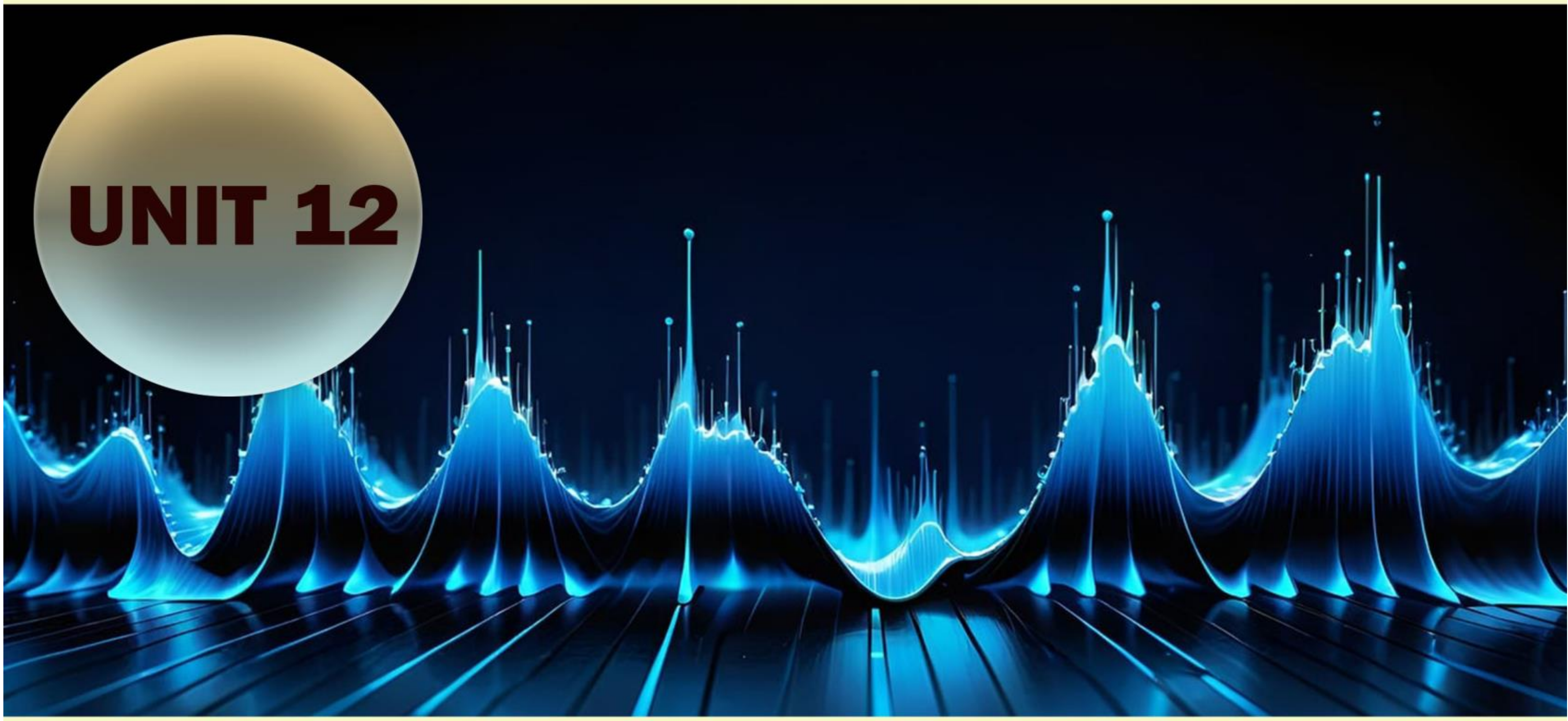
PHYSICS
XI

UNIT 12



ACOUSTICS

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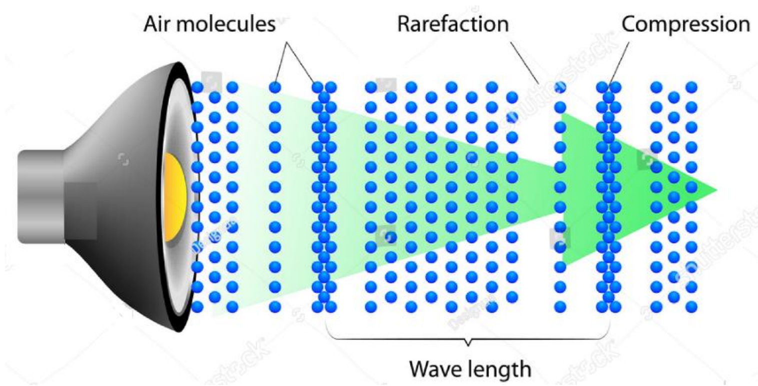
SOUND WAVES

Sound waves are the most important example of longitudinal waves. They can through any material with a speed that depends on the properties of the medium. As the waves travels, the particles in the medium vibrates to produce changes in density and pressure along the direction of the motion of the waves. These changes result in the series of high-pressure is called compression and low- pressure is called rarefaction region. A sound wave can be represented on a graph as a variation in air pressure.



FREQUENCY OF SOUND WAVE

Sound waves are divided into three categories that cover different frequencies ranges.

1- AUDIBLE WAVE

Audible waves are waves that range from the frequency of 20 Hz to 20,000 Hz. Audible waves can be generated in variety of ways, such as by musical instrument, human vocal cords, and loudspeakers.

2- INFRASONIC WAVE

Infrasonic wave are waves having frequency less than 20 Hz. Elephant can use infrasonic waves to communicate with each other, even separated by many kilometers.

3- ULTRASONIC WAVES

Ultrasonic wave are waves having frequency above 20,000Hz.
They are not detecting by a human but cat and dog may hear ultrasonic sound

NEWTON'S FORMULA FOR SPEED OF SOUND

The speed of the sound waves in a medium solid, liquid or gas depends on elasticity and density of the medium.

$$v = \sqrt{\frac{Elastic\ property\ of\ the\ medium}{density\ of\ the\ medium}}$$

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

If the elastic property of the medium is equal to bulk modulus **B** of the medium , the speed of sound wave in that medium is

$$v = \sqrt{\frac{B}{\rho}} \quad \dots\dots\dots\dots\dots\dots\dots.(i)$$

Where B = bulk modulus of medium.

$$B = \frac{excess\ pressure}{change\ of\ volume\ per\ unit\ volume}$$

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

Bulk modulus is defined as ***the ratio of increase of pressure to the fractional decrease in volume***

NEWTON'S ASSUMPTION

Newton assumed that passage of the longitudinal wave of sound through air such that heat generated during the compression during the rarefaction is dissipated or absorbed heat from the gas. So the process is isothermal. Hence Boyle's law holds good. Under this condition the bulk modulus **B** is equal to pressure **P** of a gas.

Suppose,

P = initial pressure

V = initial volume

ΔP = increase in pressure

ΔV = increase in volume

P + ΔP = final pressure

V - ΔV = final volume

Using Boyle's law under these conditions

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

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

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

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

If the small change in pressure is smaller than the corresponding change in volume is also negligible, hence neglected ΔP ΔV

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

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

Therefore

B = P (pressure)

Hence Newton's formula for speed of sound in gaseous medium is

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

Newton's Formula used to Calculate the speed of soundt

The value of speed pf sound (in air), calculated from this formula, is

At STP, Pressure of the gas

P = 76 cm of Hg column

$P = 76 \text{ x} 13.6 \text{ x } 980 \text{ dyne / cm}^2$

$\rho = 0.001293 \text{ g/cm}^3$

$$v = \sqrt{\frac{\rho_{mercury}\ g\ h}{\rho}}$$

$$v = \sqrt{\frac{13.6\ \times 981\ \times 76}{0.001293}}$$

$$v\ = 28003.447\ cms^{-1}$$

$$v = 280.003\ \ ms^{-1}$$

The experimental value determined form various experiment for speed of sound in air at S.T.P is found to be 32000 cm/s or 320 m/s. This calculated value is 16 % less than the experimental value, (the experimental value is 332 m/s)

LAPLACE'S CORRECTION

In 1816 a French mathematician "Laplace" put forward a correction to Newton's formula. He explained that sound travels through air as a combination of compression and rarefactions. At a compression the temperature of air rises and at rarefaction temperature falls. Because of very rapid occurrence of compressions and rarefactions and bad conductivity of air there is not sufficient time for heat to be conducted from hot compression to cold rarefaction. Hence the temperature of air does not remain constant and isothermal form of Boyle's law cannot be applied.

