frequency travel with the same speed along the same direction in a specific medium, then they superpose and create an effect known as the interference of waves.
2. When two waves having same frequencies travel with the same speed along opposite directions in a specific medium, then they superpose to produce stationary waves.
3. When two waves having slightly different frequencies travel with the same speed along the same direction in a specific medium, they superpose to produce beats.

Coherent Waves

When two or more light waves are traveling together in such a way that their phase difference is constant, then such waves are known as the coherent waves. This is possible if the waves have same frequency and wavelength.

The source which emits a light wave with the same frequency, wavelength and phase (or having a constant phase difference) is known as a coherent source. The laser is a highly coherent light source. Coherent light waves can also be produces by Young's Double Slit experiment.

9.4 INTERFERENCE

The waves which have constant phase difference and same frequency are called coherent waves.

The effect produced due to the superposition of waves from two coherent sources is known as interference.

There are two types of interference: constructive interference and destructive interference.

During constructive interference, crest of one wave falls on the crest of another wave and trough of one wave falls on the trough of other wave, as shown in Fig. 9.4 (a). Both of the superimposing waves have amplitude equal to X. The amplitude of resultant wave is increased to 2X.

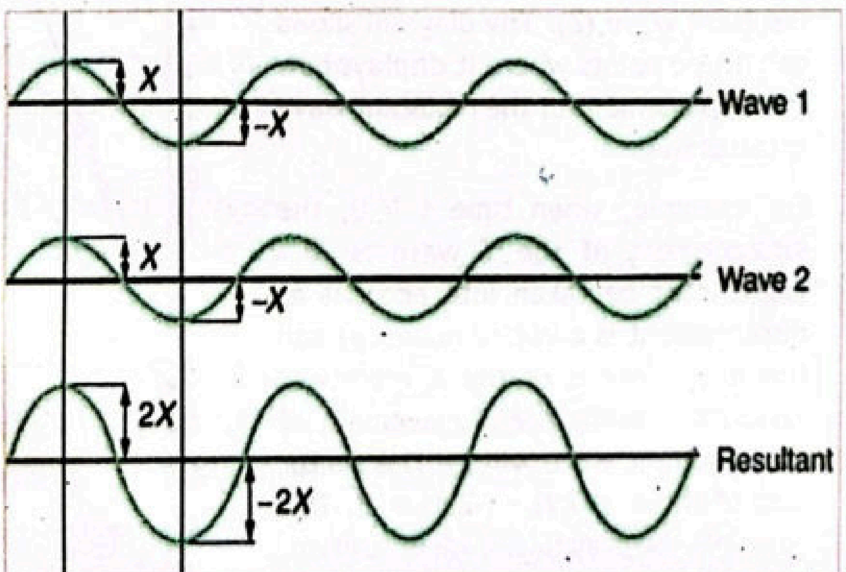


Figure 9.4 (a): Constructive Interference.

In case of longitudinal waves, constructive interference occurs when compressions of one wave overlap with the compression of another wave and rarefaction of one wave overlap with the rarefaction of other wave.

When two waves overlap at a point in the same phase then two waves reinforce each other. This is called constructive interference.

During destructive interference, crest of one wave falls on the trough of another wave. The amplitude of resultant wave is equal to the difference between the amplitude of the individual waves as i.e. $X - X = 0$, as shown in Fig. 9.4 (b).

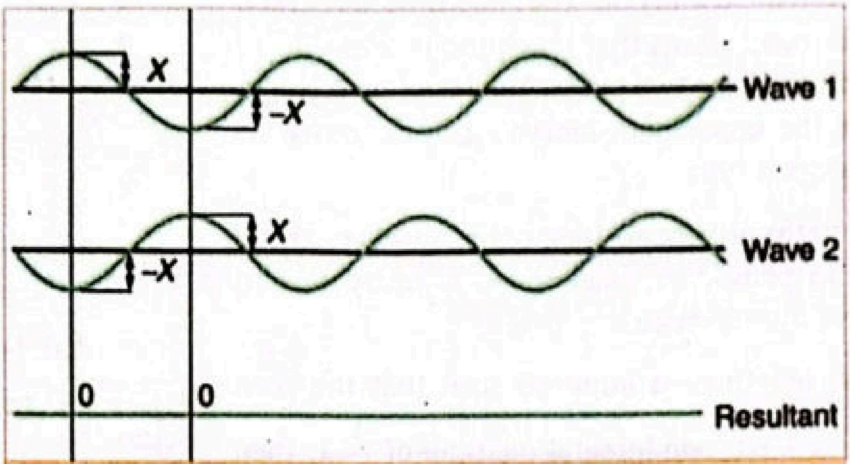


Figure 9.4 (b): Destructive Interference

In case of longitudinal waves, destructive interference occurs when compressions of one wave overlaps with the rarefaction of another wave.

When two waves overlap at a point out of phase (180°) then two waves cancel each other. This is called destructive interference.

9.4.1 Conditions for Interference

Following conditions are necessary for interference of waves:

i) waves must be travelling in the same direction.
ii) waves must arrive at the same place at the same time.
iii) waves must be,

(a) in phase, for *constructive interference*.
(b) out of phase (180°), for *destructive interference*.

iv) path difference must be,

(a) integral multiple of wavelength λ, for *constructive interference*.

$d = m\lambda$ (where $m = 0, 1, 2, 3, ...$)

(b) odd integral multiple of $\frac{1}{2}\lambda$, for *destructive interference*.

$d = (m + \frac{1}{2})\lambda$ (where $m = 0, 1, 2, 3, ...$)

9.4.2 Interference of Sound Waves

One simple device for demonstrating interference of sound waves is illustrated in Fig. 9.5 (a). Sound from a loudspeaker S is sent into a tube at point P, where there is a T-shaped junction. Half the sound energy travels in one direction, and half travels in the opposite direction. Therefore, the sound waves that reach the receiver R can travel along either of the two paths. The lower path length r_1 is fixed, but the upper path length r_2 can be varied by sliding the U-shaped tube.

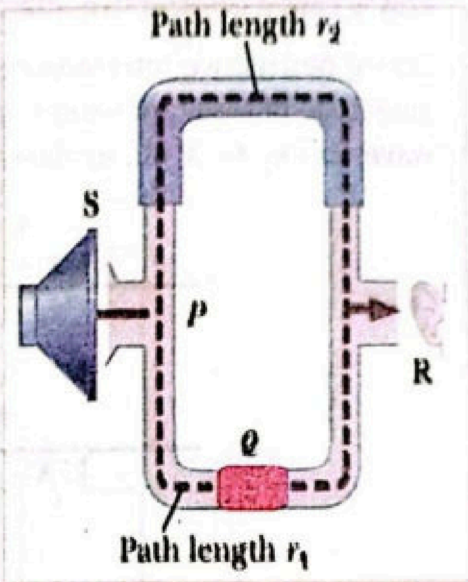


Figure 9.5 (a): Interference of Sound.

- If the two paths are equal, then both the waves arrive at R, are in phase. So, loud sound is heard due to constructive interference.
- If the path length r_2 is adjusted such that the path difference $r_2 - r_1$ is odd integral multiple of $\frac{1}{2}\lambda$, then both waves arriving at R may be out of phase. So, no sound is heard due to destructive interference.
- If the sound waves are stopped at Q by pinching the rubber portion of tube, then loud sound is heard again. This proves that silence is due to destructive interference of the two sound waves.

