CHAPTER 05

Sound

Wave

A wave is a disturbance which transfers energy from one part of a medium to another part without actual transfer or flow of matter as a whole. We are all familiar with water waves, sound waves and light waves. These waves occur when a system is disturbed from its equilibrium position and this disturbance travels from one place to another.

In other words, "a wave is any disturbance from a normal or equilibrium condition that propagates without the transport of matter. In general, a wave transports both energy and momentum."

Wave Motion

A wave motion is a means of transferring energy and momentum from one point to another without actual transport of matter between two points. Transmission of energy over considerable distances is possible through wave motion.

Necessary properties of medium for wave motion are given below

(i) The medium must possesses **inertia**, so that its particles can store kinetic energy.

(ii) In order to make the particles return to their original position after getting disturbed, the medium must possesses **elasticity**.

(iii) There should be **minimum frictional force** between the particles of medium.

Types of Waves

There are mainly three types of waves

(i) **Mechanical Waves** These are those waves which requires a material medium for their propagation. They cannot travel through vacuum. *e.g.* Sound waves, water waves, etc.

(ii) **Electromagnetic Waves** These are those waves which do not requires a material medium for their propagation. These waves travel in the form of oscillating electric and magnetic fields. *e.g.* X-rays, radio waves, etc.

(iii) **Matter Waves** Moving microscopic particles such as electrons, protons, neutrons, atoms, molecules, etc., sometimes behave like wave which are called matter waves.

In this chapter, we will discuss mechanical waves and their characteristic properties in detail.

Sound Waves

Sound is a form of energy which produces a sensation of hearing in our ears. Sound waves are longitudinal in nature. Sound waves can be classified in three groups according to their range of frequencies.

(i) **Infrasonic Waves** Longitudinal waves having frequencies below 20 Hz are called infrasonic waves. They cannot be heard by human beings.

(ii) **Audible Waves** Longitudinal waves having frequencies lying between 20-20000 Hz are called audible waves.

(iii) **Ultrasonic Waves** Longitudinal waves having frequencies above 20000 Hz are called ultrasonic waves.

Ultrasonic waves have a large range of application. Some of them are as follows

(i) The fine internal cracks in a metal can be detected by ultrasonic waves.

(ii) Ultrasonic waves can be used for determining the depth of the sea, lakes, etc.

(iii) Ultrasonic waves can be used to detect submarines, icebergs, etc.

(iv) Ultrasonic waves can be used to clean clothes, fine machinery parts, etc.

(v) Ultrasonic waves can be used to kill smaller animals like rats, fish and frogs, etc.

(vi) Ultrasonic or ultrasound is used to investigate the internal organs of human body such as liver, gall bladder, pancreas, kidneys, uterus and heart, etc.

Note *Bat search out prey and fly in dark night by emitting and detecting reflections of ultrasonic waves. The method used by some animals like bats, tortoises and dolphins to scale the objects by hearing the echoes of their ultrasonic squeaks is known as echolocation.*

Speed of Travelling Waves

Speed of waves is divided in two types as per the nature of wave, these are given below

1. Speed of Transverse Wave

The expression for speed of transverse waves in a solid and in case of a stretched string can be obtained theoretically.

- In a solids, $v = \sqrt{\frac{\eta}{d}}$

where, η is the modulus of rigidity and d is the density of the medium.

- In a stretched string, $v = \sqrt{\frac{T}{m}} = \sqrt{\frac{Mg}{\pi r^2 d}}$

where, T = the tension in the string,

m = the mass per unit length of the string,

M = mass suspended from the string,

r = radius of the string

and d = density of the material of the string.

2. Speed of Longitudinal Wave (or Sound Wave)

Following are the expressions for the speed of longitudinal waves in the different types of media.

- If the medium is solid, $v = \sqrt{\frac{B + \frac{4}{3}\eta}{\rho}}$

where, B, η and ρ are the bulk modulus, modulus of rigidity and density of the solid, respectively.

If the solid is in the form of a long rod, then $v = \sqrt{\frac{Y}{\rho}}$.

where, Y is the Young's modulus of the solid material.

- In a liquid,

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

where, B is the bulk modulus of the liquid.