Laplace proposed the adiabatic propagation of sound in which no exchange of heat takes place. In this condition

$$P\,V^{\gamma}\ =\ \text{constant}...............(i)$$

If pressure of the given mass of the gas changes from P to (P + ΔP)resulting to change of V and ΔV in volume, equation (i) can be written as

$$P\,V^{\gamma}\ =\ (P + \Delta P)\,(V - \Delta V)^{\gamma}$$

Multiplying and dividing by V^{γ} on the right hand side

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

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

Expanding above expression through binomial theorem and neglecting the square and higher power of $\frac{\Delta V}{V}$, we get

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

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

$$0 = \ -\ \left(\frac{\gamma\ \ P\,\Delta V}{V}\right)\ +\ \Delta P\ -\ \left(\frac{\gamma\ \ \Delta P\ \ \Delta V}{V}\right)$$

Neglecting the term $\left(\frac{\gamma\ \ \Delta P\ \ \Delta V}{V}\right)$

$$0 = \ -\ \left(\frac{\gamma\ \ P\,\Delta V}{V}\right)\ +\Delta P$$

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

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

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

$$\gamma P = B$$

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

Where '*γ*' *is* the ratio of molar specific heats of gases.
This is known as Laplace's correction.

$$v = \sqrt{\frac{1.4 \times 13.6 \times 981 \times 76}{0.001293}}$$

$$v = 33369.0 \ cms^{-1}$$

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

LAPLACE FORMULA FOR SPEED OF SOUND IN TERM OF TEMPERATURE

The speed of sound also depends on the temperature of the medium. For sound traveling through air, the relationship wave speed and medium temperature is

$$v = \sqrt{\frac{\gamma . p}{\frac{m}{V}}} \qquad \rho = \frac{m}{V}$$

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

$$v = \sqrt{\frac{\gamma . nRT}{m}} \qquad PV = nRT$$

$$n = \frac{m}{M}$$

$$M = \frac{m}{n}$$

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

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

Where,

T = absolute temperature

γ = ratio of molar specific heats

R = molar gas constant (8.314 J mol^{-1} K^{-1})

FACTOR AFECTING SPEED OF SOUND

1-DENSITYOF THE MEDIUM

The speed of sound is inversely proportional to the square root of the density of the medium.

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

2-ELASTICITY OF THE MEDIUM

The speed of sound is directly proportional to the square root of the modulus of elasticity of the medium.

$$v \propto \sqrt{elstic\ proprety\ of\ the\ medium(\ E)}$$

3-MOISTURE

The speed of sound in air increases with the increase in humidity, because the density of humid air is less than the density of dry air. As the density of the medium decreases, the speed of sound in the medium increases. Hence, the speed of sound is faster in humid air than the dry air.

4-PRESSURE

Speed of sound does not change with any change of pressure, providing temperature is kept constant.

$$v = \sqrt{\frac{\gamma\ R\ T}{M}}$$

The above equation shows that speed of sound is independent of pressure of gas (air)

5-TEMPERATURE

Temperature changes do not affect the speed of sound in liquid and solid medium quit significantly. But for gas (air) the rise and fall of temperature at constant pressure significantly increase and decrease speed of sound in air.
speed of sound is directly proportional to the square root of Kelvin temperature of the medium.

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

Let v_0 = velocity of sound at 0 °C or 273 K
v = velocity of sound at t °C or (273 + 1) K
The speed of sound is given by

$$\frac{v}{v_0} = \sqrt{\frac{T}{T_0}}$$

where T and T_0 are the absolute temperatures corresponding to t °C and 0 °C

$$\frac{v}{v_0} = \sqrt{\frac{273 +\ t}{273}}$$

$$v = v_0 \sqrt{\frac{273 +\ t}{273}}$$

$$v = v_0 \sqrt{1 + \frac{t}{273}}$$

$$v = v_0 \left(1 + \frac{t}{273}\right)^{\frac{1}{2}}$$

Using Binomial theorem to expand right hand side term

$$v = v_0 \left(1 + \frac{1}{2} \times \frac{t}{273}\right)$$

$$v = 331 \left(1 + \frac{t}{546}\right)$$

$$v = 331 + 0.61\,t$$

Thus the speed of sound in air increases by $0.61ms^{-1}$ per degree Celsius in temperature

6 Wind

If v_0 is the wind speed then the speed of sound along the direction of the wind relative to the ground is $(v + v_0)$ and $(v - v_0)$ against the direction of the wind.

7-AMPLITUDE, WAVELENGTH AND FREQUENCY

The speed of sound is independent of the amplitude, wavelength, and frequency of the sound wave.

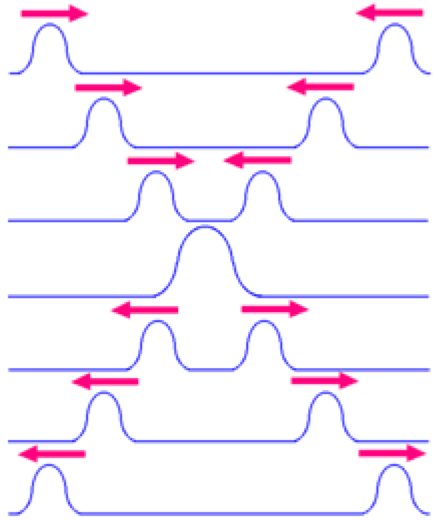
PRINCIPLE OF SUPERPOSITION OF WAVES

The Principle of Superposition states that when two waves of the same kind meet at a point in space, the resultant displacement at that point is the vector sum of the displacements that the two waves would separately produce at that point

The displacement of **n** waves is y_1, y_2, y_3 -------, y_n then the resultant displacement '**Y**' of the particle due to simultaneous action of this '*n*' wave is given by

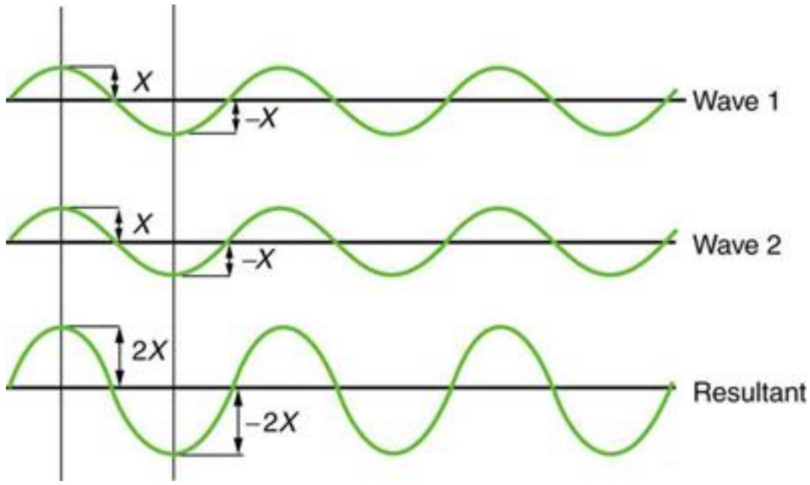
$$\mathbf{Y = Y_1 + Y_2 + Y_3 + \text{-----------} + Y_n}$$

This is known as the principle of superposition

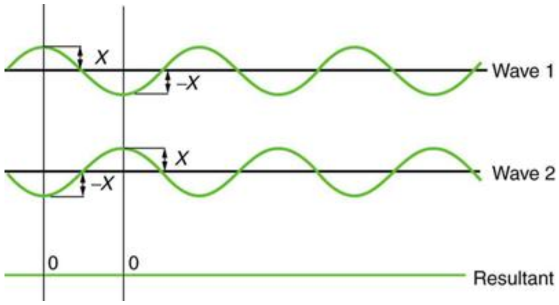


INTERFERENCE OF SOUND WAVES

When two or more sound waves from different sources are present at the same time, they interact with each other to produce a new wave. The new wave is the sum of all the different waves. Wave interaction is called **interference**. If the compressions and the rarefactions of the two waves line up, they strengthen each other and create a wave with a higher intensity. This type of interference is known as **constructive**.



When the compressions and rarefactions are out of phase, their interaction creates a wave with a dampened or lower intensity. This is **destructive interference.** When waves are interfering with each other destructively, the sound is louder in some places and softer in others. As a result, we hear pulses or beats in the sound.



FORMATION OF BEATS DUE TO INTRFERENCE OF NON-COHERENT SOURCE

EXPLANATION

Consider two harmonic waves of the same wavelength, frequency, and amplitude, which differ in phase by ΦSuppose both are traveling to the right in a medium, then.

$$Y_1 = A_o \text{ Sin } (kx - \omega t) \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots(i)$$

$$Y_2 = A_o \text{ Sin } (kx - \omega t - \Phi) \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots(ii)$$

After superposition the result wave is given by

$$Y = Y_1 + Y_2$$

$$Y = A_o \text{ Sin } (kx - \omega t) + A_o \text{ Sin } (kx - \omega t - \Phi)$$

From the trigonometric identity for the sum of Sines,

$$\text{Sin } \alpha + \text{Sin } \beta = 2..Cos\left(\frac{\alpha-\beta}{2}\right).Sin\left(\frac{\alpha+\beta}{2}\right)$$

Let, $\alpha = (kx - \omega t)$

$\beta = (kx - \omega t - \Phi)$

Now above equation becomes:

$$Y = A_o\left[Sin(kx - \omega.t) + Sin(kx - \omega.t - \Phi)\right]$$

$$= A_o\left[2Cos\left(\frac{kx-\omega.t-kx+\omega.t+\Phi}{2}\right)Sin\left(\frac{kx-\omega.t+kx-\omega.t-\Phi}{2}\right)\right]$$

$$= A_0\left[2Cos.\left(\frac{\Phi}{2}\right).Sin\left(\frac{2kx-2\omega.t-\Phi}{2}\right)\right]$$

$$= A_0\left[2.Cos\left(\frac{\Phi}{2}\right).Sin\left(\frac{2(kx-\omega.t)}{2} - \frac{\Phi}{2}\right)\right]$$

$$Y = 2A_o \text{ Cos }\left(\frac{\Phi}{2}\right)Sin\left(kx - \omega.t - \frac{\Phi}{2}\right)$$

This is the equation representing the resultant wave.

