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WAVE MOTION SOUNDS

CBSE PHYSICS

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In kinematics and dynamics we have studied about bodies in motion and have classified the different types of motion as

1. translatory motion
2. vibratory or oscillatory motion, and
3. rotatory motion

In each of these cases we find that the bodies possess kinetic energy and this kinetic energy can be transformed into other forms like potential energy, electrical energy, heat energy, sound energy etc. Electrical energy can be transmitted from the generating stations through electrical conductors and transmission of heat energy takes place by conduction, convection and radiation. To understand the transmission of sound energy we need to direct our attention to the particular effects of vibratory motion of particles.

Periodic Motion of Particles

Before we move on to study the nature and transmission of sound, we need to understand the different types of vibratory or oscillatory motions.

A motion, such as that of the earth around the sun, the movement of the hands of the clock etc., is referred to as **periodic motion**, since the motion of the object repeats itself at regular intervals of time.

A to-and-fro motion, such as the swinging of a pendulum, vertical oscillations of a mass suspended from a spring etc, is referred to as **harmonic motion**.

A harmonic motion in which the amplitude and time period of oscillation remain constant is particularly referred to as **simple harmonic motion (SHM).** In a SHM the acceleration of the body or particle executing the motion is directly proportional to its displacement from the mean position and is directed towards the mean position. The total mechanical energy of the particle is conserved.

Graphical representation of simple harmonic motion, its characteristics and relations

Consider a simple pendulum suspended by means of a thread from a rigid support and allowed to vibrate in a vertical plane as shown in figure (8.1). 'O' is the rest position or the mean position of the bob of the pendulum and 'A' and 'B' are its extreme positions. If the direction of motion of the bob towards 'A' is taken as positive, then the direction towards 'B' is negative.

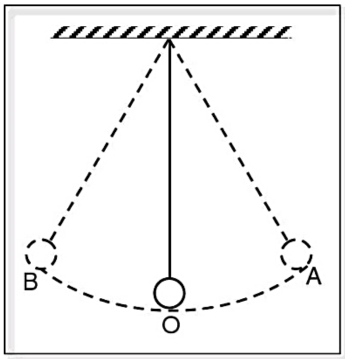


Figure 8.1

The pendulum oscillates to and fro and the time taken for one complete oscillation is known as **time period** (T). The magnitudes of the displacements from mean position is maximum when the bob is at either 'A' or 'B' and this maximum displacement of the vibrating particle from its mean position is known as '**amplitude**' (A).

A graph plotted between the displacement of the bob from its mean position and the time, is as shown in figure (8.2).

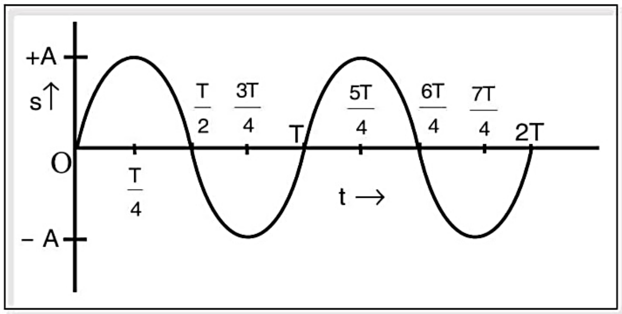


Figure 8.2

As the time increases, displacement increases to the maximum of 'A' at $t = \frac{T}{4}$ and then the bob comes to mean position at $t = \frac{T}{2}$ and so displacement is zero. It continues to move towards negative side, and when the time $t = \frac{3T}{4}$ its displacement is equal to amplitude. When t = T, it comes back to mean position completing one full vibration.

The number of vibrations the pendulum bob makes in unit time is known as **frequency** (n) and is measured in hertz (Hz)

The time period and the frequency are related as $n = \frac{1}{T}$.

Here, we find that the graph is in the form of a wave that we see on the surface of water.

Wave Motion

When a pebble is thrown into still water circular ripples are formed which spread out in all directions on the surface of water from the point where the stone hit the water surface. Thus, the kinetic energy of the stone is transferred to the water and that energy is distributed to the entire water in the pond in the form of ripples or waves. To check whether water moves along with ripples produced or not, we can observe a floating object like a cork or a leaf placed on the surface of water. As the ripples move in all possible directions on the surface of water from the point where the disturbance is produced, the leaf which is floating on the surface of water vibrates up and down, but does not have lateral translatory motion along the surface of water. We even observe that the leaf does not start vibrating till the first ripple reaches it from the point of disturbance. This is the characteristic of the propagation of waves.

