Chapter 17
Waves and Sound

Waves

Ripple on a pond

Musical sound

Seismic waves
(Earth quake)

Tsunami

on.

stem is disturbed from equilibrium and wh r propagate from one region of the system to another. Wave can carry energy and momentum. The energy in light waves from the sun warms the surface of our planet; the energy in seismic waves can crack our planet's crust.

Characteristics of Wave Motion

(1) When a wave motion passes through a medium, particles of the medium only vibrate simple harmonically about their mean position. They do leave their position and move with the disturbance.

(2) In wave motion, the phase of particles of medium keeps on changing.

(3) The velocity of the particle during their vibration is different at different position.

(4) The velocity of wave motion through a particular medium is constant. It depends only on the nature of medium not on the frequency, wavelength or intensity.

(5) Energy is propagated along with the wave motion without any net transport of the medium.

(6) For the propagation of wave, a medium should have following characteristics.

(i) Elasticity : So that particles can return to their mean position, after having been.

(ii) Inertia : So that particles can store energy and overshoot their mean position.

(iii) Minimum friction amongst the particles of the medium.

(iv) Uniform density of the medium.

Types of Waves

Waves can be classified in a number of ways based on the following characteristics

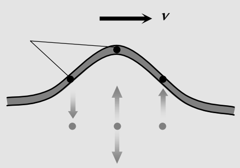
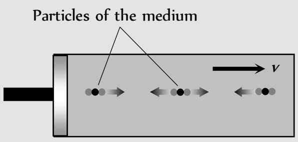
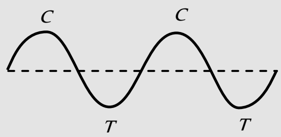
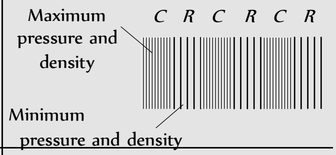
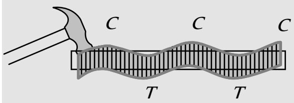
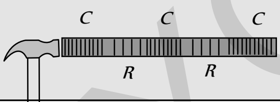
(1) **On the basis necessity of medium**

(i) **Mechanical waves :** Require medium for their propagation *e.g.* Waves on string and spring, waves on water surface, sound waves, seismic waves.

(ii) **Non-mechanical waves :** Do not require medium for their propagation are called *e.g,* Light, heat (Infrared), radio waves, γ- rays, X-rays *etc.*

(2) **On the basis of vibration of particle :** On the basis of vibration of particle of medium waves can be classified as transverse waves and longitudinal waves.

Table 17.1 : Transverse and longitudinal waves

Transverse waves	Longitudinal waves
Particles of the medium vibrates in a direction perpendicular to the direction of propagation of wave.  Transverse wave on a string	Particles of a medium vibrate in the direction of wave motion.  Longitudinal wave in a fluid
It travels in the form of crests (C) and troughs (T). 	It travels in the form of compression (C) and rarefaction (R). 
Transverse waves can be transmitted through solids, they can be setup on the surface of liquids. But they can not be transmitted into liquids and gases.  Transverse wave in a rod	These waves can be transmitted through solids, liquids and gases because for these waves propagation, volume elasticity is necessary.  Longitudinal wave in a rod
Medium should posses the property of rigidity	Medium should posses the property of elasticity
Transverse waves can be polarised.	Longitudinal waves can not be polarised.
Movement of string of a sitar or violin, movement of the membrane of a Tabla or Dholak, movement of kink on a rope, waves set-up on the surface of water.	Sound waves travel through air, Vibration of air column in organ pipes Vibration of air column above the surface of water in the tube of resonance apparatus

(3) **On the basis of energy propagation**

(i) **Progressive wave :** These waves advances in a medium with definite velocity. These waves propagate energy in the medium *e.g.* Sound wave and light waves.

(ii) **Stationary wave :** These waves remains stationary between two boundaries in medium. Energy is not propagated by these waves but it is confined in segments (or loops) *e.g..* Wave in a string, waves in organ pipes.

(4) **On the basis of dimension**

(i) **One dimensional wave :** Energy is transferred in a single direction only *e.g.* Wave propagating in a stretched string.

(ii) **Two dimensional wave :** Energy is transferred in a plane in two mutually perpendicular directions *e.g.* Wave propagating on the surface of water.

(iii) **Three dimensional wave :** Energy in transferred in space in all direction *e.g.* Light and sound waves propagating in space.

(5) **Some other waves**

(i) **Matter waves :** The waves associated with the moving particles are called matter waves.

(ii) **Audible or sound waves :** Range 20 *Hz* to 20 *KHz.* These are generated by vibrating bodies such as vocal cords, stretched strings or membrane.

(iii) **Infrasonic waves :** Frequency lie below 20 *Hz* and wavelengths are greater than 16.6 *cm. Example* : waves produced during earth quake, ocean waves *etc.*

(iv) **Ultrasonic waves :** Frequency greater than 20 *KHz.* Human ear cannot detect these waves, certain creatures such as mosquito, dog and bat show response to these. As velocity of sound in air is 332 *m/sec* so the wavelength $\lambda < 1.66$ *cm.*

These waves are used for navigation under water (SONAR).

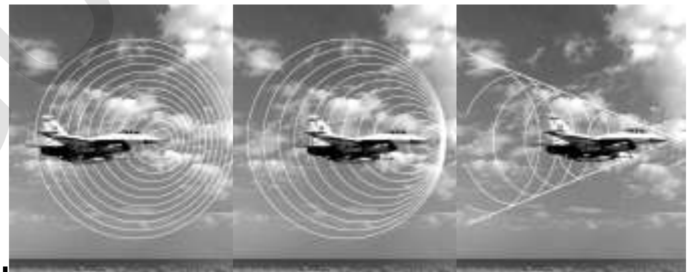
They are used in ultrasonography (in photography or scanning soft tissue of body).

Their used to repel mosquitoes or attract fishes

(v) **Shock waves :** When an object moves with a velocity greater than that of sound, it is termed as **Supersonic.** When such a supersonic body or plane travels in air, it produces energetic disturbance which moves in backward direction and diverges in the form of a cone. Such disturbance are called the shock waves.

The speed of supersonic is measured in Mach number. One mach number is the speed of sound.

Mach Number $= \dfrac{\text{Velocity of source}}{\text{Velocity of sound}}$.



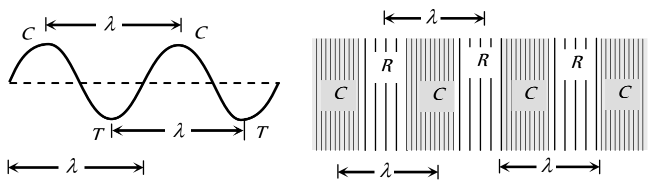
Important Terms Regarding Wave Motion

(1) **Amplitude** (a) **:** Maximum displacement of a vibrating particle of medium from it's mean position is called amplitude.

(2) **Wavelength** (λ) **:** It is equal to the distance travelled by the wave during the time in which any one particle of the medium completes one vibration about its mean position.

(i) Or distance travelled by the wave in one time period is known as wavelength.

(ii) Or is the distance between the two successive points with the same phase.



(A) Transverse wave **(B)** Longitudinal wave

Fig. 17.1

(3) **Frequency** (n) **:** Frequency of vibration of a particle is defined as the number of vibrations completed by particle in one second.

It is the number of complete wavelengths traversed by the wave in one second.

Units of frequency are hertz (Hz) and per second.

(4) **Time period** (T) **:** Time period of vibration of particle is defined as the time taken by the particle to complete one vibration about its mean position.

It is the time taken by the wave to travel a distance equal to one wavelength

Time period = 1/Frequency $\Rightarrow$ $T = 1/n$

(5) **Wave pulse :** It is a short wave produced in a medium when the disturbance created for a short time.

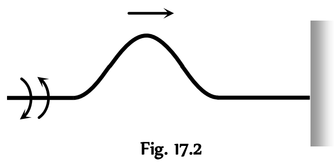


Fig. 17.2

(6) **Wave train :** A series of wave pulse is called wave train.

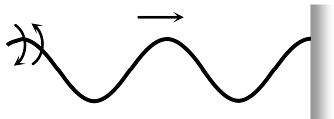
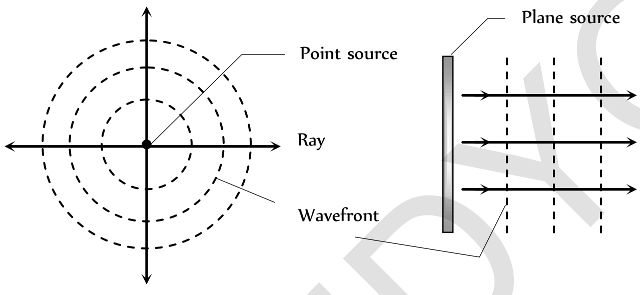


Fig. 17.3

(7) **Wave front :** A wave front is a line or surface on which the disturbance has **the** same phase at all points. If the source is periodic, it produces a succession of wave front, all of the same shape. Ripples on a pond are the example of wave fronts.



(A) Spherical wavefront (B) Plane wavefront

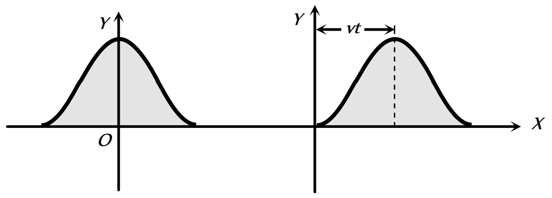
Fig. 17.4

(8) **Wave function ;** It is a mathematical description of the disturbance created by a wave. For a string, the wave function is a displacement for sound waves. It is a pressure or density fluctuation where as for light waves it is electric or magnetic field.

Now let us consider a one dimensional wave travelling along x-axis. During wave motion, a particle with equilibrium position x is displaced some distance y in the direction perpendicular to the x-axis. In this case y is a function of position (x) and time (t).

i.e. $y = f(x, t)$. This is called wave function .

Let the wave pulse is travelling with a speed v, after a time t, the pulse reaches a distance vt along the $+x$-axis as shown. The wave function now can be represented as $y = f(x - vt)$



(A) Pulse at time $t = 0$ (B) Pulse after time t

Fig. 17.5

If the wave pulse is travelling along $-$ x-axis then $y = f(x + vt)$

If order of a wave function to represent a wave, the three quantities x, v, t must appear in combinations $(x + vt)$ or $(x - vt)$

Thus $y = (x - vt)$, $\sqrt{(x - vt)}$, $Ae^{-B(x-vt)^2}$ *etc.* represents travelling waves while $y = (x^2 - v^2t^2), (\sqrt{x} - \sqrt{vt})$, $A \sin(4x - 9t)$ *etc.* doesn't represents a wave.

(9) **Harmonic wave :** If a travelling wave is a sin or cos function of $(x \pm vt)$ the wave is said to be harmonic or plane progressive wave.

(10) **The wave equation :** All the travelling waves satisfy a differential equation which is called the wave equation. It is given by $\dfrac{\partial^2 y}{\partial t^2} = v^2 \dfrac{\partial^2 y}{\partial x^2}$; where $v = \dfrac{\omega}{k}$

It is satisfied by any equation of the form $y = f(x \pm vt)$

(11) **Angular wave number or propagation constant (k) :** Number of wavelengths in the distance 2π is called the wave number or propagation constant *i.e.* $k = \dfrac{2\pi}{\lambda}$.

It is unit is *rad/m.*

(12) **Wave velocity** (v) **:** It is the distance travelled by the disturbance in one time period. It only depends on the properties of the medium and it independent of time and position.

$$v = n\lambda = \frac{\lambda}{T} = \frac{\omega}{2\pi} = \frac{\omega}{k}$$

(13) **Group velocity** (v) **:** The velocity with which the group of waves travels is known as group velocity

or the velocity with which a wave packet travels is known as group velocity $v_g = \dfrac{d\omega}{dk}$.

(14) **Phase** (ϕ) **:** The quantity which express at any instant, the displacement of the particle and it's direction of motion is called the phase of the particle.

If two particles of the medium, at any instant are at the same distance in the same direction from their equilibrium positions and are moving in the same direction then they are said to be in same phase *e.g.* In the following figure particles 1, 3 and 5 are in same phase and point 6, 7 are also in same phase.

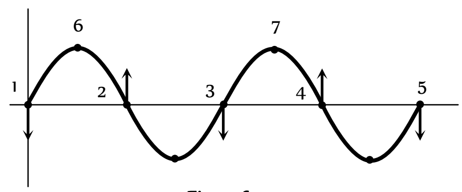


Fig. 17.6

(15) **Intensity of wave :** The wave intensity is defined as the average amount of energy flow in medium per unit time and per unit of it's cross-sectional area. It's unit is W/m^2

Hence intensity $(I) = \frac{\text{Energy}}{\text{Area} \times \text{Time}} = \frac{\text{Power}}{\text{Area}} = 2\pi n a \rho v$

$\Rightarrow I \propto a^2$ (when v, ρ = constant)

where a = Amplitude, n =Frequency, v = Wave velocity,

ρ = Density of medium.

