

Chapter # 07

Waves and Vibrations

STUDENTS LEARNING OUTCOMES (SLO's)

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

- 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 cancelling 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.
- Describe an experiment that demonstrates 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 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.
- Use intensity = power/area to solve problems. Use intensity $\propto (\text{amplitude})^2$ 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 the Doppler effect for a stationary source and a moving observer is not required].
- Use the expression 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].

7.1 WAVES



1. Define wave and different parameters or terms associated with it.

Ans. Waves

Definition

A wave is a regular disturbance or vibration that transfers energy from one point to another.

Examples:

- (i) A stone thrown in a pond of water creates a disturbance (wave) that travels through the water.
- (ii) When we wriggle a rope or a spring, waves are produced.
- (iii) Energy is transferred from the Sun to the Earth in the form of electromagnetic waves.

Parameters Associated with Waves

1. **Amplitude (A):** It is the maximum displacement of the waves or particles of the medium from its equilibrium position.
2. **Frequency (f):** The number of oscillations or vibrations or cycles per second is called frequency of a wave. It is measured in hertz (Hz).
3. **Wavelength (λ):** It is the distance between two consecutive points on the wave that are in phase. It is measured in metres (m).
4. **Speed (v):** The velocity at which a wave travels. Its unit is metre per second (ms^{-1}).

If a wave crest moves one wavelength λ in one period of oscillation T , the speed v is given by

$$v = f\lambda$$

..... (i)

5. **Period (T):** It is the time taken by the wave to complete one oscillation or cycle. It is measured in seconds (s).
6. **Phase (θ):** It is the relative position of a point on the wave at a given time. It is measured in radians (rad).

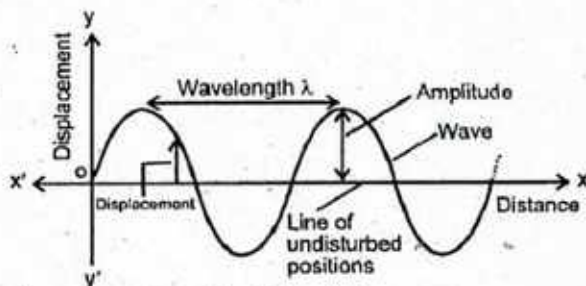


Fig. 1: Graphical description of a wave y .



2. What are different types of waves? Give examples.

Ans. Types of Waves

1. Mechanical Waves

Definition

These waves require a physical medium (solid, liquid or gas) to propagate.

Examples: Water waves, sound waves, seismic waves, (earthquakes), etc.

2. Electromagnetic Waves:

Definition

These waves do not require a medium to propagate, and can travel through vacuum.

Examples: Radiowaves (wireless communication), microwaves (cooking and heating), infrared waves (IR and heat radiations), visible light (sunlight, lamp light), ultraviolet waves (UV radiations), X-rays (medical imaging), γ -rays (high-energy radiation), etc.

3. Quantum Waves

Definition

These waves are associated with particles like electrons and photons.

Examples: Matter waves or particle waves (electron waves in atoms), de-Broglie waves, photon waves (light quanta), etc.

4. Surface Waves

Definition

Such waves propagate along surfaces or interfaces between two mediums.

Examples: Ocean surface waves, seismic surface waves, etc.



3. What are transverse and longitudinal waves? Give examples.

Ans. Transverse Waves

Definition

A transverse wave is one in which the vibrations of the particles are at right angle to the direction in which the energy of the wave is travelling.

Examples: The ripples on the surface of water, the waves on a string, the ocean waves, electromagnetic waves, stadium or human waves, the secondary waves of an earthquake, etc.

Transverse waves

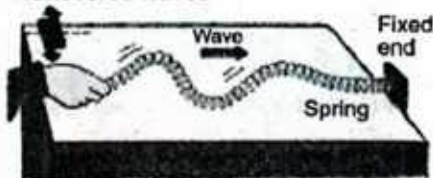


Fig. 2

Longitudinal waves

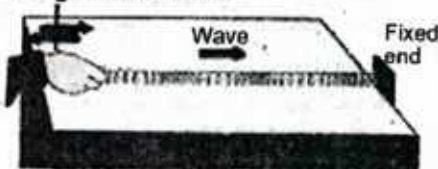


Fig. 3

Longitudinal Waves

Definition

A longitudinal wave is one in which the direction of vibrations of the particles is along or parallel to the direction in which the energy of the wave is travelling.

Examples: Sound waves in air, the vibrations of a spring, ultrasound, the primary waves of an earthquake, the fluctuations in a gas, the tsunami waves, etc.



- | | |
|---|---|
| 1. Longitudinal waves are also known as:
(A) Stationary waves
(B) Transverse waves
(C) Compressional waves ✓
(D) Electromagnetic wave | (C) Matter waves ✓
(D) Both (A) and (C) |
| 2. The distance covered by wave in 1 second is:
(A) Wavelength
(B) Wave number
(C) Frequency
(D) Wave speed ✓ | 4. Distance between a crest and a trough is:
(A) λ
(B) $\frac{\lambda}{2}$ ✓
(C) $\frac{\lambda}{4}$
(D) 2λ |
| 3. The waves associated with the particles in motion are called:
(A) Light waves
(B) Electromagnetic waves | 5. The product of time period and frequency is:
(A) 0
(B) 1 ✓
(C) π
(D) π^2 |

6. Which one of the following media can transmit both transverse and longitudinal wave:
(A) Solid ✓ (B) Liquid
(C) Gas (D) Plasma
7. The time period of wave is 0.2 s. Its frequency will be:
(A) 2 Hz (B) 3 Hz
(C) 4 Hz (D) 5 Hz ✓
8. The medium in which the speed of light is the same in all homogeneous directions is called:
(A) Homogenous ✓ (B) Heterogeneous
(C) Non Homogenous (D) Free space
9. If 20 waves pass through a medium in 1 s, with a speed of 20 m s^{-1} , then the wavelength is:
(A) 20 m (B) 400 m
(C) 40 m (D) 1 m ✓
10. The waves that do not need any medium for their propagation are called:
(A) Mechanical waves
(B) Matter waves
(C) Electromagnetic waves ✓
(D) Compressional waves
11. Half wavelength corresponds to:
(A) 0° (B) 90°
(C) 180° ✓ (D) 360°
12. The wavelength of a transverse wave travelling with speed 'v' having frequency 'f' equal to:
(A) $\frac{f}{v}$ (B) $v f$
(C) $\frac{v}{f}$ ✓ (D) $\frac{f}{v}$
13. Phase angle of 180° is equivalent to a path difference of:
(A) $\frac{\lambda}{2}$ ✓ (B) $\frac{\lambda}{4}$
(C) 2λ (D) λ
14. Sound waves in air are:
(A) Longitudinal waves ✓ (B) Transverse waves
(C) Matter waves (D) Electromagnetic waves
15. If 332 waves travel through a medium in one second with speed of 332 m s^{-1} , then wavelength will be:
(A) 7 m (B) 332 m
(C) 664 m (D) 1 m ✓
16. The example of mechanical waves is:
(A) Water waves ✓ (B) Radio waves
(C) Infrared waves (D) Ultraviolet waves
17. If the period of wave motion is 0.01 s and wave speed is 100 m s^{-1} , then frequency of wave is:
(A) 0.5 Hz (B) 1 Hz
(C) 10 Hz (D) 100 Hz ✓
18. Tuning fork is a source of:
(A) Energy ✓ (B) Heat
(C) Light (D) Sound
19. Longitudinal waves do not exhibit:
(A) Reflection (B) Refraction
(C) Diffraction (D) Polarization ✓
20. Product of frequency "f" and time period "T" is:
(A) 1 ✓ (B) Displacement
(C) Velocity (D) Amplitude
21. The frequency of sound in a medium is "f" and velocity is "v". If frequency in same medium becomes "4f", then velocity will be:
(A) v ✓ (B) $2v$
(C) $3v$ (D) $4v$
22. Waves transport:
(A) energy ✓ (B) wavelength
(C) power (D) mass
23. If the wavelength of a waves is 1500 m and moves with a velocity of $3 \times 10^3 \text{ m s}^{-1}$. What will be its frequency?
(A) $5 \times 10^{-5} \text{ Hz}$ (B) $5 \times 10^5 \text{ Hz}$
(C) $45 \times 10^{10} \text{ Hz}$ (D) $3.15 \times 10^5 \text{ Hz}$ ✓
24. The frequency range of dog ear is:
(A) 20 - 20,000 Hz (B) 60 - 70,000 Hz
(C) 100 - 120,000 Hz (D) 15 - 50,000 Hz ✓
25. Distance between node and consecutive antinode is:
(A) $\frac{\lambda}{2}$ ✓ (B) $\frac{3\lambda}{2}$
(C) $\frac{\lambda}{4}$ (D) λ
26. Sound waves cannot travel through:
(A) Air (B) Water
(C) Material medium (D) Vacuum ✓
27. The speed of sound is greater in solids due to their high:
(A) Density ✓ (B) Pressure
(C) Temperature (D) Elasticity
28. The speed of sound in air does not depend upon:
(A) Density (B) Pressure ✓
(C) Humidity (D) Temperature
29. The speed of sound is greater in:
(A) Air (B) Steel ✓
(C) Ammonia (D) Water
30. Appropriate range of audible frequencies for younger person:
(A) 20 - 200 Hz (B) 20 - 2000 Hz
(C) 20 - 20,000 Hz ✓ (D) 2000 - 20000 Hz
31. With the increase of temperature, speed of sound:
(A) Remains constant (B) Becomes zero
(C) Decreases (D) Increases ✓
32. The velocity of sound in vacuum:
(A) 333 m s^{-1} (B) 333 m s^{-1}
(C) 280 m s^{-1} (D) Zero ✓
33. Velocity of sound is independent of:
(A) Temperature (B) Pressure ✓
(C) Density (D) Medium
34. The louder the sound, the greater will be its:
(A) Speed (B) Frequency
(C) Amplitude ✓ (D) Wavelength
35. If 20 waves pass through a medium in 1 s, with speed of 20 m s^{-1} then wavelength is:

- (A) 1 m ✓ (B) 20 m
(C) 40 m (D) 400 m
36. **Speed of sound in air is independent of:**
(A) Density (B) Pressure ✓
(C) Temperature (D) Density
37. **A example of a transverse wave is:**
(A) Sound wave in air (B) Water wave ✓
(C) Seismic P-wave (D) Compression in a spring
38. **Which one is not the property of transverse waves?**
(A) Crest and trough (B) Can be polarized
(C) Compressions and rarefactions ✓
(D) Particles move perpendicular to wave motion
39. **Which part of a longitudinal wave corresponds to the crest of a transverse wave?**
(A) Compression ✓ (B) Rarefaction
(C) Amplitude (D) Trough
40. **Which wave type can travel through vacuum?**
(A) Sound wave (B) Water wave
(C) Seismic wave (D) Light wave ✓
41. **The direction of particle displacement is parallel to the direction of wave propagation in:**
(A) Light waves (B) Radiowaves
(C) Longitudinal waves ✓ (D) Transverse waves
42. **Seismic waves are an example of:**
(A) Longitudinal mechanical waves
(B) Surface waves
(C) Transverse mechanical waves ✓
(D) Electromagnetic waves
43. **Sound waves in air are an example of:**
(A) Transverse waves (B) Longitudinal waves ✓
(C) Surface waves (D) Electromagnetic waves
44. **In a longitudinal wave, areas of high pressure are called:**
(A) Crests (B) Rarefactions
(C) Nodes (D) Compressions ✓
45. **The distance between two adjacent compressions in a longitudinal wave is the:**
(A) Frequency (B) Amplitude
(C) Period (D) Wavelength ✓
46. **Water waves are best described as:**
(A) Longitudinal waves only
(B) Transverse waves only
(C) Both transverse and longitudinal waves ✓
(D) Electromagnetic waves

7.2 PRINCIPLE OF SUPERPOSITION OF WAVES



4. State and explain the principle of superposition of waves.

Ans. Principle of Superposition of Waves

Statement

If a particle of the medium is simultaneously acted upon by two waves, then the resultant displacement of the particle is the algebraic sum of their individual displacements.

This is called principle of superposition.

Explanation

In other words, the displacements of the individual waves are added together to form a new wave pattern; Fig. 4 (a) and (b), respectively.

- (i) If two waves, which overlap each other, have same phase, their resultant displacement will be:

$$y = y_1 + y_2$$

where y_1 = amplitude of wave 1

y_2 = amplitude of wave 2

and y = resultant amplitude

Particularly, if $y_1 = y_2$, then resultant displacement will be:

$$y = 2y_1, \text{ or } y = 2y_2$$

- (ii) If two waves, which cross each other, have opposite phase, their resultant displacement will be:

$$y = y_1 + (-y_2)$$

$$y = y_1 - y_2$$

Particularly, if $y_1 = y_2$, then resultant displacement will be $y = 0$.

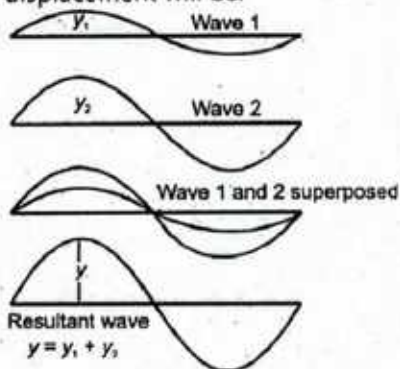


Fig. 4 (a): Superposition of two waves of the same frequency which are exactly in phase.

Thus, if a particle of a medium is simultaneously acted upon by n waves such that its displacement due to each of the individual n waves be $y_1, y_2, \dots, y_n$, then the resultant displacement y of the particle, under the simultaneous action of these n waves is the algebraic sum of all the displacements, i.e.,

$$y = y_1 + y_2 + \dots + y_n$$

This is called principle of superposition of waves. Mathematically, this can also be represented as:

$$y(x, t) = y_1(x, t) + y_2(x, t) + \dots + y_n(x, t)$$

where $y(x, t)$ is the resultant wave, whereas $y_1(x, t), y_2(x, t), \dots, y_n(x, t)$ are the individual waves.

In the context of waves, $y(x, t)$ represents the wave function or wave displacement at a given point x and time t . It describes the shape of the wave and its evolution over time.

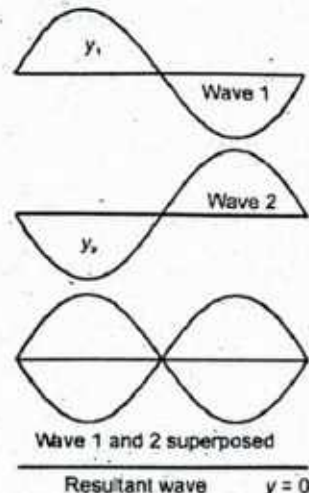


Fig. 4 (b): Superposition of two waves of the same frequency which are exactly out of phase.

Note: The principle of superposition applies to linear waves or small amplitude waves.

The Phenomenons in which Principle of Superposition is Involved

Principle of superposition of waves leads to many interesting phenomena, such as:

- Two waves having same frequency and travelling in the same direction (Interference).
- Two waves of slightly different frequencies and travelling in the same direction (Beats).
- Two waves of equal frequency travelling in opposite direction (Stationary waves).



5. Elaborate the working of noise-cancelling headphones by using the principle of superposition of waves.

Ans. Application of the Principle of Superposition in Noise-Cancelling Headphones

By applying the principle of superposition of waves, noise-cancelling headphones effectively eliminate unwanted noise, providing a more immersive and peaceful listening experience.

- The headphones contain one or more microphones that capture ambient noise (like background chatter or engine rumble or any environmental noise).
- The microphone sends the sound signals to an amplifier and a processing unit in the headphones.
- The processing unit generates an "anti-noise" signal, which is the exact opposite of the ambient noise (in terms of amplitude and phase).
- The anti-noise signal is then played through the headphones, along with the desired audio (like music or voice).
- When the anti-noise signal meets the ambient noise, the two waves cancel each other out resulting in a much quieter listening experience.

Though the above example is an oversimplification of the situation, as noise-cancelling headphones use complex algorithms and multiple microphones to achieve optimal noise cancellation, the basic principle of superposition remains a fundamental concept in understanding how they work.

7.3 INTERFERENCE AND ITS TYPES



6. Describe interference of sound waves and its types.

Ans. Interference

Definition

Superposition of two waves having the same frequency and travelling in the same direction results in the phenomenon called interference.

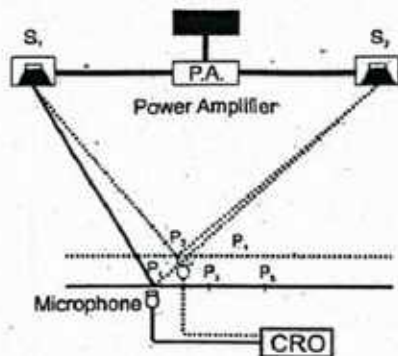


Fig. 5 (a): An experimental setup to observe interference of sound waves.

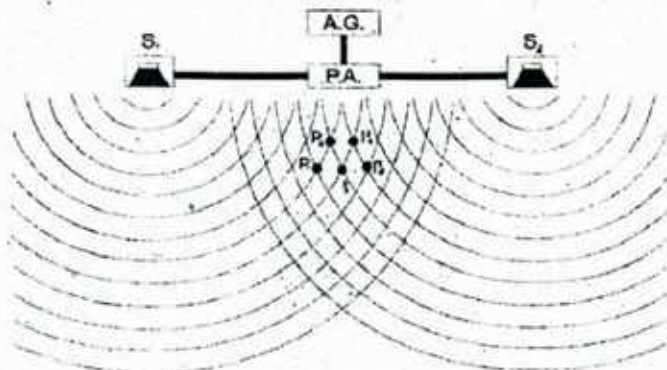


Fig. 5 (b): Interference of sound waves

An experimental setup to observe interference effect of sound waves is shown in Fig. 5(a). Two loud speakers S_1 and S_2 act as two sources of harmonic sound waves of a fixed frequency produced by an Audio Generator (AG). Since the two speakers are driven from the same generator, therefore, they vibrate in phase. Such sources of waves are called coherent sources. A microphone attached to a sensitive Cathode Ray Oscilloscope (CRO) acts as a detector of sound waves. The CRO is a device to display the input signal into waveform on its screen. The microphone is placed at various points, turn by turn, in front of the loud speakers; Fig. 5(b).