The energy is transmitted from one point to another without actual translatory motion or transport of the particles across the medium. Thus a "wave is a disturbance produced at a point in a medium or a field and is transmitted to other parts of the medium or the field without the actual translatory motion of the particles". The transfer of energy in the form of waves is known as "wave motion".

A **pulse** is a disturbance lasting for a short duration.

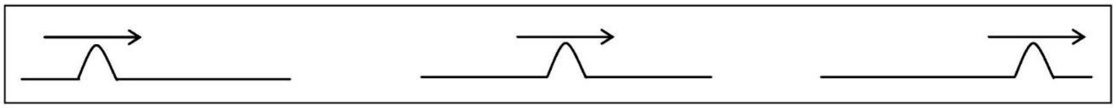


Figure 8.3

A **wave** on the other hand is a sustained disturbance lasting for a longer duration, like waves on the surface of water.

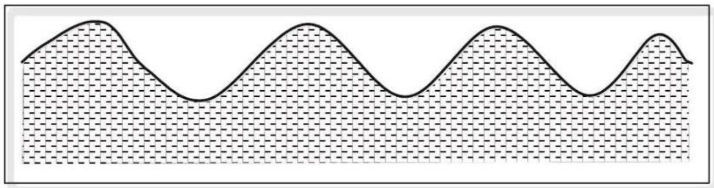


Figure 8.4

Before we proceed to study wave motion in greater detail let us first review the terms and physical quantities associated with wave motion.

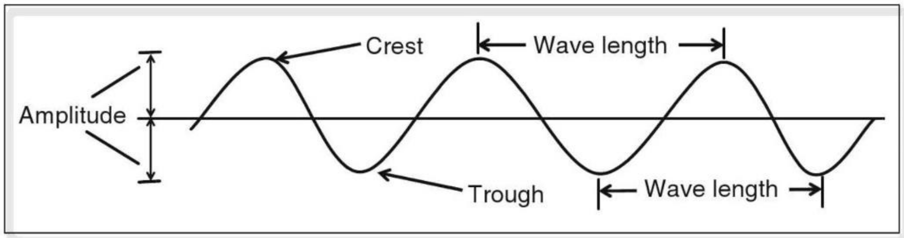


Figure 8.5

Crest is the point of maximum displacement of a particle in upward direction.

Trough is the point of maximum displacement of a particle in downward direction.

Amplitude is the maximum displacement of the particles either upwards or downwards.

Wavelength (λ) is the distance between any two successive crests or troughs.

Time period (T) is the time taken by a particle to complete one oscillation or vibration.

Frequency (n) is the number of oscillations or vibrations made by a particle in one second.

$$n = \frac{1}{T}$$

The S.I. unit of frequency is hertz (Hz).

1 hertz = 1 s^{-1}

Velocity of a wave is the speed with which the wave propagates in the medium.

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

$$v = n\lambda$$

Phase

The motion of the vibrating particles and their direction is described in terms of its phase. Thus particles in the same phase would be exactly at the same distance from their mean positions and have the same instantaneous velocity at any given moment.

If the motion of two particles is such that their displacement, motion and velocity are dissimilar to each other, then they are said to have phase difference. If two particles have same magnitude of displacement from mean position and velocity but the direction of these vector quantities are opposite to each other, then they are said to be out of phase.

Transmission of energy

Thus we see that wave motion refers to the transmission of energy from one place to another without actual movement of the particles or entities of the medium.

Classification of waves

It is found that certain type of waves require a medium for propagation, e.g., water waves, sound waves etc., whereas there exist waves which do not require a medium for their propagation, e.g., light waves.

The direction of vibration of particles differ from the direction of wave motion from one type of wave to another. Similarly some waves move endlessly in a medium whereas some are confined between two points.

Based on these factors, waves can be classified into different types as follows:

A. Classification based on the necessity of medium—**Mechanical waves** and **Electromagnetic waves**.

Mechanical waves are the waves which require a material medium for their propagation. They are also called 'elastic waves' as the main cause for their propagation in the medium is a property of the medium called 'elasticity'.

If an applied force on a body changes its shape or size or both, and when the force is taken away, if the body regains its original shape and size, the body is said to be 'elastic' and its property to regain its original shape and size after the applied force is removed is known as 'elasticity'.

Electromagnetic waves are the waves which do not require an elastic medium for their propagation. They can propagate through material media as well as vacuum. Light waves are an example of electromagnetic waves.

B. Classification based on the direction of vibration of particles with respect to the direction of wave motion–**Transverse** and **longitudinal** waves.

When a mechanical wave propagates from one place to another in a medium, the direction of vibration of particles of the medium can be either parallel or perpendicular to the direction of wave motion.