At a distance r from a point source of power P the intensity is given by $I = \frac{P}{4\pi r^2} \Rightarrow I \propto \frac{1}{r^2}$

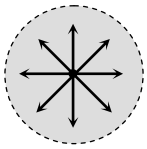


Fig. 17.7

The human ear can hear sound of intensity up to 10^{-12} W/m^2. This is called **threshold of intensity**. The upper limit of intensity of sound which can be tolerated by human ear is 1 W/m^2. This is called **threshold of pain.**

(16) **Energy density :** The energy associated with unit volume of the medium is defined as energy density

$$\text{Energy density} = \frac{\text{Energy}}{\text{Volume}} = \frac{\text{Intensity}}{\text{Velocity}} = \frac{2\pi^2 n^2 a^2 \rho v}{v} = 2\pi^2 n^2 a^2 \rho$$

Velocity of Transverse Wave

The velocity of a transverse wave in a stretched string is given by $v = \sqrt{\frac{T}{m}}$; where T = Tension in the string; m = Linear density of string (mass per unit length).

(1) If A is the area of cross-section of the wire then $m = \rho A$

$$\Rightarrow v = \sqrt{\frac{T}{\rho A}} = \sqrt{\frac{S}{\rho}} \text{ ; where } S = \text{Stress } = \frac{T}{A}$$

(2) If string is stretched by some weight then

$T = Mg$

$\Rightarrow v = \sqrt{\frac{Mg}{m}}$

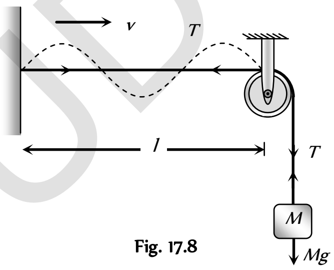


Fig. 17.8

(3) If suspended weight is immersed in a liquid of density σ and ρ = density of material of the suspended load then

$T = Mg\left(1 - \frac{\sigma}{\rho}\right)$

$\Rightarrow v = \sqrt{\frac{Mg(1-\sigma/\rho)}{m}}$

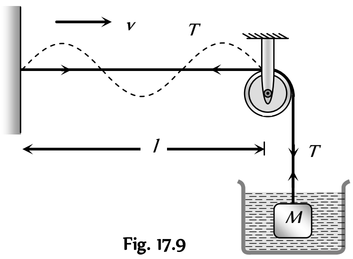


Fig. 17.9

(4) If two rigid supports of stretched string are maintained at temperature difference of $\Delta\theta$ then due to elasticity of string.

$T = YA\,\alpha\,\Delta\theta$

$\Rightarrow v = \sqrt{\frac{YA\alpha\Delta\theta}{m}}$

$= \sqrt{\frac{Y\alpha\Delta\theta}{d}}$

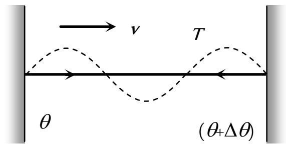


Fig. 17.10

where Y = Young's modulus of elasticity of string, A = Area of cross section of string, α = Temperature coefficient of thermal expansion, d = Density of wire $= \frac{m}{A}$

(5) In a solid body : $v = \sqrt{\frac{\eta}{\rho}}$

where η = Modulus of rigidity; ρ = Density of the material.

Velocity of Longitudinal Wave (Sound Wave)

(1) **Velocity of sound in any elastic medium :** It is given by $v = \sqrt{\frac{E}{\rho}} = \sqrt{\frac{\text{Elasticity of the medium}}{\text{Density of the medium}}}$

(i) In solids $v = \sqrt{\frac{Y}{\rho}}$; where Y = Young's modulus of elasticity

(ii) In a liquid and gaseous medium $v = \sqrt{\frac{B}{\rho}}$; where B = Bulk modulus of elasticity of liquid or gaseous medium.

(iii) As solids are most elastic while gases least *i.e.* $E_S > E_L > E_G$. So the velocity of sound is maximum in solids and minimum in gases, hence $v_{steel} > v_{water} > v_{air}$

5000 m/s > 1500 m/s > 330 m/s

(iv) The velocity of sound in case of extended solid (crust of the earth) $v = \sqrt{\frac{B + \frac{4}{3}\eta}{\rho}}$; B = Bulk modulus; η = Modulus of rigidity; ρ = Density

(2) **Newton's formula :** He assumed that when sound propagates through air temperature remains constant. *i.e.* the process is isothermal. For isothermal process

B = Isothermal elasticity (E_θ) = Pressure $(P) \Rightarrow v = \sqrt{\frac{B}{\rho}} = \sqrt{\frac{P}{\rho}}$

For air at NTP : $P = 1.01 \times 10^5$ N/m^2 and $\rho = 1.29$ kg/m^3.

$$\Rightarrow v_{air} = \sqrt{\frac{1.01 \times 10^5}{1.29}} \approx 280\, m/s$$

However the experimental value of sound in air is 332 m/sec which is greater than that given by Newton's formula.

(3) **Laplace correction :** He modified Newton's formula assuming that propagation of sound in gaseous medium is adiabatic process. For adiabatic process

B = Adiabatic elasticity $(E_\phi) = \gamma P$

$$\Rightarrow v = \sqrt{\frac{B}{\rho}} = \sqrt{\frac{E_\phi}{\rho}} = \sqrt{\frac{\gamma P}{\rho}} = \sqrt{\frac{\gamma RT}{M}}$$

For air : $\gamma = 1.41 \Rightarrow v_{air} = \sqrt{1.41} \times 280 \approx 332$ *m/sec*

(4) **Relation between velocity of sound and root mean square velocity :**

If sound travel in a gaseous medium then $v_{sound} = \sqrt{\frac{\gamma RT}{M}}$ and *r.m.s.* velocity of gas $v_{rms} = \sqrt{\frac{3RT}{M}}$

So $\frac{v_{rms}}{v_{sound}} = \sqrt{\frac{3}{\gamma}}$ or $v_{sound} = [\gamma/3]^{1/2} v_{rms}$.

Factors Affecting Velocity of Sound in Gaseous Medium

(1) **Effect of pressure at constant temperature :** Velocity of sound is independent of the pressure of gas, because as pressure increases, density also increases hence $\frac{P}{\rho}$ ratio remains constant. So from $v = \sqrt{\frac{\gamma P}{\rho}}$,

(2) **Effect of temperature :** With rise in temperature velocity of sound increases.

$$v = \sqrt{\frac{\gamma RT}{M}} \Rightarrow v \propto \sqrt{T} \Rightarrow \frac{v_1}{v_2} = \sqrt{\frac{T_1}{T_2}} = \sqrt{\frac{(273 + t_1 °C)}{(273 + t_2 °C)}}$$

When the temperature change is small then $v_t = v_0 + 0.61\,t$

where v_t = Velocity of sound at $t°C$

v_0 = Velocity of sound at $0°C$ = 332 *m/sec*

t = Small temperature change

If $t = 1°C$ then $v_t = (v_0 + 0.61)$ *m/sec*. Hence for $1°C$ rise, speed of sound in air increases by 0.61 *m/sec*.

(3) **Effect of density :** $v = \sqrt{\frac{\gamma P}{\rho}} \Rightarrow v \propto \frac{1}{\sqrt{\rho}}$

(4) **Effect of humidity :** With increase in humidity, density of air decreases. So with rise in humidity velocity of sound increases.

Sound travels faster in humid air (rainy season) than in dry air (summer) at the same temperature because

$$\rho_{moist\ air} < \rho_{dry\ air} \Rightarrow v_{moist\ air} > v_{dry\ air}$$

(5) **Effect of wind velocity :** Because wind drifts the medium (air) along its direction of motion therefore the velocity of sound in a particular direction is the algebraic sum of the velocity of sound and the component of wind velocity in that direction. Resultant velocity of sound towards observer $v' = v + w\cos\theta$.

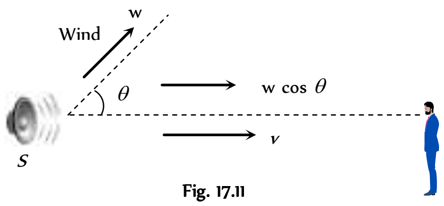


Fig. 17.11

(6) Sound of any frequency or wavelength travels through a given medium with the same velocity.

For a given medium velocity remains constant. All other factors like phase, loudness pitch, quality *etc.* have practically no effect on sound velocity.

Equation of a Plane Progressive Waves

(1) If during the propagation of a progressive wave, the particles of the medium perform SHM about their mean position, then the waves is known as a harmonic progressive wave.

(2) Suppose a plane simple harmonic wave travels from the origin along the positive direction of *x-axis* from left to right as shown in the figure.

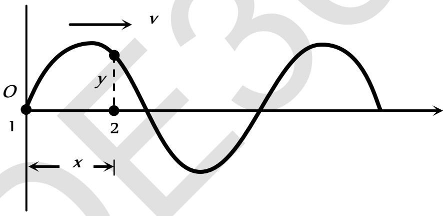


Fig. 17.12

The displacement y of a particle 1 at O from its mean position at any time t is given by $y = a\sin\omega t$.

The wave reaches the particle 2 after time $t = \frac{x}{v}$. Hence displacement y of a particle 2 is given by

$$y = a\sin\omega\left(t - \frac{x}{v}\right) = a\sin(\omega t - kx) \qquad \left(\because k = \frac{\omega}{v}\right)$$

The general equation of a plane progressive wave with initial phase is

$$\underbrace{y(x,t)}_{\text{Displacement}} = \underbrace{a}_{\text{Amplitude}} \sin\underbrace{(\omega t \pm kx \pm \phi_0)}_{\text{Oscillating term}}$$

Phase: $(\omega t \pm kx \pm \phi_0)$; Angular frequency: ω; Propagation constant: k; Position: x; Initial phase: ϕ_0

(3) Various forms of progressive wave function.

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

(ii) $y = a\sin\left(\omega t - \frac{2\pi}{\lambda}x\right)$

(iii) $y = a\sin 2\pi\left[\frac{t}{T} - \frac{x}{\lambda}\right]$

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

(v) $y = a\sin\frac{2\pi}{\lambda}(vt - x)$

(vi) $y = a\sin\omega\left(t - \frac{x}{v}\right)$

(4) **Particle velocity :** The rate of change of displacement y *w.r.t.* time t is known as particle velocity

Hence from $y = a\sin(\omega t - kx)$

Particle velocity $v_p = \frac{\partial y}{\partial t} = a\omega\cos(\omega t - kx)$

Maximum particle velocity $(v_p)_{\max} = a\omega$

Also $\frac{\partial y}{\partial t} = -\frac{\omega}{k} \times \frac{\partial y}{\partial x}$ $\Rightarrow v_p = -v \times$ Slope of wave at that point

(5) **Important relations for numerical solving**

(i) Angular frequency ω = co-efficient of t

(ii) Propagation constant k = co-efficient of x

Wave speed $v = \frac{\text{co-efficient of } t}{\text{co-efficient of } x} = \frac{\omega}{k}$

(iii) Wave length $\lambda = \frac{\text{co-efficient of } x}{2\pi}$

(iv) Time period $T = \frac{2\pi}{\text{co-efficient of } t}$

(v) Frequency $n = \frac{\text{co-efficient of } t}{2\pi}$

(vi) $(v_p)_{\max} = a\omega = a(2\pi n) = \frac{a2\pi}{T}$

(vii) If the sign between t and x terms is negative the wave is propagating along positive X-axis and if the sign is positive then the wave moves in negative X-axis direction.

(viii) Co-efficient of sin or cos functions *i.e.* Argument of sin or cos function is represented by phase *i.e.* $(\omega t - kx)$ = Phase.

(ix) **Phase difference and path difference :** 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 $\phi_2 = (\omega t - kx_2)$ $\Rightarrow$ $\phi_1 - \phi_2 = k(x_2 - x_1)$

$\Rightarrow$ Phase difference $(\Delta\phi) = \frac{2\pi}{\lambda}.\text{Path difference } (\Delta x)$

(x) **Phase difference and time difference :** 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 $\phi_1 = (\omega t_1 - kx)$ and $\phi_1 = (\omega t_2 - kx)$ $\Rightarrow$ $\phi_1 - \phi_2 = \omega(t_1 - t_2)$

$\Rightarrow$ Phase difference $(\Delta\phi) = \frac{2\pi}{T}.\text{Time difference } (\Delta t)$

Pressure Waves

A longitudinal sound wave can be expressed either in terms of the longitudinal displacement of the particles of the medium or in terms of excess pressure produced due to compression or rarefaction. (at compression, the pressure is more than the normal pressure of the medium and at rarefaction the pressure is lesser than the normal). The first type is called the displacement wave and the second type the pressure wave.