CHARACTERISTIC

The above equation shows that the resultant wave function.

1) The resultant wave is harmonic
2) has the same wavelength.
3) has the same frequency.
4) Differ in phase by $\frac{\Phi}{2}$
5) The amplitude of the resultant wave is $2A_o \text{ Cos}\left(\Phi/2\right)$
6) If $\text{Cos } \frac{\Phi}{2} = 1$, ,then $Y_0 = 2A_0$

The resultant amplitude is doubled

INTERFERENCE OF WAVE

When two or more waves combine at a point, they are said to interfere, and the phenomenon is called interference.

CONSTRUCTIVE INTERFERENCE

The wave interferes constructively if the crest falls on the crest and the trough fall on the trough. The resultant amplitude is nearly twice the amplitude of individual waves that interference is known as constructive.

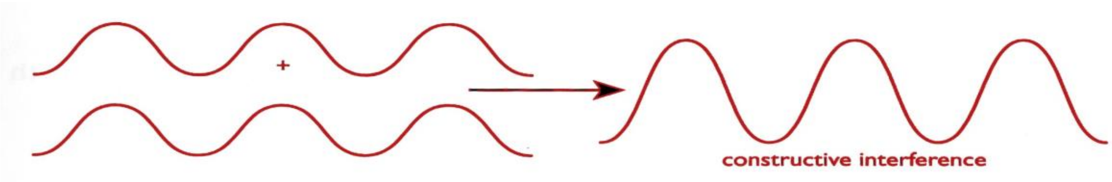
The condition is

$$\text{Cos}\,\frac{\Phi}{2} = \pm 1$$

When $\frac{\Phi}{2} = 0, \pi, 2\pi, 3\pi, \ldots\ldots, n\pi$

Where n is integer

Hence $\Phi = 0, 2\pi, 4\pi, 6\pi, \ldots\ldots, 2n\pi.$



Where two waves arrive with their crests together the waves increase in size.

DESTRUCTIVE INTERFERENCE

The wave interfere destructively if crest falls on trough and trough falls on crest. The resultant amplitude is nearly zero, the interference is known as destructive interference.

We know that,

$$Y = 2A_o\,\text{Cos}\left(\frac{\Phi}{2}\right)$$

If $\text{Cos}\left(\frac{\Phi}{2}\right) = 0$ then, $Y_0 = 0$

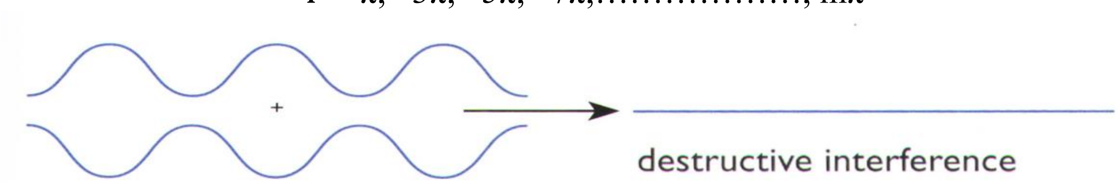
The resultant amplitude of the wave is zero.

The wave interferes destructively $\left(\frac{\phi}{2}\right) = \frac{\pi}{2}, \frac{3\pi}{2}, \frac{5\pi}{2}, \ldots\ldots, \frac{m\pi}{2}$

Where **m** is an odd number

Hence

$$\Phi = \pi, 3\pi, 5\pi, 7\pi, \ldots\ldots, m\pi$$



Where the two waves arrive with crests meeting troughs the waves cancel each other out.

INTERFERENCE OF SOUND IN TIME (BEATS)

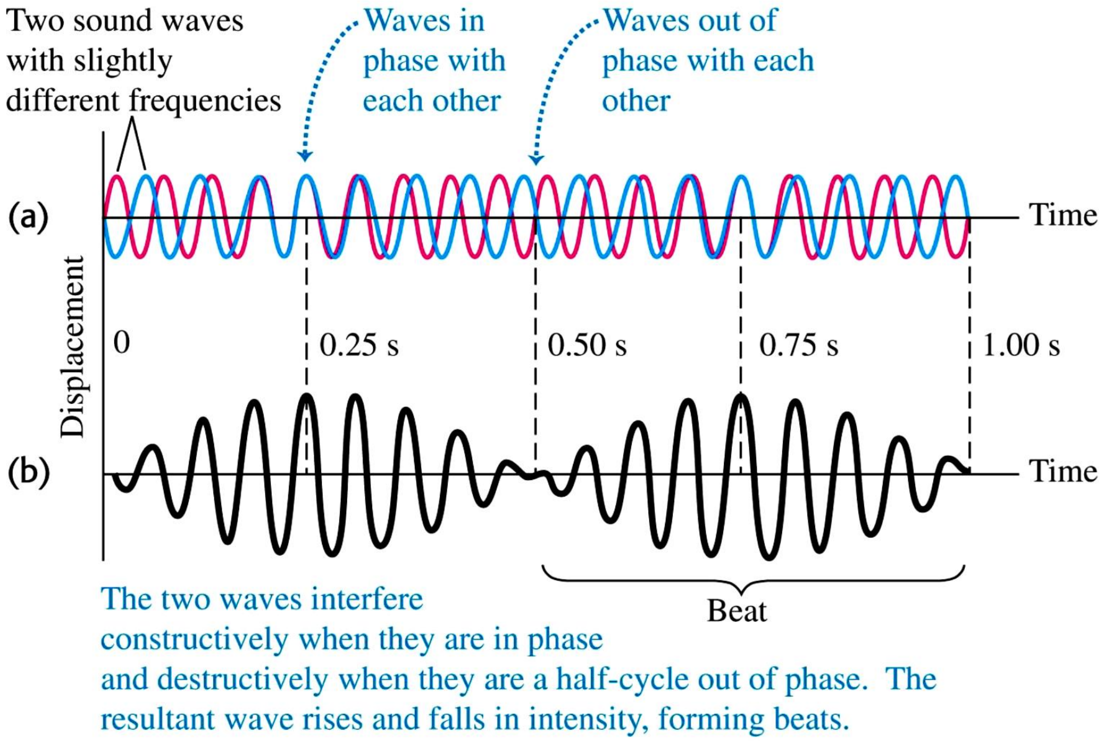
DEFINITION

Periodic variations in the intensity (Loudness) of sound due to superposition of two waves having slightly different frequencies are called beats.

PRODUCTION OF BEATS

When two sound waves of the same amplitude and wavelength but having slightly different frequencies travel in the same direction in a medium they superpose to produce beats

suppose at one instant (t = 0) in Fig, the two waves are in phase with each other and interference constructively. According to the superposition principle, their resultant amplitude is maximum. The sum of the amplitude of the two waves, is shown in the figure.



However, since the frequencies are different, the Waves do not stay in phase the high frequency wave as shorter cycle so it gets ahead of the other one. The phase difference between the two steadily increase and the resultant amplitude decreases. At a later time (t = 5T) the phase difference reaches 180^0 degree. Now the waves are half a cycle out of phase and interfere destructively. Now the resultant amplitude is maximum as the phase difference continue to increase the amplitude increase until constructive interference occurs.

BEAT FREQUENCY

we can measure the time between the beats $T_{beat} = \frac{1}{f_{beat}}$, as a time to go from one constructive interference to the next constructive interference. During this time, each wave must go through a whole number of cycles, with one of them going through one more cycle than the other. Since the frequency f is the number of cycles per second. The number of cycles waves go through during the time $T_{beat}\ is\ f_{beat}$ from figure $T_{beats}\ is\ 10T$. During that time wave 1 goes through $f_1\ T_{beat} = 10\ cycles,$ while wave 2 goes through $f_2\ T_{beat} = \frac{1.1}{T} \times 10T = 11 cycles.$ If $f_1\ is\ greater\ than\ f_1$ then wave two goes through one more cycle than wave 1 , hence

$$f_2\ T_{beat} - f_1\ T_{beat} = 1$$

$$T_{beat}(f_2 - f_1) = 1$$

$$(f_2 - f_1) = \frac{1}{T_{beat}}$$

$$f_{beat} = \frac{1}{T_{beat}}$$

$$f_{beat} = f_2 - f_1$$

In this way, we obtain a very simple result that the bit frequency is difference between the frequency of two wavs. The maximum beat frequency human ear can detect is about 7 bits per second.

STANDING (STATIONARY) WAVES

DEFINITION

- Stationary waves, or standing waves, are produced by the superposition of two waves of the same frequency and amplitude traveling in opposite directions
.