- According to Newton's formula, speed of sound in a gas is obtained by replacing B with initial pressure p of the gas, *i.e.* $B = p$.

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

Note *Speed of sound in liquids and solids is higher than that in gases.*

Laplace Correction

The result obtained for the speed of sound in air at STP from above formula is 280 ms^{-1}, which is about 15% smaller as compared to the experimental value of 331ms^{-1}.

The mistake in the formula was pointed out by Laplace and he told that the changes in pressure and volume of a gas, when sound waves are propagated through it, are not isothermal, but adiabatic.

He modified the formula as

$$\text{Speed of sound in gases, } v = \sqrt{\frac{\gamma p}{\rho}}$$

This modification of Newton's formula is referred to as the Laplace correction.

For air, $\gamma = 7/5$.

By this formula, speed of sound comes out to be 331.3 ms^{-1} which agrees with the practical value.

Example 1. If the Young's modulus of elasticity for a steel rod is 2.9×10^{11} Nm^{-2} and density is 8×10^3 kg m^{-3}. The velocity of longitudinal waves in the steel rod will be

a. 6.02×10^3 m/s
b. 7.02×10^4 m/s
c. 9.02×10^4 m/s
d. 10.02×10^4 m/s

Sol. (*a*) Given, Young's modulus, $Y = 2.9 \times 10^{11}$ Nm^{-2}

Density, $\rho = 8 \times 10^3$ kg m^{-3}

$\therefore$ Velocity of longitudinal waves in the steel,

$$v = \sqrt{\frac{Y}{\rho}} = \sqrt{\frac{2.9 \times 10^{11}}{8 \times 10^3}}$$

$$= 6.02 \times 10^3 \text{ ms}^{-1}$$

Example 2. The volumetric strain of water at a pressure of 10^5 Nm^{-2} is 5×10^{-5}. The speed of sound in water will be (Take, density of water is 10^3 kgm^{-3})

a. 2.41×10^3 m/s
b. 1.41×10^3 m/s
c. 4.2×10^3 m/s
d. 6.4×10^3 m/s

Sol. (*b*) Bulk modulus of water,

$$B = \frac{\text{Normal stress}}{\text{Volumetric strain}} = \frac{10^5}{5 \times 10^{-5}}$$

$$= 2 \times 10^9 \text{ Nm}^{-2}$$

$\because$ Density of water, $\rho = 10^3 \text{kgm}^{-3}$ (given)

$\therefore$ Speed of sound in water, $v = \sqrt{\dfrac{B}{\rho}}$

$$\Rightarrow \quad v = \sqrt{\frac{2\times10^9}{10^3}} = 1.41\times10^3 \text{ ms}^{-1}$$

Example 3. What is the speed of sound in hydrogen gas at 27° C? C_p/C_V for H_2 is 1.4. Gas constant, $R = 8.31 \text{ J mol}^{-1} \text{ K}^{-1}$.

a. 1321 m/s b. 1521 m/s
c. 1421 m/s d. 1621 m/s

Sol. (*a*) The speed of sound in a gas, $v = \sqrt{\gamma p/\rho}$

$$\therefore \quad v = \sqrt{\frac{\gamma RT}{M}} \quad (\because pV = RT \text{ and } \rho = \frac{M}{V})$$

Here, $T = 27 + 273 = 300$ K, $\gamma = \dfrac{C_p}{C_V} = 1.4$,

$R = 8.31 \text{ J mol}^{-1} \text{ K}^{-1}$,

$M = 2\times10^{-3} \text{ kg mol}^{-1}$

$$\therefore \quad v = \sqrt{\frac{1.4\times8.31\times300}{2\times10^{-3}}} = 1321 \text{ ms}^{-1}$$

Note *In the above formula, put $M = 2\times10^{-3}$ kg mol^{-1}. Do not put 2 kg.*

Factors Affecting the Speed of Sound in Air

The factors affecting the speed of sound in air (or gas) are given below

1. Effect of Temperature

Since, from the equation,

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

We can write $\quad v = \sqrt{\dfrac{\gamma RT}{M}} \quad (\because pV = RT)$

where, M = molecular mass of gas, T is absolute temperature and R is gas constant.