If the displacement wave is represented by $y = a\sin(\omega t - kx)$ then the corresponding pressure wave will be represented by $\Delta P = -B\frac{dy}{dx}$ (B = Bulk modulus of elasticity of medium)

$\Rightarrow \Delta P = \Delta P_0 \cos(\omega t - kx)$

where ΔP_0 = pressure amplitude $= akB$

Pressure wave is $\left(\frac{\pi}{2}\right)$ out of phase with displacement wave. *i.e.* pressure is maximum when displacement is minimum and vice-versa.

Reflection and Refraction of Waves

When waves are incident on a boundary between two media, a part of incident waves returns back into the initial medium (reflection) while the remaining is partly absorbed and partly transmitted into the second medium (refraction)

(1) **Rarer and denser medium :** A medium is said to be denser (relative to the other) if the speed of wave in this medium is less than the speed of the wave in other medium.

In comparison to air speed of sound is maximum in water, hence water is rarer medium for sound waves *w.r.t.* air. But it is not true for light (EM-waves). For light waves water is denser medium *w.r.t.* air.

(2) In reflection or refraction frequency remains same

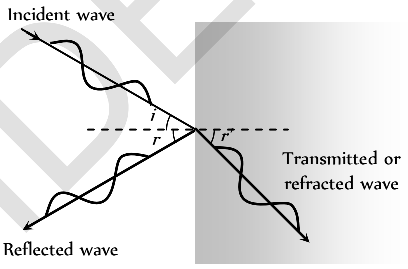


Fig. 17.13

(3) For reflection angle of incidence (i) = Angle of reflection (r)

(4) In case of refraction or transmission $\frac{\sin i}{\sin r'} = \frac{v_i}{v_t}$

(5) **Boundary conditions :** Reflection of a wave pulse from some boundary depends on the nature of the boundary.

(i) **Rigid end :** When the incident wave reaches a fixed end, it exerts an upward pull on the end, according to Newton's law the fixed end exerts an equal and opposite down ward force on the string. It result an inverted pulse or phase change of π.

Crest (C) reflects as trough (T) and vice-versa, Time changes by $\frac{T}{2}$ and Path changes by $\frac{\lambda}{2}$

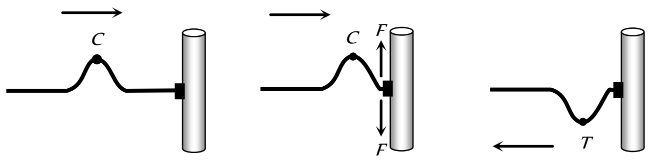


Fig. 17.14

(ii) **Free end :** When a wave or pulse is reflected from a free end, then there is no change of phase (as there is no reaction force).

Crest (C) reflects as crest (C) and trough (T) reflects as trough (T), Time changes by zero and Path changes by zero.

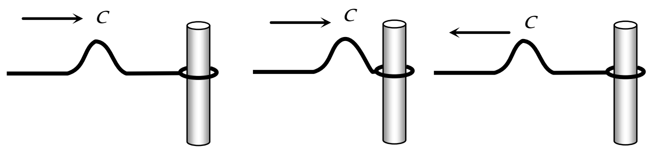


Fig. 17.15

(iii) **Exception :** Longitudinal pressure waves suffer no change in phase from rigid end *i.e.* compression pulse reflects as compression pulse. On the other hand if longitudinal pressure wave reflects from free end, it suffer a phase change of π *i.e.* compression reflects as rarefaction and vice-versa.

(iv) **Effect on different variables :** In case of reflection, because medium is same and hence, speed, frequency (ω) and wavelength λ (or k) do not changes. On the other hand in case of transmitted wave since medium changes and hence speed, wavelength (or k) changes but frequency (ω) remains the same.

(6) **Wave in a combination of string**

(i) **Wave goes from rarer to denser medium**

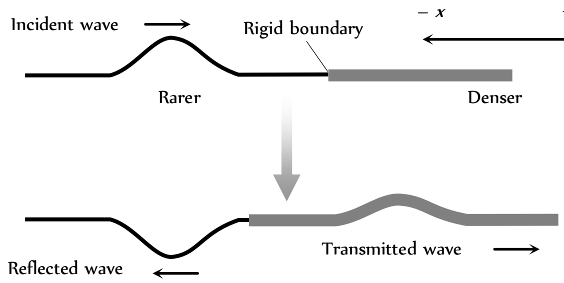


Fig. 17.16

Incident wave $y_i = a_i \sin(\omega t - k_1 x)$

Reflected wave $y_r = a_r \sin[\omega t - k_1(-x) + \pi] = -a \sin(\omega t + k_1 x)$

Transmitted wave $y_t = a_t \sin(\omega t - k_2 x)$

(ii) **Wave goes from denser to rarer medium**

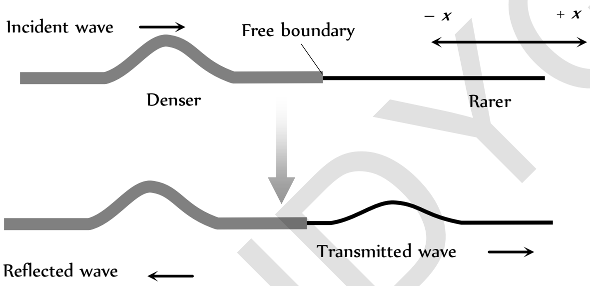


Fig. 17.17

Incident wave $y_i = a_i \sin(\omega t - k_1 x)$

Reflected wave $y_r = a_r \sin[\omega t - k_1(-x) + 0] = a \sin(\omega t + k_1 x)$

Transmitted wave $y_t = a_t \sin(\omega t - k_2 x)$

(iii) **Ratio of amplitudes :** It is given as follows

$$\frac{a_r}{a_i} = \frac{k_1 - k_2}{k_1 + k_2} = \frac{v_2 - v_1}{v_2 + v_1} \text{ and } \frac{a_t}{a_i} = \frac{2k_1}{k_1 + k_2} = \frac{2v_2}{v_1 + v_2}$$

Echo

An echo is simply the repetition of speaker's own voice caused by reflection at a distance surface *e.g.* a cliff. a row of building or any other extended surface.

If there is a sound reflector at a distance d from source, then the time interval between original source and it's echo at the site of source will be

$$t = \frac{d}{v} + \frac{d}{v} = \frac{2d}{v}$$

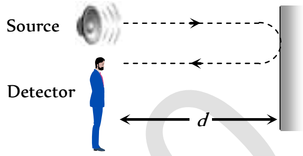


Fig. 17.18

As the persistence of hearing for human ear is 0.1 *sec*, therefore in order that an echo of short sound (*e.g.* clap or gun fire) will be heard if $t > 0.1 \Rightarrow \frac{2d}{v} > 0.1 \Rightarrow d > \frac{v}{20}$

If v = Speed of sound = 340 *m/s* then d > 17 *m*.

Principle of Superposition

(1) The displacement at any time due to any number of waves meeting simultaneously at a point in a medium is the vector sum of the individual displacements due each one of the waves at that point at the same time.

(2) If $\vec{y}_1, \vec{y}_2, \vec{y}_3$ .... are the displacements at a particular time at a particular position, due to individual waves, then the resultant displacement.

$$\vec{y} = \vec{y}_1 + \vec{y}_2 + \vec{y}_3 + ...$$

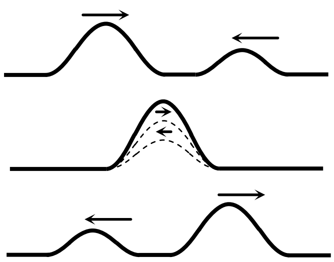


Fig. 17.19

(3) Important applications of superposition principle

(i) **Interference of waves :** Adding waves that differs in phase

(ii) **Formation of stationary waves :** Adding wave that differs in direction.

(iii) **Formation of beats :** Adding waves that differs in frequency.

(iv) **Formation of Lissaju's figure :** Adding two perpendicular simple harmonic motions. (See S.H.M. for more detail)

Interference of Sound Waves

(1) When two waves of same frequency, same wavelength, same velocity (nearly equal amplitude) moves in the same direction, Their superimposition results in the interference.

(2) Due to interference the resultant intensity of sound at that point is different from the sum of intensities due to each wave separately.

(3) Interference is of two type (i) Constructive interference (ii) Destructive interference.

(4) In interference energy is neither created nor destroyed but is redistributed.

(5) For observable interference, the sources (producing interfering waves) must be coherent.

(6) Let at a given point two waves arrives with phase difference ϕ and the equation of these waves is given by

$y_1 = a_1 \sin \omega t$, $y_2 = a_2 \sin(\omega t + \phi)$ then by the principle of superposition $\vec{y} = \vec{y}_1 + \vec{y}_2$

$\Rightarrow y = a_1 \sin \omega t + a_2 \sin(\omega t + \phi) = A \sin(\omega t + \theta)$

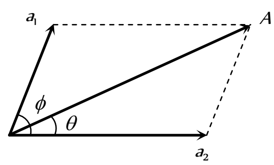


Fig. 17.20

where $A=\sqrt{a_1^2+a_2^2+2a_1a_2\cos\phi}$

and $\tan\theta = \dfrac{a_2\sin\phi}{a_1+a_2\cos\phi}$

since Intensity (I) $\propto$ (Amplitude A)^2 $\Rightarrow \dfrac{I_1}{I_2}=\left(\dfrac{a_1}{a_2}\right)^2$

Therefore, the resultant intensity is given by

$$I=I_1+I_2+2\sqrt{I_1I_2}\cos\phi$$

Table 17.2 : Constructive and destructive interference

Constructive interference	Destructive interference
When the waves meets a point with same phase, constructive interference is obtained at that point (*i.e.* maximum sound).	When the wave meets a point with opposite phase, destructive interference is obtained at that point (*i.e.* minimum sound)
Phase difference between the waves at the point of observation $\phi=0^o$ or $2n\pi$	Phase difference $\phi=180^o$ or $(2n-1)\pi$; n = 1, 2, ...
Path difference between the waves at the point of observation $\Delta=n\lambda$ (*i.e.* even multiple of $\lambda/2$)	Path difference $\Delta=(2n-1)\dfrac{\lambda}{2}$ (*i.e.* odd multiple of $\lambda/2$)
Resultant amplitude at the point of observation will be maximum $A_{max}=a_1+a_2$ If $a_1=a_2=a_0\Rightarrow A_{max}=2a_0$	Resultant amplitude at the point of observation will be minimum $A_{min}=a_1-a_2$ If $a_1=a_2\Rightarrow A_{min}=0$
Resultant intensity at the point of observation will be maximum $I_{max}=I_1+I_2+2\sqrt{I_1I_2}$ $=\left(\sqrt{I_1}+\sqrt{I_2}\right)^2$ If $I_1=I_2=I_0\Rightarrow I_{max}=4I_0$	Resultant intensity at the point of observation will be minimum $I_{min}=I_1+I_2-2\sqrt{I_1I_2}$ $=\left(\sqrt{I_1}-\sqrt{I_2}\right)^2$ If $I_1=I_2=I_0\Rightarrow I_{min}=0$

(7) $$\frac{I_{max}}{I_{min}}=\left(\frac{\sqrt{I_1}+\sqrt{I_2}}{\sqrt{I_1}-\sqrt{I_2}}\right)^2=\left(\frac{\sqrt{\dfrac{I_1}{I_2}}+1}{\sqrt{\dfrac{I_1}{I_2}}-1}\right)^2=\left(\frac{a_1+a_2}{a_1-a_2}\right)^2=\left(\frac{\dfrac{a_1}{a_2}+1}{\dfrac{a_1}{a_2}-1}\right)^2$$

Quink's Tube

This is an apparatus used to demonstrate the phenomenon of interference and also used to measure velocity of sound in air. This is made up of two U-tube A and B as shown in figure. Here the tube B can slide in and out from the tube A. There are two openings P and Q in the tube A. At opening P, a tuning fork or a sound source of known frequency n is placed and at the other opening a detector is placed to detect the resultant sound of interference occurred due to superposition of two sound waves coming from the tubes A and B.