THE FORMATION

When two waves of the same amplitude frequency and wavelength traveling through a medium in opposite directions superpose the result is a standing or stationary wave.

CHARACTERISTICS

1) It is a superposition of an incident and reflected wave.
2) The frequency and speed of the wave must be equal.
3) They do not transfer energy through the medium.
4) The points permanently at rest are called ***nodes.*** The points vibrating with maximum amplitude are called ***antinodes.*** Points between successive nodes are in phase.
5) Amplitudes of vibrating particles are different.

ANALITICAL TREATMENT OF STANDING WAVES

Consider wave function for two transverse sinusoidal waves having the same amplitude, frequency, and wavelength but traveling in opposite directions in the same medium. These waves can be written as:

$$Y_1 = A_o \text{ Sin } (kx - \omega t)$$
$$Y_2 = A_o \text{ Sin } (kx + \omega t)$$

Where, Y_1 represents a wave traveling to the right and Y_2 represents one traveling to the left. Adding these two functions gives the resultant wave amplitude Y

$$Y = Y_1 + Y_2$$
$$Y = A_o \text{ Sin } (kx - \omega t) + A_o \text{ Sin } (kx + \omega t)$$
$$Y = A_o \left[Sin(kx - \omega.t) + Sin(kx + \omega.t)\right] \quad \text{-------} \quad (1)$$

When we use the trigonometric identity

$$\text{Sin } (\alpha - \beta) + \text{Sin } (\alpha + \beta) = 2\text{Sin } \alpha \text{ Cos } \beta$$

Put $\alpha = kx$ and $\beta = \omega t$ in equation (1)

$$Y = (2A_o \text{ Sin } kx) \text{ } Cos\ \omega t$$

This is the equation representing resultant standing wave. where,

$\omega = 2\pi f = frequency$

$k = \frac{2\pi}{\lambda}$ = wave number

$Y = 2A_o \text{ Sin } kx$ = resultant amplitude of the wave

It is clear from the above equation that in a standing wave the amplitude $2A_o$ Sin kx depends on the location ***x*** of the particle in the medium.

The maximum displacement of a particle of the medium has a minimum value of zero when x satisfies the condition

NODES

In a standing wave all points of the particle of medium where the displacement is always zero are called nodes (N).

POSITIONS OF NODES

Consider,

$$A = 2A_o \text{ Sin } kx$$

When Sin kx = o

$$A = 2\ A_o\ (O)$$
$$A = O$$

The condition Sin kx = o, that is when

$$\therefore k\ x = o, \pi, 2\pi, 3\pi \ldots\ldots\ldots.\ n\,\pi$$

Because $k\ = \frac{2\pi}{\lambda}$

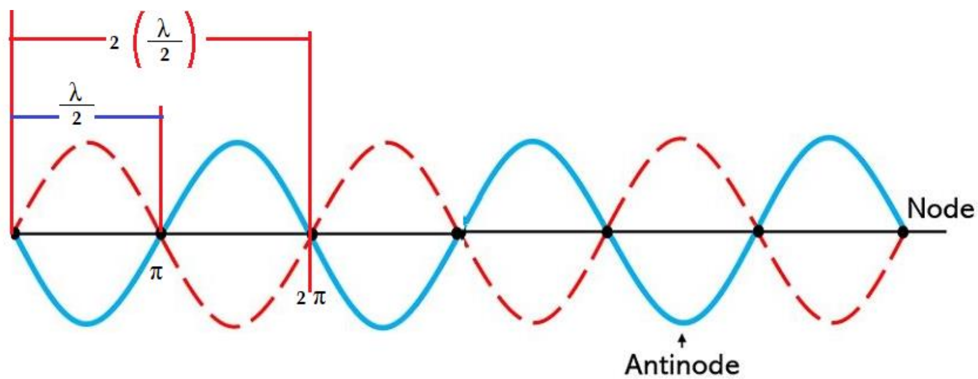
$$\frac{2\pi}{\lambda}\ \ x = o, \pi, 2\pi, 3\pi \ldots\ldots\ldots.\ n\,\pi$$

$$x = \left(\frac{\lambda}{2\pi}\right) o,\ \ \left(\frac{\lambda}{2\pi}\right) \pi,\ \ \left(\frac{\lambda}{2\pi}\right) 2\pi,\ \ \left(\frac{\lambda}{2\pi}\right) 3\pi \ldots\ldots\ldots.\ \left(\frac{\lambda}{2\pi}\right) n\,\pi$$

$$x = o,\ \ \left(\frac{\lambda}{2}\right),\ 2\left(\frac{\lambda}{2}\right),\ \ 3\left(\frac{\lambda}{2}\right) \ldots\ldots\ldots.\ n\ \left(\frac{\lambda}{2}\right)$$

n = 0, 1, 2, 3, 4, 5,…

These are the position of nodes, **The distance between adjacent nodes is equal to half wavelength $\frac{\lambda}{2}$.**



ANTINODES

In a standing wave all the particles of the medium where, the greatest possible displacement from the equilibrium are called antinodes (A)

POSITION OF ANTINODES

Consider, $A = 2A_o$ Sin kx

When Sin kx = 1; amplitude = $A = 2A_o$

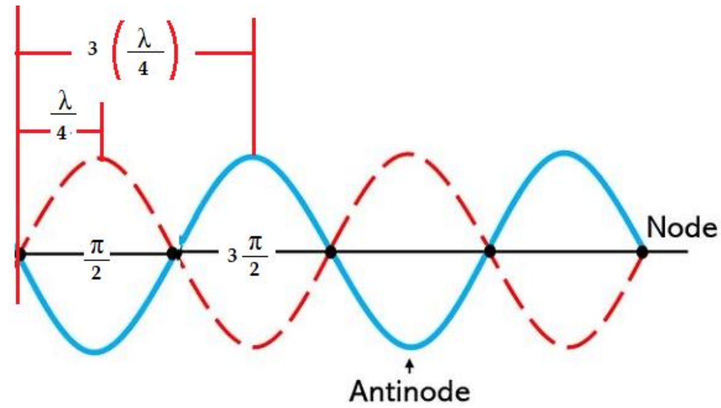
The condition Sin kx = 1, that is when

$$\therefore kx = \frac{\pi}{2}, \frac{3\pi}{2}, \frac{5\pi}{2}, \ldots\ldots$$

Because $k = \frac{2\pi}{\lambda}$, these values for kx give

$$x = \frac{\lambda}{4}, \quad \frac{3\lambda}{4}, \quad \frac{5\lambda}{4}, \ldots\ldots\ldots\ldots\ldots\ldots, \frac{n\lambda}{4} \qquad n = 1,\ 3,\ 5,\ \ 7, \ldots\ldots$$

These are the position of antinodes. The distance between adjacent antinodes is equal to half wavelength $\frac{\lambda}{2}$.



STANDING WAVES IN STRING FIXED AT BOTH ENDS

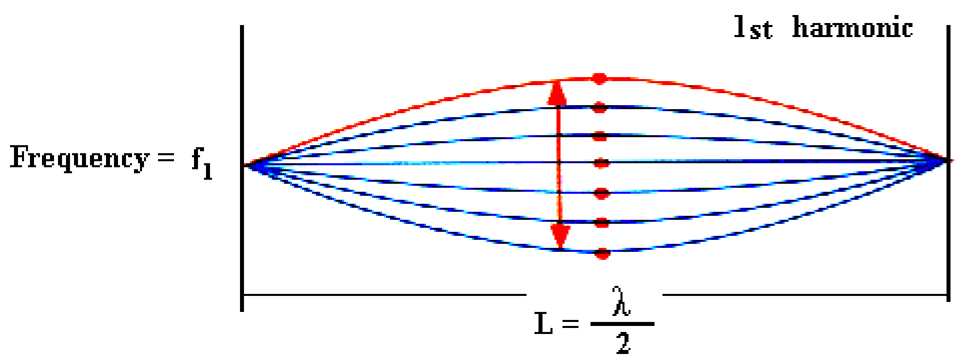
Standing waves can be set up in a stretched string by connecting one end of the string to a rigid support, and connecting the other end to a vibrating object. In this situation, traveling waves reflect from the ends, creating waves traveling in both directions on the string. The incident and reflected wave combined according to the superposition principle. If the string is vibrated at exactly the right frequency, the wave appears to stand still- hence its name, **standing wave.**

Fundamental Frequency and Harmonics

Consider a stretched string length **L** that fixed both ends. We can setup standing wave patterns on it by plucking it at different points.

FREQUENCY FOR ONE LOOP

If the string is plucked at its mid-point and released, it vibrates in one loop, the vibration shown in the following figure.



In the above standing wave pattern, the length **L** of the string equal to $\frac{\lambda}{2}$

(the distance between nodes). Thus,

$$L = \frac{\lambda_1}{2} \qquad \text{or} \qquad \lambda_1 = 2L$$

The speed of the wave is

$$v = \lambda f_1$$

and the frequency of this vibration is

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

Substituting the values of λ_1 = 2L in the above equation, we get

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

This is the lowest frequency of vibration called the **fundamental frequency** of the vibrating string or the **first harmonic** of the standing wave.