If the direction of vibration of the particles of the medium is parallel to the direction of wave motion, such a wave is called a 'longitudinal wave' and if it is perpendicular to the direction of wave motion such a wave is called a 'transverse wave'.

Longitudinal wave

Consider a long spring clamped at one of the ends, placed on a horizontal surface of a table in straight position, as shown in figure (8.6). The distance between any two adjacent rings along the length of the spring is constant. If the spring is slightly pulled and then released, the spring begins to vibrate. It can be observed that any two adjacent rings in some parts of the spring come very close to each other, while in other parts they move apart as shown in figure (8.7).

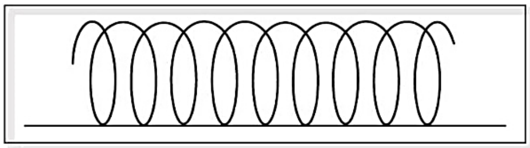


Figure 8.6

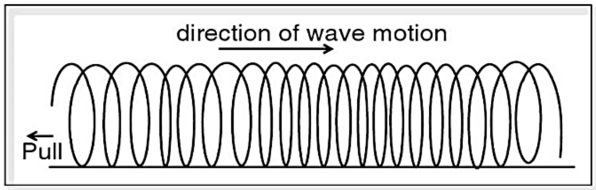


Figure 8.7 Longitudinal waves

The regions where the rings are very close to each other are called 'compressions' and the regions where they are far apart are called 'rarefactions'. The wave set in the spring is a longitudinal wave as the direction of vibration of particles (here rings) is parallel to the direction of wave motion.

So a longitudinal wave moves in a medium in the form of compressions and rarefactions. Whenever compressions and rarefactions are transmitted through a medium, a change in the volume of the medium takes place in those locations. Due to elasticity of the medium, it regains its original volume. Thus longitudinal waves can be set in a medium that opposes change in volume. Since, all the states of matter, solids, liquids and gases have this property to oppose change in volume, longitudinal waves can propagate in solids, liquids and gases.

Transverse wave

When we take a long string along the horizontal position and vibrate it at one end in a direction perpendicular to the length of the string, a wave form is set in the string as shown in figure (8.8). The original position of the string is shown by a dotted line. It is also called as mean or rest position. Here the wave moves in the horizontal direction whereas the particles of the string vibrate in the perpendicular direction (vertical).

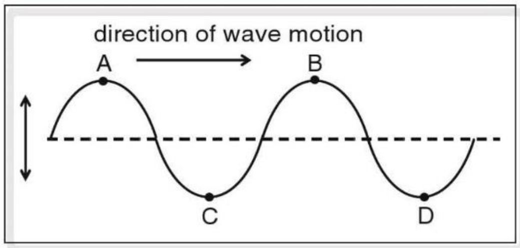


Figure 8.8 Transverse wave

The displacement of the vibrating particles is measured from the mean position. The particles at positions 'A' and 'B' have maximum displacement in the upward direction and these points are known as '**crests**'. Similarly the particles at positions 'C' and 'D' have maximum downward displacement and these points are known as '**troughs**'. As the direction of particle vibration is perpendicular to the direction of wave motion, the wave set in the string is a transverse wave.

Thus when a transverse wave is set in a medium, a series of crests and troughs propagate through the medium. These crests and troughs change the shape of the medium and due to elasticity, the medium regains its original shape. Hence, transverse waves can be set in a medium which opposes change in shape. For this reason, transverse waves can propagate only in solids and at the surface of the liquids but not through liquids and gases.

Consider the cross section of water surface when waves are propagating through its surface as shown in the figure (8.9).

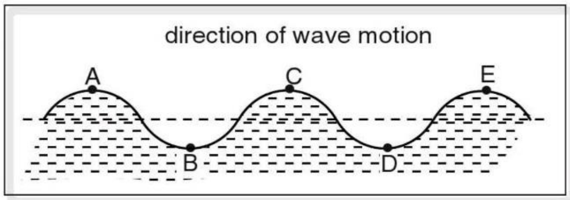


Figure 8.9

The dotted line indicates the rest position of the water surface. As the wave propagates from the left to the right, the water particles vibrate up and down forming crests and troughs. The displacement of the particles at 'A' and 'C' from the mean position is equal and their direction of motion is the same. Thus their status of vibration with respect to the direction of motion and the displacement from the mean position, which is known as '**phase**' is equal and the particles at A,C and E are said to be '**in phase**'. Similarly particles at 'B' and 'D' are in phase. If particles at 'A' and 'B' are considered, their magnitude of displacement from their mean position is equal but their direction of motion is opposite. So they are said to be '**out of phase**'. The minimum distance between the particles of the medium which are in the same phase is called '**wavelength**' of the wave, and is denoted by the Greek letter 'λ' (lambda). So the distance between 'A' and 'C' or that between 'C' and 'E' is the wavelength (λ). By the time the particle at 'A' completes one vibration i.e., after one time period (T), the wave advances by one wavelength (λ). So the velocity of propagation of the wave is given by $v = \frac{\lambda}{T}$.