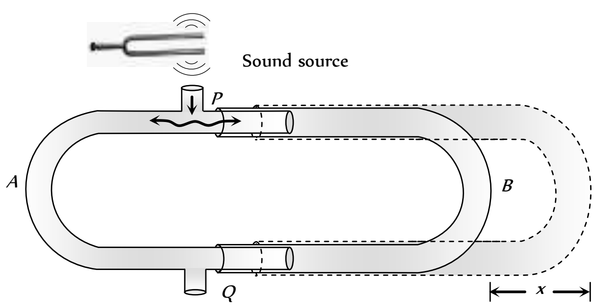


Fig. 17.21

Initially tube B is adjusted so that detector detects a maximum. At this instant if length of paths covered by the two waves from P and Q from the side of A and side of B are l_1 and l_2 respectively then for constructive interference we must have

$$l_2-l_1=N\lambda \quad \text{.... (i)}$$

If now tube B is further pulled out by a distance x so that next maximum is obtained and the length of path from the side of B is l'_2 then we have

$$l'_2=l_2+2x \quad \text{.... (ii)}$$

where x is the displacement of the tube. For next constructive interference of sound at point Q, we have

$$l'_2=l_1=(N+1)\lambda \quad \text{.... (iii)}$$

From equation (i), (ii) and (iii), we get

$$l'_2-l_2=2\times x=\lambda \Rightarrow x=\frac{\lambda}{2}$$

Thus by experiment we get the wavelength of sound as for two successive points of constructive interference, the path difference must be λ. As the tube B is pulled out by x, this introduces a path difference $2x$ in the path of sound wave through tube B. If the frequency of the source is known, n, the velocity of sound in the air filled in tube can be gives as $v=n_0.\lambda=2n_0x$

Standing Waves or Stationary Waves

When two sets of progressive wave trains of same type (both longitudinal or both transverse) having the same amplitude and same time period/frequency/wavelength travelling with same speed along the same straight line in opposite directions superimpose, a new set of waves are formed. These are called stationary waves or standing waves.

In practice, a stationary wave is formed when a wave train is reflected at a boundary. The incident and reflected waves then interfere to produce a stationary wave.

(1) Suppose that the two super imposing waves are incident wave $y_1=a\sin(\omega t-kx)$ and reflected wave $y_2=a\sin(\omega t+kx)$

(As y_2 is the displacement due to a reflected wave from a free boundary)

Then by principle of superposition

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

(By using $\sin C+\sin D=2\sin\dfrac{C+D}{2}\cos\dfrac{C-D}{2}$)

$$\Rightarrow \quad y=2a\cos kx\sin\omega t$$

(If reflection takes place from rigid end, then equation of stationary wave will be $y=2a\sin kx\cos\omega t$)

(2) As this equation satisfies the wave equation

$\frac{\partial^2 y}{\partial t^2} = v^2 \frac{\partial^2 y}{\partial x^2}$. It represents a wave.

(3) As it is not of the form $f(ax \pm bt)$, the wave is not progressive.

(4) Amplitude of the wave $A_{SW} = 2a\cos kx$.

Table 17.3 : Amplitude in two different cases

Reflection at open end	Reflection at closed end
$A_{SW} = 2a\cos kx$	$A_{SW} = 2a\sin kx$
Amplitude is maximum when $\cos kx = \pm 1$ $\Rightarrow kx = 0, \pi, 2\pi, ... n\pi$. $\Rightarrow x = 0, \frac{\lambda}{2}, \lambda .... \frac{n\lambda}{2}$ where $k = \frac{2\pi}{\lambda}$ and $n = 0, 1, 2, 3, ...$	Amplitude is maximum when $\sin kx = \pm 1$ $\Rightarrow kx = \frac{\pi}{2}, \frac{3\pi}{2} ..... \frac{(2n-1)\pi}{2}$ $\Rightarrow x = \frac{\lambda}{4}, \frac{3\lambda}{4} ....$ where $k = \frac{2\pi}{\lambda}$ and $n = 1, 2, 3, ...$
Amplitude is minimum when $\cos kx = 0$ $\Rightarrow kx = \frac{\pi}{2}, \frac{3\pi}{2} ..... \frac{(2n-1)\pi}{2}$ $\Rightarrow x = \frac{\lambda}{4}, \frac{3\lambda}{4} ....$	Amplitude is minimum when $\sin kx = 0$ $\Rightarrow kx = \frac{\pi}{2}, \frac{3\pi}{2} ..... \frac{(2n-1)\pi}{2}$ $\Rightarrow x = 0, \frac{\lambda}{2}, \lambda ...... \frac{n\lambda}{2}$

(5) **Nodes** (*N*) **:** The points where amplitude is minimum are called nodes.

(i) Distance between two successive nodes is $\frac{\lambda}{2}$.

(ii) Nodes are at permanents rest.

(iii) At nodes air pressure and density both are high.

(6) **Antinodes** (*A*) **:** The points of maximum amplitudes are called antinodes.

(i) The distance between two successive antinodes is $\frac{\lambda}{2}$

(ii) At nodes air pressure and density both are low.

(iii) The distance between a node (*N*) and adjoining antinode (*A*) is $\frac{\lambda}{4}$.

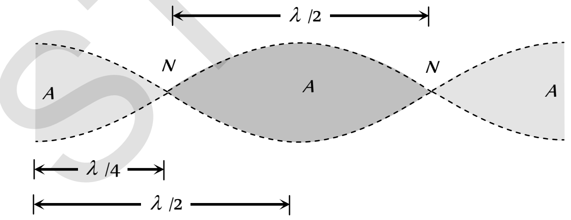


Fig. 17.22

Characteristics of Standing Waves

(1) Standing waves can be transverse or longitudinal.

(2) The disturbance confined to a particular region between the starting point and reflecting point of the wave.

(3) There is no forward motion of the disturbance from one particle to the adjoining particle and so on, beyond this particular region.

(4) The total energy associated with a stationary wave is twice the energy of each of incident and reflected wave. As in stationary waves nodes are permanently at rest. So no energy can be transmitted across then *i.e.* energy of one region (segment) is confined in that region. However this energy oscillates between elastic potential energy and kinetic energy of particles of the medium.

(5) The medium splits up into a number of segments. Each segment is vibrating up and down as a whole.

(6) All the particles in one particular segment vibrate in the same phase. Particles in two consecutive segments differ in phase by 180°.

(7) All the particles except those at nodes, execute simple harmonic motion about their mean position with the same time period.

(8) The amplitude of vibration of particles varies from zero at nodes to maximum at antinodes (2*a*).

(9) All points (except nodes) pass their mean position twice in one time period.

(10) Velocity of particles while crossing mean position varies from maximum $(\omega A_{SW} = \omega.2a)$ at antinodes to zero at nodes.

(11) In standing waves, if amplitude of component waves are not equal. Resultant amplitude at nodes will be minimum (but not zero). Therefore, some energy will pass across nodes and waves will be partially standing.

(12) Application of stationary waves

(i) Vibration in stretched string

(ii) Vibration in organ pipes (closed and open)

(iii) Kundt's tube

Table 17.4 : Progressive v/s stationary wave

Progressive wave	Stationary wave
These waves transfers energy	These wave does not transfers energy
All particles have the same amplitude	Between a node and an antinode all particles have different amplitudes
Over one wavelength span all particles have difference phase	Between a node and an antnodes all particles have same phase.
No point is at rest	Nodes are always at rest
All particles do not cross the mean position simultaneously.	All particles cross the mean position simultaneously.

Terms Related to the Application of Stationary Wave

(1) **Note :** Any musical sound produced by the simple harmonic oscillations of the source is called note.

(2) **Tone :** Every musical sound consists of a number of components of different frequencies every component is known as a Tone.

(3) **Fundamental note and fundamental frequency :** The note of lowest frequency produced by an instrument is called fundamental note. The frequency of this note is called fundamental frequency.

(4) **Harmonics :** The frequency which are the integral multiple of the fundamental frequency are known as harmonics *e.g.* if *n* be the fundamental frequency, then the frequencies *n*, 2*n*, 3*n* .... are termed as first, second, third .... harmonics.

(5) **Overtone :** The harmonics other than the first (fundamental note) which are actually produced by the instrument are called overtones. *e.g.* the tone with frequency immediately higher than the fundamental is defined as first overtone.

(6) **Octave :** The tone whose frequency is doubled the fundamental frequency is defined as Octave.

(i) If $n_2 = 2n_1$ it means n_2 is an octave higher than n_1 or n_1 is an octave lower than n_2.

(ii) If $n_2 = 2^3 n_1$, it means n_2 is 3-octave higher or n_1 is 3-octave lower.

(iii) Similarly if $n_2 = 2^n n_1$ it means n_2 is n-octave higher n_1 is n octave lower.

(7) **Unison :** If the interval is one *i.e.* two frequencies are equal then vibrating bodies are said to be in unison.

(8) **Resonance :** The phenomenon of making a body vibrate with its natural frequency under the influence of another vibrating body with the same frequency is called resonance.

Standing Waves on a String

(1) Consider a string of length l, stretched under tension T between two fixed points.

(2) If the string is plucked and then released, a transverse harmonic wave propagate along it's length and is reflected at the end.

(3) The incident and reflected waves will superimpose to produce transverse stationary waves in a string.

(4) Nodes (N) are formed at rigid end and antinodes (A) are formed in between them.

(5) Number of antinodes = Number of nodes – 1

(6) Velocity of wave (incident or reflected wave) is given by $v = \sqrt{\frac{T}{m}}$; m = Mass per unit length of the wire

(7) Frequency of vibration (n) = Frequency of wave

$$= \frac{v}{\lambda} = \frac{1}{\lambda}\sqrt{\frac{T}{m}}$$

(8) For obtaining p loops (p-segments) in string, it has to be plucked at a distance $\frac{l}{2p}$ from one fixed end.

(9) **Fundamental mode of vibration**

(i) Number of loops $p = 1$

(ii) Plucking at $\frac{l}{2}$

(from one fixed end)

(iii) $l = \frac{\lambda_1}{2} \Rightarrow \lambda_1 = 2l$

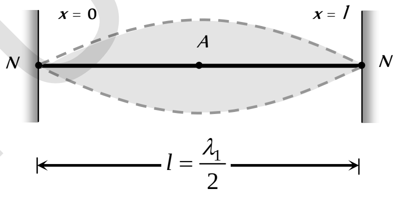


Fig. 17.23

(iv) Fundamental frequency or first harmonic

$$n_1 = \frac{1}{\lambda_1}\sqrt{\frac{T}{m}} = \frac{1}{2l}\sqrt{\frac{T}{m}}$$

(10) **Second mode of vibration** (First over tone or second harmonic)

(i) Number of loops $p = 2$

(ii) Plucking at $\frac{l}{2\times 2} = \frac{l}{4}$

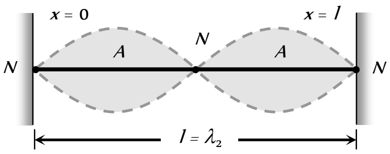


Fig. 17.24

(from one fixed end)

(iii) $l = \lambda_2$

(iv) Second harmonic or first over tone

$$n_2 = \frac{1}{\lambda_2}\sqrt{\frac{T}{m}} = \frac{1}{l}\sqrt{\frac{T}{m}} = 2n_1$$

(11) **Third normal mode of vibration** (Second over tone or third harmonic)

(i) Number of loops $p = 3$

(ii) Plucking at $\frac{l}{2\times 3} = \frac{l}{6}$

(from one fixed end)

(iii) $l = \frac{3\lambda_3}{2} \Rightarrow \lambda_3 = \frac{2l}{3}$

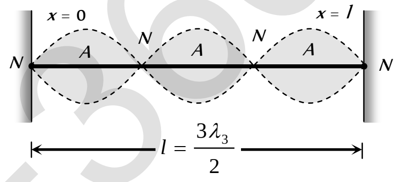


Fig. 17.25

(iv) Third harmonic or second over tone

$$n_3 = \frac{1}{\lambda_3}\sqrt{\frac{T}{m}} = \frac{3}{2l}\sqrt{\frac{T}{m}} = 3n_1$$

(12) **More about string vibration**

(i) In general, if the string is plucked at length $\frac{l}{2p}$, then it vibrates in p segments (loops) and we have the p harmonic is give $f_p = \frac{p}{2l}\sqrt{\frac{T}{m}}$

(ii) All even and odd harmonics are present. Ratio of harmonic = 1 : 2 : 3 .....

(iii) Ratio of over tones = 2 : 3 : 4 ....

(iv) General formula for wavelength $\lambda = \frac{2l}{N}$; where N = 1,2,3, ... correspond to 1st, 2nd, 3rd modes of vibration of the string.

(v) General formula for frequency $n = N \times \frac{v}{2l}$

(vi) **Position of nodes :** $x = 0, \frac{l}{N}, \frac{2l}{N}, \frac{3l}{N} ..... l$

(vii) **Position of antinodes :** $x = \frac{l}{2N}, \frac{3l}{2N}, \frac{5l}{2N} .... \frac{(2N-1)l}{2N}$

Melde's Experiment

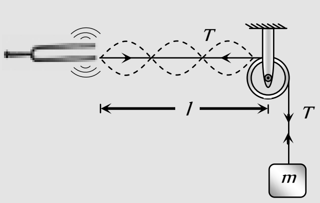
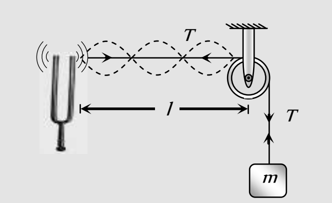
(1) It is an experimental representation of transverse stationary wave.