Velocity of the progressive waves along the string is given by

$$v = \sqrt{\frac{T \times L}{m}}$$ where T is tension in the string and m is the total mass of string

Substituting the expression for velocity in equation (i), we get

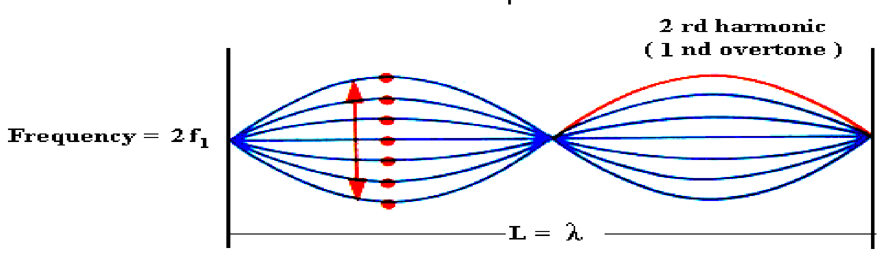
$$f_1 = \frac{1}{2L}\sqrt{\frac{T \times L}{m}}$$

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

$$f_1 = \frac{1}{2L}\sqrt{\frac{T}{\mu}}$$ where μ is the linear density ($\left(\mu = \frac{m}{L}\right)$

FREQUENCY FOR TWO LOOPS

When the string is plucked at $\frac{1}{4}th$ of its length, it vibrates in two loops.



Let,

λ_2 = wavelength

f_2 = frequency

v = speed of the wave

The length of the string is equal to the one wavelength λ_2-that is, when L = λ_2.hence,

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

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

$$f_2 = \frac{2}{2} \times \frac{v}{L}$$

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

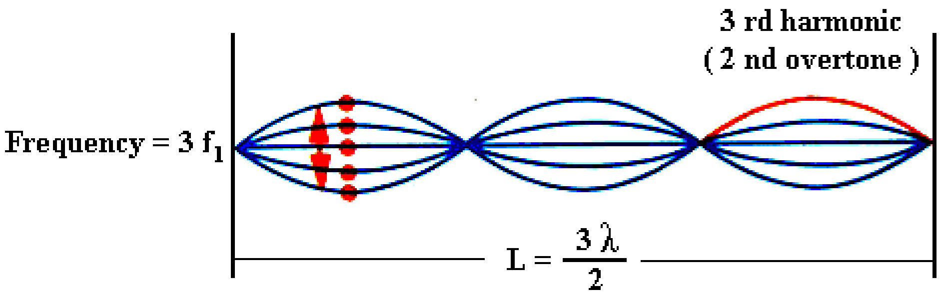
$$f_2 = 2\left(\frac{1}{2\,L}\sqrt{\frac{T}{\mu}}\right)$$

$$f_2 = 2\,f_2 \qquad\qquad f_1 = \frac{1}{2\,L}\sqrt{\frac{T}{\mu}}$$

The above expression shows that the frequency is equal to twice the fundamental frequency. This frequency of vibration is known as the **second harmonic** or **first overtone.**

FREQUENCY FOR THREE LOOPS

When string is plucked at $\frac{1}{6}th$ of its length it vibrates in three loops.



Let,

λ_3 = wave length

f_2 = frequency

v = $f\ \lambda$

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

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

$$L = 3\left(\frac{\lambda_3}{2}\right)$$

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

Substituting the wavelength $\lambda_3 = \frac{2L}{3}$ in above equation

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

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

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

$$f_3 = 3\left(\frac{1}{2\,L}\sqrt{\frac{T}{\mu}}\right)$$

$$f_3 = 3\,f_1 \qquad\qquad f_1 = \frac{1}{2\,L}\sqrt{\frac{T}{\mu}}$$

This is known as third harmonic or second overtone.

FREQUENCY FOR N LOOPS

In general if the string is made to vibrate in 'n' loops with

λ_n = wavelength

f_n = frequency

$\therefore \quad v = \lambda_n f_n$

Or $\quad f_n = \dfrac{v}{\lambda_n}$

$$f_n = \frac{v}{\frac{2L}{n}} \qquad \because \lambda_n = \frac{2L}{n}$$

$$f_n = n \times \frac{v}{2L}$$

$$f_n = nf_1 \quad \text{.............. (1)} \qquad \because f_1 = \frac{v}{2L}$$

$$v = \sqrt{\frac{T}{\mu}}$$

Where T is the tension in the string and μ is its mass per unit length, Thus we can express the equation (1) as

$$f_n = \frac{n}{2L}\sqrt{\frac{T}{\mu}}$$

ORGAN PIPES

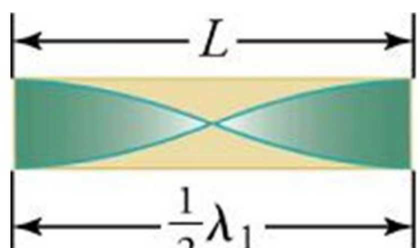
Organ pipes are a musical instruments used to produce musical sound by blowing air into the pipe. Organ pipes are two types (a) closed organ pipes, closed at one end (b) open organ pipes, open at both ends.

OPEN ORGAN PIPES

If both the ends of the pipe are open it is called an open organ pipe.
Since both ends are open, there are anti-nodes at the ends of the pipe and nodes in the middle.

FUNDAMENTAL MODE OF VIBRATION

When air is blown into the open organ pipe, the air column vibrates in the fundamental mode as shown in the figure. Antinodes are formed at the ends and a node is formed in the middle of the pipe. If L is the length of the pipe, then



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

$$\lambda_1 = 2\,L$$

The speed of the wave is

$$v = \lambda\, f_1$$

and the frequency of this vibration is

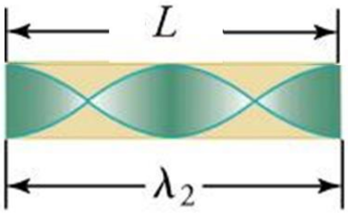
$$f_1 = \frac{v}{\lambda}$$

Substituting the values of λ_1 = 2 L in the above equation, we get

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

FIRST OVERTONE

In the next mode of vibration, additional nodes and antinodes are formed as shown in Fig



The length of the organ pipe is equal to the one-wavelength λ_2 when

$$L = \lambda_2.$$

hence,

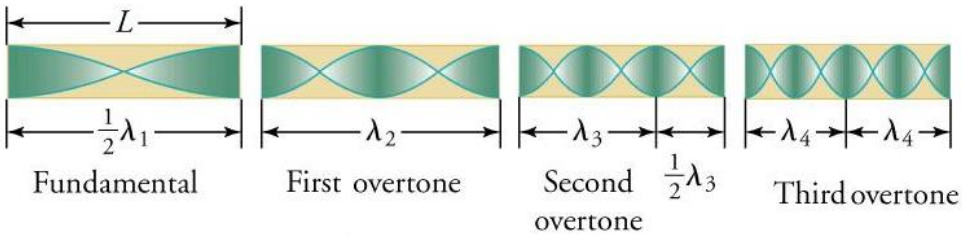
$$f_2 = \frac{v}{\lambda_2}$$

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

$$f_2 = \frac{2}{2} \times \frac{v}{L}$$

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

$$f_2 = 2\, f_1$$



Similarly

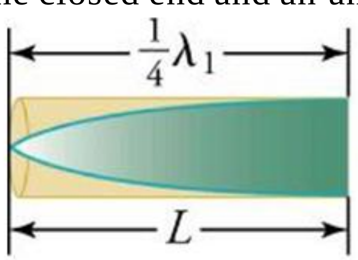
$$f_3 = 3\, f_1$$
$$f_n = n\, f_1$$

CLOSED PIPE

The pipe opens at one end and closes at the other end is known as a closed pipe. If the waves with some frequency are sent through the closed pipe, the waves get reflected from the closed end. When the incident and reflected waves with the same frequency and in the opposite directions are superimposed the stationary waves form in the closed pipe.

FUNDAMENTAL MODE OF VIBRATION

If the air is blown lightly at the open end of the closed organ pipe, then the air column vibrates in the fundamental mode. There is a node at the closed end and an antinode at the open end. If L is the length of the organ pipe, then



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

$$\lambda_1 = 4\,L$$

The speed of the wave is

$$v = \lambda\, f_1$$

and the frequency of this vibration is

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

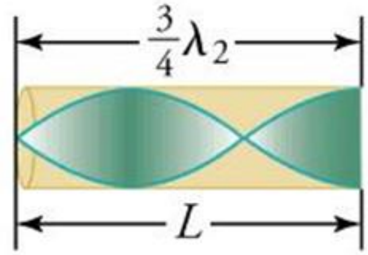
Substituting the values of $\lambda_1 = 4$ L in the above equation, we get

$$f_1 = \frac{v}{4L}$$

FIRST OVERTONE

If air is blown strongly at the open end, frequencies higher than fundamental frequency can be produced. They are called overtones. The figure shows the mode of vibration with two nodes and two antinodes.