We can see that,

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

or

$$\frac{v_1}{v_2} = \sqrt{\frac{T_1}{T_2}}$$

Example 4. The density of air at NTP is 1.29 kgm^{-3}. Assume air to be diatomic with $\gamma = 1.4$. What will be the velocity of sound at 127° C?

a. 482.8 m/s b. 582.8 m/s
c. 942.8 m/s d. 382.8 m/s

Sol. (*d*) Since, according to Laplace formula, speed of sound in air at NTP,

$$v = \sqrt{\frac{\gamma p}{\rho}} = \sqrt{\frac{1.4\times1.013\times10^5}{1.29}} = 331.6 \text{ ms}^{-1}$$

The velocity of sound is proportional to the square root of absolute temperature.

$$\frac{v_2}{v_1} = \sqrt{\frac{T_2}{T_1}} \Rightarrow v_2 = v_1\sqrt{\frac{T_2}{T_1}} = 331.6\sqrt{\frac{273+127}{273+27}} \quad (\because v = v_1)$$

$$v_2 = 382.8 \text{ ms}^{-1}$$

Example 5. In given gaseous medium at what temperature, the velocity of sound will be double that of velocity at 27°C?

a. 327° C b. 127° C c. 827° C d. 927° C

Sol. (*d*) Given, velocity of sound, $v_2 = 2v_1$

Temperature, $T_1 = 27°\text{C} = (27 + 273) = 300\text{K}$

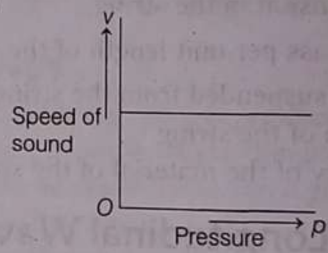
According to the relation, $\dfrac{v_1}{v_2} = \sqrt{\dfrac{T_1}{T_2}} \Rightarrow \dfrac{v_1}{2v_1} = \sqrt{\dfrac{300}{T_2}}$

$$\Rightarrow \quad T_2 = 1200\text{K} \text{ or } T_2 = 927°\text{C}$$

2. Effect of Pressure

From the formula for the speed of sound in a gas $v = \sqrt{\dfrac{\gamma p}{\rho}}$, it appears that $v \propto \sqrt{p}$. But actually it is not so.

Because $\dfrac{p}{\rho} = \dfrac{RT}{M} =$ constant at constant temperature.



Variation of speed of sound with pressure

From this, it is clear that, **if the temperature of the gas remains constant, then there is no effect of the pressure change on the speed of sound.**

3. Effect of Humidity

The density of moist air (*i.e.* air mixed with water-vapour) is less than the density of dry air. It is clear from the formula, $v = \sqrt{\gamma p/\rho}$ that **the speed of sound in moist air is slightly greater than in dry air.** So, speed of sound increases with increase in humidity.

Example 6. A sample of oxygen at NTP has volume V and a sample of hydrogen at NTP has volume $4V$. Both the gases are mixed and the mixture is maintained at NTP, if the speed of sound in hydrogen at NTP is 1270 ms^{-1}. The speed of sound in mixture will be

a. 635 m/s b. 735 m/s
c. 835 m/s d. 935 m/s

Sol. (a) $\rho_{mix} = \dfrac{\rho_{O_2}V_{O_2} + \rho_{H_2}V_{H_2}}{V_{O_2} + V_{H_2}} = \dfrac{16 \times V + 1 \times 4V}{V + 4V} = 4$

As, temperature remains same, therefore pressure remains constant.

$$\therefore \quad \frac{v_{mix}}{v_{H_2}} = \sqrt{\frac{\rho_{H_2}}{\rho_{mix}}} = \sqrt{\frac{1}{4}} = \frac{1}{2} \quad \left(\because v \propto \frac{1}{\sqrt{\rho}}\right)$$

$$\Rightarrow \quad v_{mix} = \frac{v_{H_2}}{2} = \frac{1270}{2} = 635 \text{ ms}^{-1}$$

4. Effect of Frequency

The speed of sound in air is independent of its frequency. Sound waves of different frequency travels with the same speed in air but their wavelengths in air are different.

Progressive Wave

A wave that travels from one point of the medium to another, is called a progressive wave. It can be transverse or longitudinal.

Characteristic of Progressive Wave

(i) All vibrating particles of the medium have same amplitude, period and frequency, etc.