(2) In Melde's experiment, one end of a flexible piece of string is tied to the end of a tuning fork. The other end passes over a smooth pulley carries a suitable load.

(3) If p is the number of loop's formed in stretched string and T is the tension in the string then Melde's law is $p\sqrt{T}$ = constant

$$\Rightarrow \frac{p_1}{p_2} = \sqrt{\frac{T_2}{T_1}} \text{ (For comparing two cases)}$$

Table 17.5 ; Two arrangements of connecting a string to turning fork

Transversely	Example
	
Prongs of tuning fork vibrates at right angles to the thread.	Prongs vibrated along the length of the thread.
Frequency of vibration of turning fork : frequency of vibration of the thread.	Frequency of turning fork =2 × (Frequency of vibration of thread)
If number of loops in string is P then $l=\frac{p\lambda}{2}\Rightarrow\lambda=\frac{2l}{p}$ $\Rightarrow$ Frequency of string $=\frac{v}{\lambda}=\frac{p}{2l}\sqrt{\frac{T}{m}}\ \left(\because v=\sqrt{\frac{T}{m}}\right)$ $\Rightarrow$ Frequency of tuning fork $=\frac{p}{2l}\sqrt{\frac{T}{m}}$ $\Rightarrow$ If l, m, $n\rightarrow$ constant then $p\sqrt{T}=$ constant	It number of loop so in string is p then $l=\frac{p\lambda}{2}\Rightarrow\lambda=\frac{2l}{p}$ $\Rightarrow$ Frequency of string $=\frac{v}{\lambda}=\frac{p}{2l}\sqrt{\frac{T}{m}}$ $\Rightarrow$ Frequency of turning fork $I=\frac{P}{l}\sqrt{\frac{T}{m}}$ $\Rightarrow$ If l, m, $n\rightarrow$ constant then $p\sqrt{T}=$ constant

Sonometer

(1) It is an apparatus, used to produce resonance (matching frequency) of tuning fork (or any source of sound) with stretched vibrating string.

(2) It consists of a hollow rectangular box of light wood. The experimental fitted on the box as shown.

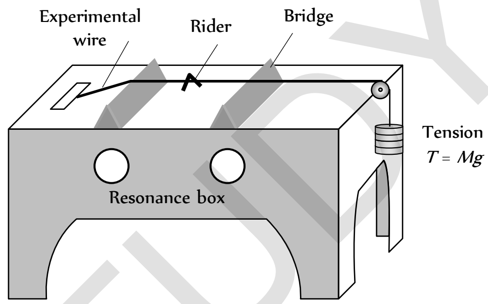


Fig. 17.26

(3) The box serves the purpose of increasing the loudness of the sound produced by the vibrating wire.

(4) If the length of the wire between the two bridges is l, then the frequency of vibration is $n=\frac{1}{2l}\sqrt{\frac{T}{m}}=\sqrt{\frac{T}{\pi r^2 d}}$

(r = Radius of the wire, d = Density of material of wire) m = mass per unit length of the wire)

(5) **Resonance :** When a vibrating tuning fork is placed on the box, and if the length between the bridges is properly adjusted then if $(n)_{Fork}=(n)_{String}\rightarrow$ rider is thrown off the wire.

(6) **Laws of string**

(i) **Law of length :** If T and m are constant then $n\propto\frac{1}{l}$

$\Rightarrow$ nl = constant $\Rightarrow n_1 l_1 = n_2 l_2$

(ii) **Law of mass :** If T and l are constant then $n\propto\frac{1}{\sqrt{m}}$

$\Rightarrow n\sqrt{m}$ = constant $\Rightarrow \frac{n_1}{n_2}=\sqrt{\frac{m_2}{m_1}}$

(iii) **Law of density :** If T, l and r are constant then $n\propto\frac{1}{\sqrt{d}}$

$\Rightarrow n\sqrt{d}$ = constant $\Rightarrow \frac{n_1}{n_2}=\sqrt{\frac{d_2}{d_1}}$

(iv) **Law of tension :** If l and m are constant then $n\propto\sqrt{T}$

$\Rightarrow \frac{n}{\sqrt{T}}$ = constant $\Rightarrow \frac{n_1}{n_2}=\sqrt{\frac{T_2}{T_1}}$

Vibration of Composite Strings

Suppose two strings of different material and lengths are joined end to end and tied between clamps as shown. Now after plucking, stationary waves are established only at those frequencies which matches with any one harmonic of both the independent string S_1 and S_2

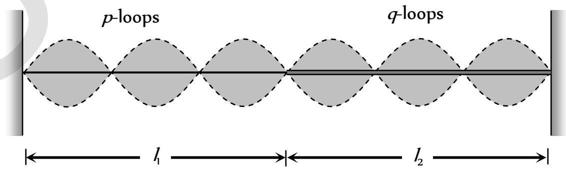


Fig. 17.27

As the frequency of the wave in both strings must be same so

$$\frac{p}{2l_1}\sqrt{\frac{T}{m_1}}=\frac{q}{2l_2}\sqrt{\frac{T}{m_2}}\Rightarrow\frac{p}{q}=\frac{l_1}{l_2}\sqrt{\frac{m_1}{m_2}}=\frac{l_1}{l_2}\sqrt{\frac{\rho_1}{\rho_2}}$$

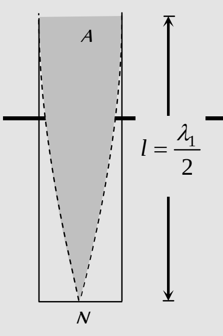
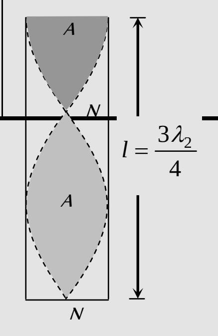
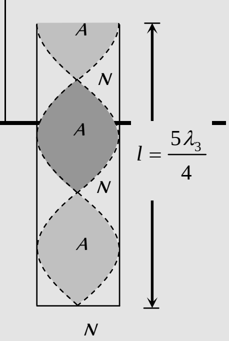
Standing Wave in a Organ Pipe

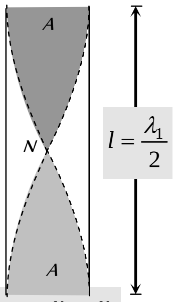
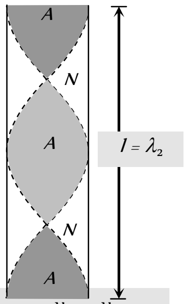
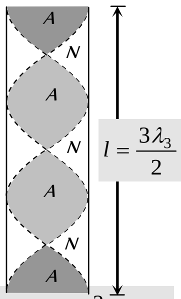
Organ pipes are the musical instrument which are used for producing musical sound by blowing air into the pipe. Longitudinal stationary waves are formed on account of superimposition of incident and reflected longitudinal waves.

Equation of standing wave y = $2a\cos\frac{2\pi vt}{\lambda}\sin\frac{2\pi x}{\lambda}$

Frequency of vibration $n=\frac{v}{\lambda}$

Table 17.6 : Different mode of vibration in organ pipe

Closed organ pipe		
Fundamental mode	Third harmonic First over tone	Fifth harmonic Second over tone
		

$n_1 = \frac{v}{4l}$	$n_2 = \frac{v}{\lambda_2} = \frac{3v}{4l} = 3n_1$	$n_3 = \frac{5v}{4l} = 5n_1$
Open organ pipe		
Fundamental mode	**Second harmonic**	**Third harmonic**
 $l = \frac{\lambda_1}{2}$	 $l = \lambda_2$	 $l = \frac{3\lambda_3}{2}$
$n_1 = \frac{v}{\lambda_1} = \frac{v}{2l}$	$n_2 = \frac{v}{\lambda_2} = \frac{v}{L} = 2n_1$	$n_3 = \frac{v}{\lambda_3} = \frac{3v}{2l} = 3n_1$

(1) **Closed organ pipe**

(i) In closed organ pipe only odd harmonic are present. Ratio of harmonic is $n_1 : n_2 : n_3$ ....= 1 : 3 : 5 ....

(ii) p^{th} overtone = $(2p + 1)^{th}$ harmonics

(iii) Ratio of overtones = 3 : 5 : 7 ....

(iv) The maximum possible wavelength is $4l$

(v) General formula for wavelength is $\lambda = \frac{4l}{(2N-1)}$; where N = 1, 2, 3, ... corresponds to order of mode of vibration.

(vi) General formula for frequency $n = \frac{(2N-1)v}{4l}$

(vii) Position of nodes from closed end $x = 0, \frac{\lambda}{2}, \lambda, \frac{3\lambda}{2}$.....

(viii) Position of antinodes from closed end $x = \frac{\lambda}{4}, \frac{3\lambda}{4}, \frac{5\lambda}{4}$...

(2) **Open organ pipe**

(i) In open organ pipe all (even and odd) harmonic are present. Ratio of harmonic is $n_1 : n_2 : n_3$ ....= 1 : 2 : 3 ....

(ii) p^{th} overtone = $(p + 1)^{th}$ harmonics

(iii) Ratio of overtones = 2 : 3 : 5 ....

(iv) The maximum possible wavelength is $2l$

(v) General formula for wavelength is $\lambda = \frac{2l}{N}$; where N = 1, 2, 3, ... corresponds to order of mode of vibration.

(vi) General formula for frequency $n = \frac{Nv}{2l}$

(vii) Position of nodes from one end $x = \frac{\lambda}{4}, \frac{3\lambda}{4}, \frac{5\lambda}{4}$.....

(viii) Position of antinodes from one end $x = 0, \frac{\lambda}{2}, \lambda, \frac{3\lambda}{2}$.....

Tuning Fork

(1) The tuning fork is a metallic device that produces sound of a single frequency.

(2) A tuning fork is really a transversely vibrating rod of rectangular cross-section bent into the shape of U as shown.

Fig. 17.28

(3) The prongs execute transverse vibrations and the stem executes the longitudinal vibration. Both vibrate with the same frequency.

(4) The phase difference between the vibrations produced by both prongs of tuning fork is zero.

(5) Tuning forks are generally taken as the standards of frequency of pure notes.

The frequency of the tuning fork is given by $n \propto \frac{t}{l^2} \cdot \sqrt{\frac{Y}{\rho}}$

where t = Thickness of the prongs, l = Length of the prongs, Y = Young's modulus of elasticity and ρ = Density of the material of tuning fork.

(6) If one prong is broken tuning fork does not vibrate.

Effect on frequency of tuning fork

(i) A fork of shorter prongs gives high frequency tone

(ii) The frequency of a tuning fork decreases when it's prongs are loaded (say with wax) near the end.

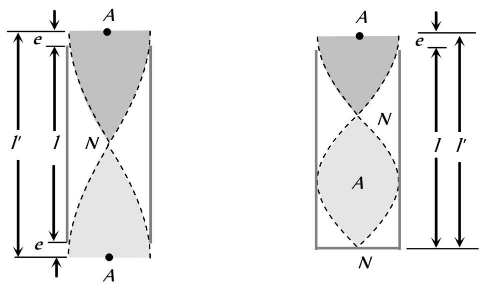
(iii) The frequency of tuning fork increases when prongs are filed near the ends.

(iv) The frequency of a tuning fork decreases if temperature of the fork is increases.

End Correction

Due to finite momentum of air molecules in organ pipe reflection takes place not exactly at open end but some what above it. Hence antinode is not formed exactly at the open end rater it is formed at a little distance away from open end outside it.

The distance of antinode from the open end is known as end correction (e). It is given by e = 0.6 r where r = radius of pipe.



(A) Open pipe (B) Closed pipe

Fig. 17.29

Effect length in open organ pipe $l' = (l + 2e)$

Effect length in closed organ pipe $l = (l + e)$

Resonance Tube

It is used to determine velocity of sound in air by the help of a tuning fork of known frequency.

It is a closed organ pipe having an air column of variable length. When a tuning fork is brought over it's mouth. It's air column vibrates with the frequency of the fork. If the length of the air column is varied until it's natural frequency equals the frequency of the fork, then the column resonants and emits a loud note.