Types of Interference

There are two types of interference:

1. Constructive Interference

2. Destructive Interference

1. Constructive Interference

Definition

Whenever the path difference is an integral multiple of wavelength, the two waves are added up. This effect is called constructive interference:

Explanation

At points P_1 , P_3 and P_5 , we find that a compression meets a compression and a rarefaction meets a rarefaction. So, the displacements of two waves are added up at these points according to the principle of superposition and a large resultant displacement is seen on the CRO screen; Fig. 5 (c).

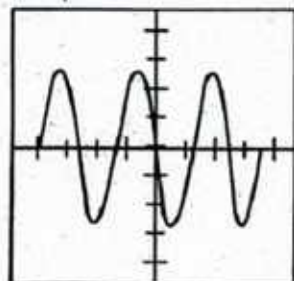


Fig. 5 (c): Constructive Interference: Large displacement is displayed on the CRO screen

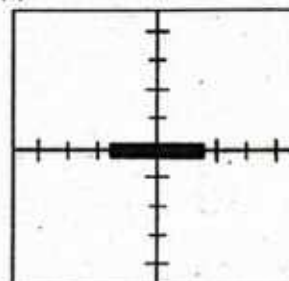


Fig. 5 (d): Destructive Interference: Zero displacement is displayed on the CRO screen

From Fig. 5 (b), we find that the path difference ΔS between the waves at the point P_1 , is:

$$\Delta S = S_2P_1 - S_1P_1$$

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

Similarly, at point P_3 and P_5 , path difference is zero and λ , respectively. Here, λ is the wavelength which is the distance between any two successive solid or dashed lines.

Therefore, the path difference (condition) for constructive interference can be written as:

$$\Delta S = n\lambda \quad \text{where } n = 0, \pm 1, \pm 2, \pm 3, \dots$$

2. Destructive Interference

Definition

The points on a wave where the displacements of two waves cancel each other's effect, the path difference is an odd integral multiple of half the wavelength. This effect is called destructive interference.

Explanation

At points P_2 and P_4 , a compression meets a rarefaction, so that they cancel each other's effect according to the principle of superposition. The resultant displacement becomes zero, as shown in Fig. 5(d).

The path difference ΔS between the waves at points P_2 and P_4 is:

$$\Delta S = S_2P_2 - S_1P_2$$

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

Similarly, at P_4 , the path difference is $\frac{1}{2}\lambda$.

Therefore, the path difference (condition) for destructive interference can be written as:

$$\Delta S = (2n + 1) \lambda/2 \quad \text{where } n = 0, \pm 1, \pm 2, \pm 3, \dots$$

Example 7.1: Two speakers are arranged as shown in the figure. The distance between them is 3.0 m and they emit a constant tone of 344 Hz. A microphone P is moved along a line parallel to and 4.0 m from the line connecting the two speakers. It is found that tone of maximum loudness is heard and displayed on the CRO when microphone is on the centre of the line and directly opposite to each speaker. Calculate the speed of sound.

Solution:

Given that;

Distance between speakers S_1S_2 = 3.0 m

Tone frequency f = 344 Hz

Distance between speakers and line of motion of PS_2P = 4.0 m

To Find:

Speed of sound

$v = ?$

Calculations: For tone of maximum loudness or the condition for constructive interference, the path difference must be $0, \pm 1\lambda, \pm 2\lambda, \pm 3\lambda, \dots$

At middle point 'O' the path difference between two sound waves is zero ($S_1O = S_2O$), thus at that point 'O' constructive interference takes place.

For the next point P of constructive interference, the path difference between waves should be λ . So,

$$\lambda = \text{Path difference} = S_2P_1 - S_1P_1$$

Now, we calculate values of S_2P_1 from right angle triangle $S_1S_2P_1$

$$S_2P_1 = \sqrt{(S_1S_2)^2 + (S_1P_1)^2} \quad (\text{By Pythagoras Theorem})$$

$$S_2P_1 = \sqrt{(3 \text{ m})^2 + (4 \text{ m})^2} = \sqrt{(9 + 16) \text{ m}} = \sqrt{25 \text{ m}} = 5 \text{ m}$$

Therefore $\lambda = S_2P_1 - S_1P_1$ or $\lambda = 5 \text{ m} - 4 \text{ m} = 1 \text{ m}$

This is the path difference for constructive interference.

As $v = f\lambda$

Putting the values, we have

$$v = 344 \text{ m s}^{-1} \times 1 \text{ m} = 344 \text{ m s}^{-1} \quad \text{Ans.}$$

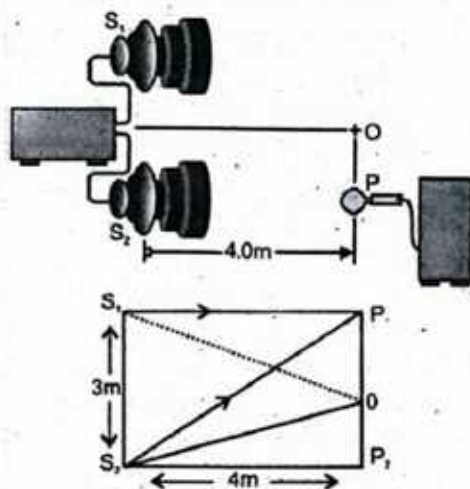
Example 7.2: The wavelength of a signal from a radio transmitter is 1500 m and the frequency is 200 kHz. What is the wavelength for a transmitter operating at 1000 kHz and with what speed the radiowaves travel?

Solution:

Given that;

$$\lambda_1 = 1500 \text{ m} = 1.5 \times 10^3 \text{ m}, \quad f_1 = 200 \text{ kHz} = 2.0 \times 10^5 \text{ Hz}$$

$$f_2 = 1000 \text{ kHz} = 1 \times 10^6 \text{ Hz},$$



To Find:

$$\lambda_2 = ? \text{ and } v = ?$$

Calculations:

As $v = f\lambda$

Since, the speed of both the signals is same, so

$$v = f_1\lambda_1$$

$$v = 2.0 \times 10^5 \text{ Hz} \times 1500 \text{ m}$$

$$v = 3.0 \times 10^8 \text{ m s}^{-1} \text{ Ans.}$$

Also $v = f_2\lambda_2$

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

$$\lambda_2 = \frac{3 \times 10^8 \text{ m s}^{-1}}{1 \times 10^8 \text{ Hz}}$$

$$\lambda_2 = 3 \times 10^2 \text{ m Ans.}$$

For Your Information

Monochromatic Light

Sodium chloride in a flame gives out pure yellow light. This light is not a mixture of red and green.



- The principle of superposition of waves states that when two or more waves overlap, the resultant displacement is:**
 - The product of individual displacements
 - The sum of individual displacements ✓
 - The difference between the largest and the smallest displacements
 - Always zero
- The superposition principle applies to:**
 - Only mechanical waves
 - Only electromagnetic waves
 - Only transverse waves
 - All types of waves ✓
- When two waves of equal amplitude and frequency meet in phase, the result is:**
 - Constructive interference ✓
 - Destructive interference
 - Stationary waves
 - Beats
- Destructive interference occurs when two waves meet with a phase difference of:**
 - 0°
 - 90°
 - 180° ✓
 - 360°
- When two waves interfere destructively, the resultant amplitude is:**
 - Greater than either wave
 - Less than either wave
 - Equal to the sum of the amplitude
 - Zero, if perfectly out of phase and equal amplitude ✓
- Constructive interference occurs when:**
 - Two waves cancel each other
 - Two waves are in phase
 - Two waves have different amplitudes
 - Two waves are out of phase by 180° ✓
- The phenomenon which is not explained by the superposition principle:**
 - Reflection of light ✓
 - Interference of sound
 - Formation of beats
 - Stationary waves
- When two identical waves superpose in phase, the resultant is:**
 - Destructive interference
 - Complete cancellation
 - A wave of reduced amplitude
 - Constructive interference ✓
- What type of interference occurs when crest meets trough of equal amplitude?**
 - Constructive ✓
 - Destructive
 - Stationary
 - Resonant
- In the superposition of waves, interference is said to be constructive when the waves:**
 - Are of different types
 - Are exactly out of phase
 - Arrive at a point with crest meeting crest ✓
 - Travel in opposite directions
- The phenomenon of interference occurs in:**
 - Sound waves only
 - Visible light waves only
 - All types of waves ✓
 - Radiowaves only



7. What are stationary waves? How are they formed?

Ans. Stationary Waves

Definition

Stationary waves or standing waves, are the waves that oscillate in a fixed position, without moving or propagating.

Formation of Stationary Waves

They are formed by the superposition of two waves with the same frequency and amplitude, travelling in opposite directions. The resulting wave pattern remains stationary, with nodes (points of zero amplitude) and antinodes (points of maximum amplitude) at fixed positions. Examples include waves on a string, and sound waves in a pipe.

The term "**standing wave**" describes that the wave pattern remains fixed in space, oscillating between positive and negative values, without moving forward or backward.

Explanation

Let us consider the superposition of two waves moving along a string in opposite directions. Figures 6(a) and (b) show the profile of two such waves at instants $t = 0, T/4, T/2, 3T/4$ and T , where T is the time period of the wave. We are interested in finding out the displacements of the points 1, 2, 3, 4, 5, 6 and 7 at these instants as the waves superpose. It is obvious that the points 1, 2, ..., 7 are distant $\lambda/4$ apart, λ being the wavelength of the waves. We can determine the resultant displacement of these points by applying the principle of superposition.

Figure 6(c) shows the resultant displacement of the points 1, 3, 5 and 7 at the instants $t = 0, T/4, T/2, 3T/4$ and T . It can be seen that the resultant displacement of these points is always zero. These points of the medium are known as nodes. Here, the distance between two consecutive nodes is $\lambda/2$.

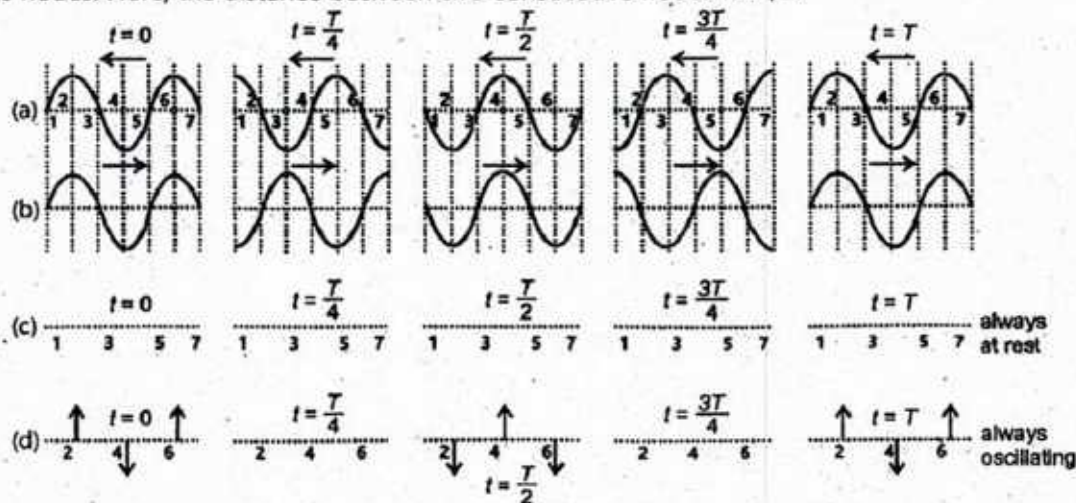


Fig. 6: Stationary waves

Figure 6(d) shows the resultant displacement of the points 2, 4 and 6 at the instants $t = 0, T/4, T/2, 3T/4$ and T . The figure shows that these points are moving with an amplitude which is the sum of the amplitudes of the component waves represented by arrows. These points are known as antinodes. They are situated midway between the nodes and are $\lambda/2$ apart. The distance between a node and the next antinode is $\lambda/4$. Such a pattern of nodes and antinodes is known as a stationary or standing wave.

How is Energy Transferred in a Wave?

Energy in a wave transfers because of the motion of the particles of the medium. The nodes always remain at rest, so energy cannot flow past these points. Hence, energy remains "standing" in the medium between nodes, although it alternates between potential and kinetic forms at the antinodes. When the antinodes are all at their extreme displacements, the energy stored is wholly potential and when they are simultaneously passing through their equilibrium positions, the energy is wholly kinetic.



8. What are stationary or standing waves? Illustrate a detailed experiment that demonstrates the standing waves using stretched strings.

Ans. Stationary Waves

Stationary waves or standing waves can also be defined as:

Definition

The standing waves are a type of wave pattern that occurs when two waves of the same frequency and amplitude travel in opposite directions and interfere with each other.

This interference creates a wave that appears to be stationary.

Standing or Stationary Waves on a Stretched String

Consider a string of length l which is kept stretched by clamping its ends so that the tension in the string is F .

(a) When String is Plucked at its Middle Point

If the string is plucked at its middle point, two transverse waves will originate from this point. One of them will move towards the left end of the string and the other towards the right end. When these waves reach the two clamped ends, they are reflected back thus giving rise to stationary waves. As the two ends of the string are clamped, no motion will take place there. So, nodes will be formed at the two ends and one mode of vibration of the string will be as shown in Fig. 7(a) with the two ends as nodes with one antinode in between. Visually, the string seems to vibrate in one loop.

As the distance between two consecutive nodes is one half of the wavelength of the waves set up in the string, so in this mode of vibration, the length l of the string is

$$l = \lambda/2 \quad \dots\dots (i)$$

$$\lambda_1 = 2l \quad \dots\dots (ii)$$

where λ_1 is the wavelength of the waves set up in this mode. The speed v of the waves in the string depends upon the tension F of the string and m , the mass per unit length of the string. It is independent of the point from where string is plucked to generate wave. It is given by

$$v = \sqrt{\frac{F}{m}} \quad \dots\dots (iii)$$

Knowing the speed v and wavelength λ_1 , the frequency f_1 of the waves is:

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

Substituting the value of v ,

$$f_1 = \frac{1}{2l} \sqrt{\frac{F}{m}} \quad \dots\dots (iv)$$

Thus, in the first mode of vibration shown in Fig. 7 (a), waves of frequency f_1 only will be set up in the given string.

(b) When String is Plucked at Quarter Length

If the same string is plucked from one quarter of its length, again stationary waves will be set up with nodes and antinodes as shown in Fig. 7 (b). Note that now the string vibrates in two loops. This particular configuration of nodes and antinodes has developed because the string was plucked from the position of an antinode. As the distance between two consecutive nodes is half the wavelength, so the length l of string is equal to the wavelength of the waves set up in this mode. If λ_2 is the measure of wavelength of these waves, then,

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

$$l = 2 \times \frac{\lambda_2}{2}$$

$$\lambda_2 = l \quad \dots\dots (v)$$

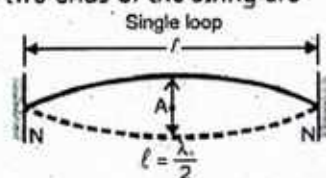


Fig. 7 (a): First mode of vibration

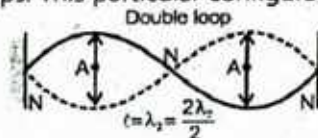


Fig. 7 (b): Second mode of vibration.

Comparison of Eq. (v) with Eq. (i) shows that the wavelength in this case is half of that in the first case. Equation (ii) shows that the speed of the waves depends on tension and mass per unit length of the string, it is independent of the point where the string is plucked. So, speed v remains the same in both cases.

If f_2 is frequency of vibration of string in its second mode, then

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

Since $\lambda_2 = l$

Therefore $f_2 = \frac{v}{l}$

Multiplying and dividing by 2, we have

$$f_2 = \frac{2v}{2l}$$

We know that;

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

So $f_2 = 2f_1$

Thus, when the string vibrates in two loops, its frequency becomes double than when it vibrates in one loop.

(c) When String is Plucked at an Arbitrary Point

Let the string resonates in n number of loops with $(n + 1)$ nodes and n antinodes. Thus, we can say that if the string is made to vibrate in n loops, the frequency of stationary waves set up on the string will be:

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

$$f_n = nf_1 \quad \dots (vi)$$

and the corresponding wavelength is,

$$\lambda_n = \frac{2l}{n} \quad \dots (vii)$$

where $n = 1, 2, 3, \dots$

It is clear that as the string vibrates in more than one loop, its frequency f goes on increasing and the wavelength λ gets correspondingly shorter. However, the product of the frequency f and wavelength λ is always equal to v , the speed of waves.

Facts Established by Standing or Stationary Waves

The above discussion clearly establishes that;

1. The stationary waves have a discrete set of frequencies $f_1, 2f_1, 3f_1, \dots, nf_1$ which is known as harmonic series. The lowest characteristic frequency of vibration is the fundamental frequency f_1 corresponds to the first harmonic. The frequency $f_2 = 2f_1$ corresponds to the second harmonic and so on.
2. In other words, quantum jumps in frequency exist between the resonance frequencies. This phenomenon is known as the Quantization of frequencies. It means $f_n = nf_1$ where $n = 1, 2, 3, \dots$ (Integral multiples). The stationary waves can be set up on the string only with the frequencies of harmonic series determined by the tension, length and mass per unit length of the string. Waves which are not in harmonic series are quickly damped out.
3. The frequency of a string on a musical instrument can be changed either by varying the tension or by changing the length. For example, the tension in guitar and violin strings is varied by tightening the pegs on the neck of the instrument. Once the instrument is tuned, the musicians vary the frequency by moving their fingers along the neck, thereby changing the length of the vibrating portion of the string.

Harmonics

Harmonics are frequencies that are integral multiples of fundamental frequencies. They are a key concept in Physics, music and engineering.

Brain Teaser

A guitar string is plucked at its centre. What harmonic is produced?

Ans. When a guitar string is plucked at its centre, the fundamental frequency (also known as first harmonic) is primarily produced. However, even-numbered harmonics, are suppressed or greatly reduced because of the symmetry of the plucking point.

In the above example, the set of all the possible standing waves, having frequencies $f_1, 2f_1, 3f_1, \dots, nf_1$ are called harmonics of the system. The lowest or fundamental frequency of all the harmonics is called the fundamental or first harmonic. While subsequent frequencies are called as second harmonic, third harmonic, etc.

Example 7.3: A stationary wave is established in a string which is 120 cm long and fixed at both ends. The string vibrates in four segments; at a frequency of 120 Hz. Determine its wavelength and the fundamental frequency?