Noise-canceling Headphones

Noise-canceling headphones (as shown in Fig. 9.5 b) uses the principle of superposition to attenuate the environmental noise inside the ear cup of the headphone. The basic idea is to sense the unwanted sound wave coming from the noisy environment and produce an appropriate canceling sound wave through a loudspeaker. The canceling wave should match the noise in amplitude and has the opposite phase (i.e., 180° out of phase).

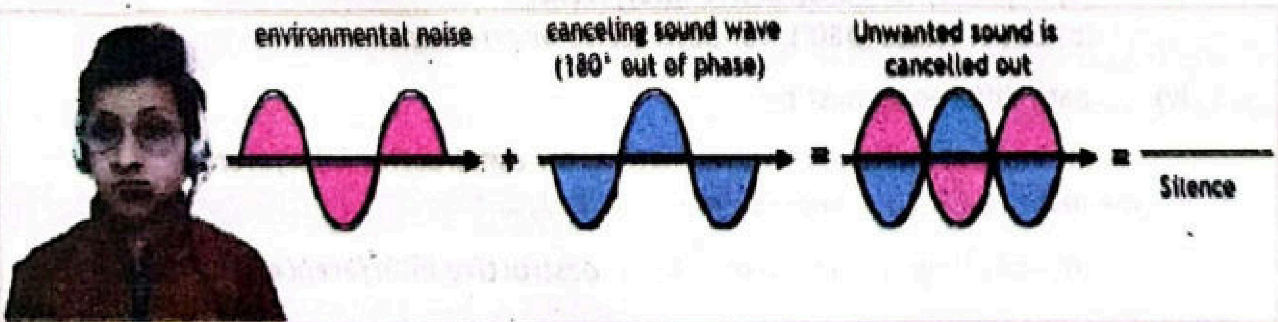


Figure 9.5 (b): Noise-canceling headphones.

In this way, the cancelling sound wave will destructively interfere with the environmental noise and the noise component will be effectively attenuated.

9.5 Beats

Beats are the interference effect results from the superposition of two waves with slightly different frequencies. When two sound waves having slightly different frequencies encounter each other, then the amplitude of sound waves is added and subtracted alternatively through a given period. Hence, the sound grows louder and softer through the given period and fluctuating sound (alternate soft and loud sound) is heard. It is important to note that, the loud sensation of sound is produced by the constructive interference. On the other hand, the soft sound is instigated due to destructive interference.

When two waves of slightly different frequencies are played simultaneously then periodic alternations of sound between maximum and minimum loudness are produced which are called beats.

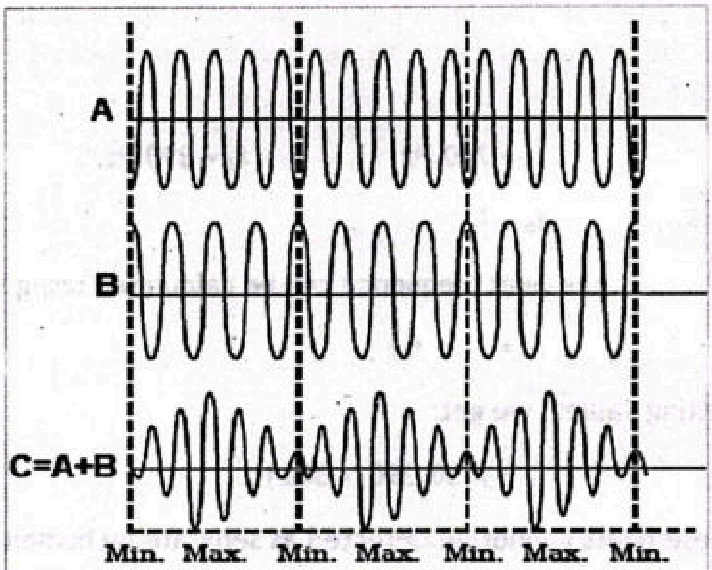


Figure 9.6: Generation of beats.

Let us consider two sound waves, A and B of slightly different frequencies but having similar amplitude propagating in the same medium. A resultant wave C is obtained by the superposition of A and B, as shown in Fig. 9.6. When these two sound waves encounter, a fluctuating sound can be heard. Note that for a certain time, the crest of A overlaps the crest of B. Hence, this causes constructive interference. Therefore, the sound intensity rises for this certain period. However, for an interval of time, the crest of B overlaps the trough of A. This causes destructive interference.

Beats Frequency

The number of beats generated per second is called beats frequency.

The beats frequency is equal to the absolute value of the difference in frequencies of the two waves. It is denoted by f_b.

$$f_b = |f_1 - f_2| \quad \text{------} \quad (9.10)$$

So, if two sound waves with frequencies of 32 Hz and 30 Hz are played simultaneously, a beat frequency of 2 Hz will be detected. If the numbers of beats per second are more than 10, then the beats can't be heard as separate.

Application of Beats

Beats are very useful to compare frequencies, finding the unknown frequency, tuning the musical instrument, in ultrasonic imaging and radar speed traps.

Musicians utilizes the phenomenon of beats to tune a piano string. They pluck the string and tap a tuning fork at the same time. If the two sound sources: the piano string and the tuning fork, produce detectable beats then their frequencies are not identical. They will then adjust the tension of the piano string and repeat the process until the beats can no longer be heard. As the piano string becomes more in tune with the tuning fork, the beat frequency will be reduced and approach 0 Hz. When beats are no longer heard, the piano string is tuned to the tuning fork; that is, they play the same frequency as the tuning fork. This process allows a musician to match the strings' frequency to the frequency of a standardized set of tuning forks.

Example 9.3: Two musical instruments are sounded together to produce beats. Evaluate the beat frequency of these two sound waves having frequencies 750 Hz and 390 Hz respectively?

Given: $f_1 = 750$ Hz $f_2 = 390$ Hz

To Find: $f_b = ?$

Solution: The beat frequency can be calculated using the formula:

$$f_b = |f_1 - f_2|$$

Putting values, we get:

$$f_b = |750 - 390| = 380 \text{ Hz}$$

These beats cannot be detected as separate by human ear. Can you tell why?

9.6 STATIONARY WAVES (OR STANDING WAVES)

Sometimes waves do not seem to move; rather, they just vibrate about mean position. Such standing waves can be seen on the rubber band. If a rubber band is tied at both ends and plucked from the middle then stationary waves are produced due to the reflections of waves from the ends of the rubber band.

When two identical waves having same speed, amplitude and frequency traveling in opposite direction are superposed then a wave obtained is called stationary wave.

Stationary wave is formed by the superposition of two or more identical waves, moving in opposite directions, each having the same amplitude and frequency, as illustrated in Fig. 9.7. The wave reflected at the boundary interferes constructively or destructively with the incoming wave. The two waves move through each other with their amplitude adding as they go by. The displacement of the particles of waves are shown at seven different positions at t = 0, (1/4)T, (1/2)T, (3/4)T and T. It can be noted from the Fig. 9.7 (c) that displacement of points 1, 3, 5 and 7 are always zero, these points of the medium do not vibrate at all and are called nodes.