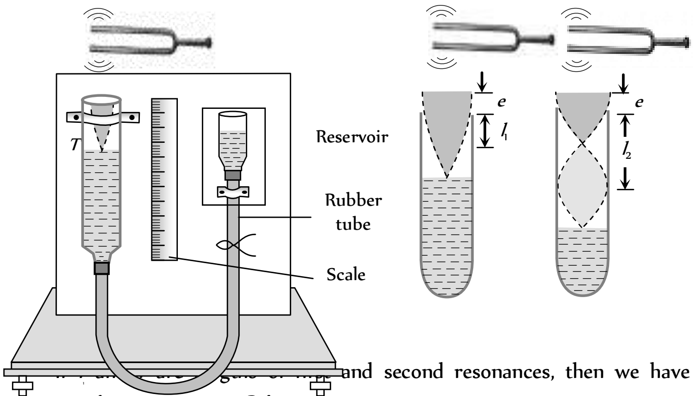


Fig. 17.30

...and second resonances, then we have $l_1 + e = \frac{\lambda}{4}$ and $l_2 + e = \frac{3\lambda}{4}$

$$\Rightarrow l_2 - l_1 = \frac{\lambda}{2} \Rightarrow \lambda = 2(l_2 - l_1)$$

Speed of sound in air at room (temperature) $v = n\lambda = 2n(l_2 - l_1)$

Also $\frac{l_2 + e}{l_1 + e} = 3 \Rightarrow l_2 = 3l_1 + 2e$ *i.e.* second resonance is obtained at length more than thrice the length of first resonance.

Kundt's Tube

The apparatus consists of a long glass tube about 5 *cm* in diameter, fixed horizontally. A metal rod *R* clamped firmly at the centre is mounted so that its one end carrying a light disc P_1 (of cork or card board) projects some distance into the glass tube. The other end of the glass tube is closed with a moveable piston P_2. Any desired length of the air or gas can be enclosed in between the two discs P_1 and P_2. A small amount of dry lycopodium powder or cork dust is spread along base of the entire length of the tube.

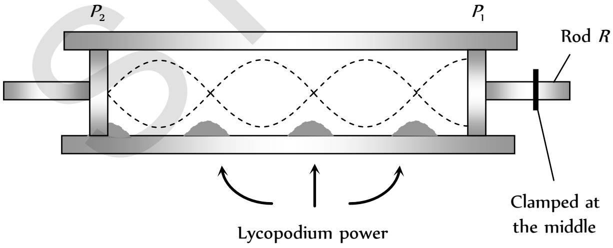


Fig. 17.31

The free end of the metal rod *R* is rubbed (stroked) along the length with resined cloth. The rod begins to vibrate longitudinally and emits a very high pitched shrill note. These vibrations are impressed upon the air column in the tube through disc P_1. Let disc P_2 is so adjusted, that the stationary waves are formed in the air (gas) column in the tube. At antinodes powder is set into oscillations vigorously while it remains uneffected at nodes. Heaps of power are formed at nodes.

Let *n* is the frequency of vibration of the rod then, this is also the frequency of sound wave in the air column in the tube.

For rod : $\frac{\lambda_{rod}}{2} = l_{rod}$, For air : $\frac{\lambda_{air}}{2} = l_{air}$

where l_{air} is the distance between two heaps of power in the tube (*i.e.* distance between two nodes). If v_{air} and v_{rod} are velocity of sound waves in the air and rod respectively, then

$$n = \frac{v_{air}}{\lambda_{air}} = \frac{v_{rod}}{\lambda_{rod}} . \text{ Therefore } \frac{v_{air}}{v_{rod}} = \frac{\lambda_{air}}{\lambda_{rod}} = \frac{\lambda_{air}}{\lambda_{rod}}$$

Thus knowledge of v_{rod}, determiens v_{air}

Kundt's tube may be used for

(i) Comparison of velocities of sound in different gases.

(ii) Comparison of velocities of sound in different solids

(iii) Comparison of velocities of sound in a solid and in a gas.

(iv) Comparison of density of two gases.

(v) Determination of γ of a gas.

(vi) Determination of velocity of sound in a liquid.

Beats

When two sound waves of slightly different frequencies, travelling in a medium along the same direction, superimpose on each other, the intensity of the resultant sound at a particular position rises and falls regularly with time. This phenomenon of regular variation in intensity of sound with time at a particular position is called beats.

(1) **Persistence of hearing :** The impression of sound heard by our ears persist in our mind for 1/10th of a second. If another sound is heard before 1/10 second is over, the impression of the two sound mix up and our mind cannot distinguish between the two.

So for the formation of distinct beats, frequencies of two sources of sound should be nearly equal (difference of frequencies less than 10)

(2) **Equation of beats :** If two waves of equal amplitudes '*a*' and slightly different frequencies n_1 and n_2 travelling in a medium in the same direction are.

$y_1 = a \sin \omega_1 t = a \sin 2\pi n_1 t$; $y_2 = a \sin \omega_2 t = a \sin 2\pi n_2 t$

By the principle of super position : $\vec{y} = \vec{y_1} + \vec{y_2}$

$y = A \sin \pi(n_1 + n_2)t$ where $A = 2a \cos \pi (n_1 - n_2)t$ = Amplitude of resultant wave.

(3) **One beat :** If the intensity of sound is maximum at time $t = 0$, one beat is said to be formed when intensity becomes maximum again after becoming minimum once in between.

(4) **Beat period :** The time interval between two successive beats (*i.e.* two successive maxima of sound) is called beat period.

$$n = n_1 \sim n_2$$

(5) **Beat frequency :** The number of beats produced per second is called beat frequency.

$$T = \frac{1}{\text{Beat frequency}} = \frac{1}{n_1 \sim n_2}$$

Determination of Unknown Frequency

Suppose a tuning fork of known frequency (n) is sounded together with another tuning fork of unknown frequency (n) and x beats heard per second.

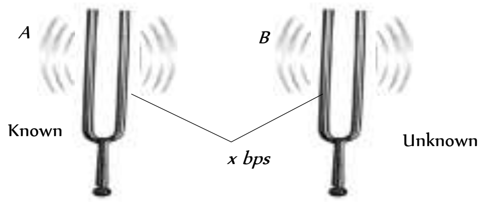


Fig. 17.32

There are two possibilities known frequency of unknown tuning fork.

$$n_A - n_B = x \quad \text{... (i)}$$

or $$n_B - n_A = x \quad \text{... (ii)}$$

To find the frequency of unknown tuning fork (n) following steps are taken.

(1) Loading or filing of one prong of known or unknown (by wax) tuning fork, so frequency changes (decreases after loading, increases after filing).

(2) Sound them together again, and count the number of heard beats per sec again, let it be x'. These are following four condition arises.

(i) $x' > x$ (ii) $x' < x$ (iii) $x' = 0$ (iv) $x' = x$

(3) With the above information, the exact frequency of the unknown tuning fork can be determined as illustrated below.

Suppose two tuning forks A (frequency n_A is known) and B (frequency n_B is unknown) are sounded together and gives x *beats/sec*. If one prong of unknown tuning fork B is loaded with a little wax (so n_B decreases) and it is sounded again together with known tuning fork A, then in the following four given condition n_B can be determined.

(4) If $x' > x$ than x, then this would happen only when the new frequency of B is more away from n_A. This would happen if originally (before loading), n_B was less than n_A.

Thus initially $n_B = n_A - x$.

(5) If $x' < x$ than x, then this would happen only when the new frequency of B is more nearer to n_A. This would happen if originally (before loading), n_B was more than n_A.

Thus initially $n_B = n_A + x$.

(6) If $x' = x$ then this would means that the new frequency (after loading) differs from n_A by the same amount as was the old frequency (before loading). This means initially $n_B = n_A + x$

(and now it has decreased to $n'_B = n_A - x$)

(7) If $x' = 0$, then this would happen only when the new frequency of B becomes equal to n_A. This would happen if originally n_B was more than n_A.

Thus initially $n_B = n_A + x$.

Table 17.7 ; Frequency of unknown tuning fork for various cases

By loading	
If B is loaded with wax so its frequency decreases	**If A is loaded with wax its frequency decreases**
If x increases $n_B = n_A - x$	If x increases $n_B = n_A + x$
If x decrease $n_B = n_A + x$	If x decrease $n_B = n_A - x$
If remains same $n_B = n_A + x$	If remains same $n_B = n_A - x$
If x becomes zero $n_B = n_A + x$	If x becomes zero $n_B = n_A - x$
By filing	
If B is filed, its frequency increases	**If A is filed, its frequency increases**
If x increases $n_B = n_A + x$	If x increases $n_B = n_A - x$
If x decrease $n_B = n_A - x$	If x decrease $n_B = n_A + x$
If remains same $n_B = n_A - x$	If remains same $n_B = n_A + x$
If x becomes zero $n_B = n_A - x$	If x becomes zero $n_B = n_A + x$

Doppler's Effect

Whenever there is a relative motion between a source of sound and the observer (listener), the frequency of sound heard by the observer is different from the actual frequency of sound emitted by the source.

The frequency observed by the observer is called the apparent frequency. It may be less than or greater than the actual frequency emitted by the sound source. The difference depends on the relative motion between the source and observer.

(1) **When observer and source are stationary**

(i) Sound waves propagate in the form of spherical wavefronts (shown as circles)

(ii) The distance between two successive circles is equal to wavelength λ.

(iii) Number of waves crossing the observer = Number of waves emitted by the source

(iv) Thus apparent frequency (n') = actual frequency (n).

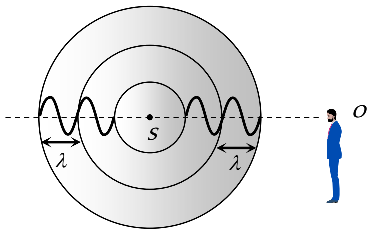


Fig. 17.33

(2) **When source is moving but observer is at rest**

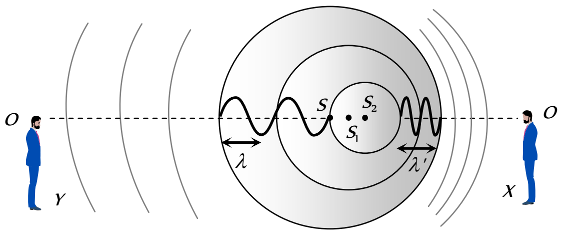


Fig. 17.34

(i) S_1, S_2, S_3 are the positions of the source at three different positions.

(ii) Waves are represented by non-concentric circles, they appear compressed in the forward direction and spread out in backward direction.

(iii) For observer (X)

Apparent wavelength λ' < Actual wavelength λ

$\Rightarrow$ Apparent frequency n' > Actual frequency n

For observer (Y) : $\lambda' > \lambda \Rightarrow n' < n$

(3) **When source is stationary but observer is moving**

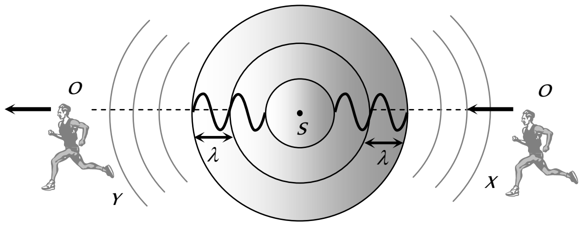


Fig. 17.35

(i) Waves are again represented by concentric circles.

(ii) No change in wavelength received by either observer X or Y.

(iii) Observer X (moving towards) receives wave fronts at shorter interval thus $n' > n$.

(iv) Observer Y receives wavelengths at longer interval thus $n' < n$.

(4) **General expression for apparent frequency** : Suppose observed (O) and source (S) are moving in the same direction along a line with velocities v_o and v_s respectively. Velocity of sound is v and velocity of medium is v_m then apparent frequency observed by observer is given by $n' = \left[\frac{(v + v_m) - v_O}{(v + v_m) - v_S}\right] n$

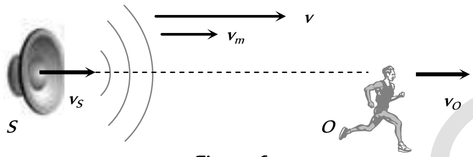


Fig. 17.36

If medium is stationary *i.e.* $v_m = 0$ then $n' = n\left(\frac{v - v_O}{v - v_S}\right)$

Sign convection for different situation

(i) The direction of v is always taken from source to observer.

(ii) All the velocities in the direction of v are taken positive.

(iii) All the velocities in the opposite direction of v are taken negative.

Common Cases in Doppler's Effect

***Case 1 :* Source is moving but observer at rest.**

(1) Source is moving towards the observer

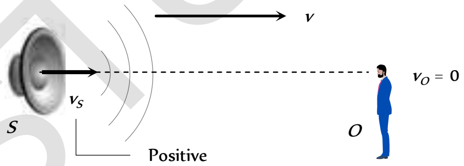


Fig. 17.37

Apparent frequency $n' = n\left[\frac{v - 0}{v - (+v_S)}\right] = n\left(\frac{v}{v - v_S}\right)$

Apparent wavelength $\lambda' = \lambda\left(\frac{v - v_S}{v}\right)$

(2) Source is moving away from the observer.