Solution:

Given that;

$$l = 120 \text{ cm} = \frac{120}{100} \text{ m} = 1.2 \text{ m}$$

$$n = 4$$

$$f_4 = 120 \text{ Hz}$$

To Find:

$$f_1 = ?$$

$$\lambda = ?$$

Calculations:

- (i) As the string vibrates in four segments and the distance between two consecutive nodes is $\lambda/2$, so the wavelength of the string is:

$$l = n \frac{\lambda_n}{2}$$

$$\lambda_n = \frac{2l}{n}$$

$$\lambda_4 = \frac{2 \times 1.2 \text{ m}}{4}$$

$$\lambda_4 = 0.6 \text{ m} \quad \text{Ans.}$$

- (ii) If string vibrates in n loops, then frequency of stationary waves will be:

$$f_n = nf_1$$

$$f_4 = 4f_1$$

$$120 \text{ Hz} = 4f_1$$

$$f_1 = \frac{120 \text{ Hz}}{4}$$

$$f = 30 \text{ Hz} \quad \text{Ans.}$$

7.6 STATIONARY WAVES IN AIR COLUMNS



9. What is an organ pipe?

Ans. Organ pipe:

An organ pipe is a wind instrument in which sound is produced, due to setting up of stationary waves in air column.

It consists of a hollow long tube with both ends open or with one end open and the other closed. The relationship between the incident wave and the reflected wave depends upon whether the reflecting end of the pipe is open or closed.

- (i) If the reflecting end is open, the air molecules have complete freedom of motion and this behaves as an antinode.
- (ii) If the reflecting end is closed, then it behaves as a node because the movement of the molecules is restricted.



10. Find the frequencies of the harmonics produced in a organ pipe when it is open at both ends and when it is closed at one end.

Ans. Case (1): Modes of vibrations in an organ pipe open at both ends

Let us consider an organ pipe of length l which is open at both ends. As at the open end, an air molecule has complete freedom of motion so it acts as antinode; Fig. 8. In this figure, longitudinal waves set up inside the

pipe have been represented by transverse curved lines which represent the displacement and amplitude of vibration of air particles at various points along the axis of pipe.

(a) Fundamental Mode of Vibration:

In this case; Fig. 8(a), there is only one node N at the middle of the pipe. As both ends of pipe are open, there are two antinodes at both the ends. If λ_1 is the wavelength of sound, then

$$l = \frac{\lambda_1}{4} + \frac{\lambda_1}{4}$$

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

or $\lambda_1 = 2l$ (i)

If f_1 is the frequency of sound, then the velocity of sound is;

$$v = f_1 \lambda_1$$

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

Putting the value of λ_1 , we have

$$f_1 = \frac{v}{2l} \text{ (ii)}$$

This frequency is called fundamental frequency or first harmonic.

(b) Second Mode of Vibration:

If there are three antinodes and two nodes, frequency will be twice that of fundamental frequency. It is second mode of vibration; Fig. 8(b). In this case, there are three antinodes and two nodes.

If λ_2 is the wavelength of sound, then

$$l = \frac{\lambda_2}{4} + \frac{\lambda_2}{2} + \frac{\lambda_2}{4}$$

$$l = (1 + 2 + 1) \frac{\lambda_2}{4}$$

or $\lambda_2 = l$

If f_2 is the frequency of sound, then speed v of sound becomes:

$$v = f_2 \lambda_2$$

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

Putting the value of λ_2 , we have

$$f_2 = \frac{v}{l}$$

or $f_2 = 2f_1 \quad \left(\because \frac{v}{2l} = f_1 \right)$

(c) nth mode of vibration

Similarly, frequency for air column vibrating in n loops is:

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

$$f_n = nf_1$$

and wavelength is

$$\lambda_n = \frac{2l}{n} \text{ (iii)}$$

where $n = 1, 2, 3, 4, 5, \dots$

So, the longitudinal stationary waves have a discrete set of frequencies $f_1, 2f_1, 3f_1, \dots, nf_1$, which is known as harmonic series.

The frequency f_1 is known as fundamental frequency and the others are called harmonics.

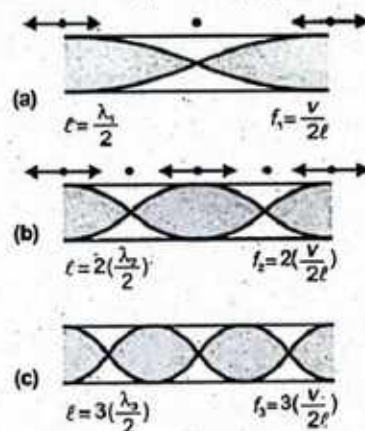


Fig. 8: Stationary longitudinal waves in a pipe open at both ends.

Brain Teaser

A stationary wave is formed on a string with a frequency of 100 Hz. If the string is 2 m long, how many nodes and antinodes are formed?

Ans. Fundamental mode (1st Harmonics)

In the fundamental mode, the string supports half a wavelength:

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

In this mode:

- There are 2 nodes; one at each end.
- There is 1 antinode in the middle.

If higher harmonics are allowed

In general, for the n th harmonic:

- The number of antinodes = n
- The number of nodes = $n + 1$
- The length of the string $l = \frac{n\lambda}{2}$

Case (2): Modes of vibration in an organ pipe closed at one end

Let us consider an organ pipe of length l which is closed at one end. Then at the closed end, we get a node while at the open end, we get an anti-node as shown in the Fig. 7.9.

(a) Fundamental Mode of Vibration

Fundamental mode of vibration has one node and one anti-node as shown in Fig. 9(a). If λ_1 is the wavelength of fundamental mode, then length of the pipe is:

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

or $\lambda_1 = 4l$

So, the speed v becomes

$$v = f_1 \lambda_1$$

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

$$f_1 = \frac{v}{4l} \quad (\because \lambda_1 = 4l)$$

The frequency f_1 is called fundamental frequency.

(b) Second Mode of Vibration

Second mode of vibration contains two nodes and two anti-nodes as shown in Fig. 9(b).

If λ_3 is the wavelength, then length of the pipe is:

$$l = \frac{\lambda_3}{4} + \frac{\lambda_3}{2}$$

$$l = \frac{3}{4} \lambda_3$$

$$\lambda_3 = \frac{4l}{3} \quad \dots\dots (iv)$$

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

Putting value of λ_3 , we have $v = f_3 \lambda_3$

$$f_3 = \frac{v}{\frac{4l}{3}}$$

or $f_3 = \frac{3v}{4l}$

so $f_3 = 3f_1 \quad \left[\because \frac{v}{4l} = f_1 \right]$

This is called second harmonic.

(c) nth Mode of Vibration:

If air column vibration in n loops, then frequency f_n is:

$$f_n = n \left(\frac{v}{4l} \right)$$

$$f_n = n f_1 \quad \text{where } n = 1, 3, 5, \dots$$

and the wavelength λ_n is:

$$\lambda_n = \frac{4l}{n} \quad \dots\dots (v)$$

By studying both cases, we conclude that the pipe which is open at both ends is richer in harmonics than that of closed at one end.

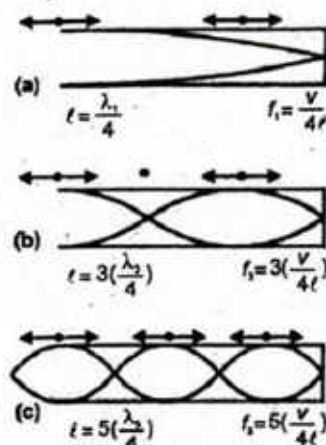


Fig. 9: Stationary longitudinal waves in a pipe closed at one end. Only odd harmonics are present.

Example 7.4: An organ pipe has a length of 50 cm. Find the frequency of its fundamental note and the next harmonic, when it is:

(a) open at both ends

(b) closed at one end

(Speed of sound = 350 m s^{-1})

Solution:

Given that;

$$l = 50 \text{ cm} = \frac{50}{100} \text{ m} = 0.5 \text{ m}$$
$$v = 350 \text{ m s}^{-1}$$

To Find:

(a) When pipe is open at both ends:

Fundamental frequency $f_1 = ?$

Next harmonic frequency $f_2 = ?$

Calculations: The frequency for n th harmonic in an open organ pipe is:

$$f_n = n \frac{v}{2l} \quad \text{when } n = 1, 2, 3, \dots$$

So the fundamental frequency is,

$$f_1 = \frac{1 \times 350 \text{ m s}^{-1}}{2 \times 0.5 \text{ m}} \quad \text{put } n = 1$$

$$f_1 = 350 \text{ Hz}$$

Next harmonic frequency i.e., $n = 2$ is:

$$f_2 = \frac{2v}{2l}$$

$$f_2 = \frac{v}{l} = \frac{350 \text{ m s}^{-1}}{0.5 \text{ m}} = 700 \text{ s}^{-1}$$

$$f_2 = 700 \text{ Hz Ans.}$$

(b) When pipe is closed at one end:

Fundamental frequency $f_1 = ?$

Next harmonic frequency $f_3 = ?$

When the pipe is closed at one end, then frequency for n th harmonic is:

$$f_n = n \frac{v}{2l} \quad \text{when } n = 1, 3, 5, 7, \dots$$

So the fundamental frequency is,

$$f_1 = \frac{1 \times 350 \text{ m s}^{-1}}{4 \times 0.5 \text{ m}} \quad \text{put } n = 1$$

$$f_1 = 175 \text{ Hz}$$

Next harmonic frequency i.e., $n = 3$ is:

$$f_3 = \frac{3v}{4l} = \frac{3 \times 350 \text{ m s}^{-1}}{4 \times 0.5 \text{ m}}$$

$$f_3 = 525 \text{ Hz Ans.}$$

Example 7.5: A church organ consists of pipes, each open at one end, of different lengths. The minimum length is 30 mm and the longest is 4 m. Calculate the frequency range of the fundamental notes. (Speed of sound = 340 m s^{-1})

Solution:

Given that;

$$l_{\min} = 30 \text{ mm} = \frac{30}{1000} \text{ m} = 30 \times 10^{-3} \text{ m}$$

$$l_{\max} = 4 \text{ m}$$

$$v = 340 \text{ m s}^{-1}$$

Ponder upon!

Open pipes produce all harmonics, while closed pipes produced only odd harmonics. Why?

Ans. The difference in harmonics between open and closed pipes arises from the boundary conditions at the ends of the pipes, which affect how standing waves form.

1. Open pipes (both ends open):

At both open ends air is free to move, so these are pressure modes. The standing wave must have nodes at both ends.

- The fundamental (1st harmonic) has half a wavelength fitting in the pipe:

$$\lambda_1 = 2l$$

- Higher harmonics are formed by adding more half-wavelengths:

$$\lambda_n = \frac{2l}{n}, \quad n = 1, 2, 3, 4, \dots$$

Thus, all harmonics (1st, 2nd, 3rd, etc.) are allowed.

2. Closed pipe (one end closed, one end open):

- At the closed end, air cannot move $\rightarrow$ displacement node (pressure antinode).

- At the open end, air moves freely $\rightarrow$ displacement antinode (pressure node)

- The fundamental has a quarter of a wavelength in the pipe:

$$\lambda_1 = 4l$$

- The next possible standing wave fits three quarters of a wavelength:

$$\lambda_3 = \frac{4l}{3}$$

- Then five quarters, and so on.

So, only odd-numbered harmonics fit:

$$\lambda_n = \frac{4l}{n}, \quad n = 1, 3, 5, \dots$$

Thus, only odd harmonics (1st, 3rd, 5th ...) are produced.

To Find:

Frequency range = ?

Calculations: For an organ pipe open at one end only:

$$f_n = \frac{nv}{4l}$$

(i) Minimum length

For fundamental frequency, put $n = 1$

$$f_{1,max} = \frac{nv}{4l_{min}}$$

$$f_{1,max} = \frac{1 \times 340 \text{ m s}^{-1}}{4 \times 30 \times 10^{-3} \text{ m}}$$

$$f_{1,max} = 2833.33 \text{ Hz Ans.}$$

(ii) Maximum length:

For fundamental frequency, put $n = 1$

$$f_{1,min} = \frac{nv}{4l_{max}}$$

$$f_{1,min} = \frac{1 \times 340 \text{ m s}^{-1}}{4 \times 4 \text{ m}}$$

$$f_{1,min} = 21.25 \text{ Hz Ans.}$$

So, the fundamental frequency range is approximately from 21 Hz to 2833 Hz.

Brain Teaser

A flute player notices that the flute is producing a pitch which is slightly sharp. What could be the cause of this problem?

Ans. If a flute is producing a pitch that is slightly sharp (i.e., higher in pitch than it should be), the most common cause is that the flute is too short acoustically. This usually happens when the head joint is pushed in too far.

7.7 EXPERIMENT DEMONSTRATING STATIONARY WAVES USING MICROWAVES



11. What are microwaves? How are stationary waves created by using microwave source?

Ans. Microwaves

Definition

These are type of electromagnetic radiation with wavelength ranging from about 1 millimetre to 30 centimetres (or frequencies between 300 MHz and 300 GHz).

Stationary waves or standing waves, can be produced by microwaves when they are confined to a specific region or cavity such as wave guides or resonant chambers. In these structures, microwaves can bounce back and forth, creating a standing wave pattern with nodes and antinodes. It occurs when the microwave frequency matches the resonant frequency of the cavity. The stationary waves can be created using microwaves by the following simple method as shown in Fig. 10

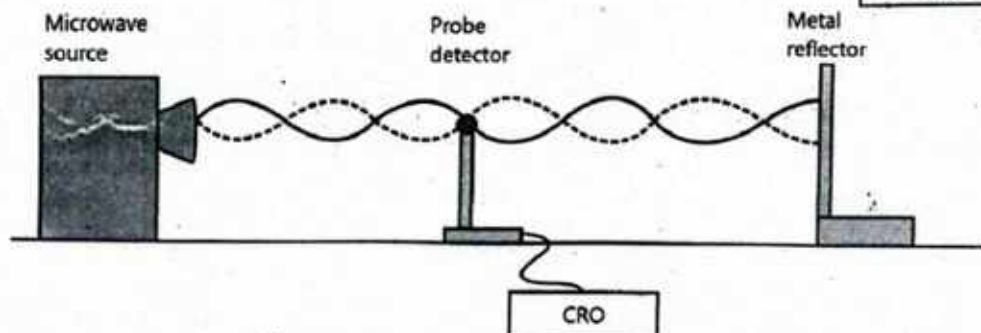
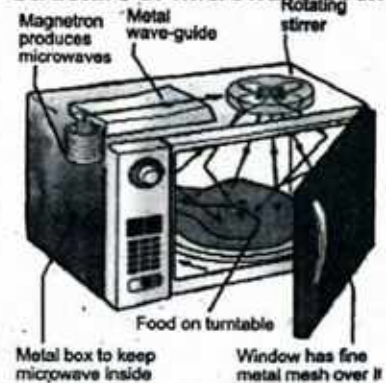


Fig. 10: Experimental setup for stationary waves using microwave.

The experiment setup consists of a microwave source (transmitter), a probe detector and a metal reflector (a metallic plate for the reflection of microwave). Three of the mentioned are placed in line.

Structure of Microwave Oven

The waves coming out of microwave source are moving towards the metal plate and then reflected back. The reflected wave and incident wave superpose and create a stationary wave pattern. This can be detected by a probe detector placed between transmitter and metallic plate. The intensity of the signal can be observed by the detector. You can move the plate or detector to observe antinode and node. By finding the distance from one antinode to the next antinode, the wavelength of stationary wave can be found.



- When two identical waves move in opposite direction they give rise to:
(A) Stationary waves ✓
(B) Beats
(C) Constructive interference
(D) Destructive interference
- The distance between the two consecutive nodes or antinodes is:
(A) $\frac{\lambda}{2}$ ✓
(B) $\frac{\lambda}{4}$
(C) λ
(D) 2λ
- On increasing the tension, the frequency of the vibration of string:
(A) increases ✓
(B) Decreases
(C) Remains constant
(D) First increases then decreases
- In stationary waves, the velocity of particle at the node is:
(A) Maximum
(B) Infinite
(C) Variable
(D) Zero ✓
- Wavelength of a wave for closed pipe having the length ℓ in fundamental mode is:
(A) 2ℓ
(B) 4ℓ ✓
(C) $\frac{\ell}{2}$
(D) ℓ
- On reflection from the denser medium light wave undergoes a phase change of:
(A) π rad ✓
(B) $\frac{\pi}{2}$ rad
(C) $\frac{3\pi}{2}$ rad
(D) 2π rad
- Which one is true for organ pipe closed at one end:
(A) $\lambda_n = \frac{2\ell}{n}$
(B) $\lambda_n = \frac{4\ell}{n}$ ✓
(C) $\lambda_n = \frac{2\ell}{v}$
(D) $\lambda_n = 2(v \times \ell)$
- Stationary waves are generated on a string of length ℓ , its fundamental frequency is:
(A) $f_1 = \frac{v}{\ell}$
(B) $f_1 = \frac{v}{2\ell}$ ✓
(C) $f_1 = \frac{2\ell}{v}$
(D) $f_1 = 2(v \times \ell)$
- At the open end of an organ pipe:
(A) Nodes are formed
(B) Antinode are formed ✓
(C) Antinodes maybe formed
(D) Neither is formed
- A stationary wave is established if a string vibrates in four segments at a frequency of 120 Hz. Its fundamental frequency will be:
(A) 15 Hz
(B) 30 Hz ✓
(C) 60 Hz
(D) 450 Hz
- A set of frequencies, which is the multiple of its fundamental frequency is called:
(A) Beat frequency
(B) Harmonics ✓
(C) Nodal frequency
(D) Doppler frequency
- The point of maximum displacement on stationary wave is:
(A) Antinode ✓
(B) Node
(C) Trough
(D) Crest
- The string of length ℓ fixed at the both ends is vibrating in two segments, the wavelength of wave is:
(A) $\frac{\ell}{4}$
(B) $\frac{\ell}{2}$
(C) ℓ ✓
(D) 2ℓ
- The fixed ends of vibrating string are:
(A) Antinodes
(B) Nodes ✓
(C) Overtones
(D) Neither node nor
- For same mass per unit length of a string, if tension of a vibrating string is increased by 4 times, then frequency will become:
(A) 2 times ✓
(B) 4 times
(C) 6 times
(D) $\sqrt{2}$ times
- A stretched string of length 2 m vibrates in 2 segments. The distance between consecutive nodes is:
(A) 1 m ✓
(B) 2 m
(C) 0.5 m
(D) 4 m
- In an open pipe, the fundamental frequency is given by
(A) $f = \frac{v}{2\ell}$ ✓
(B) $f = \frac{v}{4\ell}$
(C) $f = \frac{2\ell}{v}$
(D) $f = \frac{4\ell}{v}$
- The distance between node and antinode is equal to:
(A) λ
(B) $\frac{\lambda}{2}$
(C) $\frac{\lambda}{3}$
(D) $\frac{\lambda}{4}$ ✓
- If the organ pipe is closed at one end, the frequency of fundamental harmonic is:
(A) $f_1 = \frac{v}{2\ell}$
(B) $f_1 = \frac{v}{4\ell}$ ✓