As $\frac{1}{T} = n$, (the frequency of the wave)

$v = n\lambda$

The velocity of the vibrating particles is not constant throughout their vibration. It is minimum at the extreme positions and maximum at the mean position. But the velocity of the wave propagating through the medium is constant.

The wave considered in figure (8.9) is a transverse wave, and it produces crests and troughs. Similarly when a longitudinal wave such as a sound wave propagates through a medium like gas, it causes compressions and rarefactions while propagating through the medium, causing change in density and pressure throughout the medium.

The graph of pressure (p) or density (d), of a gas, taken along the Y-axis versus the distance from the source of sound to the element of gas vibrating, taken along the X-axis is as shown in figure (8.10).

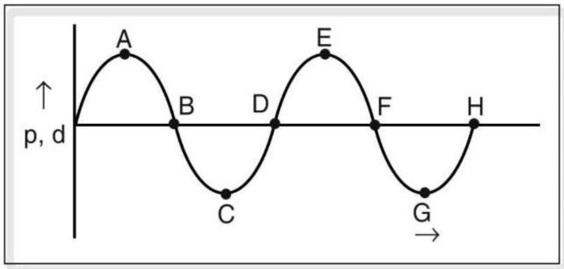


Figure 8.10 Distance of element of gas from source of sound

At positions 'A' and 'E' which correspond to compressions, the density and pressure of a gas are maximum and are more than the normal values. Similarly at positions 'C' and 'G' which correspond to rarefactions, the density and pressure of a gas are minimum and are less than the normal values. The positions, 'B', 'D', 'F', and 'H' show normal pressure and density of the gas.

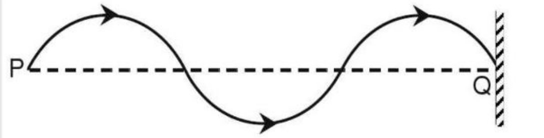
Comparative study of transverse and longitudinal waves

1. The direction of vibration of particles is perpendicular to the direction of propagation of a wave.	1. The direction of vibration of particles is parallel to the direction of propagation of a wave.
2. The wave propagates in the form of crests and troughs.	2. The wave propagates in the form of compressions and rarefactions.
3. These waves can travel through solids and on surface of liquids only, as the propagation of these waves causes change in the shape of the medium.	3. These waves can pass through solids, liquids and gases also, as the propagation of these waves causes change in the volume of the medium.
4. As there is no variation of volume, there is no variation in the density of the medium while the wave propagates through it.	4. When the wave propagates through a medium, there is a change in volume and this causes a variation in the density.
5. There is no difference in pressure created in the medium while the wave propagates.	5. Propagation of longitudinal waves causes pressure difference in the medium.

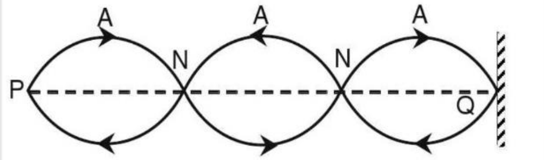
C. Classification based on the limitations of motion — **Progressive** and **stationary** waves.

Some waves start at the point of origin of the waves and progress endlessly into other parts of the medium. Such waves are known as 'Progressive waves'.

Consider a progressive transverse water wave moving from left (point P) to right and striking a hard surface at 'Q' as shown in figure 8.11(a). It then gets reflected at 'Q', and travels towards 'P'. Thus the two waves, one going from 'P' to 'Q' and the other going from 'Q' to 'P' overlap resulting in the formation of 'nodes' and 'antinodes'. Points, where the displacement of a vibrating particle of the medium is zero or minimum are called 'nodes' (shown as N in figure 8.11) and points, where the displacement of the vibrating particles is maximum are called 'antinodes' (shown as A in figure 8.11).



(a) progressive wave striking a hard surface



(b) Stationary wave

Figure 8.11

On the whole, the wave appears to be standing or stationary, contained between two positions 'P' and 'Q' and so called as 'standing' or 'stationary waves'.

Thus a 'progressive wave is a wave which is generated at a point in a medium and travels to all parts of the medium infinitely carrying the energy' and a 'stationary wave is a wave which is formed by a combination of two similar progressive waves traveling in opposite directions'.