The length of the organ pipe is equal to the one-wavelength λ_2 when



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

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

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

Substituting the values of $\lambda_2 = \frac{4\ L}{3}$ in the above equation, we get

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

$$f_2 = 3\left(\frac{v}{4\ L}\right)$$

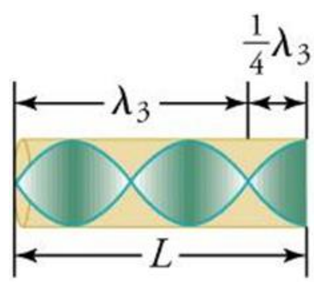
$$f_2 = 3\ f_1$$

This is called first overtone or third harmonic

SECOND OVERTONE

The figure shows the mode of vibration with three nodes and three antinodes.

The length of the organ pipe is equal to the wavelength λ_3 , when



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

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

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

Substituting the values of $\lambda_3 = \frac{4\ L}{5}$ in the above equation, we get

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

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

$$f_3 = 5\ f_1$$

This is called as second overtone or fifth harmonic.

In a closed pipe the f_n *term is*

$$f_n = n\ f_1 \qquad \text{n = 1,3,5,7,9,11}$$

In closed organ pipe only odd harmonic are present. Ratio of harmonic is

$$f_1 : f_2 : f_3 : f_4 \ldots\ldots = 1 : 3 : 5 : 7 \ldots\ldots$$

Therefore, the P^{th} *overtone* $= (2\,P + 1)^{th}$ *harmonics*

THE DOPPLER EFFECT

An Austrian physicist Christian Johan Doppler mentioned this effect in a research paper in 1842.

DEFINITION

The apparent change in the frequency of sound due to relative motion between source and observer is called "DOPPLER effect".

Example

A common example is the pitch of the whistle of a train or the siren of a fire engine. The pitch increases when the source is approaching the listener and decreases when is moving away from the listener.

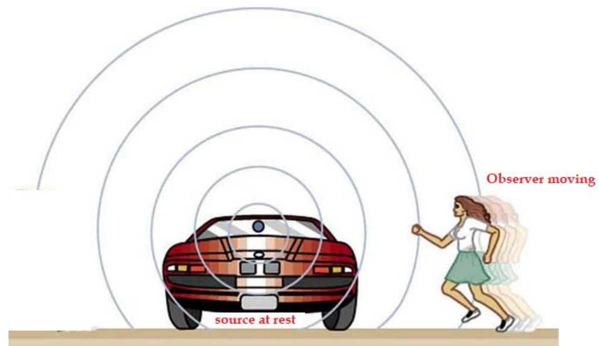
This effect can be applied to any type of wave in general. Following are the cases to discuss the effect of sound waves treating only the special case in which the source and observer move along the line joining them.

MOVING OBSERVER AND SOURCE AT REST

Case I a) Observer moves toward the source

Let,

λ = actual wavelength of sound
f = actual frequency of sound
v = velocity of sound
v_0 = velocity of the observer.



The relation between the parameters of the sound wave is given by

$$v = f\lambda$$

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

Now suppose the listener is moving toward the stationary source with velocity v_0 which emits sound waves. Then the relative velocity of sound waves is $(v + v_0)$. The apparent frequency of sound will be

$$\text{apparent frequency} = \frac{relative.velocity}{wavelength}$$

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

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

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

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

$$f' = \left(1 + \frac{v_o}{v} \right) f$$

The apparent frequency is greater than the actual frequency hence the observer receives a higher pitch.

Case (*Ib*)

OBSERVER MOVES AWAY FROM THE SOURCE

suppose the listener is moving away from the stationary source with velocity v_0 which emits sound waves. Then the relative velocity of sound waves is $(v - v_0)$. The apparent frequency of sound will be

$$\text{apparent frequency} = \frac{relative.velocity}{wavelength}$$

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

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

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

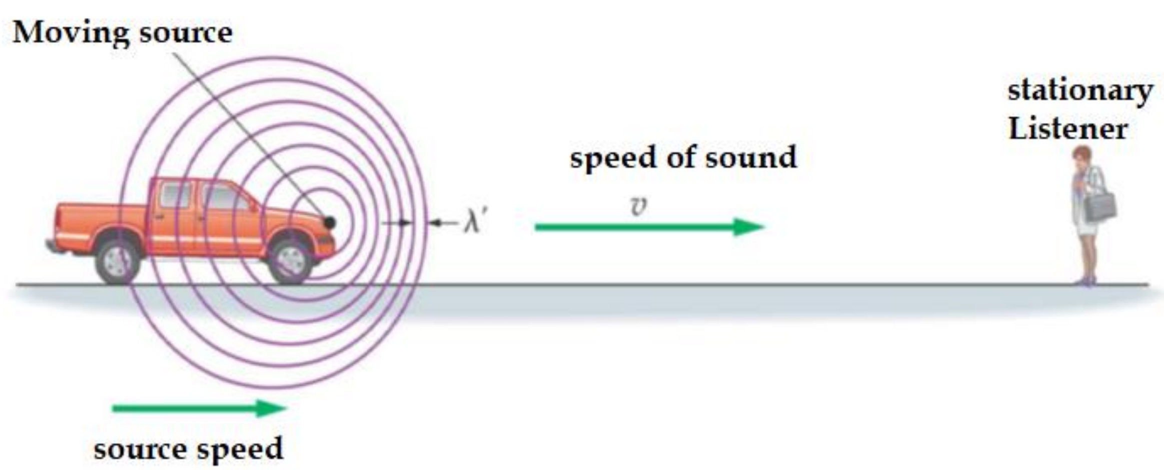
$$f' = \left(\frac{v}{v} - \frac{v_o}{v} \right) f$$

$$f' = \left(1 - \frac{v_o}{v} \right) f$$

Apparent frequency is smaller than actual frequency hence observer receives a low pitch sound.

MOVING SOURCE OBSERVER AT REST

Case (IIa)



If Source moves toward the stationary listener, then the wavelength received by the listener will be decreased by $\frac{v_s}{f}$, if λ' shorter wavelength of the wave received by listener, then it is given by

$$\lambda' = \lambda - \lambda_s$$

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

$$\lambda' = \left(\frac{v - v_s}{f}\right) \ldots\ldots\ldots\ldots\text{(i)}$$

The apparent frequency of the sound heard by the listener will be

$$f' = \frac{v}{\lambda'} \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots (ii)$$

Substituting the expression for λ' from equation (i) in equation (ii)

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

Apparent frequency is greater than actual frequency hence listener receives a higher pitch.

Case (*IIb*)

If Source moves away from the stationary listener, then the wavelength received by the listener will be increased by $\frac{v_S}{f}$, if λ' longer wavelength of the wave received by listener, then it is given by

$$\lambda' = \lambda + \lambda_s$$
$$\lambda' = \frac{v}{f} + \frac{v_S}{f}$$
$$\lambda' = \left(\frac{v + v_S}{f}\right) \text{.............(i)}$$

Then apparent frequency of sound heard by the listener will be

$$f' = \frac{v}{\lambda'} \quad \dots\dots\dots\dots\dots\dots\dots\dots..(ii)$$

Substituting the expression for λ' from equation (i) in equation (ii)

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

Apparent frequency heard by the listener is smaller than actual frequency hence listener receives a low pitch.

III Both Source and Observer Moving

Case (*IIIa*):

Source and observer move toward each other

Let,

v_o = velocity of observer

v_s = velocity of source

v = velocity of sound

$\therefore (v + v_0)$ = velocity of sound relative to observer

$\lambda' = \left(\frac{v - v_S}{f}\right)$ = apparent wavelength. (According to case *IIa*)

$$(\text{apparent frequency}) = \frac{\text{relative velocity of sound}}{\text{Apparent wavelength}}$$

$$f' = \frac{(v + v_0)}{\left(\frac{v - v_S}{f}\right)}$$

$$f' = \left(\frac{v + v_0}{v - v_S}\right) f$$

Apparent frequency is greater than the actual frequency hence the observer receives a higher pitch.

Case (*III*b)

Source and observer move away from each other

Let,

v_o = velocity of the observer

v_s = velocity of the source

v = velocity of sound

$\therefore (v - v_0)$ = velocity of sound relative to the observer

$\lambda' = \left(\frac{v + v_S}{f}\right)$ = apparent wavelength. (According to case *II*b)

$$(\text{apparent frequency}) = \frac{\text{relative velocity of sound}}{\text{Apparent wavelength}}$$

$$f' = \frac{(v - v_0)}{\left(\frac{v + v_S}{f}\right)}$$

$$f' = \left(\frac{v - v_0}{v + v_S}\right) f$$

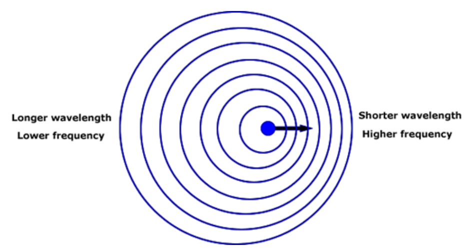
Apparent frequency is less than actual frequency hence observer receives a lower pitch.