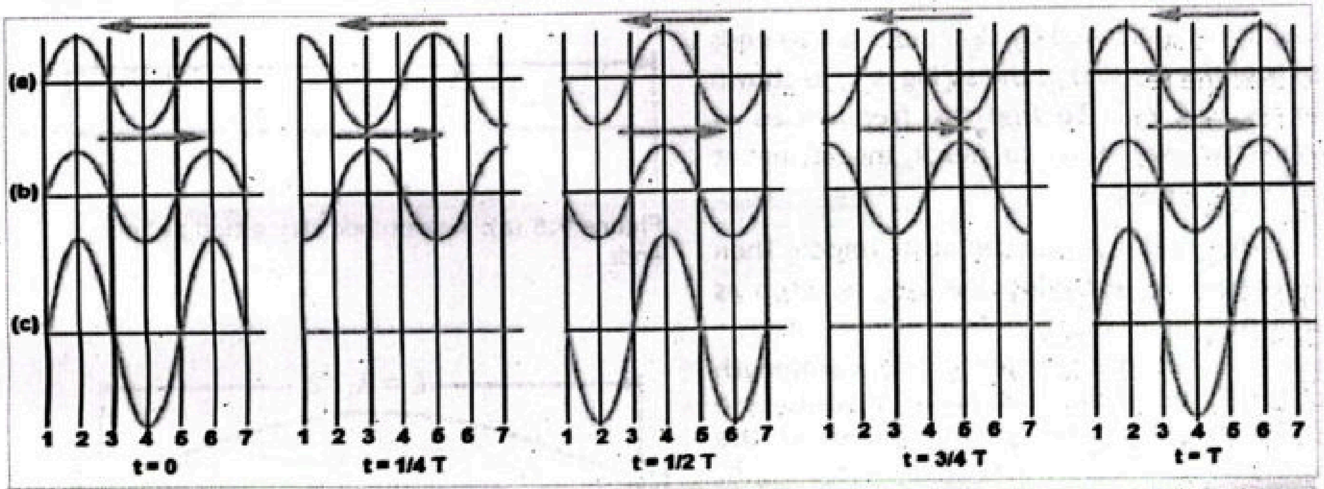


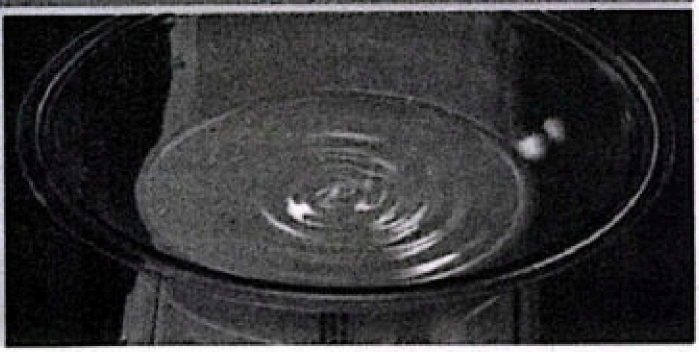
Figure 9.7: Standing wave created by the superposition of two identical waves moving in opposite directions.

The displacement of points 2, 4 and 6 has maximum amplitude but rapidly oscillating up and down, these points are called antinodes. Antinodes are oscillating with amplitude which is equal to the sum of amplitude of the component waves. Antinodes are usually represented by A and node are usually represented by N. This pattern of nodes and antinodes form a stationary wave because they appear to be standing, not moving through space like progressive waves. So, standing wave is confined in a given region of space.

Activity 9.2

The picture shows stationary wave on the surface of some liquid placed on a vibrator. The waves are visible in the photo due to the reflection of light from a lamp.

You can try this experiment at home. Take a bowl of milk and place it on a common box fan. Vibrations from the fan will produce circular standing waves on the surface of the milk.



Characteristics of Stationary Waves

A stationary wave has the following important characteristics:

(i) No energy is transferred from particle to particle in stationary waves.

(ii) The distance between two successive nodes or anti-nodes is equal to $\lambda/2$.

(iii) The distance between adjacent node and anti-node is equal to $\lambda/4$.

9.6.1 Stationary Waves in a Stretched String

Stationary waves can be setup in any media which do not transmit energy from one point to another point. Standing waves are also found on the strings of musical instruments and are produced due to the reflections of waves from the ends of the string. Consider a string of length

L which is stretched by clamping its two ends so that the tension in the string is T, as shown in Fig. 9.8 (a). To find the frequencies of vibration, we have to pluck the string at different points.

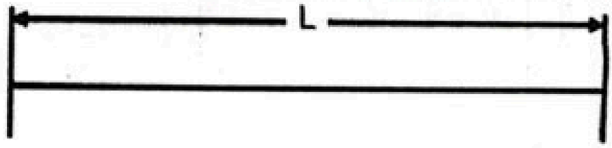


Figure 9.8 (a): A stretched string tied at both ends.

(1) When string is plucked at its middle then stationary wave having one loop is setup as shown in Fig. 9.8 (b).

Let f_1, λ_1 be the frequency and wavelength of the either of the component of transverse wave then from figure, the length of the string is equal to one-half of the wavelength. Therefore,

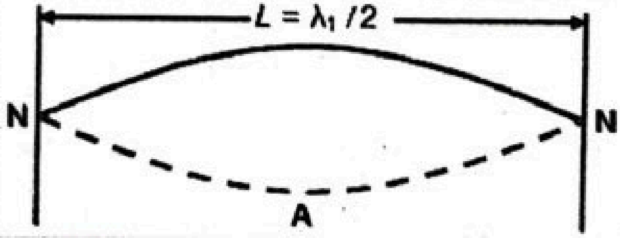


Figure 9.8 (b): Stationary wave having one loop.

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

$$\lambda_1 = 2L$$

If M is the total mass of the string, then speed v of progressive wave along the string is:

$$v = \sqrt{\frac{T \times L}{M}}$$

As $$v = f_1 \lambda_1$$

$$f_1 = \frac{v}{\lambda_1} = \frac{v}{2L}$$

$$f_1 = \frac{1}{2L}\sqrt{\frac{T \times L}{M}} \quad \text{\_\_\_\_\_ (9.11 a)}$$

If m is mass per unit length M/L, then

$$f_1 = \frac{1}{2L}\sqrt{\frac{T}{m}} \quad \text{\_\_\_\_\_ (9.11 b)}$$

This is called fundamental frequency, first harmonic or first mode of vibration.

(2) When string is plucked at one quarter of its length then stationary wave having two loops are setup, as shown in Fig. 9.8 (c). Let f_2, λ_2 be the frequency and wavelength of the either of the component transverse wave then from figure it can be seen that, the length of the string is equal to two-halves of the wavelength, since each loop is equivalent to one-half of a wavelength. Therefore,

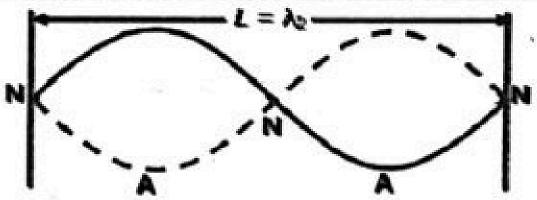


Figure 9.8 (c): Stationary wave having two loops.

$$L = \frac{\lambda_2}{2} + \frac{\lambda_2}{2} = \lambda_2$$

or $\lambda_2 = L$

As $v = f_2 \lambda_2$

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

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

because $\left(\frac{v}{2L}\right) = f_1$, so

$$f_2 = 2 f_1 \quad \text{(9.12)}$$

Hence when the string vibrates in two loops its frequency of vibration will be doubled as compared to its fundamental frequency, which is called second harmonic or second mode of vibration.

(3) When string is plucked at one sixth of its length then stationary wave having three loops is setup, as shown in Fig. 9.8 (d). Let f_3, λ_3 be the frequency and wavelength of the either of the component transverse wave then from figure it can be seen that, the length of the string is equal to three-halves of the wavelength, since each loop is equivalent to one-half of a wavelength:

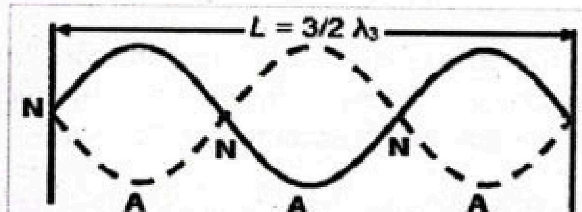


Figure 9.8 (d): Stationary wave having three loops.