(ii) State of oscillation, *i.e.* phase changes from particle to particle.

Plane Progressive Harmonic Wave

During the propagation of a wave through a medium, if the particles of the medium vibrate simple harmonically about their mean positions, then the wave is said to be plane progressive harmonic wave.

Displacement relation for a wave travelling in $+x$-direction is given by

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

while displacement relation for a wave travelling in $-x$-direction is given by

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

In terms of speed of wave (v), above relation can be written as

For $+x$-direction, $y = A \sin\left\{\dfrac{2\pi}{\lambda}(vt - x) \pm \phi\right\}$

For $-x$-direction, $y = A \sin\left\{\dfrac{2\pi}{\lambda}(vt + x) \pm \phi\right\}$

In the above equation, v represent speed of wave and not that of the particle.

Other forms of displacement relation for progressive waves are

$$\begin{aligned} y &= A \sin\{(\omega t \pm kx) \pm \phi\} \\ &= A \sin\{k(vt \mp x) \pm \phi\} \\ &= A \sin\left\{\omega\left(t \mp \frac{x}{v}\right) \pm \phi\right\} \end{aligned}$$

Here, angular frequency, $\omega = \dfrac{2\pi}{T}$

and $\quad k = \dfrac{2\pi}{\lambda} = \dfrac{\omega}{v}$

where, λ = wavelength and v = wave velocity

k is called **angular wave number or propagation constant.**

Important Points Related to Progressive Wave

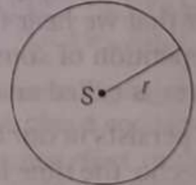
- **Relation between the Phase Difference and Path Difference of Progressive Wave**
  At any instant t, if ϕ_1 and ϕ_2 are the phases of two particles whose distances from the origin are x_1 and x_2 respectively, then $\phi_1 = (\omega t - kx_1)$ and $\phi_2 = (\omega t - kx_2)$.
  $\because \phi_1 - \phi_2 = k(x_2 - x_1)$
  Phase difference, $\Delta\phi = \dfrac{2\pi}{\lambda}$(Path difference Δx)
- **Relation between Phase Difference and Time Difference of a Plane Progressive Wave**
  If the phases of a particle distance x from the origin is ϕ_1 at time t_1 and ϕ_2 at time t_2, then $\phi_1 = (\omega t_1 - \omega t_2)$ and $\phi_2 = (\omega t_2 - \omega t_1)$.
  $\therefore \phi_2 - \phi_1 = \omega(t_2 - t_1)$
  Phase difference, $\Delta\phi = \dfrac{2\pi}{T} \times$ (Time difference Δt)

Intensity of Wave

A flow of energy of a wave per unit area of cross-section of the medium in unit time is called intensity

Intensity, $I = \dfrac{\text{Energy flow per unit time}}{\text{Area of cross-section}} = \dfrac{1}{2}\rho\omega^2 A^2 v$

- The intensity of wave emitting in all directions due to a point sources varies inversely as the square of the distance r.
  i.e. $\quad I = \dfrac{P}{4\pi r^2}, I \propto \dfrac{1}{r^2}$



where, P is the power.

- **Energy density** The energy associated with per unit volume of the medium is defined as energy density.

$$\text{Energy density} = \frac{\text{Energy}}{\text{Volume}} = \frac{\text{Intensity}}{\text{Velocity}} = \frac{\rho\omega^2 A^2 v}{2v}$$
$$= \frac{1}{2}\rho\omega^2 A^2$$

Example 7. The equation of a wave is given by

$$y(x,t) = 0.05\sin\left[\frac{\pi}{2}(10x - 40t) - \frac{\pi}{4}\right]\text{m}$$