- (C) $f_1 = \frac{4\ell}{v}$ (D) $f_1 = \frac{2\ell}{v}$
20. The number of node (s) between two consecutive antinode is:
 (A) One ✓ (B) Two
 (C) Three (D) Four
21. A stretched string 4 m long and it has 4 loops of stationary waves, then the wavelength is:
 (A) 1 m (B) 2 m ✓
 (C) 3 m (D) 4 m
22. The distance between 1st node and 4th antinodes is:
 (A) $\frac{7}{4}\lambda$ ✓ (B) $5\frac{\lambda}{4}$
 (C) $13\frac{\lambda}{4}$ (D) $11\frac{\lambda}{4}$
23. In a stretched string, if speed of wave is doubled, the tension will be:
 (A) 2 times (B) 4 times ✓
 (C) 8 times (D) 6 times
24. When one end of organ pipe is closed, then the frequency of stationary waves of any harmonic in it is given by
 (A) $f_n = \frac{nv}{2\ell}$ (B) $f_n = \frac{n\ell}{4v}$
 (C) $f_n = \frac{4v}{n\ell}$ (D) $f_n = \frac{nv}{4\ell}$ ✓
25. If a stretched string is 4 m and it has 4 loops of stationary waves, then wavelength is:
 (A) 1 m (B) 2 m ✓
 (C) 3 m (D) 4 m
26. If a stretched string vibrate in three loops, then relation between its length and wavelength of stationary wave is:
 (A) $\ell = \frac{3\lambda}{2}$ ✓ (B) $\ell = 3\lambda$
 (C) $\ell = \frac{2\lambda}{3}$ (D) $\lambda = 3\ell$
27. Waves produced in organ pipes are:
 (A) Transverse stationary waves
 (B) Longitudinal stationary waves ✓
 (C) Electromagnetic waves
 (D) Matter waves
28. The dimension of $\sqrt{\frac{F \times \ell}{m}}$ is same as that of:
 (A) Speed ✓ (B) Tension
 (C) Acceleration (D) Torque
29. Two identical waves moving in same direction produce:
 (A) Interference ✓ (B) Beats
 (C) Stationary waves (D) Diffraction
30. Distance between adjacent node and antinode is:
 (A) λ (B) $\frac{\lambda}{2}$
- (C) $\frac{\lambda}{4}$ ✓ (D) $\frac{\lambda}{3}$
31. Distance between two adjacent crests and troughs is:
 (A) λ ✓ (B) $\frac{\lambda}{2}$
 (C) $\frac{\lambda}{4}$ (D) $\frac{\lambda}{3}$
32. If a string vibrates in "n" loops, the wavelength of stationary wave will be:
 (A) $\frac{2\ell}{n}$ ✓ (B) $\frac{2\ell}{2}$
 (C) $\frac{2n}{\ell}$ (D) $\frac{\ell}{2n}$
33. If a stationary wave is established along a stretched string of length ℓ and it vibrate in one loop, the wavelength is equal to:
 (A) ℓ (B) $\frac{\ell}{2}$
 (C) $\frac{\ell}{3}$ (D) 2ℓ ✓
34. If an organ pipe is open at both ends, frequency of fundamental harmonic is given by
 (A) $\frac{v}{2\ell}$ ✓ (B) $\frac{v}{4\ell}$
 (C) $\frac{4\ell}{v}$ (D) $\frac{2\ell}{v}$
35. When a transverse wave travelling in a rare medium is incident on a denser medium, after reflection phase change, by
 (A) 360° (B) 180° ✓
 (C) 90° (D) 0°
36. The distance between a consecutive node and antinode is:
 (A) λ (B) $\frac{\lambda}{2}$
 (C) $\frac{\lambda}{4}$ ✓ (D) 2λ
37. Distance between two adjacent crests and troughs is:
 (A) λ ✓ (B) $\frac{\lambda}{2}$
 (C) $\frac{\lambda}{4}$ (D) 2λ
38. When the stretched string is plucked from one quarter of length, then stretched string will vibrate in:
 (A) One loop (B) Two loops ✓
 (C) Three loops (D) Four loops
39. The wavelength of nth mode of stationary waves in closed pipe is:
 (A) $\frac{2\ell}{n}$ ✓ (B) $\frac{4\ell}{2n-1}$
 (C) $\frac{4\ell}{n}$ (D) $\frac{4\ell}{2n+1}$

40. A stretched string vibrates in n -loops, its length in terms of wavelength is:
- (A) $n\lambda$ ✓ (B) $(n+1)\frac{\lambda n}{2}$
 (C) $\left(n + \frac{1}{2}\right)\frac{\lambda n}{2}$ (D) $\left(n + \frac{1}{2}\right)\lambda n$
41. Which of the following instruments works on the principle of stationary waves in air columns?
 (A) Guitar (B) Violin
 (C) Flute ✓ (D) Tuning fork
42. In a pipe open at both ends, the displacement node is found at:
 (A) The centre ✓ (B) Both ends
 (C) One end only (D) No displacement node
43. If a pipe is closed at one end and open at the other, which of the following harmonics are possible?
 (A) Only even harmonics (B) Only odd harmonics ✓
 (C) All harmonics (D) No harmonics
44. In an open pipe, the number of antinodes in the third harmonic is:
 (A) 1 (B) 2
 (C) 3 (D) 4 ✓
45. Which of the following pipes can produce both even and odd harmonics?
 (A) A pipe open at one end (B) A pipe closed at one end
 (C) A pipe open at both ends ✓ (D) None of these
46. In a pipe closed at one end, the harmonic which is not possible?
 (A) First (B) Second ✓
 (C) Third (D) Fifth
47. The harmonics which are present in a pipe closed at one end are:
 (A) Only even harmonics (B) Only odd harmonics ✓
 (C) All harmonics (D) No harmonics
48. The node in a stationary wave is a point where:
 (A) The amplitude is maximum
 (B) The phase of the wave changes
 (C) The medium remains stationary ✓
 (D) The speed of waves is maximum
49. The second harmonic of a stretched string has:
 (A) One antinode (B) Two nodes
 (C) Two antinodes and three nodes ✓
 (D) Three antinodes and two nodes
50. The speed of sound in an air column depends on:
 (A) The material of pipe (B) The colour of the pipe
 (C) The temperature of pipe ✓
 (D) The diameter of pipe

7.8 DIFFRACTION OF WAVES



12. Define and exemplify diffraction of waves. Describe this phenomenon by ripple tank experiment.

Ans. Diffraction of Waves

Definition

Diffraction of waves is the bending of waves around the sharp edges or corners of obstacles or the spreading of waves beyond a barrier.

It occurs when a wave encounters a physical barrier or an opening (a slit) that is comparable in size to the wavelength of the wave. The longer the wavelength, the greater the spreading and vice versa.

Diffraction can be observed in various types of waves, including water waves, sound waves, light waves and electromagnetic waves.

Examples

Some examples of the phenomenon of diffraction include:

- Hearing of sound waves around corners or through door way from where they were generated as sound waves bend around the corners.
- Diffraction of X-rays by crystals as the spacing between the regular arrays of atoms is of the order of X-rays wavelength.

Diffraction is a fundamental aspect of wave behaviour and has many practical applications in various fields.

The Ripple Tank

Figure 11 shows a ripple tank. It is a very useful apparatus not only to generate water waves, but also to demonstrate wave properties (such as reflection, diffraction and refraction).

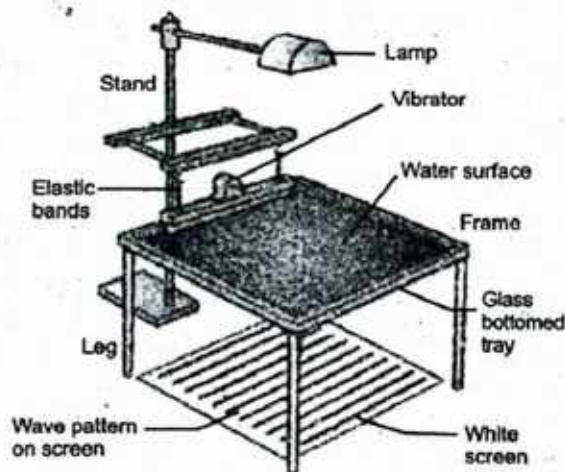


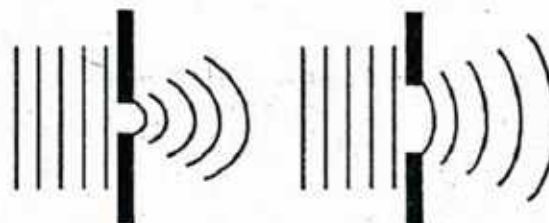
Fig. 11: A ripple tank

Construction and Working

Ripple tank contains water, vibrator (e.g. a motorized oscillating needle), obstacles (e.g. a small rectangular block or a semicircular barrier) and gap widths of different sizes. It creates a series of concentric circles or parallel waves using the vibrator. An obstacle is placed for creating a gap with a specific width. The experiment can be repeated with different gap widths.

It is observed that when the gap width is small compared to the wavelength, diffraction is significant and the waves bend around the obstacle, creating a semicircular pattern. As the gap width increases relative to wavelength, diffraction decreases and the waves pass through the gap with less bending.

This experiment demonstrates the qualitative effect of gap width on diffraction in a ripple tank, illustrating how the relationship between gap width and wavelength affects wave behaviour.



Small gap, Increased diffraction

Large gap, Decreased diffraction

Fig. 12

Example 7.6: In a ripple tank, a wave generator produces 500 pulses in 10 s. Find the frequency at time period of the pulses produced?

Solution:

Given that;

$$n = 500 \text{ pulses and } t = 10 \text{ s}$$

To Find:

$$f = ?$$

Calculations:

$$\text{As Frequency} = \frac{\text{Number of pulses}}{\text{Time}}$$

$$f = \frac{500}{10 \text{ s}} = 50 \text{ Hz}$$

$$\text{We know that; } T = \frac{1}{f} = \frac{1}{50 \text{ Hz}}$$

$$T = 0.02 \text{ s Ans.}$$

Interesting Information



The fine rulings, each 0.5 mm wide, on a compact disc function as a diffraction grating: When a small source of white light illuminates a disc, the diffracted light forms coloured lanes that are composite of the diffraction patterns from the rulings.

- | | |
|---|--|
| <p>1. The waves that can exhibit diffraction are:
 (A) Sound waves only (B) Light waves only
 (C) Water waves only (D) All types of waves ✓</p> <p>2. When a wave passes through a narrow slit, diffraction causes it to:
 (A) Accerate (B) Refract
 (C) Spread out ✓ (D) Disappear</p> <p>3. Which of the following change will increase the diffraction of light?
 (A) Increase in frequency (B) Use of wider slit
 (C) Use light with a shorter wavelength
 (D) Use light with a longer wavelength ✓</p> <p>4. Sound waves diffract more than light waves because:
 (A) Sound travels slower
 (B) Sound has longer wavelengths ✓
 (C) Light is absorbed easily
 (D) Light has lower energy</p> <p>5. Diffraction does not significantly occur when:
 (A) Wavelength $\approx$ Size of the slit
 (B) Wavelength $\ll$ Size of the slit ✓
 (C) Wavelength $\approx$ Obstacle size
 (D) Waves pass a narrow aperture</p> <p>6. When sound waves diffract around an object, what is observed?
 (A) The sound bends and can be heard even behind the object ✓
 (B) The sound is completely blocked
 (C) The sound gets louder
 (D) The frequency of the sound increases</p> <p>7. The diffraction of water waves in a ripple tank depends on:</p> | <p>(A) Depth of water only
 (B) Width of the gap and wavelength ✓
 (C) Speed of light in water
 (D) Angle of incidence</p> <p>8. If the gap in the ripple tank is made narrow, the diffraction becomes:
 (A) Less noticeable (B) More noticeable ✓
 (C) Unchanged (D) Completely blocked</p> <p>9. A ripple tank is mainly used to study:
 (A) Refraction of light
 (B) Wave motion in solids
 (C) Properties of sound waves
 (D) Behaviour of water surface waves ✓</p> <p>10. The waves commonly demonstrated in ripple tank are:
 (A) Longitudinal sound waves
 (B) Transverse water waves ✓
 (C) Electromagnetic waves
 (D) Seismic waves</p> <p>11. When water waves pass from deep to shallow regions in a ripple tank, they:
 (A) Speed up and their wavelength increases
 (B) Slow down and their wavelength decreases ✓
 (C) Change direction and increase in frequency
 (D) Reflect completely</p> <p>12. In a ripple tank, the frequency of waves is increased by
 (A) Increasing the water depth
 (B) Using a small wave generator
 (C) Increasing the power to the vibrator ✓
 (D) Narrowing the slit</p> |
|---|--|

7.9 BEATS



13. What is meant by the term beats? Prove that number of beats per second is equal to the difference between the frequencies of vibrating tuning forks.

Ans. Beats

Definition

When two waves of slightly different frequencies, travelling in the same direction overlap each other then there is a periodic variation of sound between maximum and minimum loudness which is called as beats.

Explanation

Tuning forks give out pure notes (single frequency). If two tuning forks A and B of the same frequency say 32 Hz are sounded separately, they will give out pure notes. If they are sounded simultaneously, it will be difficult to differentiate the notes of one tuning fork from that of the other. The sound waves of the two will be superposed on each other and will be heard by the human ear as a single pure note.

If the tuning fork B is loaded with some wax or plasticine, its frequency will be lowered slightly, say it becomes 30 Hz. If now the two tuning forks are sounded together, a note of alternately increasing and decreasing intensity will be heard. This note is called **beat note** or a beat which is due to interference between the sound waves from tuning forks A and B.

Figure 13(a) shows the waveform of the note emitted from a tuning fork A. Similarly, Fig. 13(b) shows the waveform of the note emitted by tuning fork B. When both the tuning forks A and B are sounded together, the resultant waveform; Fig. 13(c). It shows how do the beat note occur. At some instant X, the displacement of the two waves is in the same direction. The resultant displacement is large and a loud sound is heard. After $\frac{1}{4}$ s the displacement of the wave due to one tuning fork is opposite to the displacement of the wave due to the other tuning fork resulting in minimum displacement at Y, hence, faint sound or no sound is heard.

Another $\frac{1}{4}$ s later, the displacements are again in the same direction and a loud sound is heard again at Z.

Thus, during one second, we observe two faintest sounds or two loudest. As the difference of the frequency of the two tuning forks is also 4 Hz so, we find that the number of beats per second is equal to the difference between the frequencies of the tuning forks.

$$f_A = 32 \text{ Hz}, f_B = 30 \text{ Hz}$$

$$f_A > f_B$$

$$\text{No. of beats} = f_A - f_B = 32 \text{ Hz} - 30 \text{ Hz} = 2$$

However, when the difference between the frequencies of the two sounds is more than 10 Hz, it becomes difficult to recognize the beats.

The difference between the frequencies of the two waves is termed as beat frequency f_{beat} .

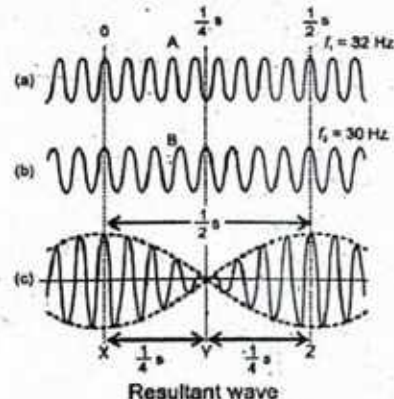
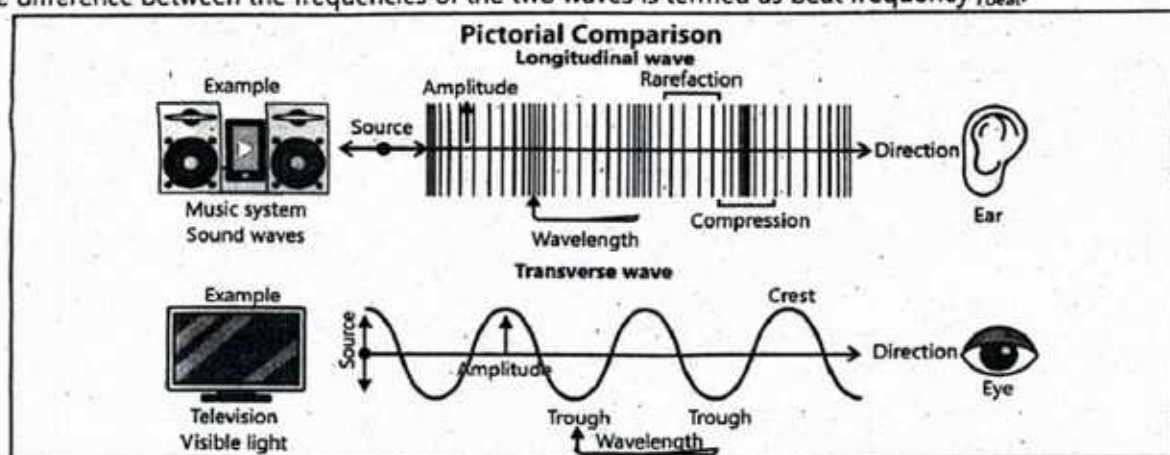


Fig. 13: Formation of beats



14. Give some examples to elaborate how beats are used for tuning musical instruments.

Ans. Use of Beats in Tuning Musical Instruments

Here are some examples of how beats are generated in musical instruments:

- Guitar:** When playing two strings with slightly different tunings, beats are created. For example, playing a standard tuned string and a string tuned a few cents higher or lower.
- Piano:** Playing two keys white and black, adjacent to each other, creates beats.
- Violin:** When playing two strings with slightly different bow pressures or speeds, beats are generated.
- Drums:** When two drums with slightly different tunings are played simultaneously, beats are created.
- Flute:** When playing two notes with slightly different embouchure (lip and facial muscles) positions, beats are generated.
- Organ:** When playing two pipes with slightly different tunings, beats are created.
- Synthesizer:** Generating two oscillators with slightly different frequencies



creates beats.