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

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

As $v = f_3 \lambda_3$

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

because $\left(\frac{v}{2L}\right) = f_1$, so

$$f_3 = 3 f_1 \quad \text{(9.13)}$$

Hence when the string vibrates in three loops its frequency of vibration will be three times as compared to its fundamental frequency, which is called third harmonic or third mode of vibration. Similarly, if frequency is increased to $4f_1$, $5f_1$, $6f_1$, ..., then stationary waves of 4^{th}, 5^{th}, 6^{th}..., harmonic are setup and the cord will vibrate in 4, 5, 6, ..., loops respectively.

When string is vibrating having n loops, and f_n, λ_n are the frequency and wavelength of the either of the component transverse wave then:

$$L = \frac{\lambda_n}{2} + \frac{\lambda_n}{2} + \frac{\lambda_n}{2} + \ldots = \frac{n\lambda_n}{2}$$

or $\lambda_n = \frac{2L}{n}$ ______ (9.14)

The lowest frequency, called the fundamental frequency, corresponds to the longest wavelength. Also, frequency f_n of n-loop is:

$f_n = n f_1$ OR $f_n = \frac{n}{2L}\sqrt{\frac{T}{m}}$ ______ (9.15)

Thus, it can be concluded that:

(i) The string resonates only if it is a whole number multiple of half wavelength, i.e.,

$$L = \frac{\lambda}{2}, 2\frac{\lambda}{2}, 3\frac{\lambda}{2}, \ldots$$

(ii) Stationary waves on the string can be setup only with discrete set of frequencies f_1, f_2, f_3, ...f_n. This is called quantization of frequency.

(iii) The lowest frequency f_1 is called fundamental frequency and its higher multiples are called overtones or harmonics.

(iv) As the string vibrate in more and more loops its frequency goes on increasing but the wavelength gets correspondingly decreasing, such that product of frequency and wavelength is always constant and is equal to speed of wave.

9.7 STATIONARY WAVES IN AIR COLUMN

Standing waves can also be generated in air columns such as organ pipes. Organ pipe is a musical instrument. It consists of a long tube which produces sound by mean of vibrating air column, Flute, trombone, clarinet, etc. are familiar examples of organ pipes. Organ pipes can be open or closed. If both ends of an organ pipe are open, then it is called open organ pipe. If one end of an organ pipe is closed, then it is called closed organ pipe.

Suppose we have a tube that is closed at one end and open at the other. If we hold a vibrating tuning fork near the open end of the tube, an incident sound wave travels through the tube and reflects off the closed end. The reflected sound has the same frequency and wavelength as the incident sound wave, but is traveling in the opposite direction. At the closed end of the tube, the molecules of air have very little freedom to oscillate, and a node arises. At the open end, the molecules are free to move, and at the right frequency, an antinode occurs and the air column in the tube resonates loudly. The standing wave formed in the tube has an antinode at the open end and a node at the closed end. A portion of the sound wave is reflected back into the tube even at an open end. The distance from a node to an antinode is one-fourth of a wavelength, and *this equals* the length of the tube thus, $L = 1/4\ \lambda_1$.

9.7.1 Modes of Vibration in Open Pipe

Let a vibrating tuning fork be held at one end of open pipe of length L. There are anti-nodes at both the ends with a node at the middle. The modes of vibration in open organ pipe are given below.

(1) Fundamental Frequency: Let f_1, λ_1 be the frequency and wavelength of stationary wave, as shown in Fig. 9.9 (a), the length L and wavelength are related as:

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

$$\lambda_1 = 2L$$

As $\quad v = f_1\lambda_1$

So, $\quad f_1 = \frac{v}{\lambda_1}$

or $\quad f_1 = \frac{v}{2L}$ ______ (9.16)

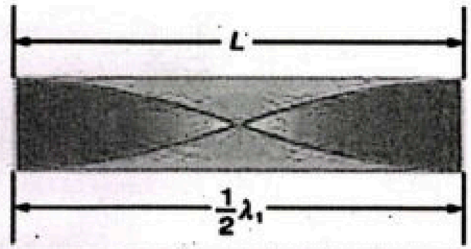


Figure 9.9 (a): Fundamental Frequency

This is called fundamental frequency or first harmonic for open pipe.

(2) Second Harmonic: Let f_2, λ_2 be the frequency and wavelength of stationary wave, as shown in Fig. 9.9 (b), the length L and wavelength are related as:

$$L = \lambda_2$$

$$\lambda_2 = L$$

As $\quad v = f_2\lambda_2$

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

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

Since, $\left(\frac{v}{2L}\right) = f_1$, so

$$f_2 = 2f_1 \quad \text{______ (9.17)}$$

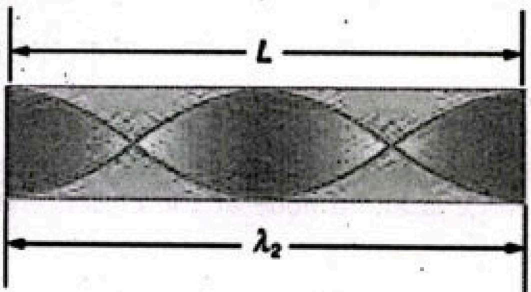


Figure 9.9 (b): Second harmonic.

This is called second harmonic for open pipe.

(3) Third Harmonic: Let f_3, λ_3 be the frequency and wavelength of stationary wave, as shown in Fig. 9.9 (c). The length L and wavelength are related as:

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

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

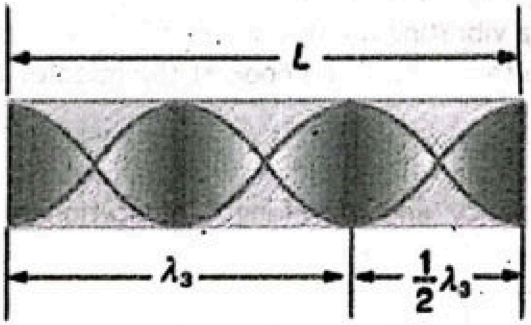


Figure 9.9 (c): Third harmonic.

As $v = f_3 \lambda_3$

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

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

Since, $\left(\frac{v}{2L}\right) = f_1$, so

$$f_3 = 3 f_1 \quad \text{\_\_\_\_\_ (9.18)}$$

This is the formula for third harmonic for open pipe. Similarly, from the above results, the wavelength λ_n and frequency f_n for nth harmonic is given by:

$$\lambda_n = \frac{2L}{n} \quad \text{\_\_\_\_\_ (9.19)}$$

and $$f_n = n f_1 \quad \text{\_\_\_\_\_ (9.20)} \qquad \text{where } n = 1,2,3, \ldots$$

Hence all harmonics are present in an open pipe.

9.7.2 Modes of Vibration in Closed Pipe

Let a vibrating tuning fork be held at one end of closed pipe of length L. There is an anti-node at open end and a node at the closed end. The modes of vibration in closed organ pipe are given below.

(1) Fundamental Frequency or First Harmonic: Let f_1, λ_1 be the frequency and wavelength of stationary wave, as shown in Fig. 9.10 (a), the length L and wavelength are related as:

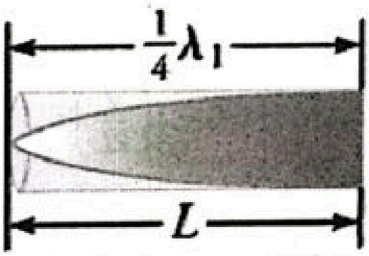


Figure 9.10 (a): First harmonic.