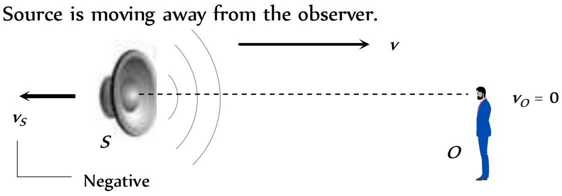


Fig. 17.38

Apparent frequency $n' = n\left[\frac{v - 0}{v - (-v_S)}\right] = n\left(\frac{v}{v + v_S}\right)$

Apparent wavelength $\lambda' = \lambda\left(\frac{v + v_S}{v}\right)$

***Case* 2: Source is at rest but observer is moving.**

(1) Observer is moving towards the source.

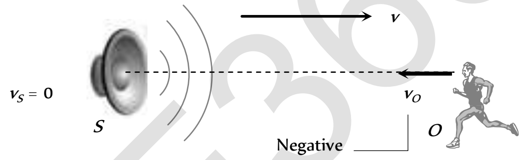


Fig. 17.39

Apparent frequency $n' = n\left[\frac{v - (-v_O)}{v - 0}\right] = n\left[\frac{v + v_O}{v}\right]$

Apparent wavelength $\lambda' = \frac{(v + v_O)}{n'} = \frac{(v + v_O)}{n\frac{(v + v_O)}{v}} = \frac{v}{n} = \lambda$

(2) Observer is moving away from the source

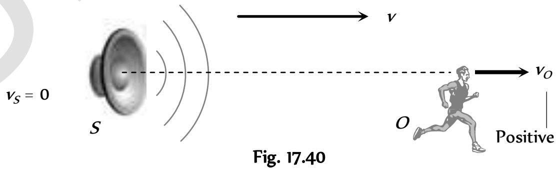


Fig. 17.40

Apparent frequency $n' = n\left[\frac{v - (+v_O)}{v - 0}\right] = n\left[\frac{v - v_O}{v}\right]$

Apparent wavelength $\lambda' = \lambda$

***Case* 3: When source and observer both are moving**

(1) When both are moving towards each other

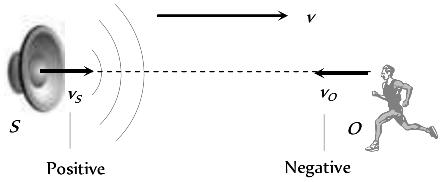


Fig. 17.41

(i) Apparent frequency $n' = n\left[\frac{v - (-v_O)}{v - (+v_S)}\right] = n\left[\frac{v + v_O}{v - v_S}\right]$

(ii) Apparent wavelength $\lambda' = \lambda\left(\frac{v - v_S}{v}\right)$

(iii) Velocity of wave with respect to observer $= (v + v_O)$

(2) When both are moving away from each other.

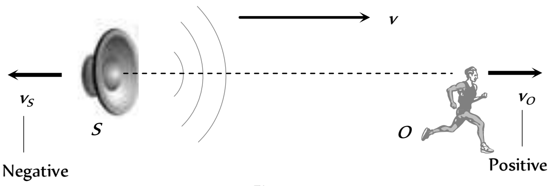


Fig. 17.42

(i) Apparent frequency $n' = n\left[\frac{v-(+v_O)}{v-(-v_S)}\right] = n\left[\frac{v-v_O}{v+v_S}\right]$

($n' < n$)

(ii) Apparent wavelength $\lambda' = \lambda\left(\frac{v+v_S}{v}\right)$

($\lambda' > \lambda$)

Velocity of waves with respect to observer = $(v - v)$

(3) When source is moving behind observer

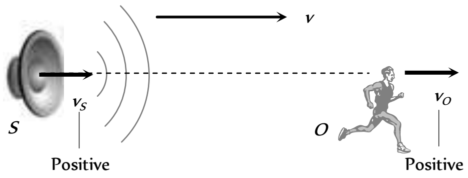


Fig. 17.43

(i) Apparent frequency $n' = n\left(\frac{v-v_O}{v-v_S}\right)$

(a) If $v_O < v_S$, then $n' > n$

(b) If $v_O > v_S$ then $n' < n$

(c) If $v_O = v_S$ then $n' = n$

(ii) Apparent wavelength $\lambda' = \lambda\left(\frac{v-v_S}{v}\right)$

(iii) Velocity of waves with respect to observer = $(v - v_O)$

(4) When observer is moving behind the source

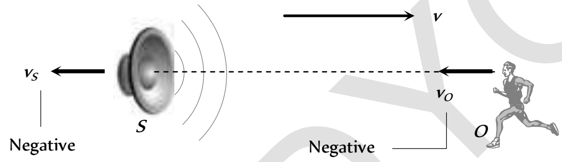


Fig. 17.44

(i) Apparent frequency $n' = n\left(\frac{v-(-v_O)}{v-(-v_S)}\right)$

(a) If $v_O > v_S$, then $n' > n$

(b) If $v_O < v_S$ then $n' < n$

(c) If $v_O = v_S$ then $n' = n$

(ii) Apparent wavelength $\lambda' = \lambda\left(\frac{v+v_S}{v}\right)$

(iii) The velocity of waves with respect to observer = $(v + v_O)$

***Case* 4: Crossing**

(1) Moving sound source crosses a stationary observer

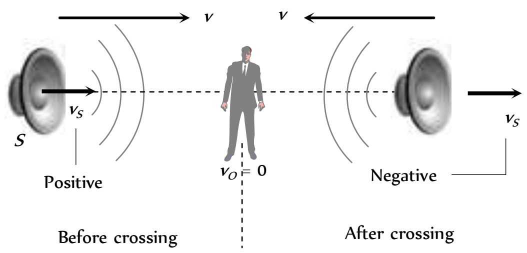


Fig. 17.45

Apparent frequency before crossing

$$n'_{Before} = n\left[\frac{v-0}{v-(+v_S)}\right] = n\left[\frac{v}{v-v_S}\right]$$

Apparent frequency

$$n'_{After} = n\left[\frac{v-0}{v-(-v_S)}\right] = n\left[\frac{v}{v+v_S}\right]$$

Ratio of two frequency $\frac{n'_{Before}}{n'_{After}} = \left[\frac{v+v_S}{v-v_S}\right] > 1$

Change in apparent frequency $n'_{Before} - n'_{After} = \frac{2nv_S v}{(v^2 - v_S^2)}$

If $v_S << v$ then $n'_{Before} - n'_{After} = \frac{2nv_S}{v}$

(2) **Moving observer crosses a stationary source**

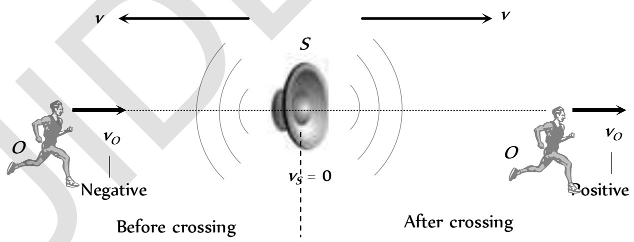


Fig. 17.46

Apparent frequency before crossing

$$n'_{Before} = n\left[\frac{v-(-v_O)}{v-0}\right] = n\left[\frac{v+v_O}{v}\right]$$

Apparent frequency

$$n'_{After} = n\left[\frac{v-(+v_O)}{v-0}\right] = n\left[\frac{v-v_O}{v}\right]$$

Ratio of two frequency $\frac{n'_{Before}}{n'_{After}} = \left[\frac{v+v_S}{v-v_S}\right]$

Change in apparent frequency $n'_{Before} - n'_{After} = \frac{2nv_O}{v}$

***Case* 5:** Both moves in the same direction with same velocity $n' = n$, *i.e.* there will be no Doppler effect because relative motion between source and listener is zero.

***Case* 6:** Source and listener moves at right angle to the direction of wave propagation. $n' = n$

It means there is no change in frequency of sound heard if there is a small displacement of source and listener at right angle to the direction of wave propagation but for a large displacement the frequency decreases because the distance between source of sound and listener increases.

Some Typical Cases of Doppler's Effect

(1) **Moving car towards wall :** When a car is moving towards a stationary wall as shown in figure. If the car sounds a horn, wave travels toward the wall and is reflected from the wall. When the reflected wave is

heard by the driver, it appears to be of relatively high pitch. If we wish to measure the frequency of reflected sound then the problem.

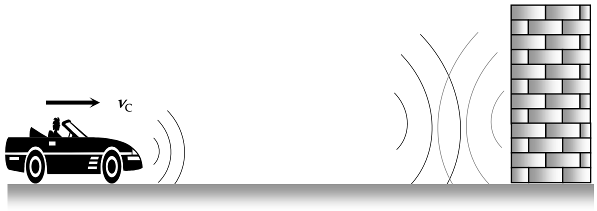


Fig. 17.47

Can be solved in a different manner by using method of sound images. In this procedure we assume the image of the sound source behind the reflector.

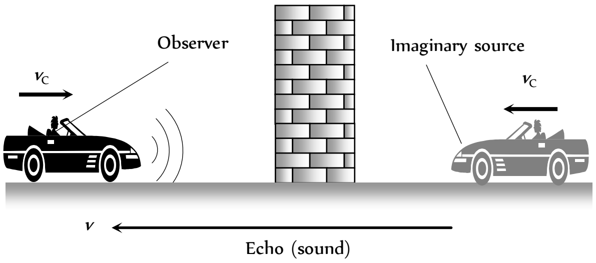


Fig. 17.48

Here we assume that the sound which is reflected by the stationary wall is coming from the image of car which is at the back of it and coming toward it with velocity v_c. Now the frequency of sound heard by car driver can directly be given as

$$n' = n\left[\frac{v-(-v_C)}{v-(+v_C)}\right] = n\left[\frac{v+v_C}{v-v_C}\right]$$

This method of images for solving problems of Doppler effect is very convenient but is used only for velocities of source and observer which are very small compared to the speed of sound and it should not be used frequently when the reflector of sound is moving.

(2) **Moving target :** Let a sound source S and observer O are at rest (stationary). The frequency of sound emitted by the source is n and velocity of waves is v.

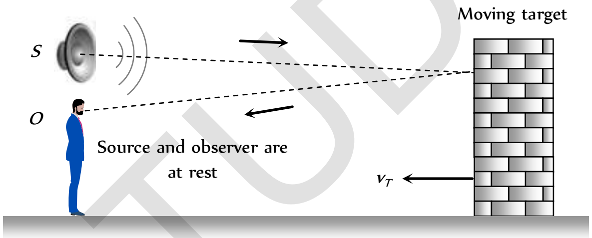


Fig. 17.49

A target is moving towards the source and observer, with a velocity v_t. Our aim is to find out the frequency observed by the observer, for the waves reaching it after reflection from the moving target. The formula is derived by applying Doppler equations twice, first with the target as observer and then with the target as source.

The frequency n' of the waves reaching surface of the moving target (treating it as observer) will be $n' = \left(\frac{v+v_T}{v}\right)n$

Now these waves are reflected by the moving target (which now acts as a source). Therefore the apparent frequency, for the real observer O will be $n'' = \frac{v}{v-v_T}n' \Rightarrow n'' = \frac{v+v_T}{v-v_T}n$

(i) If the target is moving away from the observer, then

$$n' = \frac{v-v_T}{v+v_T}n$$

(ii) If target velocity is much less than the speed of sound, $(v_T << v)$, then $n' = \left(1+\frac{2v_T}{v}\right)n$, for approaching target

and $n' = \left(1-\frac{2v_T}{v}\right)n$, for receding target

(3) **Transverse Doppler's effect**

(i) If a source is moving in a direction making an angle θ *w.r.t.* the observer

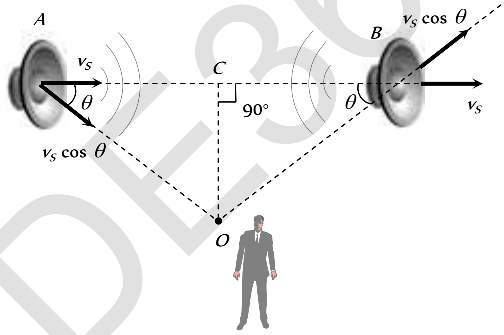


Fig. 17.50

The apparent frequency heard by observer O at rest

At point A : $n' = \frac{nv}{v - v_S\cos\theta}$

As source moves along AB, value of θ increases, $\cos\theta$ decreases, n' goes on decreasing.

At point C : $\theta = 90^o$, $\cos\theta = \cos 90^o = 0$, $n' = n$.