In each of these examples, the slight difference in frequency between the two sound sources creates a periodic increase and decrease in amplitude, resulting in a "beat" or pulsation effect.

Musicians often use beats intentionally to create interesting rhythmic effects, add texture, or produce a sense of tension and release. However, in some cases, beats can be unwanted and may require adjustments to tuning, pitch, or playing technique to minimize their impact.

instruments is due to the formation of stationary waves or standing waves in these instruments.

Example 7.7: Two tuning forks exhibit beats at a beat frequency of 3 Hz. The frequency of one fork is 256 Hz. Its frequency is then lowered slightly by adding a bit of wax to one of its prongs. The two forks then exhibit a beat frequency of 1 Hz. Determine the frequency of the second tuning fork.

Solution:

Given that;

Frequency of first tuning fork $= f_1 = 256 \text{ Hz}$

Beat frequency before loading $= 3 \text{ Hz}$

Beat frequency after loading $= 1 \text{ Hz}$

To Find:

Frequency of second tuning fork $= f_2 = ?$

Calculations:

As $f_1 - f_2 = \pm n$

Then $f_2 = f_1 \pm n$

Putting the values, we have

$$f_2 = 256 \text{ Hz} \pm 3 \text{ Hz}$$

Either $f_2 = 256 \text{ Hz} + 3 \text{ Hz}$

or $f_2 = 256 \text{ Hz} - 3 \text{ Hz}$

$$f_2 = 259 \text{ Hz} \text{ or } 253 \text{ Hz}$$

Let us consider 259 Hz as correct answer (i.e., frequency of second tuning fork). When first fork is loaded with wax, the frequency of first fork must fall below 256 Hz i.e., 255 Hz, 254 Hz and thus the number of beats produced per second will increase and will be greater than 3 beats. Since the number of beats per second decreases on loading first fork is one, therefore 259 Hz is not correct frequency of second tuning fork.

Thus, Correct frequency $= f_2 = 253 \text{ Hz}$ Ans.



- | | |
|---|---|
| 1. Beats can be heard when difference of frequency is not more than:
(A) 8 Hz
(B) 10 Hz ✓
(C) 4 Hz
(D) 6 Hz | (A) 0 ✓
(C) 2
(B) 1
(D) 3 |
| 2. In order to produce beats, the two sound waves should have:
(A) Same amplitude
(B) Slightly different amplitudes
(C) Same frequencies
(D) Slightly different frequencies ✓ | 5. Beats are used to find:
(A) Frequency ✓
(B) wavelength
(C) speed
(D) intensity |
| 3. Two tuning forks of frequencies 240 Hz and 243 Hz are sounded together, the number of beats per second will be:
(A) Zero
(B) 4
(C) 3 ✓
(D) 2 | 6. The periodic increase and decrease in loudness of sound is called:
(A) Resonance
(B) Interference
(C) Beats ✓
(D) Polarization |
| 4. Two identical tuning forks are operating simultaneously, the number of beats per second will be: | 7. Which of the following changes due to interference of two sound waves of same frequency:
(A) Frequency
(B) Time period
(C) Wave length
(D) Amplitude ✓ |
| | 8. The basic principle of beats is:
(A) Interference ✓
(B) Diffraction
(C) Reflection
(D) Refraction |

9. On loading the prong of a tuning fork with wax, the frequency of sound:
 (A) Increases (B) Decreases ✓
 (C) Increases
 (D) First increases then decreases
10. The path difference for constructive interference should be:
 (A) $\frac{\lambda}{2}$ (B) $\frac{5\lambda}{2}$
 (C) $m\lambda$ ✓ (D) $\frac{3\lambda}{2}$
11. The pitch of sound depends upon:
 (A) Intensity of sound (B) Wavelength of sound
 (C) Frequency of sound ✓ (D) Loudness of sound
12. The number of beats produced per second in two tuning forks is equal to:
 (A) Sum of two frequencies
 (B) Ratio of two frequencies
 (C) The frequency of either of two tuning fork
 (D) The difference of their frequencies ✓
13. Two tuning forks of frequencies 261 Hz and 258 Hz are sounded together, the number of beats per second is:
 (A) 3 ✓ (B) 2
 (C) 261 (D) 258
14. Human ear can recognize beats having maximum frequency equal to:
 (A) 40 Hz (B) 30 Hz
- (C) 5 Hz ✓ (D) 101 Hz
15. What causes the phenomenon of beats?
 (A) Reflection of sound waves
 (B) Diffraction of sound waves
 (C) Doppler effect
 (D) Interference of two waves of slightly different frequencies ✓
16. The time interval between two successive beats is known as:
 (A) Frequency (B) Wavelength
 (C) Beat period ✓ (D) Resonance
17. In the phenomenon of beats, the amplitude of the resultant wave:
 (A) Remains constant (B) Varies with time ✓
 (C) Increases continuously (D) Decreases continuously
18. The beat frequency is equal to:
 (A) The sum of two frequencies
 (B) The average of two frequencies
 (C) The product of two frequencies
 (D) The difference between two frequencies ✓
19. In beat formation, the intensity of sound:
 (A) Remain constant (B) Varies periodically ✓
 (C) Increases continuously (D) Decreases
20. Beats are not audible when:
 (A) Frequencies are widely different ✓
 (B) Amplitudes are equal
 (C) Frequencies are very close
 (D) Both waves are in phase

7.10 INTENSITY (I) OF A WAVE



15. What do you understand by progressive waves? Discuss the intensity of progressive waves.

Ans. Progressive Waves

Definition

Progressive waves are waves that transfer energy from one point to another through a medium (like air, water, or a solid) or even through vacuum (as in the case of light).

As the wave moves, the particles of the medium oscillate about their equilibrium positions, but there is no net movement of matter; only energy is transferred.

Example: A water ripple moving outward in a pond after a stone is dropped; the wave travels outwards but water molecules only move up and down at their equilibrium position.

Intensity (I) of a Wave

Definition

Intensity is defined as the amount of energy transmitted per unit area per unit time in the direction of propagation of progressive wave.

Explanation

It is a measure of the power of a wave and is usually denoted by the symbol "I". It is measured in units of watts per square metre (W m^{-2}).

A progressive wave or travelling wave is one that travels through a medium in a consistent direction and transferring energy from one point to another. It is a wave that propagates or moves forward, as opposed to a stationary or standing wave. Examples of progressive waves include water waves, sound waves, light waves, etc.

By definition, the intensity of a wave is:

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

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

$$I = \frac{P}{A} \quad \left(\because \frac{E}{t} = P \right)$$

Here I = Intensity of wave in (W m^{-2})

E = Energy in joules (J)

t = Time in seconds (s)

P = Power in watts (W)

We know that in mechanical waves, such as sound waves, water waves, or waves on a vibrating string, energy is stored as kinetic energy and potential energy of the medium's particles. How much energy is stored depends upon the displacement (amplitude) of the particles from the mean position. Therefore, the intensity I of waves is proportional to the square of the amplitude A , i.e.,

$$I \propto A^2$$

$$\text{or } I = kA^2$$

Here k is the constant of proportionality and depends upon the physical properties of the wave and the medium.

Example 7.8:

- (a) A wave has an intensity of 0.5 W m^{-2} at a distance of 3.0 m from the source. What is the power of the wave?
 (b) Two progressive waves have intensities of 0.5 W m^{-2} and 0.25 W m^{-2} . Find total intensities of two waves.

Solution:

Given that;

(a) $I = 0.5 \text{ W m}^{-2}$
 $r = 3.0 \text{ m}$

To Find:

$$P = ?$$

Calculations:

As $I = \frac{P}{A}$

or $I = \frac{P}{4\pi r^2}$

Putting the values,

$$0.5 \text{ W m}^{-2} = \frac{P}{4 \times 3.14 (3.0 \text{ m})^2}$$

$$P = 0.51 \times 13.04$$

$$P = 56.52 \text{ W} \text{ Ans.}$$

(b) **Given that;**

$$I_1 = 0.5 \text{ W m}^{-2}$$

$$I_2 = 0.25 \text{ W m}^{-2}$$

To Find:

$$I = ?$$

$$I = I_1 + I_2$$

$$I = 0.5 \text{ W m}^{-2} + 0.25 \text{ W m}^{-2}$$

$$I = 0.75 \text{ W m}^{-2} \text{ Ans.}$$

Tidbits

Frequency and amplitude of a travelling wave are independent of each other. That is why you can turn up the volume of a song (increase amplitude) without changing its pitch (which depends on frequency).

Brain Teaser

Can you find the decibel level of a travelling wave whose intensity is 10 W m^{-2} ?

Ans. Yes, to find the decibel (dB) level of a sound wave given its intensity, we can use the formula:

$$L = 10 \log_{10} \left(\frac{I}{I_0} \right)$$

where $I = 10 \text{ W m}^{-2}$ $I_0 = 10^{-12} \text{ W m}^{-2}$

$$L = 10 \log_{10} \left(\frac{10 \text{ W m}^{-2}}{10^{-12} \text{ W m}^{-2}} \right)$$

$$= 10 \log_{10} (10^{13})$$

$$= 10 \times 13 = 130 \text{ dB}$$

Example 7.9: A speaker is emitting sound waves with a power of 50 watts. If the sound waves are spreading out evenly in all directions and the intensity of the sound waves is measured at a distance of 5 m from the speaker, what is the intensity of the sound waves if the area of the sphere (the surface area of a sphere) at that distance is

approximately 314 m^2 ?

Solution:

Given that;

$$\text{Power } P = 50 \text{ W}$$

$$\text{Area } A = 314 \text{ m}^2$$

To Find:

Intensity of wave $I = ?$

Calculations:

$$\text{As } \text{Intensity} = \frac{\text{Power}}{\text{Area}}$$

$$\text{or } I = \frac{P}{A}$$

$$I = \frac{50 \text{ W}}{314 \text{ m}^2}$$

$$I = 0.159 \text{ W m}^{-2} \text{ Ans.}$$

Tidbit

Sound cannot travel through vacuum, as there are no particles to transmit the sound wave.



- The Intensity of a wave is the:**
(A) Total energy carried by the wave
(B) Power transmitted per unit area ✓
(C) Speed at which the wave travels
(D) Maximum displacement of the medium
- The Intensity I of a wave is proportional to:**
(A) Amplitude (A)
(B) Amplitude squared (A^2) ✓
(C) Frequency (f) (D) Wavelength (λ)
- If the amplitude of a wave is doubled, its intensity becomes:**
(A) Half (B) Double
(C) Four times ✓ (D) Unchanged
- The SI unit of wave intensity is:**
(A) watt (W)
(B) newton (N)
(C) watt per metre squared (Wm^{-2}) ✓
(D) joule (J)
- Which factor does not affect the intensity of a wave?**
(A) Distance from the source
(B) Frequency of the wave ✓
(C) Amplitude of the wave
(D) Medium's absorption properties
- A listener moves twice as far from a sound source. What happens to the sound intensity?**
(A) It doubles
(B) It becomes one-half
(C) It becomes one-fourth ✓
(D) It stays the same
- Intensity of a wave is a measure of:**
(A) Its loudness only
(B) Its wavelength
(C) Phase difference between waves
(D) Energy carried per second per unit area ✓
- The intensity of a sound wave decreases as:**
(A) The frequency increases
(B) The source moves closer
(C) The distance from the source increases ✓
(D) The wavelength increases

7.11 DOPPLER EFFECT



16. What is Doppler's effects? Using Doppler's effect, analyze the following cases.

(a) When source of sound moves towards the stationary observer.

(b) When source of sound moves away from the stationary observer.

Ans. Doppler Effect

Definition

The apparent change in the frequency (or pitch) of waves due to the relative motion between the source and observer (listener) is called Doppler Effect.

Explanation

This effect can be observed with sound waves also. For example, when an observer is standing on a railway platform, the pitch of whistle of an engine coming towards the platform appears to become higher to an

observer standing on the platform. However, the pitch of whistle of an engine going away from the platform appears to become lower to an observer standing on the platform.

Consider a source of sound S at rest which emits sound waves having wavelength λ . Let speed of the sound for a stationary observer (i.e., listener) is v then the number of waves received by observer in one second i.e., frequency f is:

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

Case 1: When source of sound moves towards the stationary observer

When the source moves towards the stationary observer A with velocity u_s then waves are compressed and their wavelength is decreased; Fig. 14. In this case, the waves are compressed by an amount given as

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

The compression of the waves is due to the fact that same number of waves are contained in a shorter space depending upon the velocity of the source. The wavelength observed by the observer A is then,

$$\lambda_A = \lambda - \Delta\lambda$$

or

$$\lambda_A = \frac{v}{f} - \frac{u_s}{f}$$

$$\lambda_A = \frac{v - u_s}{f}$$

Here $\Delta\lambda$ is the decrease in wavelength in one second and is called Doppler shift.

Thus, the number of waves received by observer A in one second (i.e., changed or apparent frequency) is

$$f_A = \frac{v}{\lambda_A}$$

Putting the value of λ_A , we have

$$f_A = \left[\frac{v}{\frac{v - u_s}{f}} \right]$$

$$f_A = \left[\frac{v}{v - u_s} \right] f$$

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

Therefore $f_A > f$

Thus, the apparent frequency of sound heard by the observer increases which in turn will increase the pitch of sound.

Case 2: When source of sound moves away from the stationary observer

When the source moves away from the stationary observer B with velocity u_s , then waves are expanded and their wavelength is increased. In this case, the waves expanded by an amount:

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

The expansion of the waves is due to the fact that same number of waves are now contained in a large distance. The wavelength observed by the observer B is then,

$$\lambda_B = \lambda + \Delta\lambda$$

where $\Delta\lambda$ is the increase in wavelength in one second and is called Doppler shift.

Thus, the number of waves received by observer B in one second (i.e., changed or apparent frequency) is:

$$f_B = \frac{v}{\lambda_B}$$

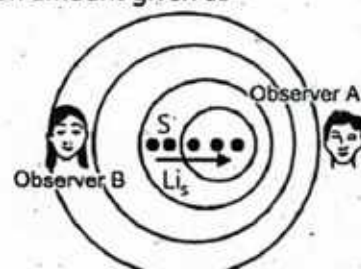


Fig. 14 : A source moving with velocity u_s towards a stationary observer A and away from stationary observer B respectively. Observer A hears an increased and observer B hears a decreased frequency

Info Corner	
Hearing Ranges	
Organisms	Frequencies in Hz
Dolphin	150 – 150,000
Bat	1000 – 120,000
Cat	60 – 70,000
Dog	15 – 50,000
Human	20 – 20,000

Putting the value of λ_B , we have

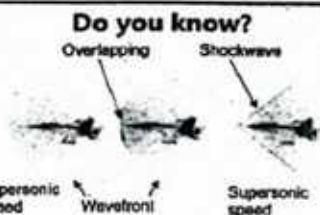
$$f_B = \left[\frac{v}{(v + u_s)} \right] f$$

$$f_B = \left[\frac{v}{(v - u_s)} \right] f$$

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

Therefore $f_B > f$

Thus, the apparent frequency of sound heard by the observer decreases which in turn will decrease the pitch of sound.



As a plane accelerates, it builds up a front of air pressure by pushing air in front of it. When it passes the speed of sound, the pressure trails behind like a boat's wake, forming a sonic shockwave.

Example 7.10: Two trucks P and Q travelling along a motorway in the same direction. The loading truck P travels at a steady speed of 12 m s^{-1} , the other truck Q, travelling at a steady speed of 20 m s^{-1} , sound its horn to emit a steady note which P's driver estimate, has a frequency of 830 Hz . What frequency does Q's own driver hear?

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

Solution:

Given that;

$$u_P = 12 \text{ m s}^{-1}$$

$$u_Q = 20 \text{ m s}^{-1}$$

$$v = 340 \text{ m s}^{-1}$$

$$f_P = 830 \text{ Hz}$$

To Find:

$$f_Q = ?$$

Calculations: Speed of Q relative to P = $u_s = u_Q - u_P = 20 \text{ m s}^{-1} - 12 \text{ m s}^{-1} = 8 \text{ m s}^{-1}$

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

$$f_P = \left(\frac{v}{v - u_s} \right) f_Q$$

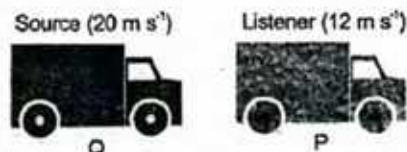
Putting the values,

$$830 \text{ Hz} = \left(\frac{340 \text{ m s}^{-1}}{340 \text{ m s}^{-1} - 8 \text{ m s}^{-1}} \right) f_Q$$

$$830 \text{ Hz} = \left(\frac{340 \text{ m s}^{-1}}{332 \text{ m s}^{-1}} \right) f_Q$$

or $f_Q = \left(\frac{830 \text{ Hz} \times 332 \text{ m s}^{-1}}{340 \text{ m s}^{-1}} \right)$

$$f_Q = 810.47 \text{ Hz} \text{ Ans.}$$



Example 7.11: A train sounds its horn before it sets off from the station and an observer waiting on the platform estimates its frequency at 1200 Hz . The train then moves off and accelerates steadily. Fifty seconds after departure, the driver sounds the horn again and the platform observer estimates the frequency at 1140 Hz . Calculate the train speed 50 s after departure. How far from the station is the train after 50 s .

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

Solution:

Given that;

Original frequency of horn $= f = 1200 \text{ Hz}$

Apparent frequency $= f' = 1140 \text{ Hz}$

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

Time $= t = 50 \text{ s}$

To Find:

Speed of source (i.e., train) $= u_s = ?$

Distance covered by the train $= S = ?$

Calculations:

$$(i) \quad f' = \left(\frac{v}{v + u_s} \right) f$$

Putting the values,

$$1140 \text{ Hz} = \left(\frac{340 \text{ m s}^{-1}}{340 \text{ m s}^{-1} + u_s} \right) \times 1200 \text{ Hz}$$

$$340 \text{ m s}^{-1} + u_s = \frac{340 \text{ m s}^{-1} \times 1200 \text{ Hz}}{1140 \text{ Hz}}$$

$$u_s = 357.89 - 340$$

$$u_s = 17.89 \text{ m s}^{-1} \text{ Ans.}$$

(ii)

$$S = v_{av} t$$

$$S = \left(\frac{v_i + v_f}{2} \right) t$$

$$S = \left(\frac{0 + 17.89 \text{ m s}^{-1}}{2} \right) 50 \text{ s}$$

$$S = 448 \text{ m Ans.}$$

Do You Know?