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

or $$\lambda_1 = 4L$$

As

$$v = f_1 \lambda_1$$

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

$$f_1 = \frac{v}{4L} \quad \text{\_\_\_\_\_ (9.21)}$$

(2) **Second Harmonic:** Let f_2, λ_2 be the frequency and wavelength of stationary wave, as shown in Fig. 9.10 (b). The length L and wavelength are related as:

$$L = \frac{\lambda_2}{2} + \frac{\lambda_2}{4} = 3\frac{\lambda_2}{4}$$

or $$\lambda_2 = \frac{4L}{3}$$

As

$$v = f_2 \lambda_2$$

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

or $$f_2 = 3\frac{v}{4L}$$

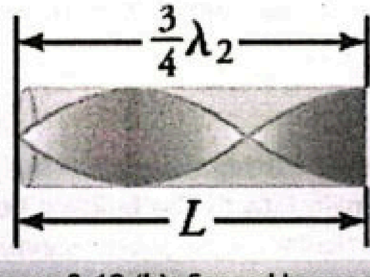


Figure 9.10 (b): Second harmonic.

Since, $\frac{v}{4L} = f_1$, so

$$f_2 = 3 f_1 \quad \text{(9.22)}$$

(3) **Third Harmonic:** Let f_3, λ_3 be the frequency and wavelength of stationary wave, as shown in Fig. 9.10 (c), the length L and wavelength are related as:

$$L = \lambda_3 + \frac{\lambda_3}{4} = 5\frac{\lambda_3}{4}$$

or $$\lambda_3 = \frac{4L}{5}$$

As $v = f_3 \lambda_3$

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

or $$f_3 = 5\frac{v}{4L}$$

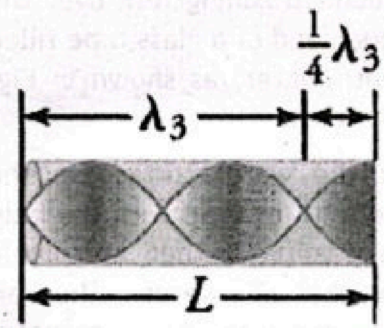


Figure 9.10 (c): Third harmonic.

Since, $\frac{v}{4L} = f_1$, so

$$f_3 = 5 f_1 \quad \text{(9.23)}$$

Similarly, from the above results, the wavelength λ_n and frequency f_n for nth harmonic is given by

$$\lambda_n = \frac{4L}{2n-1} \quad \text{(9.24)}$$

and $$f_n = (2n-1) f_1 \quad \text{or} \quad f_n = (2n-1)\frac{v}{4L} \quad \text{(9.25)}$$

where n = 1, 2, 3, ... Thus, it can be seen that in an open pipe, fundamental frequency is $\frac{v}{2L}$ and all harmonics are present while in a closed pipe, fundamental frequency is $\frac{v}{4L}$ and only odd harmonics are present.

For Your Information

During earthquakes, often buildings of a certain height are devastated while other taller buildings remain intact. The building height matches the condition for setting up a standing wave for that particular height provides evidence for conditions appropriate for resonance, and constructive and destructive interference. As the earthquake waves travel along the surface of the Earth and reflect off denser rocks, constructive interference occurs at certain points. A building may be vibrated for several seconds with a driving frequency matching that of the natural frequency of vibration of the building, producing a resonance resulting in one building collapsing while neighboring buildings do not. Often areas closer to the epicenter are not damaged while areas farther away are damaged.

9.7.3 Experiment to Demonstrate Stationary Waves

Stationary wave can be setup in air column by holding a sounded tuning fork over the open end of a glass tube filled with water, as shown in Fig. 9.10 (d).

If the water surface in the tube is lowered with the help of reservoir, then at certain height of water, the air column in the tube resonates loudly. There will be several other heights at which the air column in the tube resonates.

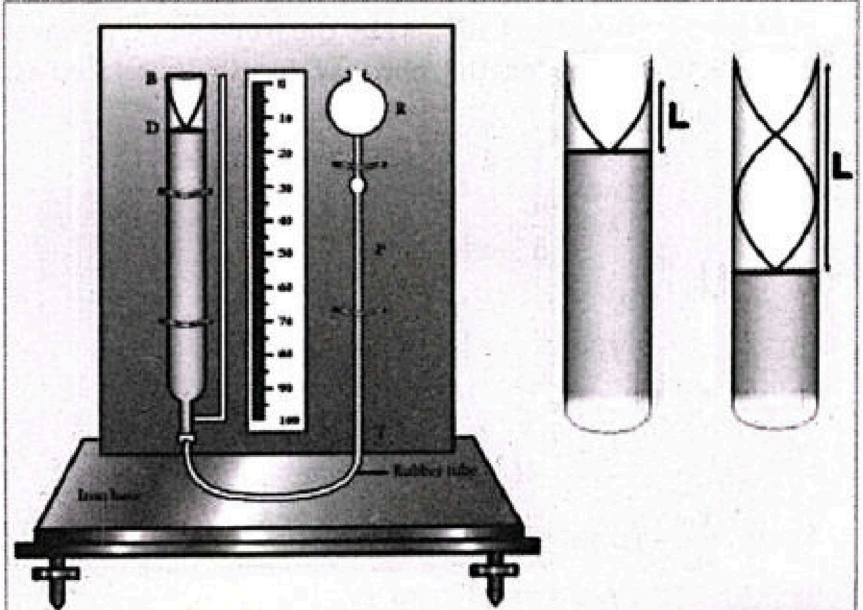


Figure 9.10 (d): Resonance tube.

***Example* 9.4: A guitar string with a length of 80.0 cm is plucked. The speed of a wave in the string is 400 m s^{-1}. Calculate the frequency of the first, second, and third harmonics?**

Given: L = 0.80 m $\quad v$ = 400 m s^{-1}

To Find: First harmonic = f_1 = ? $\quad$ Second Harmonic = f_2 = ?

Third harmonic = f_3 = ?

Solution: For first harmonic

$$f_1 = \frac{v}{2L}$$

$$= \frac{400}{2(0.8)} = 250 \text{ Hz}$$

Second harmonic: $f_2 = 2(f_1) = 500$ Hz

Third harmonic: $f_3 = 3\ (f_1) = 750$ Hz

Assignment 9.3

A frequency of the first harmonic is 587 Hz is sounded out by a vibrating guitar string. The speed of the wave is 600 m s^{-1}. Find the length of the string.

9.8 POLARIZATION

Polarization is a phenomenon associated to transverse waves. A light wave is an electromagnetic wave. An electromagnetic wave is a special type of transverse wave that has both an electric and a magnetic component, as shown in Fig. 9.11 (a).

Ordinarily, a ray of light consists of a number of waves vibrating in all the directions perpendicular to its line of propagation. Light emitted by the sun, a lamp, or by a candle flame are created by electric charges that vibrate in various directions, thus creating a variety of electromagnetic wave that vibrates in several planes perpendicular to its line of propagation, as shown in Fig. 9.11 (b). A light wave that is vibrating in more than one plane is referred to as unpolarized light. It is possible to transform unpolarized light into polarized light.