The velocity of wave is

a. 4 m/s b. 6 m/s c. 8 m/s d. 9 m/s

Sol. (*a*) The equation may be rewritten as

$$y(x,t) = 0.05\sin\left(5\pi x - 20\pi t - \frac{\pi}{4}\right)\text{m}$$

Comparing this with equation of progressive wave

$$y(x,t) = A\sin(kx - \omega t + \phi)$$

then wave number, $k = \frac{2\pi}{\lambda} = 5\pi \text{ rad/m}$

$$\lambda = 0.4 \text{ m}$$

Angular frequency, $\omega = 2\pi\nu = 20\pi \text{ rad/s}$

$$\nu = 10 \text{ Hz}$$

Wave velocity, $v = \nu \cdot \lambda = 10 \times 0.4 = 4 \text{ m/s}$

Example 8. The frequency of a progressive wave travelling in a medium is 40 Hz. The change in phase at 0.02 s will be

a. $\frac{18\pi}{5}$ b. $\frac{8\pi}{5}$ c. $\frac{28\pi}{5}$ d. $\frac{0.08\pi}{5}$

Sol. (*b*) Time, $\Delta t = 0.02$ s

$$\therefore \quad T = \frac{1}{\nu} = \frac{1}{40} \text{ s}$$

Change in phase, $\Delta\phi = \frac{2\pi}{T} \times \Delta t = \frac{2\pi}{1/40} \times 0.02$

$$= 2\pi \times 40 \times \frac{2}{100} = \frac{8\pi}{5}$$

Reflection of Sound

The bouncing back of sound when it strikes a hard surface is known as reflection of sound, *e.g.* echo. It can be reflected from any surface whether, it is smooth or rough.

Echo

When a person shouts in a big empty hall, we first hear his original sound, after that we hear the reflected sound of that shout. So, the repetition of sound caused by reflection of sound waves is called an echo.

The sensation of sound persists in our brain for about 0.1 s. Thus, to hear a distinct echo, the time interval between the original sound and the reflected one must be atleast 0.1 s.

The distance travelled by the sound in 0.1 s

$$= \text{Speed} \times \text{Time}$$
$$= 344 \times 0.1 = 34.4 \text{ m}$$

So, echo will be heard, if the minimum distance between the source of sound and the obstacle is $= \frac{34.4}{2} \text{ m} = 17.2 \text{ m}$.

This distance will change with the change in temperature.

Echoes may be heard more than once due to successive multiple reflections. The rolling of thunder is due to successive reflections of sound from a number of reflecting surfaces, such as clouds and the land.

Characteristics of Sound

Sound has following three characteristics

1. Loudness

Loudness is related to the intensity $\left(\frac{\text{energy}}{\text{time} \times \text{area}}\right)$ of sound and is measured in the unit 'bel' as $L_1 - L_2 = 10\log_{10}\frac{I}{I_0}$

where, I is the intensity of sound to be measured and I_0 is a constant reference intensity 10^{-12} Wm^{-2}.

The reference intensity I_0 represents roughly the minimum intensity that is just audible at frequency around 1 kHz.

- 'bel' is a large unit, so it is more commonly represented as 'decibel' (dB). As one metre is 10 decimetre, so 1 bel is 10 decibel. Hence, loudness in decibel will be represented as $10\log_{10}(I/I_0)$.
- Loudness of a sound of given intensity may be different for different listeners. So, two sounds of equal intensity but different frequency may not appear to be equally loud even to the same listener because the sensitivity of the ear is different for different frequencies.
- When intensity of a sound doubles its loudness increases by almost 3dB and if the intensity quadruples, the loudness increases by 6dB and so on.
- Some common sound levels in decibel are as follows: Whispering is at around 10 decibel. Normal talk is at around 60 decibel. Car horn is at around 100 decibel and maximum tolerable sound is at around 120 decibel.

2. Pitch

It is related to the frequency of sound. A shrill or sharp sound has high frequency, hence higher pitch and a grave or dull sound has low frequency, hence lower pitch. *e.g.* The buzzing of a bee or humming of a mosquito has high pitch but low loudness while the roar of a lion has large loudness but lower pitch.

3. Quality

The property of sound due to which difference between two sounds can be made is quality of sound. A particular sound may have a number of frequencies and overtones attached to it, that makes its quality. We can recognise a person by listening to his sound as it has a definite quality.