Bats navigate and find food by echo location.

7.12 APPLICATIONS OF DOPPLER EFFECT



17. Describe briefly some applications of Doppler's effect.

Ans. Applications of Doppler Effect

Doppler effect is also applicable to electromagnetic waves. One of its important applications is the radar system, which uses radio-waves to determine the elevation and speed of an aeroplane.

RADAR (Radio Detection and Ranging) is a device, which transmits and receives radiowaves. If an aeroplane approaches towards the radar, then the wavelength of the wave reflected from aeroplane would be shorter and if it moves away, then the wavelength would be larger; Fig. 15(a) and (b), respectively. Similarly, speed of satellites moving around the Earth can also be determined by the same principle.

SONAR is an acronym derived from "Sound Navigation And Ranging". It is the general name for sonic or ultrasonic underwater echo-ranging and echo-sounding system. Sonar is the name of a technique for detecting the presence of objects under water by acoustical echo. In **Sonar**, "Doppler detection" relies upon the relative speed of the target and the detector to provide an indication of the target speed. It employs the Doppler effect, in which an apparent change in frequency occurs when the source and

the observer are in relative motion to one another. Its known military applications include the detection and location of submarines, control of antisubmarine weapons, mine hunting and depth measurement of sea.

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

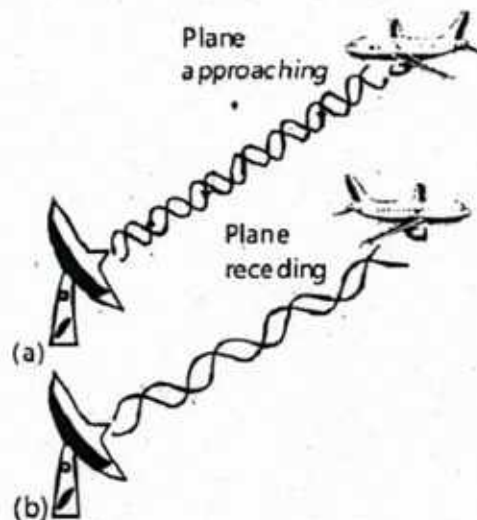


Fig. 15: A frequency shift is used in a radar to detect the motion of an aeroplane.

(i) Stars moving away from the Earth show a red shift as shown in Fig. 16(b). The emitted waves have a longer wavelength than if the star had been at rest. So, the spectrum is shifted towards longer wavelength, i.e., towards the red end of the spectrum. Astronomers have also discovered that all the distant galaxies are moving away from us and by measuring their red shifts, they have estimated their speeds.

(ii) Stars moving towards the Earth show a blue shift as shown in Fig. 16(c). This is because the wavelengths of light emitted by the star are shorter than if the star had been at rest. So, the spectrum is shifted towards shorter wavelength, i.e., to the blue end of the spectrum.

Another important application of the Doppler shift using electromagnetic waves is the **radar speed trap**. Microwaves are emitted from a transmitter in short bursts. Each burst is reflected off by any car in the path of microwaves in between sending out bursts. The transmitter is open to detect reflected microwaves. If the reflection is caused by a moving obstacle, the reflected microwaves are Doppler shifted. By measuring the Doppler shift, the speed at which the car moves is calculated by computer programme.

Satellite Navigation uses Doppler shift to determine satellite velocity and position, enabling accurate location tracking.

Satellite Communication also uses Doppler shift compensation ensuring stable communication signals.

Doppler radar detects wind velocity and precipitation patterns. **Doppler shift** helps measure Earth's surface velocity and deformation.

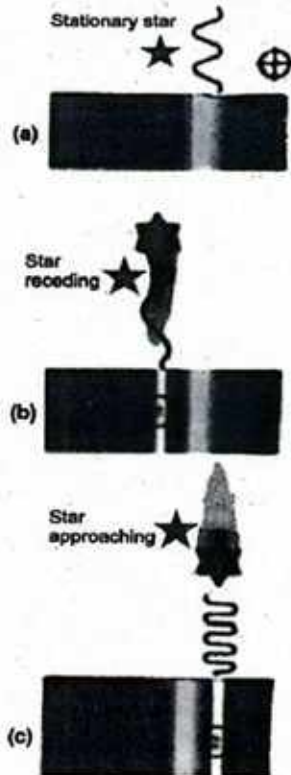


Fig. 16

Doppler echocardiography measures blood flow velocity and detects cardiac abnormalities, such as valve stenosis or regurgitation. Doppler echocardiography optimizes pacemaker settings.

Doppler ultrasound measures blood flow and calculates cardiac output. Doppler ultrasound detects vascular stenosis or occlusion.

Example 7.12: The wavelength of one of its lines of the absorption spectrum of a faint galaxy is identified as Ca- α line found to be 478 nm. The wavelength of same line is observed and measured as 397 nm in the laboratory.

- (a) Is the galaxy moving towards or away from the Earth?
 (b) Compute the speed of the galaxy relative to the Earth.

Solution:

Given that;

Laboratory measured original wavelength

$$\lambda = 397 \text{ nm} = 397 \times 10^{-9} \text{ m}$$

Changed or Apparent wavelength $\lambda' = 478 \text{ nm} = 478 \times 10^{-9} \text{ m}$

Speed of light $c = 3 \times 10^8 \text{ m s}^{-1}$

To Find:

- (a) Is the galaxy moving towards or away from the Earth?

Calculations:

As $v = f\lambda$

or $c = f\lambda$ ($\because v = c$)

or $f = \frac{c}{\lambda}$

Putting the values

$$f = \frac{3 \times 10^8 \text{ m s}^{-1}}{397 \times 10^{-9} \text{ m}}$$

$$f = 7.56 \times 10^{-3} \times 10^8 \times 10^9 \text{ s}^{-1}$$

Laboratory frequency $f = 7.56 \times 10^{14} \text{ Hz}$

$$\text{Apparent frequency } f' = \frac{c}{\lambda'}$$

$$= \frac{3 \times 10^8 \text{ m s}^{-1}}{478 \times 10^{-9} \text{ m}}$$

$$f' = 6.28 \times 10^{14} \text{ Hz}$$

$$\lambda' > \lambda \quad \text{or} \quad f' < f \quad \text{Ans.}$$

The galaxy is moving away from the Earth.

- (b) Compute the speed of the galaxy relative to the Earth.

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

$$f' = \left(\frac{c}{c + u_s} \right) f \quad (\because v = c)$$

Putting the values,

$$6.28 \times 10^{14} \text{ Hz} = \left(\frac{3 \times 10^8 \text{ m s}^{-1}}{3 \times 10^8 \text{ m s}^{-1} + u_s} \right)$$

$$3 \times 10^8 + u_s = \frac{3 \times 10^8 \text{ m s}^{-1} \times 7.56 \times 10^{14} \text{ Hz}}{6.28 \times 10^{14} \text{ Hz}}$$

$$u_s = \frac{22.68 \times 10^8}{6.28} - 3 \times 10^8 \text{ m s}^{-1}$$

$$u_s = 6.12 \times 10^7 \text{ m s}^{-1} \quad \text{Ans.}$$

Galactic Motion

A galaxy is moving away from us at 20% of the speed of light (i.e., 0.2 c). We observe a spectral line from this galaxy that is normally emitted at a wavelength of 500 nm.



- The Doppler effect is applicable to:**
(A) Only sound waves (B) Only light waves
(C) Both sound and electromagnetic waves ✓
(D) Only water waves
- When a source of sound moves towards a stationary observer, the observer hears:**
(A) A lower frequency (B) The same frequency
(C) A higher frequency ✓ (D) No sound
- The Doppler effect is used in:**
(A) Measuring blood flow in medical imaging
(B) Radar speed detection
(C) Astronomy to detect star motion
(D) All of these ✓
- When the source moves away from a stationary observer, what happens to the wavelength of the sound?**
(A) Increases ✓ (B) Decreases
(C) Remains constant (D) Becomes zero
- The Doppler effect is the change in:**
(A) Wavelength due to interference
(B) Frequency due to motion between source and observer ✓
(C) Speed due to medium variation
(D) Amplitude due to distance
- If an observer is moving away from a stationary sound source, the frequency heard will be:**
(A) Higher (B) Lower ✓
(C) The same (D) Zero
- In sonar, waves in use are:**
(A) Ultraviolet waves (B) Ultrasonic waves ✓
(C) Radio waves (D) Microwaves
- Radar is the application of:**
(A) Chemical effect (B) Electric effect
(C) Doppler's effect ✓ (D) Magnetic effect
- Stars moving towards the earth show:**
(A) Blue shift ✓ (B) Red shift
(C) No shift (D) Longer wavelength
- Car A has a siren sounding a note of 540 Hz. A listener in car B hears a note of 544 Hz. Both move in the same direction, one concludes that:**
(A) B leads A and move faster
(B) B is behind A and moves faster
(C) B leads A and move slower ✓
(D) B is behind A and moves slower
- The location of submarines can be detected by:**
(A) Doppler effect ✓ (B) Temperature effect
(C) Diffraction (D) Compton's effect
- Star moving away from earth shows:**
(A) Green shift (B) Blue shift
(C) Red shift ✓ (D) Yellow shift
- Types of wave used in sonar are:**
(A) Sound waves ✓ (B) Light waves
(C) Heat waves (D) Water waves
- Radar system is an application of:**
(A) Electric effect (B) Doppler effect ✓
(C) Magnetic effect (D) Chemical effect
- When an observer is moving away from a stationary source sending waves with speed v, the waves are received by him at the rate of:**

$$(A) \frac{v - u_o}{\lambda} \checkmark$$

$$(B) \frac{v + u_o}{\lambda}$$

$$(C) \frac{\lambda}{v - u_o}$$

$$(D) \frac{\lambda}{v + u_o}$$

16. Types of waves used in sonar are:

(A) Sound waves $\checkmark$

(B) Light waves

(C) Heat waves

(D) Water waves

17. A source of sound moves towards stationary observer with a speed one third of sound. If the frequency of the sound from the source is 100 Hz, the apparent frequency of the sound heard by the observer is:

(A) 60 Hz

(B) 200 Hz

(C) 100 Hz

(D) 150 Hz $\checkmark$

18. The red shift measurement of Doppler Effect of galaxies indicates that the universe is:

(A) Expanding $\checkmark$

(B) Contracting

(C) Stationary

(D) Oscillating

19. The wavelength ' λ ' of a wave depends on the speed ' v ' of the wave and its frequency ' f '. Decide which of the following is correct?

$$(A) f = \frac{v}{\lambda} \checkmark$$

$$(B) f = v \lambda$$

$$(C) f = \frac{\lambda}{v}$$

$$(D) f = v \lambda^{-2}$$

20. When the dimensions of both sides of an equation are equal then the equation is said to be:

(A) Simultaneous

(B) Homogenous $\checkmark$

(C) Instantaneous

(D) Quadratic

21. The spectrum of a star's light is measured and the wavelength of one of the lines as the Sodium's line is found to be 589 nm. The same line has the wavelength of 497 nm when observed in the laboratory. This means the star is:

(A) Moving away from the earth $\checkmark$

(B) Moving towards the earth

(C) Stationary

(D) Revolving around the planet

22. A source of sound wave emits waves of frequency ' f '. If ' v ' is the speed of sound waves, then what will be the wavelength of the waves is:

$$(A) \frac{v}{f} \checkmark$$

$$(B) vf$$

$$(C) \frac{(v - u)}{f}$$

$$(D) (v - u) f$$

23. When the source of sound moves towards the stationary observer, then value of apparent frequency ' f_o ' is:

$$(A) f_o = \left(\frac{v + u_s}{v} \right) f$$

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

$$(C) f_o = \left(\frac{v}{v - u_s} \right) f$$

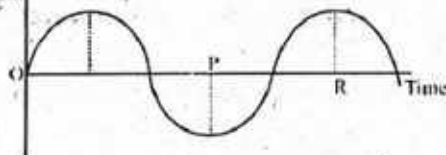
$$(D) f_o = \left(\frac{v - v_s}{v} \right) f$$

24. In the diagram below, the displacement of an oscillating particle is plotted against time. What does the length 'PR' on the time axis represents?

Displacement



Displacement



(A) Twice the frequency

(B) Half the period $\checkmark$

(C) Half the frequency

(D) Twice the period

25. Two progressive waves of frequency 250 Hz are superimposed to produce a stationary wave in which adjacent nodes are 2 m apart. The speed of the progressive waves is:

(A) 125 m/sec

(B) 250 m/sec

(C) 500 m/sec

(D) 1000 m/sec $\checkmark$

26. An ambulance moves around a large round-about with its sirens on. For a person standing at the centre of the round-about, the frequency of ambulance siren heard will be:

(A) Equal to actual siren frequency $\checkmark$

(B) Less than the actual frequency

(C) Greater than the actual siren frequency

(D) Changing as the ambulance moves frequency

ADDITIONAL SHORT ANSWER QUESTIONS

1. What is period of 250 cycles per second of sound wave?

$$\text{Ans. } T = \frac{1}{f}$$

$$(\because f = 250 \text{ cycles per second})$$

$$\text{or } = \frac{1}{250}$$

$$\text{or } T = 0.004 \text{ s}$$

Q.2 Find the temperature of air, if the velocity of sound is 340 ms^{-1} at the temperature.

$$\text{Ans. } v_t = v_o + 0.61 t$$

$$(v_t = 340 \text{ ms}^{-1})$$

$$\text{or } 340 = 332 + 0.61 t$$

$$(v_o = 332 \text{ ms}^{-1})$$

$$\text{or } 8 = 0.61 t$$

or

$$t = 13.11^{\circ}\text{C}$$

Q.3 What are the factors upon which speed of sound in air depends?

Ans. The speed of sound in air depends upon the following two factors:

- Compressibility i.e. elastic modulus (E)
- Inertia i.e. density of the medium (ρ)

Formula:

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

Q.4 What causes interference?

Ans. Interference is caused by the superposition of coherent waves (waves with a constant phase difference).

Q.5 What is coherent light?

Ans. Light waves are coherent if they have a constant phase difference and the same frequency.

Q.6 Give an example of interference in daily life.

Ans. Colour patterns in soap bubbles or oil films on water are due to interference of light.

Q.7 What is the difference between interference and diffraction?

Ans. Interference is due to superposition of waves from different sources whereas diffraction is the spreading of a wave after encountering an obstacle or slit.

Q.8 Can diffraction occur in water waves?

Ans. Yes, water waves diffract when waves passing through narrow gaps or around barriers.

Q.9 What happens to diffraction pattern if the slit width is decreased?

Ans. The diffraction pattern spreads out more.

Q.10 How can you demonstrate diffraction using a ripple tank?

Ans. By passing straight waves through narrow gap; the waves spread out after passing through.

Q.11 Why is a white screen placed beneath the ripple tank?

Ans. To observe the wave patterns clearly through the shadows cast by the waves.

Q.12 What is the difference between interference and beats?

Ans. (i) Interference

When two waves having same frequency and travelling in the same direction produce the phenomenon of interference.

(ii) Beats

When two waves of slightly different frequencies and travelling in the same direction produce beats.

Q.13 Why ultrasonic waves are preferred on radio waves for the use of undersea communication?

Ans. Radiowaves are electromagnetic waves and ultrasonic waves are mechanical waves. The mechanical waves (ultrasonic waves) can produce disturbance in matter and therefore can travel for long distance through matter (water) without any loss of energy. The electromagnetic waves travel through matter for very short distance and lose their energy because they are absorbed.

Q.14 Which is richer in harmonics, and why?

$$\text{For open end pipe} \quad f_n = n \left(\frac{v}{2l} \right), \quad n = 1, 2, 3, \dots$$

$$\text{For closed pipe system} \quad f_n = n \left(\frac{v}{4l} \right), \quad n = 1, 3, 5, \dots$$

Ans. By studying the both these cases, we concluded that the pipe which is open at both ends is richer in harmonics.

Q.15 Do stationary waves transfer energy?

Ans. No, Stationary waves do not transfer energy across the medium.

Q.16 Give an example of stationary waves in real life.

Ans. Vibrating strings of musical instruments like a guitar or violin.

Q.17 Can stationary waves be formed in air columns?

Ans. Yes, in open and closed pipes, such as organ pipes or wind instruments.

Q.18 What is the phase difference between particles in a stationary wave?

Ans. All particles between two consecutive nodes vibrate in phase, but particles in adjacent segments vibrate in opposite phase.

Q.19 What are the quantities which affect the frequency of standing wave along a string?
(or)

On what factors does the fundamental frequency in a stretched string depend?

Ans. The fundamental frequency of standing wave in the string is given by

$$f_1 = \frac{1}{2l} \sqrt{\frac{F}{m}}$$

Dependence

It depends upon the following three factors:

(i) Length (l) (ii) Tension (F) (iii) Mass per unit length (m)

Q.20 How the K.E. and P.E. alternates in stationary waves?

Ans. Energy oscillates between P.E. and K.E. between nodes.

When all the particles are at their extreme positions the whole energy is P.E. while at passing through equilibrium position, the whole energy is K.E.

Q.21 What is the frequency and wavelength of third harmonic in a closed organ pipe?

Ans. It contains three nodes and three anti-nodes Let ' λ_3 ' be the wavelength and ' f_3 ' be the frequency of the stationary wave.

The distance between one node and the next and the next anti-node is $\frac{\lambda_3}{4}$ so the length of the pipe is given by

$$l = \frac{\lambda_3}{4} + \frac{\lambda_3}{4} + \frac{\lambda_3}{4} + \frac{\lambda_3}{4} + \frac{\lambda_3}{4}$$

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

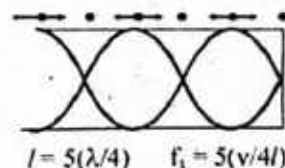
or
$$\lambda_3 = \frac{4l}{5}$$

As
$$v = f_3 \lambda_3$$

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

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

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



Q.22 What is effect on frequency of sound waves, when source and observer are moving towards each other?