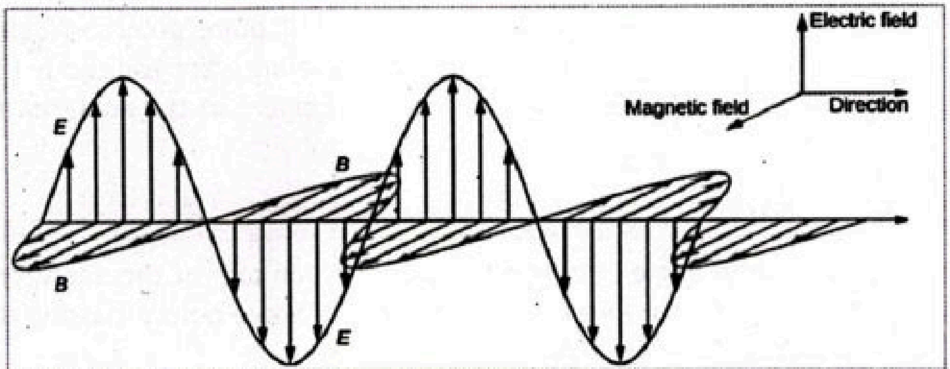


Figure 9.11 (a): An electromagnetic wave.

Polarized light waves are light waves in which the vibrations occur in a single plane.

The process of transforming unpolarized light into polarized light is known as polarization.

There are a variety of methods of polarizing light, as discussed below.

9.8.1 Polarization by a Polaroid Filter

The one most common method of polarization includes the use of a Polaroid filter.

Polaroid filters are made of a special material that is capable of blocking all the planes of vibration of an electromagnetic wave and transmit only one plane of vibration, as shown in Fig. 9.11 (b). So, a Polaroid serves as a device that filters out one plane of the vibrations upon transmission of the light through the filter. When unpolarized light is transmitted through a Polaroid filter, it emerges as polarized light, i.e., its intensity reduces to half and with vibrations in a single plane.

A Polaroid filter is able to polarize light because of the chemical composition of the filter's material. In the same manner, two Polaroid filters oriented with their polarization axis perpendicular to each other will block all the light. This observation could never be explained by a particle nature of light.

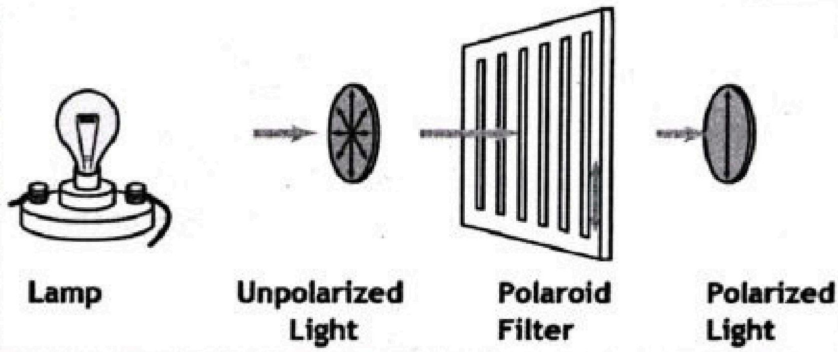


Figure 9.11 (b): Polaroid filters is blocking all the planes of vibration of an electromagnetic wave and transmit only one plane of vibration.

When unpolarized light passes through a polaroid filter its intensity reduces and only light parallel to the grid axis within the polarizing filter is allowed to pass.

The axis of polarization of transmitted light is the same as the filter that polarizing it. It is then perfectly plane polarized light. When perfectly plane polarized light is incident on an analyzer, the intensity I of the light transmitted by the analyzer is directly proportional to the square of the cosine of angle between the transmission axis of the analyzer and the polarizer.

i.e., $I \propto \cos^2\theta$

or $I = I_o \cos^2\theta$ ______ (9.26)

Where θ is the angle between the transmission axis of the analyzer and the polarizer. I_o is the intensity unpolarized wave i.e., intensity of wave before passing through the polarizing filter. The equation (9.26) is known as Malus's law.

9.8.2 Polarization by Reflection

Unpolarized light can also polarized by reflection from nonmetallic surfaces, as shown in Fig. 9.11 (c). The amount to which polarization occurs is dependent upon the angle at which the light incident to the surface and material of the surface. Metallic surfaces reflect light with a variety of vibrational directions; such reflected light is unpolarized. However, nonmetallic surfaces such as water and asphalt roadways, reflect light such that there is a large concentration of vibrations in a plane parallel to the reflecting surface. A person viewing objects by means of light reflected off of nonmetallic surfaces will often perceive a glare if the extent of polarization is large. Fishermen are familiar with this glare since it prevents them from seeing fish that lie below the water surface. Light reflected

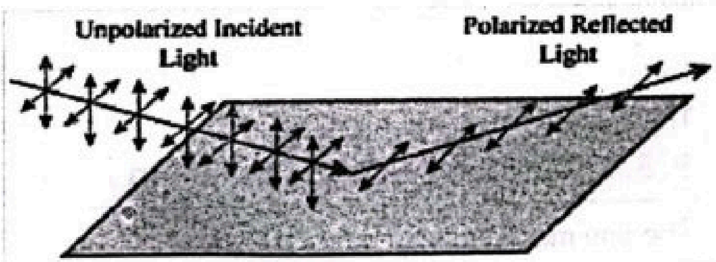


Figure 9.11 (c): Polarization by reflection.

off a lake is partially polarized in a direction parallel to the water's surface. Fishermen know that the use of glare-reducing sunglasses with the proper polarization axis allows for the blocking of this partially polarized light. By blocking the plane-polarized light, the glare is reduced and the fisherman can more easily see fish located under the water.

9.8.3 Uses of Polaroids

Polaroids in Sky Photography: Polaroid sunglasses are familiar to most of us. They have a special ability to reduce the glare of light reflected from water or sky. A camera used to photograph the clouds is fitted with a polaroid before the camera lens. The light coming from sky is polarized by polaroid. Thus, the background becomes sufficiently dark against which a clear photograph is obtained.

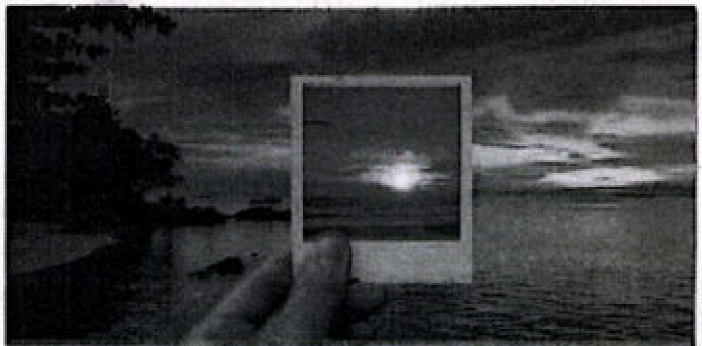


Figure 9.11 (d): Polaroids can be used in Sky Photography.

Polaroids in Stress Analysis: In plastic industry, polaroid is used to perform stress analysis tests on transparent plastics. As light passes through a plastic, each color of visible light is polarized with its own direction. If such a plastic is placed between two polarizing plates, a colorful pattern is observed. As the top plate is turned, the color pattern changes as new colors become blocked and the formerly blocked colors are transmitted. Structural stress in plastic is signified at locations where there is a large concentration of colored bands. This location of stress is usually the location where structural failure will most probably occur.

Polaroids are also used in the entertainment industry to display 3-D movies.

Example 9.5: An Unpolarized light having intensity of = 16 W m^{-2} is incident on a pair of polarizers. The first polaroid filter has its transmission axis at 50° from the vertical. The second polaroid filter has its transmission axis at 20° from the vertical. Calculate the intensity of the light transmitted through both the filters.