Example 9. What is the intensity of sound of 70 dB? (Take, the reference intensity $I_0 = 10^{-12}\ \text{Wm}^{-2}$)

a. $10^{-6}\ \text{W/m}^2$ b. $10^{-5}\ \text{W/m}^2$
c. $10^{-8}\ \text{W/m}^2$ d. $10^{-8}\ \text{W/m}^2$

Sol. (b) Loudness (in decibel) $= 10\log_{10}\dfrac{I}{I_0}$

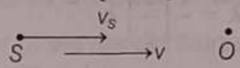
or, $$70 = 10\log_{10}\frac{I}{I_0} \quad \text{or} \quad \frac{I}{I_0} = 10^7$$

or $$I = I_0 10^7 = 10^{-12} \times 10^7 = 10^{-5}\ \text{Wm}^{-2}$$

Doppler's Effect

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

- **When Source is Moving and Observer is at Rest** When source is moving with velocity v_s, towards an observer at rest, then apparent frequency,



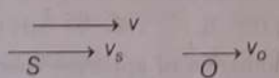
$$n' = n\left(\frac{v}{v - v_s}\right)$$

If source is moving away from observer, then

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

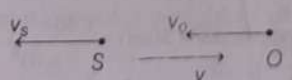
- **When Source and Observer Both are Moving**
  (a) When both are moving in same direction along the direction of propagation of sound, then

$$n' = n\left(\frac{v - v_o}{v - v_s}\right)$$



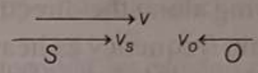
  (b) When both are moving in same direction but opposite to the direction of propagation of sound, then

$$n' = n\left(\frac{v + v_o}{v + v_s}\right)$$



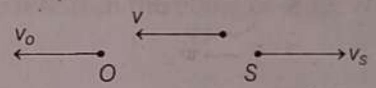
  (c) When both are moving towards each other, then

$$n' = n\left(\frac{v + v_o}{v - v_s}\right)$$



  (d) When both are moving in opposite direction, away from each other, then

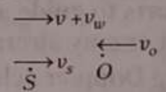
$$n' = n\left(\frac{v - v_o}{v + v_s}\right)$$



Effect of Motion of Medium (Air) on Apparent Frequency

Till now, while studying Doppler's effect, we have assumed medium at rest. If medium is in motion, then following cases are possible

(i) **When Medium (Air) Moves from Source to Observer that is in the Direction of Velocity of Sound** As the medium (air) itself starts moving, appropriate changes must be made in general equation of Doppler's effect. If wind blows at a speed v_w from the source to the observer, as shown in figure, take $v \to v + v_w$ (both in numerator and denominator), *i.e.*



$$f' = \left(\frac{v + v_w \pm v_o}{v + v_w \mp v_s}\right) f$$

(ii) **When Medium (Air) Moves from Observer to Source that is in the Opposite Direction of Velocity of Sound** As the wind blows in opposite direction of velocity of sound as shown in figure, take $v \to v - v_w$ (both in numerator and denominator)

$\therefore$ $$f' = \left(\frac{v - v_w \pm v_o}{v - v_w \mp v_s}\right) f$$

Note

- *Assuming medium, source and observer in motion, general equation for Doppler's effect can be written as*

$$f' = \left(\frac{v \pm v_w \pm v_o}{v \pm v_w \mp v_s}\right) f$$

According to situation and given conditions, we will put signs of velocities in above equation.

- *There will be no Doppler effect, i.e. frequency will not change when both source and observer are at rest and wind blows.*

Example 10. A person going away from a factory on his scooter at a speed of 36 km/h listen to the siren of the factory. If the main frequency of the siren is 600 Hz and a wind is blowing along the direction of the scooter at 36 km/h, the main frequency as heard by the person, is (Take, velocity of sound in air = 340 m/s)

a. 583 Hz b. 580 Hz c. 584 Hz d. 586 Hz

Sol. (*a*) According to the question, we can draw the following situation

$$\underset{S}{\bullet} \xrightarrow{} v_s = 0 \qquad \underset{O}{\bullet} \xrightarrow{} v_o = 36 \text{ km/h} = 10 \text{ m/s}$$

$$\longrightarrow v$$
$$\longrightarrow w$$

Wind speed; $w = 36 \text{ km/h} = 10 \text{ m/s}$

$$\therefore \quad f' = f\left(\frac{v + w - v_o}{v + w - v_s}\right) = 600\left(\frac{340 + 10 - 10}{340 + 10 - 0}\right) \simeq 583 \text{ Hz}$$

Applications of Doppler's Effect in Sound

Applications of Doppler's effect in sound are given below

(i) The change in frequency due to Doppler effect is used to measure velocities in diverse areas such as military, medical science, astrophysics, etc.