At point B : the apparent frequency of sound becomes

$$n'' = \frac{nv}{v+v_s\cos\theta}$$

(ii) When two cars are moving on perpendicular roads : When car-1 sounds a horn of frequency n, the apparent frequency of sound heard by car-2 can be given as $n' = n\left[\frac{v+v_2\cos\theta_2}{v-v_1\cos\theta_1}\right]$

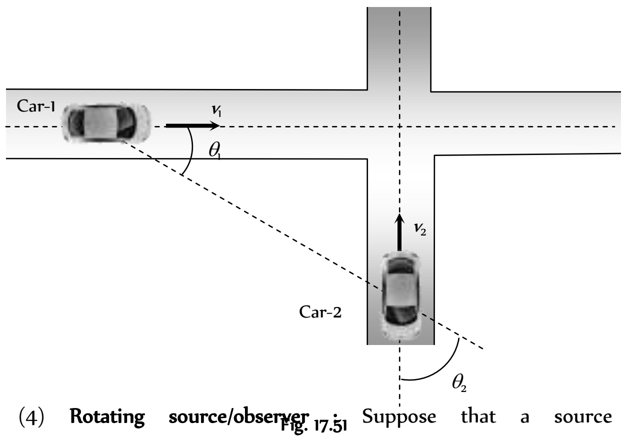


Fig. 17.51

(4) **Rotating source/observer :** Suppose that a source of sound/observer is rotating in a circle of radius r with angular velocity ω (Linear velocity $v_s = r\omega$)

(i) **When source is rotating**

(a) Towards the observer heard frequency will be maximum

i.e. $n_{\max} = \dfrac{nv}{v - v_S}$

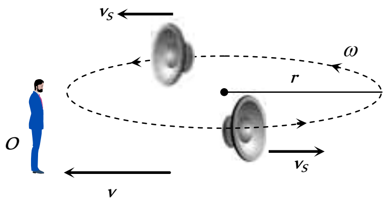


Fig. 17.52

(b) Away from the observer heard frequency will be minimum

and $n_{\min} = \dfrac{nv}{v + v_S}$

(c) Ratio of maximum and minimum frequency

$$\frac{n_{\max}}{n_{\min}} = \frac{v + v_S}{v - v_S}$$

(ii) **When observer is rotating**

(a) Towards the source heard frequency will be maximum

i.e. $n_{\max} = \dfrac{nv}{v - v_S}$

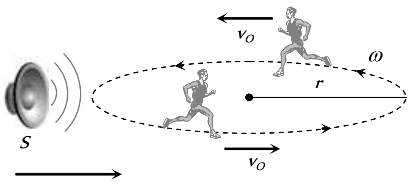


Fig. 17.53

(b) Away from the source heard frequency will be minimum

and $n_{\min} = \dfrac{nv}{v + v_S}$

(c) Ratio of maximum and minimum frequency

$$\frac{n_{\max}}{n_{\min}} = \frac{v + v_S}{v - v_S}$$

(iii) **Observer is situated at the centre of circle :** There will be no change in frequency of sound heard, if the source is situated at the centre of the circle along which listener is moving..

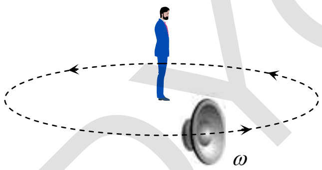


Fig. 17.54

(5) **SONAR :** Sonar means Sound Navigation and Ranging.

(i) Ultrasonic waves are used to detect the presence of big rocks, submarines *etc* in the sea.

(ii) The waves emitted by a source are reflected by the target and received back at the SONAR station.

(iii) If v is velocity of sound waves in water and v_{sub} is velocity of target (submarine), the apparent frequency of reflected waves will be

$$n' = \left(1 \pm \frac{2v_{sub}}{v}\right) n$$

+ sign is for target approaching the receiver and – sign for target moving away.

Conditions for No Doppler's Effect

(1) When source (S) and listener (L) both are at rest.

(2) When medium alone is moving.

(3) When S and L move in such a way that distance between S and L remains constant.

(4) When source S and listener L, are moving in mutually perpendicular directions.

(5) If the velocity of source and listener is equal to or greater than the sound velocity then Doppler effect is not seen.

Musical Sound

other rapidly at regular interval of time without a sudden change in amplitude.

(1) **Noise :** A noise consists of a series of waves following each other at irregular intervals of time with sudden changes in amplitude.

(2) **Pitch :** The pitch of a sound is the characteristic which distinguishes between a shrill (or sharp) sound and a grave (or flat) sound.

(i) A sound of high pitch is said to be shrill and it's frequency is high.

(ii) A sound of low pitch is said to be grave and it's frequency is low.

(iii) The pitch of female voice is higher than the pitch of male voice.

(iv) The pitch of sound produced by roaring of lion is lower where as the pitch of sound produced by mosquito whisper is high.

(3) **Quality (or timbre) :** A musical instrument vibrates with many frequencies at the same time. The quality of any musical sound is determined by the number of overtones and their relative intensities.

(i) The quality of sound enables us to distinguish between two sounds having same intensity and pitch.

(ii) The sounds of different instruments (such as Tabla and Mridang) are said to differ in quality.

(iii) Due to quality of sound one can recognise the voice of his friend without seeing him.

(4) **Loudness :** Characteristic of sound, on account of which the sound appears to be intense or slow.

(i) The loudness that we sense is related to the intensity of sound though it is not directly proportional

(ii) The loudness depends on intensity as well as upon the sensitiveness of ear.

(iii) Our perception of loudness is better co–related with the sound level measured in decible (dB) and defined as follows $\beta = 10\log_{10}\left(\dfrac{I}{I_0}\right)$;

where I_0 = The minimum intensity that can be heard called threshold of hearing = 10^{-12} W/m^2 at 1 KHz.

(iv) At the threshold of hearing β = 0. At the threshold of pain

$$\beta = 10\log_{10}\frac{1}{10^{-2}} = 120\, dB.$$

(v) When the intensity doubles, the intensity level changes by 3 dB.

(vi) When the intensity increases 10 times the level increases by 10 dB.

Table 17.8 ; Different sound intensity level

Source of sound	dB

Rustling leaves	10
Whisper	20
Quiet room	30
Normal level of speech (inside)	30
Street traffic (inside car)	65
Riveting tool	80
Thunder	100
Indoor rock concert	120

Interval : The ratio of the frequencies of the two notes is called the interval between them *e.g.* interval between two notes of frequencies 256 *Hz* and 512 *Hz* is 1 : 2.

Table 17.9 ; Different interval

Name of interval	Frequency ratio
Unison	1 : 1
Octave	2 : 1
Major tone	9 : 8
Minor tone	10 : 9
Semi tone	16 : 15

Musical scale : It consists of a series of notes of successively increasing frequency, having constant intervals. The note of the lowest frequency is called the key note.

These are many kinds of musical scales. The most commonly used scale is called major diatonic scale. It is formed by introducing six more notes between a given note and it's octave, so that these are eight notes in all.

Table 17.10 : Major diatonic scale

Symbol	Indian name	Western name	Frequency in the base of 256 *Hz*	Interval between successive notes
C	*SA*	*DO*	256	9/8
D	*RE*	*RE*	288	10/9
E	*GA*	*MI*	320	16/15
F	MA	*FA*	341	9/8
G	PA	SOL	384	10/9
A	*DHA*	*LA*	427	9/8
B	Ni	*SI*	480	16/15
C_1	*SA*	*DO*	512	

Accoustics of Buildings

Accounstics is the branch of physics that deals with the generation, propagation and reception of sound.

W.C. Sabine was the first to carry out the scientific study of architectural acoustics by laying down following rules.

The sound must be loud enough.

The quality of sound must be unaltered.

The successive sounds of speech or music must remain distinct.

These should not be unnecessary interference or resonance of sound in the auditorium.

These should be no echoes in the auditorium.

(1) **Reverberation :** Phenomenon of persistence or prolongation of sound in the auditorium is called reverberation.

(2) **Reverberation time :** The time gap between the initial direct note and the reflected note upto the minimum audibility level is called reverberation time.

(3) **Sabine law :** Sabine derived an expression of the reverberation time which is $t = K.\frac{V}{\alpha S}$; where K is constant, V = Volume of the hall, S = Surface area exposed to the sound α =Co-efficient of absorption.

(4) **Controlling the reverberation time :** It may be controlled as follows :

By hanging heavy curtains on the doors.

By having few open windows in the hall.

By having large audience.

By using absorbing materials in the walls and roofs of the hall.

Tips & Tricks

✍ In an open pipe all harmonics are present whereas in a closed organ pipe, only alternate harmonics of frequencies $n_1, 3n_1, 5n_1,.....$ *etc.* are present.

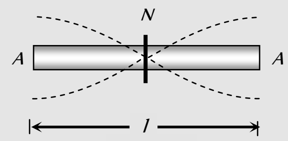
The harmonics of frequencies $2n_1, 4n_1, 6n_1....$ are missing. Hence musical sound produces by an open organ pipe is sweeter than that produced by a closed organ pipe.

✍ If an open pipe is half submerged in water, it will become a closed organ pipe of length half that of a open pipe. It's fundamental frequency will become $n' = \frac{v}{4\left(\frac{l}{2}\right)} = \frac{v}{2l} = n_1$ *i.e.,* equal to that of open pipe.

i.e., frequency remains unchanged.

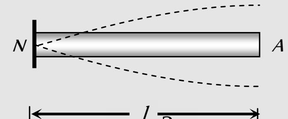
✍ **Vibrating clamped rod :** Frequency of vibration of clamped rod are same as that of organ pipes

Middle clamping : Similar to open organ pipe



$n_1 = \frac{v}{2l}$ $n_2 = 2n_1$ $n_3 = 3n_1$

End clamping : Similar to closed organ pipe



$n_1 = \frac{v}{4l}$ $n_2 = 2n_1$ $n_3 = 3n_1$

✍ Sound produced in air is not heard by the diver deep inside the water because most of the sound is reflected from the surface of water in comparison to the refraction.

✍ If the difference between the apparent frequency of a source of sound as perceived by an observer during it's approach and recession is x% of the natural frequency of source then speed of $v_s = \frac{v_{sound}}{200} x$

$(v^2 >> v_s^2)$

✍ In a Tabla, the membrane is loaded about the centre why? a note is musical when it is rich in harmonics and not partial overtones. Ordinarily a stretched membrane vibrates with such overtones. But when the stretched membrane is loaded at the centre, its overtones become nearly harmonics, so it's sound becomes fairly musical.

✍ All harmonics are overtones but all overtones are not harmonics.

✍ Stethoscope work on the principle of reflection of sound.

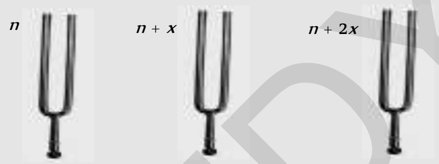
✍ Ultrasonic waves can be produced by utilizing piezoelectric effect.

✍ There is no atmosphere on moon, therefore propagation of sound is not possible there. To do conversation on moon, the astronaut uses an instrument which can transmit and detect electromagnetic waves.

✍ Doppler effect gives information regarding the change in frequency only. It does not says about intensity of sound.

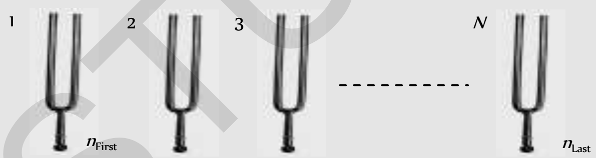
✍ Doppler effect in sound is asymmetric but in light it is symmetric.

✍ If three tuning forks of frequencies n, $n + x$ and $n + 2x$ are sounded together to produce waves of equal amplitude these three wave produces beats with beat frequency = x *beats/sec*

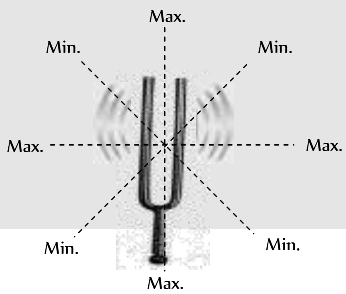


✍ If N tuning forks are so arranged that every fork gives x *beats per sec* with the next then the frequency of last fork will be

$n_{Last} = n_{First} + (N - 1)\, x$



✍ If a vibrating tuning fork is rotated about it's stem, maximum and minimum number of beats heard by an observer in one revolution of tuning fork are 4.



✍ The tuning of radio receiving set to a particular station is based on forced vibration.

✍ Two avoid resonant vibration of the bridge, soldiers are orderd to break steps while crossing a bridge.

✍ **Confusion :** So many students often confuse whether the equation of a plan progressive wave should be

$$y = a \sin (\omega t - kx) \text{ or } y = a \sin (kx - \omega t)$$

Both the equations represent a travelling wave but these two are not same. These waves are differ by a phae difference of π.

✍ **Audibility of sound in day/night :** During the day temperature of air is maximum and it dimnished upwards. Therefore velocity of sound is also decreases upwards ($v \propto \sqrt{T}$). The plane wavefronts, initially vertical are turned, upwards so sound rays curl up during the day. At night the conditions are reversed hence audibility of sound is better in night as compare to day.