Given: Intensity unpolarized light = I_o = 16 W m^{-2}

Transmission axis of 1st polarizer from the vertical = 50°

Transmission axis of 2nd polarizer from the vertical = 20°

To Find: Intensity of the light transmitted = I = ?

Solution: First, we calculate the intensity of the light when it emerges from the first polarizer. As the light is unpolarized, so

$$I_1 = I_o / 2 = 16/2 = 8 \text{ W m}^{-2}$$

Now we calculate the intensity of the light when it emerges from the second polaroid filter. As, when it emerges from the first polaroid filter the light is linearly polarized at 50°. The angle between this light and the transmission axis of the second polaroid filter is 50°- 20° = 30°

Therefore, $I_2 = I_1 \cos^2 30^\circ = 8 \times (0.866)^2 = 8 \times 0.75 = 6 \text{ W m}^{-2}$

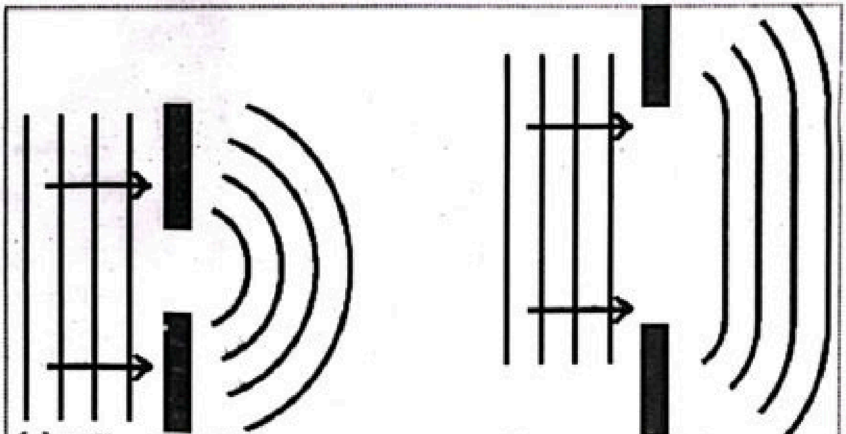
Assignment 9.4

What angle is required between the direction of polarized light and the axis of a polaroid filter to reduce its intensity by 90% ?

9.9 DIFFRACTION

The bending of waves around the sharp edges or corners of an obstacles (or slits) and spreading into its geometrical shadow is called diffraction.

To observe the diffraction effect in water, we generate plane waves of water in a ripple tank and place two obstacles in line in such a way that separation between them is equal to the wavelength of water waves, as shown in Fig. 9.12. After passing through the small slit between the two obstacles, the water waves will spread around the slit and change into almost semicircular pattern (Fig. 9.12 a).



(a): Diffraction of water waves through a small slit

(b): Diffraction of water waves through a large slit

Figure 9.12: For observable diffraction separation between obstacles must be equal to the wavelength.

Diffraction of waves can only be observed clearly if the size of the obstacle is comparable with the wavelength of the wave. If the size of the obstacle is larger than the wavelength of the wave, then only a small diffraction occurs near the corners of the obstacle, as shown in Fig. 9.12 (b).

Diffraction can also be observed in light waves, when a beam of monochromatic light passes through a narrow slit or beam of monochromatic light passes over a knife edge. The diffraction of light can be observed only if size of the opening or obstacle is small enough to be comparable with wavelength of light used.

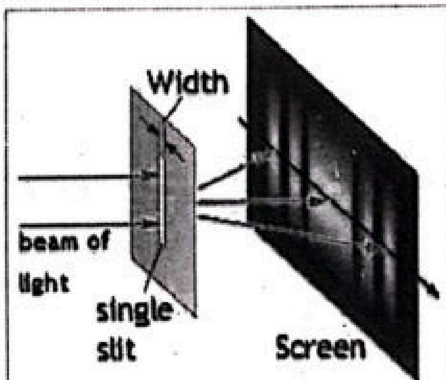


Figure 9.13: Diffraction of light.

Consider a beam of light passing through a single slit and falls on the photographic film, as shown in Fig. 9.13. The central bright band (also called fringe) is of high intensity and very wider than the slit and other surrounding bands. These bands are the result of interference effect.

9.10 GRAVITATIONAL WAVE

Albert Einstein predicted the existence of gravitational waves in 1916.

A gravitational wave is a stretch and compress of space and so can be found by measuring the change in length between two objects.

Gravitational waves are actually the ripples in spacetime. When objects move, the curvature of spacetime changes and these changes move away (like ripples on water surface) as gravitational waves.

> **For Your Information**
> Spacetime is a mathematical model that fuses the three dimensions of space and the one dimension of time into a single four-dimensional continuum.

Every physical object, that accelerates, produces gravitational waves. This includes humans, vehicles, airplanes etc. But the masses and accelerations of objects on Earth are too much small to make gravitational waves big enough to be detected with our instruments. To find big enough gravitational waves, we have to see far away outside of our solar system. The Universe is filled with extremely massive objects undergoing quick accelerations that generate gravitational waves which can be detected. Examples of some events that could cause a gravitational wave are:

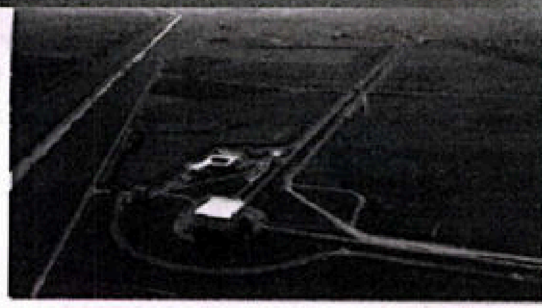
- When a star explodes asymmetrically, called a supernova.
- When two big stars orbit each other.
- When two black holes orbit each other and collide to merge.

9.10.1 Interferometer

Interferometer are tools used for investigation in many fields of science and engineering. They are called interferometers because they work on interference of two or more light to create an interference pattern. This pattern can be measured and analyzed. The interference patterns generated by interferometers contain information about the object or phenomenon being studied. They are often used to make very small measurements that are not possible by any other way. That is why they are so powerful for detecting gravitational waves. LIGO's interferometers are designed to measure a distance of 1/10,000th the width of a proton, small enough!

For Your Information

The Laser Interferometer Gravitational-Wave Observatory (LIGO) is a large-scale physics experiment and observatory designed to detect gravitational waves and to develop gravitational-wave observations as an astronomical tool. This project is a collaboration between USA, India, Germany, Australia and U.K. LIGO consists of two instruments called interferometers, each with two 4 km (2.5 mile) long arms arranged in the shape of an "L". The interferometers act



as 'antennae' to detect gravitational waves. Gravitational waves cause space itself to stretch in one direction and simultaneously compress in a perpendicular direction. In LIGO, this causes one arm of the interferometer to get longer while the other gets shorter, then vice versa, back and forth as long as the wave is passing. Since the arms are simultaneously changing lengths in opposing ways. This effect is measured by laser beam in interferometer. Hence gravitational waves are detected.