SHOCK WAVES

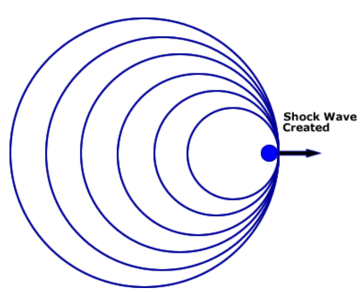
the sheet of highly compressed air along a cone shaped wave front moving with the Supersonic source of sound is called shock waves.

EXPALANATION

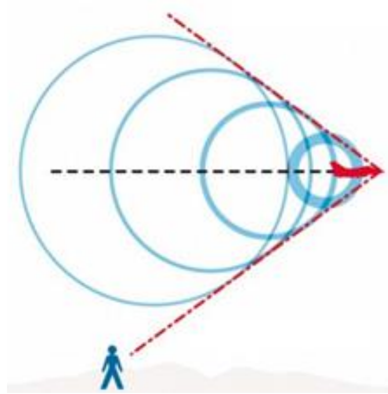
when a source of sound moves towards observer the result is a shortening of the wavelength and the wavefront come close together.



when the speed of source is equal to speed of sound the wavefront cannot move ahead of the source and Pile up to form a plane waves front that extends in the direction perpendicular to the direction of the motion of a source.



When the source moves with a speed greater than that of speed of sound (supersonic speed) the wave front take the shape of a cone with the moving source at its Apex. Along these cones the air is highly compressed containing a very concentrated amount of sound energy this is known as shock wave.

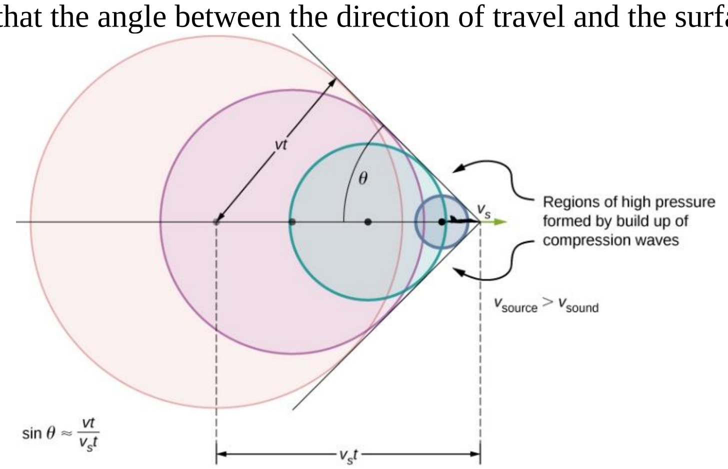


SONIC BOOM

when the edge of that cone-shaped wave front associated with this Supersonic aircraft intercepts the ground below a loud sound is heard known as a "Sonic boom" it is the effect of the concentration of aircraft radiated sound energy on the surface of the cone. it is also possible to hear Sonic booms from the same aircraft one from the leading edge and another from the railing edge.

MACH NUBER

It clear from figure that the angle between the direction of travel and the surface of cone is given by



$$Sin\ \theta = \frac{v \times t}{v_s \times t}$$

$$Sin\ \theta = \frac{v}{v_s}$$

Where

v is the speed of sound

v_s is the speed of the source

In aerodynamics the ratio of $\frac{v_s}{v}$ is called the Mach number

$$Mach\ number = \frac{v_s}{v}$$

APPLICATION OF DOPPLER EFFECT

SONAR

WORKING

The transmitter produces echoes or ultrasonic waves that travel across the water. Once the waves hit an object or any obstacle, the detector immediately receives a signal. These ultrasonic sounds are then converted into electronic signals which are interpreted accordingly.

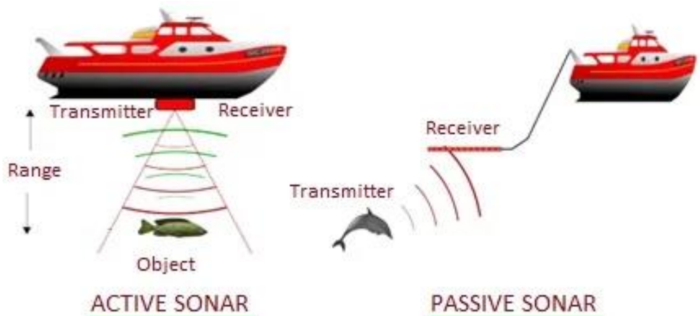
TYPES OF SONAR

There are two type of sonar.

Active Sonar: A pulse of sound is sent inside the water which hits the object and is reflected back. The distance is measured by the time taken by the waves (echoes) to return back.

Passive Sonar:

As the name suggests, Passive Sonar doesn't send attention or soundwaves. The applications of this type of Sonar is mainly used in receiving sounds or noise of the water body or to locating other ships, submarines and icebergs.



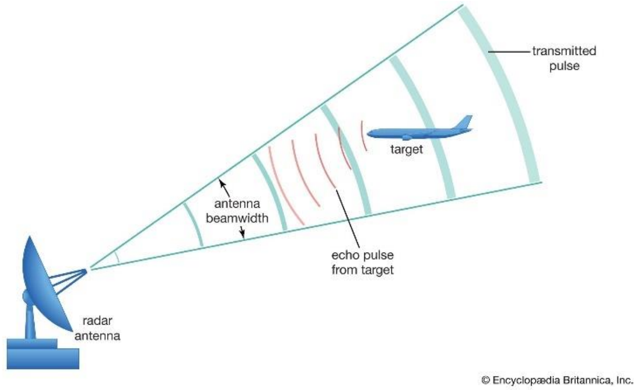
VOR

Very High Frequency (VHF) Omni-Directional Range (VOR) is a type of short-range radio navigation system for aircraft, enabling aircraft with a receiving unit to determine its position and stay on course by receiving radio signals transmitted by a network of fixed ground radio beacons.

Pakistani airports doppler VOR system operates at a frequency in the range (30 MHz – 300 MHz)

RADAR:

Radar electromagnetic sensor used for detecting, locating, tracking, and recognizing objects of various kinds at considerable distances. It operates by transmitting electromagnetic energy toward objects, commonly referred to as targets, and observing the echoes returned from them. The targets may be aircraft, ships, spacecraft, automotive vehicles, and astronomical bodies, or even birds and insects.



RADAR SPEED TRAP

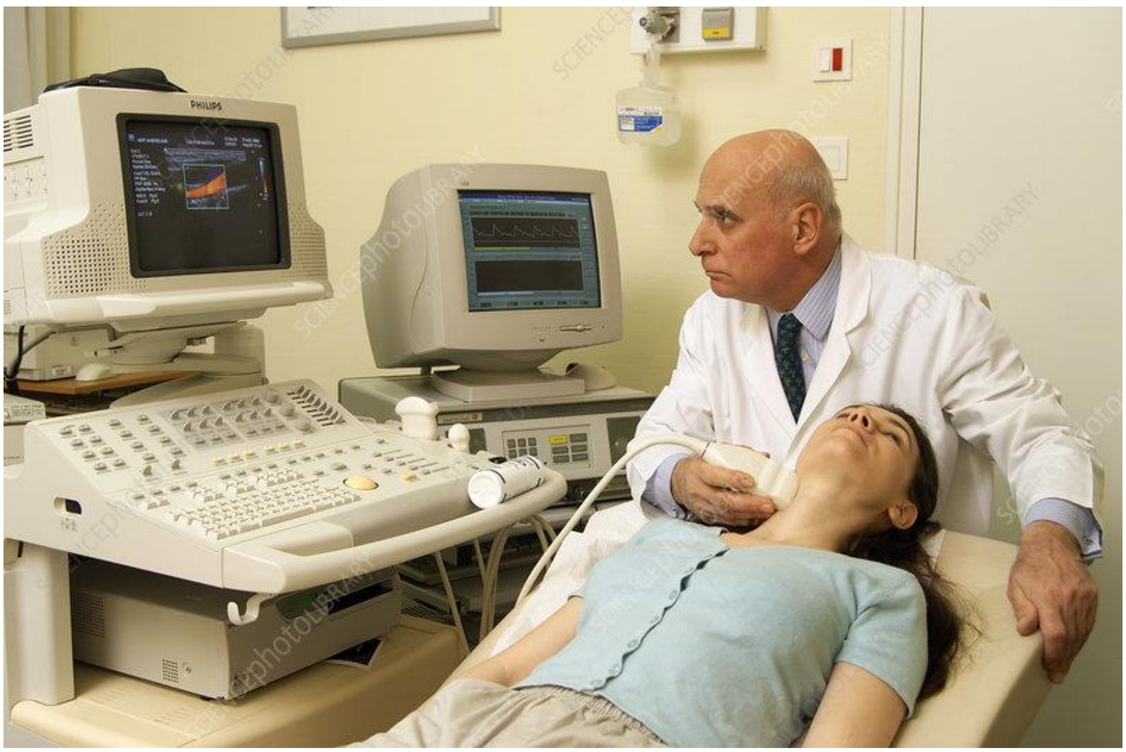
A **radar speed gun**, also known a **radar gun**, **speed gun**, or **speed trap gun**, is a device used to measure the speed of moving objects. It is commonly used by police to check the speed of moving vehicles while conducting traffic enforcement, and in professional sports to measure speeds such as those of baseball pitches, tennis serves, and cricket bowls.