Ans. If source is moving towards stationary observe, then

$$f' = \frac{v}{v - u_s} f$$

If observer is moving toward stationary source, then

$$f' = \frac{v + v_o}{v - v} f$$

If both of them are moving towards each other, then

$$f' = \frac{v + v_o}{v - v_s} f$$

$$\therefore \frac{v + v_o}{v - v_s} > 1$$

So, the observed frequency will increase.

Q.23 How the doppler shift can be used in Radar speed trap?

Ans. In radar speed trap, microwaves emitting from a transmitter in short bursts reflected from a moving car. If reflected beam from any moving car received by transmitter. With the measurement of doppler shift in the related beam, the speed of moving car is calculated by computer program.

Q.24 What features do longitudinal waves have in common with transverse waves?

Ans. Common Features of Longitudinal Waves and Transverse Waves

- (i) Both types of waves transfer energy.
- (ii) Both types of waves can produce interference, diffraction, refraction.
- (iii) For determination of speed of wave, $v = f\lambda$ is applicable for both these waves.

Q.25 Can beats be used to tune musical instruments?

Ans. Yes, beats help in tuning by adjusting the instrument until the beat frequency becomes zero (i.e, frequencies match).

Q.26 What types of waves produce beats?

Ans. Beats are produced by sound waves (longitudinal mechanical waves) of nearly the same frequency.

Q.27 Why is intensity important in wave phenomena?

Ans. Because it determines the energy transfer, loudness (in sound), and brightness (in light).

Q.28 Does intensity of a wave depend on frequency?

Ans. Yes, for some types of waves like electromagnetic waves, intensity can depend on both amplitude and frequency.

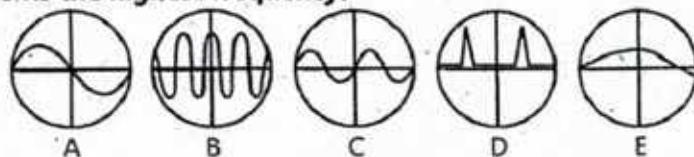
Q.29 What is the difference between loudness and intensity of a wave?

Ans. Loudness is a subjective perception by the ear, while intensity is an objective physical quantity.

Q.30 The five possible waveforms obtained, when the output from a microphone is fed into the Y-input of cathode ray oscilloscope, with the time base on, are shown in Fig. These waveforms are obtained under the same adjustment of the cathode ray oscilloscope controls. Indicate the waveform

(a) Which trace represents the loudest note?

(b) Which trace represents the highest frequency?



Ans. (a) Loudest Note

In Fig. (D), the amplitude is maximum, so loudness is maximum for this case.

(b) Maximum Frequency

In Fig. (B), the number of waves is maximum so frequency is maximum in this case.

Q.31 Is it possible for two identical waves travelling in the same direction along a string to give rise to a stationary wave?

Ans. Stationary waves are produced only when two identical waves move along the same line in opposite directions. Therefore, it is not possible for two identical waves travelling in the same direction along a string to give rise to a stationary wave.

Q.32 A wave is produced along a stretched string but some of its particles permanently show zero displacement. What type of wave is it?

Ans. These are stationary waves:

Reason: Only in stationary waves some points of the medium permanently show zero displacement called nodes and some points show maximum displacement called antinodes.

Q.33 Explain the terms crest, trough, node and anti-node.

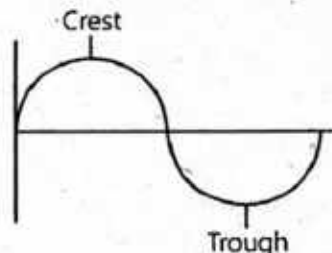
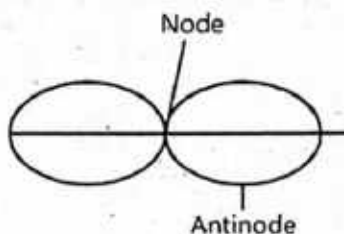
Ans. Crest:

The portion of transverse wave above the equilibrium position is called crest.

Trough: The portion of transverse wave below the equilibrium position is called trough.

Node: The points of zero displacement on stationary waves are called node.

Antinode: The points of maximum displacement on stationary waves are called antinodes.



Q.34 Why does sound travel faster in solids than in gases?

Ans. Sound travels faster in solids than in gases.

Reason: Speed of sound in a medium is given by the relation:

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

Thus, speed of sound in a medium depends upon modulus of elasticity E and density ρ of the medium. In the case of solids, E is Young's modulus of elasticity. In the case of a gas, E is bulk modulus of elasticity. Density ρ for solids is greater than that of gases. At the same time, Young's modulus of elasticity E for a solid is much more greater than bulk modulus of elasticity E for a gas. Consequently, the ratio $\frac{E}{\rho}$ is greater for solids than that for gases. Thus speed of sound is greater in a solid than the speed of sound in a gas. In other words, sound travels faster in solids than in gases.

Q.35 How are beats useful in tuning musical instruments?

Ans. Tuning a Musical Instrument by Beats:

Number of beats per second is equal to the difference of two frequencies. A musical instrument of unknown frequency is sounded together with a standard musical instrument of known frequency. By observing the number of beats per second, we find the difference between the two frequencies. The musical instrument of unknown frequency is gradually adjusted such that number of beats becomes zero. Under this condition, both the musical instruments have the same frequency. In this way, unknown frequency of the musical instrument is determined. This is called tuning of a musical instrument. Thus beats are useful in tuning a musical instrument.

Q.36 When two notes of frequencies f_1 and f_2 are sounded together, beats are formed. If $f_1 > f_2$, what will be the frequency of beats?

- (i) $f_1 + f_2$ (ii) $\frac{1}{2} (f_1 + f_2)$ (iii) $f_1 - f_2$ (iv) $\frac{1}{2} (f_1 - f_2)$

Ans. Since beat frequency is equal to the difference of individual interfering frequencies:

Beat frequency is $f_1 - f_2$

Q.37 As a result of a distant explosion, an observer senses a ground tremor and then hears the explosion. Explain the time difference.

Ans. Explanation:

The speed of sound is given by

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

Since the speed of sound in solid (earth) is much greater than the speed of sound in gases (air) due to the much greater value of elastic modulus. That is why the observer senses the ground tremor first and then hears the explosion.

Q.38 Explain, why sound travels faster in warm air than in cold air?

Ans. Speed of sound in a gas is given by

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

This equation shows that;

$$v \propto \frac{1}{\sqrt{\rho}}$$

This means that speed of sound is inversely proportional to the square root of density. When temperature of air increases, density of air decreases and consequently speed of sound increases. In other words, speed of sound is directly proportional to the square root of absolute temperature T

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

That is why sound travels faster in warm air than in cold air.

Q.39 Can the Doppler effect be observed in light waves?

Ans. Yes, but only at very high speeds (comparable to the speed of light).

Q.40 What is the use of Doppler effect in real life?

Ans. Applications include radar, weather forecasting, medical imaging (Doppler ultrasound), and astronomy.

Q.41 Does the Doppler effect occur in all types of waves?

Ans. Yes, it occurs in all types of waves including sound, light and electromagnetic waves.

Q.42 How should a sound move with respect to an observer such that its frequency does not change.

Ans. If the relative velocity between the source and the observer is zero, there will be no change in frequency of sound and the apparent frequency will be zero.

Example: When both source and observer are travelling in the same direction with same velocity.

SOLVED EXERCISE

MULTIPLE CHOICE QUESTIONS

Tick (✓) the correct answer.

7.1 The simple wave speed equation is represented by:

(a) $v = f\lambda$ ✓

(b) $v = \frac{s}{t}$

(c) $v = r\omega$

(d) $v = \frac{d}{t}$

7.2 The principle of superposition in waves is stated as:

(a) the displacement of a wave is the sum of the displacements of its individual components ✓

(b) the velocity of a wave is the product of its individual components

(c) the frequency of a wave is the difference of its individual components

(d) the amplitude of a wave is the ratio of its individual components

7.3 A node in a stationary wave is:

(a) a point of maximum displacement

(b) a point of intermediate displacement

(c) a point of zero displacement ✓

(d) a point of infinite displacement

7.4 An anti-node in a stationary wave is:

(a) a point of maximum displacement ✓

(b) a point of minimum displacement

(c) a point of zero displacement

(d) a point of infinite displacement

7.5 Stationary waves are defined as:

(a) waves that move with a constant velocity

(b) waves that move with a changing velocity

(c) waves that oscillate in a fixed position ✓

(d) waves that propagate through a medium

7.6 Harmonics are:

(a) integer multiples of a fundamental frequency ✓

(b) integer submultiples of a fundamental frequency

(c) random frequencies

(d) non-integer multiples of a fundamental frequency

7.7 The result of constructive interference between two waves is represented as:

(a) a decrease in amplitude

(b) an increase in amplitude ✓

(c) no change in amplitude

(d) a shift in phase

7.8 If the amplitude of the wave is tripled, then the amount of energy is increased by:

(a) 3 times

(b) 6 times

(c) 9 times ✓

(d) 12 times

7.9 What type of waves do headphones use to produce sound?

(a) Electromagnetic waves ✓

(b) Mechanical waves

(c) Pressure waves

(d) Longitudinal waves

7.10 The typical frequency range of microwaves is:

(a) 10^3 - 10^5 Hz

(b) 10^5 - 10^7 Hz

(c) 10^7 - 10^9 Hz ✓

(d) 10^9 - 10^{11} Hz

- 7.11 The bending of waves around an obstacle is called as:
 (a) refraction (b) reflection (c) diffraction ✓ (d) interference
- 7.12 The Doppler Effect used in astronomy is for:
 (a) measuring the diameters of stars (b) determining velocity of galaxies ✓
 (c) analyzing properties of black holes (d) studying behaviour of electromagnetic waves

SHORT ANSWER QUESTIONS

7.1. What are the conditions for interference to occur?

Ans. For interference to occur, the following conditions must be fulfilled:

1. Two or More Coherent Sources

- (i) The sources must emit waves that have a constant phase difference and the same frequency.
- (ii) Coherence ensures that the interference pattern is stable over time.

2. Same Frequency and Wavelength

The interfering waves should have the same frequency (or nearly the same) and wavelength to produce clear and stable interference patterns.

3. Superposition Principle

- (i) The waves must meet at a point where they can superimpose, meaning their displacements add algebraically.
- (ii) This leads to either constructive interference (amplitudes add up) or destructive interference (amplitudes cancel out).

4. Constant Phase Relationship

A stable interference pattern requires that the waves maintain a constant phase relationship over time.

5. Similar Amplitudes (Optional for Clear Patterns)

- (i) For the interference pattern to be visible and distinct, the waves should have similar amplitudes.
- (ii) If one wave is much stronger than the other, the interference effects might be hard to detect.

7.2. Differentiate between constructive and destructive interference of waves.

Ans. Constructive and destructive interference of waves are two fundamental phenomena that occur when two or more waves meet or overlap in space. Let us know how they differ:

1. Constructive Interference: It occurs when two or more waves combine to form a resultant wave with a greater amplitude than the individual waves.

Condition: The waves must be in phase, meaning their crests (high points) and troughs (low points) align.

Result: The amplitudes of the waves add up, leading to a stronger or louder wave (in sound) or brighter light (in optics).

Example:

Sound Waves: When two speakers produce the same sound in phase, the sound is louder at certain points.

Light Waves: Bright fringes in a double-slit experiment are due to constructive interference.

2. Destructive Interference: It occurs when two or more waves combine to form a resultant wave with a reduced (or even zero) amplitude.

Condition: The waves must be out of phase, meaning the crest of one wave aligns with the trough of another.

Result: The amplitudes subtract from each other, which can completely cancel out the wave if the amplitudes are equal, leading to silence (in sound) or darkness (in optics).

Example:

Noise-Cancelling Headphones: They produce sound waves that are out of phase with external noise, cancelling it out.

Light Waves: Dark fringes in the double-slit experiment are caused by destructive interference.

7.3. What are coherent waves and coherent sources? Give examples.

Ans. Coherent Waves

Coherent waves are waves that have a constant phase difference, the same frequency, and the same waveform. Coherence is essential for phenomena like interference, where waves superimpose to produce constructive or destructive patterns.

Characteristics of Coherent Waves

Constant phase difference The phase relationship between the waves does not change over time.

Same frequency: Both waves oscillate at the same rate.

Same waveform: They often have similar shapes, especially in ideal cases.

Examples of Coherent Waves

- (i) **Lasers:** The light emitted from a laser is highly coherent, with all the light waves having the same frequency and phase relationship.
- (ii) **Microwave signals:** Used in communication systems where coherence is crucial for signal clarity.

Coherent Sources

Coherent sources are two or more wave sources that emit waves with a constant phase difference and the same frequency. These sources are necessary to produce stable interference patterns, such as in the famous Young's double-slit experiment.

Characteristics of Coherent Sources

- (i) Emit waves of the same frequency.
- (ii) Maintain a constant phase relationship over time.

Examples of Coherent Sources

- (i) Two slits in Young's double-slit experiment: When illuminated by a single monochromatic light source, the slits act as coherent sources.
- (ii) Radio antennas broadcasting the same signal: They can maintain coherence to improve signal strength through constructive interference.

7.4 Distinguish between longitudinal and transverse waves.

Ans. Longitudinal waves and transverse waves are two primary types of mechanical waves, distinguished based on the direction of particle vibration relative to the direction of wave propagation.

1. Longitudinal Waves

Direction of Vibration: The particles of the medium vibrate parallel to the direction of wave propagation.

Wave Features: Composed of compressions (regions of high pressure) and rarefactions (regions of low pressure).

Medium Requirement: Can travel through solids, liquids, and gases.

Examples

- (i) Sound waves in the air
- (ii) Seismic P-waves (primary waves)
- (iii) Ultrasound waves

2. Transverse Waves

Direction of Vibration: The particles of the medium vibrate perpendicular to the direction of wave propagation.

Wave Features: Characterized by crests (highest points) and troughs (lowest points).

Medium Requirement: Generally travel through solids and on the surface of liquids, but cannot travel through gases efficiently.

Examples

- (i) Light waves (electromagnetic wave)
- (ii) Water waves
- (iii) Seismic S-waves (secondary waves)
- (iv) Waves on a string

7.5 Is it possible for two identical waves travelling in the same direction along a string to give rise to a stationary wave? How is it so?

Ans. Yes, two identical waves travelling in the same direction along a string can give rise to a stationary wave, but it happens under specific conditions. This occurs when two waves of equal amplitude and frequency, but travelling in opposite directions, interfere with each other.

Let us know, how does this happens:

- 1. **Superposition Principle:** The two waves combine according to the superposition principle, so, the displacements of the waves are added together. If the waves are in phase (meaning their crests and troughs align), their displacements reinforce each other, creating regions of maximum displacement (antinodes).

2. **Opposite Directions:** To form a stationary wave, one of the waves needs to travel in the opposite direction of the other. This creates a condition where some points on the string (called nodes) remain at rest (zero displacement), while other points (antinodes) experience maximum displacement.
3. **Resulting Stationary Wave:** When two waves traveling in opposite directions superpose, the result is a stationary wave where the amplitude varies along the string. The points that experience no displacement (nodes) stay still, while points between them (antinodes) oscillate with maximum amplitude. Thus, if two identical waves travel in opposite directions along the same string, the interference between them can produce a stationary wave. However, if both waves are traveling in the same direction, they would just pass through each other without forming a stationary wave.

7.6 How would you apply Doppler effect in studying cardiac problems in humans?

Ans. The Doppler effect can be incredibly useful in studying cardiac problems through a technique called Doppler ultrasound. This method is commonly used to assess blood flow, heart valve function, and detect abnormalities in the cardiovascular system. Here's how it applies:

1. **Blood Flow Measurement:** The Doppler effect is used to measure the velocity and direction of blood flow in vessels. By emitting sound waves that bounce off moving blood cells, the ultrasound system detects changes in the frequency of the sound waves. These frequency shifts help determine how fast blood is moving through arteries or veins. Abnormal flow speeds can indicate blockages, narrowing (stenosis), or regurgitation.
2. **Heart Valve Function:** Doppler ultrasound is effective in evaluating heart valve conditions, such as stenosis (narrowing of the valves) or insufficiency (improper closing). When blood flows through a narrowed valve, the Doppler signal shows increased velocity, while a leaky valve can be detected by abnormal flow patterns.
3. **Detecting Cardiac Abnormalities:** The Doppler effect can highlight abnormal heart rhythms or assess the efficiency of the heart's pumping action. This information is essential in diagnosing conditions like heart failure, congenital heart defects, or issues with the heart chambers.
4. **Measuring Cardiac Output:** By studying blood flow velocities in major arteries (like the aorta or pulmonary artery), Doppler ultrasound can help estimate the amount of blood the heart pumps per minute, providing insights into heart function and capacity.

Overall, Doppler ultrasound is a non-invasive, safe, and effective way to evaluate various aspects of heart health, guide treatment, and monitor conditions over time.

7.7 What is meant by diffraction of waves? For what purpose, the ripple tank is used?

Ans. Diffraction of waves refers to the bending of waves around obstacles or the spreading of waves as they pass through small openings. It occurs when a wave encounters an obstacle or slit that disrupts its regular propagation. Diffraction is most noticeable when the wavelength of the wave is comparable to the size of the obstacle or opening. It can be observed in different types of waves, including light, sound, and water waves. Ripple tanks are used to study the behavior of water waves, and they help visualize wave phenomena such as diffraction, reflection, refraction, and interference. A ripple tank consists of a shallow tray of water with a light source above it. When waves are generated in the water (often by a vibrating plate or a small motor), they can be observed as ripples and their interactions (like diffraction) can be easily demonstrated. This is a common tool in physics classrooms for experiments related to wave properties.

CONSTRUCTED RESPONSE QUESTIONS

7.1. Which measurement of a wave is the most important when determining the wave's intensity?

Ans. The amplitude of a wave is the most important measurement when determining the wave's intensity. Intensity is directly proportional to the square of the amplitude. Mathematically,

$$I \propto A^2$$

where I = Intensity of the wave
 A = Amplitude of the wave

This applies to many types of waves, including sound waves, light waves, and water waves.

7.2. Can you apply Doppler effect to light waves? Describe briefly.

Ans. Yes, the Doppler effect can be applied to light waves, and it is known as the relativistic Doppler effect because it involves the principles of special relativity when dealing with high-speed motion.