(ii) In Doppler effect, a sound wave of known frequency is sent towards a moving object. Some part of that wave is reflected from the object whose frequency can be measured by monitoring the stations. This change in frequency (*i.e.* due to reflection of the sound wave) is called Doppler shift.

(iii) It is used at airports to guide aircraft and in the military to detect enemy aircraft.

(iv) Doctors are using Doppler echocardiography to examine the heart. It uses high frequency sound waves to create an image of the heart. While the use of Doppler technology allows to find the speed and direction of blood flow by using the concept of Doppler effect.

Doppler's Effect in Light

Light waves also show Doppler's effect. If a light source is moving away from a stationary observer, then the frequency of light waves appears to be decreased and wavelength appears to be increased and *vice-versa*. If the light source or the observer is moving with a velocity v, such that the distance between them is decreasing, then the apparent frequency of the source will be given by

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

where, f = frequency emittted by source, v is relative velocity of approach and c is speed of light.

If the distance between the light source and the observer is increasing, then the apparent frequency of the source is given by

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

where, v = relative velocity of recession.

The change in wavelength can be determined by

$$\Delta\lambda = \frac{v}{c} \cdot \lambda$$

Note *Doppler's effect in light depends only on the relative motion between the source and the observer while the Doppler's effect in sound also depends upon whether the source is moving or the observer is moving.*

Red Shift and Violet Shift

If the light source is moving away from the observer, the shift in the spectrum is towards red and it is called **red shift**. If it is moving towards the observer, the shift is towards the violet and it is called **violet shift**.

Red shift $\Delta\lambda = \lambda' - \lambda = \left(\frac{v}{c}\right)\lambda$

$$\Rightarrow \quad \Delta\lambda = \frac{v}{c}\lambda$$

Violet shift (or blue shift)

$$\Delta\lambda = \lambda' - \lambda = -\left(\frac{v}{c}\right)\lambda$$

$$\Rightarrow \quad \Delta\lambda = -\frac{v}{c}\lambda$$

In case of approach frequency increases while wavelength decreases, *i.e.* shift $\Delta\lambda$ is towards blue end of the spectrum while in case of recession frequency decreases and wavelength increases, *i.e.* shift is towards red end.

Example 11. A star which is emitting radiation at a wavelength of 5000 Å is approaching the earth with a velocity of $1.50 \times 10^6 \text{ ms}^{-1}$. The change in wavelength of the radiation as received on the earth will be

a. 25 Å b. 35 Å c. 45 Å d. 65 Å

Sol. (*a*) The phenomenon of apparent change in frequency (or wavelength) of the light due to the relative motion between the source of light and the observer is called Doppler effect in light.

So, $\Delta\lambda = \lambda \times \frac{v}{c}$

Given, wavelength, $\lambda = 5000$ Å

Velocity of source, $v = 1.50 \times 10^6 \text{ ms}^{-1}$

and velocity of light, $c = 3 \times 10^8 \text{ ms}^{-1}$

$\therefore$ Change in wavelength, $\Delta\lambda = 5000 \times \frac{1.50 \times 10^6}{3 \times 10^8} = 25$ Å

Applications of Doppler's Effect in Light

Applications of Doppler's effect in light are given below

(i) **In Estimation of Velocity of Stars and Galaxies** Spectral lines of elements like sodium, hydrogen and helium are found in spectrum coming from stars and galaxies. We compare these spectral lines from standard spectral lines of an element in the laboratory. If spectral lines of the star shifts towards red wavelength (red shift), then the star must be moving away from the earth.

Similarly, if the spectral lines are shifting towards violet wavelength (violet shift), then the star must be moving towards the earth.

If $\Delta\lambda$ is Doppler shift in spectral lines, then $\Delta\lambda = \frac{\lambda_0 v}{c}$

using this formula, we can find speed of stars and galaxies.

(ii) **RADAR** Radio Detection and Ranging abbreviated as RADAR. It is a method used to find position and speed of a plane or ship. Radio waves are sent from RADAR centre towards ship and returns to it after reflection from the plane or ship.