DOPPLER EFFECT AND CARDIOVASCULAR PROBLEMS

Ultrasound is also used to examine organs such as heart, liver kidney, breasts and eyes. a Doppler ultrasound (or Doppler echocardiography) is a test in which very high frequency sound waves are bounced off your heart and blood vessels. The returning sound waves (echoes) are picked up and turned into pictures showing blood flow through the arteries or the heart itself. Doppler ultrasound testing allows doctors to clearly see how blood flows through the heart and blood vessels. It also lets them see and measure obstructions in arteries and measure the degree of narrowing or leakage of heart valves. It may be recommended for patients with atherosclerosis or coronary artery disease. It is used to assess blood flow through the coronary arteries (the blood vessels supplying the heart), the carotid artery (the main artery in the neck), the major arteries in the arms and legs, or in the heart itself.

DOPPLER ULTRASOUND

A Doppler ultrasound is a newer technique that is used to examine blood flow. It can help reveal blockage to blood flow, show the formation of plaque in arteries, and provide detail information on the heartbeat of the patient. In ultrasonic imaging, ultrasound waves (> 20,000 Hz) rather than sound waves of audible frequencies (20Hz to 20,000Hz) are used. Waves with small wavelengths diffract less around the same obstacle than do waves with larger wavelengths. The frequencies used in imaging are typically in the range of 1 to 15 MHz, which means that the wavelengths in human tissue are in the range of 0.1 to 1.5 mm. As a comparison if sound waves at 15 MHz were used, the wavelength inside the body would be l 0 cm. Higher frequencies give better resolution but at expense of less penetration; sound waves are absorbed within a distance of 500λ, in tissue



SHORT REASONING QUESTIONS

1 Why sound cannot travel through vacuum.

Ans Sound waves are mechanical waves that require a medium, such as air or water, to propagate. They involve the oscillation of particles in the medium, which then transfer energy to neighboring particles, allowing the wave to travel. In a vacuum, where there are no particles or medium, sound waves cannot be transmitted.

2 On what factors speed of sound depends on

Ans ***FACTOR AFECTING SPEED OF SOUND***

1-DENSITYOF THE MEDIUM

The speed of sound is inversely proportional to the square root of the density of the medium.

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

2-ELASTICITY OF THE MEDIUM

The speed of sound is directly proportional to the square root of the modulus of elasticity of the medium.

$$v \propto \sqrt{elstic\ proprety\ of\ the\ medium(\ E)}$$

3-MOISTURE

The speed of sound in air increases with the increase in humidity, because the density of humid air is less than the density of dry air. As the density of the medium decreases, the speed of sound in the medium increases. Hence, the speed of sound is faster in humid air than the dry air.

4-PRESSURE

Speed of sound does not change with any change of pressure, providing temperature is kept constant.

$$v = \sqrt{\frac{\gamma R T}{M}}$$

The above equation shows that speed of sound is independent of pressure of gas (air)

5-TEMPERATURE

Temperature changes do not affect the speed of sound in liquid and solid medium quit significantly. But for gas (air) the rise and fall of temperature at constant pressure significantly increase and decrease speed of sound in air.

speed of sound is directly proportional to the square root of Kelvin temperature of the medium.

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

3 What are the conditions for the interference of waves

Ans Necessary conditions for the interference of two sound waves:

(i) The phase difference between the wave must remain constant.

(ii) The amplitudes of the waves should be nearly equal.

(iii) The displacement produced by the two waves should be along the same straight line.

4 Is the energy of a wave is maximum or minimum at nodes?

Ans The nodes are the points where the amplitude of the wave is minimum, corresponding to the locations where the incident and reflected waves destructively interfere, cancelling each other out. The energy is minimum at the nodes.

5 Why is it possible to understand the words spoken by two people at the same time?

Ans It is possible to understand the words spoken by two people at the same time because the brain extremely flexible, two people can recognize sounds as words at lightning speed, in around a tenth of a second. when people are speaking at a rate of about three words per second. They understand the speaking words.

SELF ASSESMENTS QUESTIONS

1 What is meant by the term's isothermal and adiabatic in terms of propagation of sound?

Ans An isothermal process is a process that happens when there are no variations in the temperature of the compression and rarefaction, when the sound wave propagates in the air.
In adiabatic process, there is no transfer of heat or matter takes place. The compression and rarefaction of sound waves do not gain or lose heat energy from or to its surroundings, and neither does it exchange matter.

2 Why is speed of sound in solids generally much faster than speed of sound in air (gas)?

Ans In solid structure, as the particles are very closely placed to each other and there is less movement of the particles. This close proximity allows the energy of the sound wave to be transferred more quickly from particle to particle, resulting in a faster speed of sound.
In contrast, the particles in air are much further apart. When a sound wave travels through air, it has to transfer its energy from one particle to the next over these greater distances. This takes more time, so the speed of sound is slower in air than in solids.

3 Why the change in pressure rather than actual pressure is considered in determining the speed of sound in air?

Ans Speed of sound in cases is independent of pressure because $v = \sqrt{\frac{\gamma P}{\rho}}$,

but we know that

$$\gamma P = \frac{\Delta P}{\frac{\Delta V}{V}} \qquad (B = \gamma P)$$

At constant temperature, if P changes then density ρ also changes in such a way that the ratio $\frac{P}{\rho}$ remains constant. Hence there is no effect of the pressure change on the speed of sound.

4 What is tuning of musical instruments? What is the importance of Beats in this process?

Ans When two notes are perfectly in tune, the beats stop, and the interference becomes purely constructive. Musicians can use this beat frequency to tune their instruments compared to a reference pitch.

5. When a standing wave existing on a string, the vibration of incident and reflected waves cancel at the nodes. Does this means that energy was destroyed? explain

Ans The energy of a wave is not localized at one point, because the wave is not localized at one point, and so to talk about the energy "at a node" being zero is not really a meaningful statement. Due to the interference of the waves the total energy of the medium particles at the nodes points is zero, but the energy of the medium is not zero at points of the medium that are not nodes. In fact, the anti-node points have more energy than they would have if only one of the two waves were present.

6. What is the evidence that sound is a form of energy

Ans Evidence that sound is a form of energy is found in the fact that sound can do work. A sound wave created in one location can cause the mechanical vibration of an object at a different location. For example, sound can set eardrums in motion, make windows rattle, or shatter a glass.

7. Is there a Doppler shift if the source and observer move in the same direction, with the same velocity? Explain.

Ans. There is no Doppler shift if the source and observer move in the same direction, with the same velocity. Doppler shift is caused by relative motion between source and observer, and if both source and observer move in the same direction with the same velocity, there is no relative motion.

8. As a result of a distant explosion, an observer first senses a ground tremor and then hears the explosion later. Explain.

Ans The ground tremor represents a sound wave moving through the Earth. Sound waves move faster through the Earth than through air because rock and other ground materials are much stiffer against compression. Therefore—the vibration through the ground and the sound in the air having started together—the vibration through the ground reaches the observer first.

9 An airplane flying with a constant velocity moves from a cold air mass into a warm air mass. Does the Mach number increase, decrease, or stay the same?

Ans The Mach number is the ratio of the plane's speed (which does not change) to the speed of sound, which is greater in the warm air than in the cold. The denominator of this fraction increases while the numerator stays constant. Therefore, the fraction as a whole—the Mach number—decreases.

10. If the tension in a string is doubled, what will be the effect on the speed of standing waves in the string?

Ans. The equation of velocity of the transverse waves on a stretched string is given by′

$$V = \sqrt{\frac{T}{\mu}} \quad \text{----------------------(i)}$$

If the tension is the string is doubled (T′ = 2 T) then transverse waves velocity is

$$V' = \sqrt{\frac{T'}{\mu}}$$

$$V' = \sqrt{\frac{2\,T}{\mu}}$$

$$V' = \sqrt{2} \times \sqrt{\frac{T}{\mu}}$$

Substituting the expression of velocity of transverse waves from equation (i), in above equation

$$V' = \sqrt{2} \times V$$

It means the velocity of the transverse waves on stretched string will be increased by $\sqrt{2}$ or 1.414 times to its initial value.

11 ls the vibration of a string in piano, guitar or violin a sound wave? Explain

Ans Yes. This is the reason we have violins, harps, pianos, guitars, etc. As a string vibrates, it pushes air molecules away from it, thus forming a sound wave.

A guitar, piano and violin are a musical instrument with one or twelve strings and a long-fretted fingerboard that are being played using by strumming (plucking) with the fingers, usually in a downward direction. Basically, these are a musical instrument that produces sound through regular vibrations and as a result of this, it is used for creating uniform and melodious sounds.