The Doppler effect for light refers to the change in the observed frequency (or wavelength) of light due to the relative motion between the light source and the observer.

Redshift: When the light source is moving away from the observer, the light's wavelength increases (shifts towards the red end of the spectrum), and the frequency decreases.

Blueshift: When the light source is moving towards the observer, the wavelength decreases (shifts towards the blue end), and the frequency increases.

Formula (Relativistic Doppler Effect):

$$f' = f \sqrt{\frac{1 - \frac{v}{c}}{1 + \frac{v}{c}}}$$

Applications

Astronomy: Measuring the speed of stars, galaxies, and the expansion of the universe (e.g., cosmological redshift).

Radar and LIDAR: Detecting motion and speed of objects.

Medical Imaging: Doppler effect in lasers for blood flow measurement.

Since light does not require a medium (unlike sound), the relativistic Doppler effect accounts for both special relativity and the constant speed of light in all reference frames.

7.3. Can you compare the compressions and rarefactions of the longitudinal wave with the peaks and troughs of the transverse wave? Discuss.

Ans. Let us compare the compressions and rarefactions in a longitudinal wave with the peaks (crests) and troughs in a transverse wave:

1. Nature of the Waves

- (i) **Longitudinal Waves:** Particles of the medium move parallel to the direction of the wave's propagation. Examples include sound waves in air.
- (ii) **Transverse Waves:** Particles of the medium move perpendicular to the direction of wave propagation. Examples include light waves and water waves.

2. Key Features of Longitudinal Waves:

Compressions: Where particles are close together, creating high pressure.

Rarefactions: where particles are spread apart, creating low pressure.

Key Features of Transverse Waves:

Crests (Peaks): The highest point of the wave above the rest position.

Troughs: The lowest point of the wave below the rest position.

3. Comparison:

Compressions ↔ Crests: Both represent regions of maximum energy:

Compression: Maximum density or pressure in the medium (for longitudinal waves).

Crest: Maximum displacement from the equilibrium position (for transverse waves).

Rarefactions ↔ Troughs: Both represent regions of minimum energy:

Rarefaction: Minimum density or pressure (particles are spread out).

Trough: Maximum displacement in the opposite direction from the crest.

Wave Representation: A longitudinal wave can be represented as alternating compressions and rarefactions along the direction of motion. When a transverse wave is shown as oscillations with peaks (crests) and dips (troughs).

7.4. How should a source of sound move with respect to an observer so that the frequency of its sound does not change? Write two examples.

Ans. For the frequency of sound to remain unchanged relative to an observer, the source of the sound must either remain stationary with respect to the observer or move at a constant velocity along a path perpendicular to the line of sight between the source and the observer.

This ensures that the distance between the source and the observer doesn't change in such a way that would alter the frequency (via Doppler shift).

Examples

Stationary Source: If the sound source is stationary and the observer is also stationary, the frequency will remain unchanged.

Example: A car horn sounding while both the car (source) and the observer are at fixed positions.

Source Moving Perpendicular to the Observer: If the sound source moves at a constant speed in a direction that is perpendicular to the line connecting the source and the observer, the frequency will not change.

Example: A person walking across a park with a portable speaker in hand, playing a consistent tone. As long as they walk in a straight line at constant speed perpendicular to the observer's position, the frequency of the sound remains unchanged.

7.5. Why is it difficult to recognize beats when the frequency difference is greater than 10 Hz? Exemplify.

Ans. The difficulty in recognizing beats when the frequency difference is greater than 10 Hz arises because of the way our auditory system processes sound. Beats occur when two sounds of slightly different frequencies are played together. The brain perceives a periodic variation in volume as the waves interfere constructively and destructively, creating a rhythmic pulse.

When the frequency difference between the two sounds is small (usually within 1-10 Hz), the brain can easily detect the slow variation in amplitude (the beat), because the fluctuations are within the range of human perception.

However, when the frequency difference exceeds around 10 Hz, the fluctuations become faster than the brain can track effectively as a rhythmic pulse. Instead of perceiving a "beat," the sounds begin to blend together more smoothly, and it becomes harder for the brain to distinguish between the individual tones.

Examples

Small Frequency Difference (e.g., 1 Hz): If you play a 440 Hz and a 441 Hz sound together, you will hear a slow, periodic "thumping" or "wobbling" sound at 1 Hz.

Larger Frequency Difference (e.g., 20 Hz): If you play a 440 Hz and a 460 Hz sound together, the fluctuation in volume happens too rapidly for your brain to follow as a distinct beat. You might hear two separate pitches instead of a clear beat.

COMPREHENSIVE QUESTIONS

7.1 State and explain the principle of superposition of waves. Apply this principle to elaborate the working of noise canceling headphones.

Ans. See Q.4 and Q.5.

7.2 What are standing waves? Illustrate a detailed experiment that demonstrates the standing waves using stretched strings.

Ans. See Q.8.

7.3 Find the frequencies of the harmonics produced in organ pipe when it is open at one end and when it is open at both ends.

Ans. See Q.10.

7.4 Define and exemplify diffraction of waves. Describe this phenomenon by ripple tank experiment.

Ans. See Q.13.

7.5 What is meant by the term beats? Prove that number of beats per second is equal to the difference between the frequencies of vibrating tuning forks.

Ans. See Q.14.

7.6 What do you understand by progressive waves? Discuss the intensity of progressive waves.

Ans. See Q.16.

7.7 Keeping in mind "Doppler effect", analyze the following cases:

(a) when source of sound moves away from the stationary observer.

(b) when source of sound moves towards the stationary observer

Ans. See Q.21.

NUMERICAL PROBLEMS

7.1 The speed of a wave on a typical string is 24 m s^{-1} . What driving frequency will it resonate if its length is 6.0 m ?

Solution:

Given data:

Speed of wave $v = 24 \text{ m s}^{-1}$

Length of string $L = 6.0 \text{ m}$

To Find:

Frequency $f = ?$

Calculations: The resonant frequency of a wave on a string depends on its speed, length and the harmonic being considered. The formula for the fundamental frequency (first harmonic) is:

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

Putting the values

$$f = \frac{24 \text{ ms}^{-1}}{2 \times 6 \text{ m}} = \frac{24 \text{ ms}^{-1}}{12 \text{ m}} = 2 \text{ s}^{-1}$$

$$f = 2 \text{ Hz}$$

The string will resonate at a driving frequency of 2 Hz for its fundamental frequency.

7.2 The lowest resonance frequency for a guitar string of length 0.75 m is 400 Hz. Calculate the speed of a transverse wave on the string.

Solution:

Given data:

Lowest resonance frequency $f_1 = 400 \text{ Hz}$

Length of the string $L = 0.75 \text{ m}$

To Find:

Speed of wave $v = ?$

Calculations: To calculate the speed of a transverse wave on the string, we use the formula for the fundamental frequency (lowest resonance frequency) of a vibrating string:

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

Rearranging for v

$$v = 2L \times f_1$$

Putting the values

$$v = 2 \times 0.75 \text{ m} \times 400 \text{ Hz}$$

$$v = 600 \text{ ms}^{-1} \quad (\because \text{Hz} = \text{s}^{-1})$$

The speed of the transverse wave on the string is 600 ms^{-1} .

7.3 A tuning fork A produces 4 beats per second with another tuning fork B. It is found that by loading B with some wax, the beat frequency increases to 6 beats per second. If the frequency of A is 320 Hz, determine the frequency of B when loaded.

Solution:

Given data:

Frequency of tuning fork $A = 320 \text{ Hz}$

Beat frequency with the unloaded tuning fork

$$f_{\text{beats}} = 4 \text{ Hz}$$

Frequency of tuning fork

$$B = f_A \pm f_{\text{beats}} = 320 \text{ Hz} \pm 4$$

Hence, f_B could be 324 Hz or 316 Hz.

When B is loaded with wax, its frequency decreases and the beat frequency increases to:

$$F_{\text{beats, loaded}} = 6 \text{ Hz}$$

To Find:

The unloaded frequency of tuning fork $B = ?$

The loaded frequency of tuning fork $B = ?$

Calculations:

Step 1: If $f_B = 324 \text{ Hz}$, then decreasing f_B would decrease the beat frequency, but this is inconsistent with the observation that the beat frequency increases.

Thus, $f_B \neq 324 \text{ Hz}$

If $f_B = 316 \text{ Hz}$, then decreasing f_B further (due to wax) will increase the beat frequency. This is consistent with the observation. So, the loaded frequency of B is:

$$f_B = 316 \text{ Hz}$$

Step 2: When loaded, the frequency of B decreases further. The beat frequency increases to 6 Hz. Therefore,

$$|f_A - f_{B, \text{loaded}}| = 6$$

Putting $f_A = 320 \text{ Hz}$

$$f_{B, \text{loaded}} = 320 - 6 = 314 \text{ Hz}$$

Thus, the frequency of tuning fork B when loaded is 314 Hz.

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

Solution:

Given data:

Weight $= w = T = 80 \text{ N}$

Diameter of the wire $= D = 0.50 \text{ mm}$

Radius of the wire $= r = \frac{D}{2} = 0.25 \text{ mm} = 0.00025 \text{ m}$

Length of the wire $= L = 1.5 \text{ m}$

Density of the wire $= \rho = 7.8 \times 10^3 \text{ kg m}^{-3}$

To Find:

Fundamental frequency of the wire $f = ?$

Calculations: We can use the formula for the frequency of a vibrating string:

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

where μ is the linear mass density of the wire. The linear mass density is given by

$$\mu = \frac{\text{Mass}}{\text{Length}}$$

The mass of the wire is calculated using the density of steel and the volume of the wire.

$$\text{Mass} = \text{Density} \times \text{Volume} = \rho \times \pi r^2 L$$

$$\text{Here Density} = \rho = 7.8 \times 10^3 \text{ kg m}^{-3}$$

Radius = $r = 0.00025$ m

Length = $L = 1.5$

Putting the values

$$\text{Mass} = (7.8 \times 10^3) \times \pi \times (0.00025)^2 \times 1.5$$

$$\mu = \frac{\text{Mass}}{L} = \rho \times \pi \times r^2 = (7.8 \times 10^3) \times \pi \times$$

$(0.00025)^2$

Putting the values in the Formula:

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

$$f = \frac{1}{2 \times 1.5} \sqrt{\frac{80 \text{ N}}{(7.8 \times 10^3) \times \pi \times (0.00025)^2}}$$

$$\boxed{f = 76.2 \text{ Hz}}$$

Thus, the fundamental frequency of the steel wire is 76.2 Hz.

- 7.5 Average intensity of sunlight on the surface of the Earth is nearly 500 W m^{-2} . Determine the amount of energy that falls on a solar panel having an area of 0.50 m^2 in four hours.**

Solution:

Given data:

Intensity of sunlight = $P = 500 \text{ W m}^{-2}$

Area of solar panel = $A = 0.50 \text{ m}^2$

Time $t = 4$ hours
 $= 4 \times 60 \times 60 \text{ s} = 14400 \text{ s}$

To Find:

Energy $E = ?$

Calculations:

$$E = P \times A \times t$$

Putting the values

$$E = 500 \times 0.50 \times 14400$$

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

Thus, the amount of energy that falls on the solar panel in 4 hours is $3.6 \times 10^6 \text{ J}$.

- 7.6 (a) If the intensity of a wave is 16 W m^{-2} and the amplitude is 2 m, what is the value of constant k ?**
(b) If the intensity of a wave is 25 W m^{-2} and the constant k is 5 W m^{-4} , what is the amplitude?

Solution:

Given data:

- (a)** Intensity of a wave $I = 16 \text{ W m}^{-2}$
 Amplitude $A = 2 \text{ m}$

To Find:

Constant $k = ?$
 Intensity of a wave $I = 25 \text{ W m}^{-2}$
 Constant $k = 5 \text{ W m}^{-4}$

To Find:

Amplitude $A = ?$

Calculations: (a) The intensity I of a wave is proportional to the square of its amplitude A and can be written as:

$$I = kA^2$$

Rearranging for k

$$k = \frac{I}{A^2}$$

Putting the values

$$k = \frac{16 \text{ W m}^{-2}}{(2 \text{ m})^2}$$

$$\boxed{k = 4 \text{ W m}^{-4}}$$

- (b) As** $I = kA^2$

Rearranging for A

$$A^2 = \frac{I}{k}$$

$$\text{or } A = \sqrt{\frac{I}{k}}$$

Putting the values

$$A = \sqrt{\frac{25 \text{ W m}^{-2}}{5 \text{ W m}^{-4}}} \approx 2.236 \text{ m}$$

$$\boxed{A = 2.24 \text{ m}}$$

- 7.7 (a) A sound system produces 200 watts of power. If the sound is directed at a crowd with an area of 150 m^2 , what is the intensity of the sound?**
(b) A light bulb emits 100 watts of power. If the light is spread out evenly over a sphere with a surface area of 400 m^2 , what is the intensity of the light?

Solution:

Given data:

- (a)** Power $P = 200 \text{ W}$
 Area $A = 150 \text{ m}^2$

To Find:

Intensity of sound $I = ?$

- (b)** Power $P = 100 \text{ W}$
 Area $A = 400 \text{ m}^2$

To Find:

Intensity of sound $I = ?$

Calculations: The intensity of a wave (sound or light) is defined as the power per unit area. Therefore,

$$I = \frac{P}{A}$$

- (a)** Putting the values

$$I = \frac{200 \text{ W}}{150 \text{ m}^2}$$

$$\boxed{I = 1.33 \text{ W m}^{-2}}$$

- (b)** As $I = \frac{P}{A}$

Putting the values

$$I = \frac{100 \text{ W}}{400 \text{ m}^2}$$

$$I = 0.25 \text{ Wm}^{-2}$$

7.8 A radio antenna broadcasts 500 watts of power. If the signal is received at a distance of 10 km, what is the intensity of the signal?

Solution:

Given data:

Power $P = 500 \text{ W}$

Distance $r = 10 \text{ km} = 10,000 \text{ m}$

To Find:

Intensity of the signal $I = ?$

Calculations: Using the formula:

$$I = \frac{P}{A} \quad \dots\dots (i)$$

I = Intensity, P = Power of the source It and A = surface area over which the power is distributed.

For a radio antenna, the power radiates uniformly in all directions, forming a spherical wave. The surface area of the sphere is given by

$$A = 4\pi r^2$$

Equation (1) becomes:

$$I = \frac{P}{4\pi r^2}$$

Putting the values

$$I = \frac{500 \text{ W}}{4\pi (10,000 \text{ m})^2}$$

$$I = 4 \times 10^{-7} \text{ Wm}^{-2}$$

Thus, the intensity of the signal at a distance 10 km is $4 \times 10^{-7} \text{ Wm}^{-2}$.

7.9 An organ pipe has a length of 1 m. Determine the frequencies of the fundamental and the first two harmonics:

(a) if the pipe is open at both ends and

(b) if the pipe is closed at one end. (Speed of sound in air is 340 m s^{-1})

Solution:

Given data:

Length of pipe $L = 1 \text{ m}$

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

To Find:

(a) Fundamental frequency and the first two harmonic = ? (If the pipe is open at both ends)

(b) Fundamental frequency and the first two harmonics = ? (If the pipe is closed at one end)

Calculations: (a) For open pipe at both ends:

• Fundamental frequency $f_1 = \frac{v}{2L}$

• Harmonics $f_n = n \cdot f_1$, where $n = 1, 2, 3, \dots\dots$

$$f_1 = \frac{340 \text{ ms}^{-1}}{2 \times 1 \text{ m}}$$

$$f_1 = 170 \text{ Hz}$$

$$(\because \text{s}^{-1} = \text{Hz})$$

Second harmonic $f_2 = 2 \cdot f_1 = 2 \times 170 \text{ Hz}$

$$f_2 = 340 \text{ Hz}$$

Third harmonic $f_3 = 3 \cdot f_1 = 3 \times 170 \text{ Hz}$

$$f_3 = 510 \text{ Hz}$$

(b) For pipe closed at one end:

• Fundamental frequency $f_1 = \frac{v}{2L}$

• Harmonics $f_n = (2n - 1) \cdot f_1$ where $n = 1, 2, 3, \dots\dots$

$$f_1 = \frac{340 \text{ ms}^{-1}}{4 \times 1 \text{ m}}$$

$$f_1 = 85 \text{ Hz}$$

First overtone (third harmonic)

$$f_3 = 3 \cdot f_1 = 3 \times 85 \text{ Hz}$$

$$f_3 = 255 \text{ Hz}$$

Second overtone (Fifth harmonic), $f_5 = 5 \cdot f_1 = 5 \times 85 \text{ Hz}$

$$f_5 = 425 \text{ Hz}$$

7.10 A train is approaching a station at 90 km h^{-1} , sounding a whistle of frequency 1000 Hz . What will be the apparent frequency of the whistle as heard by a listener sitting on the platform? What will be the apparent frequency heard by the same listener if the train moves away from the station with the same speed? (Speed of sound is 340 m s^{-1})

Solution:

Given data:

Source frequency $f = 1000 \text{ Hz}$

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

Velocity of listener $v_{\text{listener}} = 0 \text{ ms}^{-1}$

($\because$ Listener is stationary)

Velocity of listener (train) $v_{\text{source (train)}} = 90 \text{ kmh}^{-1} =$

$$\frac{90 \times 1000 \text{ m}}{60 \times 60 \text{ s}} = 25 \text{ ms}^{-1}$$

To Find:

(a) Apparent frequency of the whistle heard by a stationary listener $f' = ?$

(b) Apparent frequency by the same listener if train is moving away $f' = ?$

Calculation: (a) When the train is approaching Using Doppler's Formula:

$$f' = f \left(\frac{v}{v - v_{\text{source}}} \right)$$

Putting the values

$$f' = 1000 \text{ Hz} \times \left(\frac{340 \text{ ms}^{-1}}{340 \text{ ms}^{-1} - 25 \text{ ms}^{-1}} \right)$$

$$\boxed{f' = 1079.4 \text{ Hz}}$$

(b) When the train is moving away.

Using the Doppler formula

$$f' = f \left(\frac{v}{v + v_{\text{source}}} \right)$$

Substituting the values

$$f' = 1000 \text{ Hz} \left(\frac{340 \text{ ms}^{-1}}{340 \text{ ms}^{-1} + 25 \text{ ms}^{-1}} \right)$$

$$\boxed{f' = 931.5 \text{ Hz}}$$