SUMMARY

- **Superposition of waves** occur two or more waves are passing through the same region at the same time, the total displacement at the point where they interact, is equal to the vector sum of the individual displacements due to each pulse at that point.
- The effect produced due to the superposition of waves from two coherent sources is known as **interference.**
- When two waves meet at a point in the same phase then two waves reinforce each other. This is called **constructive interference.**
- When two waves meet at a point out of phase (180°) then two waves cancel each other. This is called **destructive interference.**
- When two waves of slightly different frequencies are played simultaneously then periodic alternations of sound between maximum and minimum loudness are produced which are called **Beats.**
- The number of beats generated per second is called **beats frequency.**
- When two identical waves having same speed, amplitude and frequency traveling in opposite direction superpose then a wave obtain is called **stationary wave.**
- **The distance between two successive nodes or anti-nodes** is equal to $\lambda/2$. The distance between adjacent node and anti-node is equal to $\lambda/4$.
- The apparent change in the frequency of sound due to the relative motion between the listener and source of sound is called **Doppler's effect.**
- **Coherent Light:** Light made up of waves with the same wavelength that are in phase with each other.
- **Polarized light waves** are light waves in which the vibrations occur in a single plane.
- The process of transforming un-polarized light into polarized light is known as **polarization.**

EXERCISE

Multiple Choice Questions

Encircle the Correct option.

1) On doubling amplitude of the wave, intensity is increased:

A. 1/2 times B. 2 times C. 4 times D. 3 times

2) Two waves, each with amplitude of 0.5 m are superimposed with constructive interference such that they are in phase. What is the resultant amplitude?

A. 0.25 m B. 0.5 m C. 0 m D. 1 m

3) What happens when two sound waves of frequencies differing by more than 10 Hz reach our ear simultaneously?

A. beats are not produced. B. the waves destroy each other's effect.

C. interference of sound does not take place.

D. beats are produced but cannot be heard by human ear.

4) A car has two horns; one is emitting a frequency of 199 Hz and the other is emitting a frequency of 203 Hz. What beat frequency do they produce?

A. 4 Hz B. 199 Hz C. 201 Hz D .203 Hz

5) Which of the following frequencies are higher harmonics of a string with fundamental frequency of 150 Hz?

A. 200 Hz, 300 Hz B. 300 Hz, 600 Hz C. 250 Hz, 450 Hz D. 250 Hz, 500 Hz

6) What is the wavelength of the third harmonic (n=3) of a standing wave established on a string of length 3 m fixed at both ends?

A. 1 m B. 1.5 m C. 2 m D. 3 m

7) A node is a point located along the medium where there is always ____.

A. a double crest. B. constructive interference.

C. destructive interference . D. a double rarefaction.

8) Which phenomenon is produced when two or more waves passing simultaneously through the same medium meet up with one another?

A. refraction B. diffraction C. interference D. reflection

9) A standing wave is formed by waves of frequency 256 Hz. The speed of the waves is 128 m/s. The distance between the nodes must be:

A. 2.00 m B. 1.00 m C. 0.500 m D. 0.250 m

10) An air column that is closed at one end is used to determine the speed of sound. The frequency of the tuning fork used is 329.6 Hz. The length of the shortest air column producing the resonance is 25.0 cm. The speed of the sound must be:

A. 380.6 m s^{-1} B. 282.4 m s^{-1} C. 3.30×10^2 m s^{-1} D. 3.50×10^2 m s^{-1}

11) The intensity of beam observed through polarizer:

A. is increased B. is decreased C. is always zero D. remains unchanged

Short Questions

Give short answers of the following questions.

9.1 Two identical waves undergo pure constructive interference. Is the resultant intensity twice that of the individual waves? Explain your answer.

9.2 Circular water waves decrease in amplitude as they move away from where a rock is dropped. Explain why.

9.3 Differentiate between constructive and destructive interference?

9.4 The frequency of a stretched string depends on its length. Give two other factors that affect the frequency of a stretched string.

9.5 The pitch of the sound emitted by the siren of a moving fire engine appears to change as it passes a stationary observer. (i) Name this phenomenon. (ii) Will the crew in the fire engine notice this phenomenon? Give a reason for your answer. (iii) Give an application of this phenomenon.

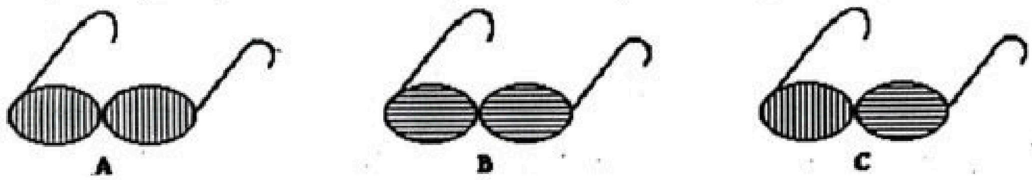
9.6 How should a sound source move with respect to an observer so that the frequency of its sound does not change?

9.7 Can sound waves be polarized? Explain.

9.8 Suppose that light passes through two Polaroid filters whose polarization axis are parallel to each other. What would be the result?

9.9 Give any three examples of a gravitational wave?

9.10 Consider the three pairs of sunglasses below. Which pair of the glasses is capable of eliminating the glare resulting from sunlight reflecting off the calm waters of a lake? Explain you option. (The polarization axes are shown by the straight lines)



Comprehensive Questions

Answer the following questions in detail.

9.1 What is superposition principle? Discuss.

9.2 What is interference? Discuss its types and corresponding conditions.

9.3 What are stationary waves? How stationary wave is formed? Discuss.

9.4 Discuss the formation of stationary waves in (a) stretched string (b) open pipe (c) closed pipe.

9.5 What are beats? Explain.

9.6 Explain the use of polaroids in (a) sky photography (b) stress analysis of materials.

9.7 What is meant by the Doppler's effect? Discuss its cases. Also give some application of the Doppler's effect.

9.8 Describe an experiment to demonstrate the interference of sound.

9.9 What is polarization? How is plane polarized light produced and detected?

9.10 What is meant by the term 'Gravitational Waves'? Explain in detail.

9.11 Explain the use of interferometer in detecting gravitational waves.

Numerical Problems

9.1 Ultrasound of intensity 1.50×10^2 W m^{-2} is produced by the rectangular head of a medical imaging device measuring 3.00 cm by 5.00 cm. What is its power output? **(Ans: 0.225 W)**

9.2 Two tuning forks of frequencies 440 Hz and 437 Hz are sounded together. How many beats will be heard over a period of 10 seconds? **(Ans: 30 beats)**

9.3 Suppose that a string is 1.2 m long and vibrates in first, second and third harmonic standing wave patterns. Determine the wavelength of the waves for each of the three patterns.

(Ans: 2.4 m, 1.2 m, 0.8 m)

9.4 The string is 6.0 m long and is vibrating at the third harmonic. The string vibrates up and down with 45 complete vibrational cycles in 10 seconds. Determine the frequency, period, wavelength and speed for this wave. **(Ans: 4.5 Hz, 0.22 sec, 4.0 m, 18 m s^{-1})**

9.5 An air column closed at one end resonates at the second maximum or the second resonant length. The frequency of the sound wave is 1024 Hz. The air temperature is 18.6°C.

a) Draw a diagram of the displacement wave pattern inside the column.

b) Calculate the speed of sound in air.

c) Calculate the wavelength.

d) Calculate the length of the closed air column. **(Ans: 343 m s^{-1}, 0.335 m, 0.251 m)**

9.6 Suppose a train that has a 150 Hz horn is moving at 35.0 m s^{-1} in still air on a day when the speed of sound is 340 m s^{-1}. What frequencies are observed by a stationary person at the side of the tracks

(a) as the train approaches. (b) after it passes.

(c) What frequency is observed by the train's engineer traveling on the train?

(Ans: 167 Hz, 136 Hz, same frequency as emitted by the horn)

9.7 A polarized light of intensity I_o is passed through another polarizer whose axis makes an angle of 60° with the axis of the polaroid filter. What is the intensity of transmitted polarized light from second polaroid filter? **(Ans: $I_o/4$)**