Comparative study of progressive and stationary waves

1. These waves start at a point and move indefinitely and infinitely to all parts of the medium or space.	1. These waves appear to be standing at a place and are confined between two points in a medium or space.
2. These waves transmit energy from one place to another.	2. These waves store energy in them.
3. The energy possessed by these waves is kinetic in nature.	3. The energy associated with these waves is potential in nature.
4. These waves contain crests and troughs or compressions and rarefactions.	4. These waves contain nodes and antinodes.
5. All the particles in the wave have equal amplitude	5. Different particles in the wave have different amplitudes.
6. There is a continuous phase difference between the particles in the wave.	6. The phase difference between the particles in a given loop in the wave is zero.

Sound

Sound is a form of energy. It causes sensation in our ears. It is produced by bodies which vibrate.

Consider a tuning fork which is excited by hitting on a rubber hammer. When such a tuning fork is kept near our ears, we hear the sound but are unable to detect the vibrations of the tuning fork. When the fork producing sound is brought into contact with a pith ball suspended from a rigid support by means of a thread, the ball is flicked by the fork (figure 8.12). The ball is flicked by the vibrations of the fork and this proves that sound is produced by vibrating bodies. However, the sound produced by all vibrating is not audible.

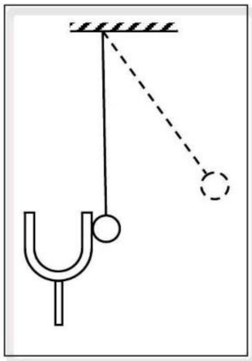


Figure 8.12

When we speak, sound is produced by the vibration of vocal chords present in a cavity called larynx, in our throat. Sound is transmitted in the form of mechanical waves. Thus sound needs a medium to travel, since mechanical waves can propagate only through material medium.

Experiment to prove that sound requires a medium for propagation

Consider an electric bell suspended in a glass jar containing an outlet. The bell is suspended from the lid (which is made of cork) of the jar through strings and there are two small holes to the lid through which electric wires are connected to the bell (figure 8.13). Initially, air is present in the jar and when the electric current is passed through the circuit of the bell by switching it on (switch not shown in the figure), the bell rings and the sound is heard.

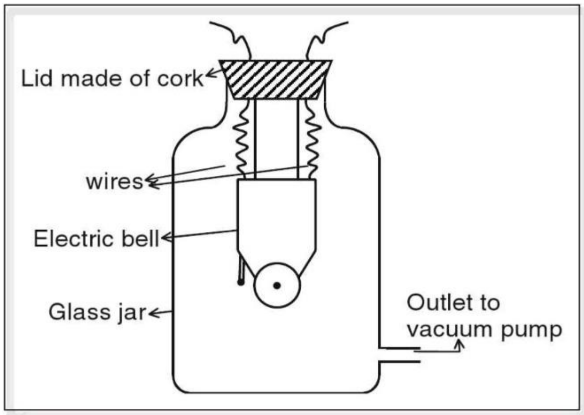


Figure 8.13 Bell-jar experiment

Now the jar outlet is connected to a vacuum pump and the air is removed from the jar. Thus there is no medium surrounding the bell in the jar. If we switch on the circuit, we can see the bell ringing but the sound cannot be heard. This shows that sound cannot travel through vacuum.

Frequency (An important characteristic of sound)

We know that sound is produced by a vibrating body. But we cannot sense the sounds produced by all vibrating bodies. For example, we cannot sense the sound produced by a vibrating pendulum. This is because the frequency of the pendulum is very less. We will be able to sense the sounds having frequencies from 20 Hz to 20,000 Hz; and cannot sense the sounds having frequencies either less than 20 Hz or greater than 20,000 Hz. The frequency which ranges from 20 Hz to 20,000 Hz is known as '**audible range**'. The sounds having frequency less than 20 Hz are known as '**infrasonics**' and the sounds having frequency greater than 20,000 Hz are known as '**ultrasonics**'.

Uses of ultrasonics

1. For homogenizing milk, ultrasonic waves are used.
2. These waves are used in dish washers in the process of cleaning the vessels.

3. These waves are used in ultrasound scanning technique, which is helpful in knowing the condition of the internal organs of a human body.
4. Bats are sensitive to ultrasonic waves and with the help of those waves they can move easily in the dark.
5. Dolphins communicate with each other by using ultrasounds.
6. Dogs can hear sounds upto 40000 Hz and hence they can be trained to respond to these sounds using a Galton whistle, producing high frequency sounds outside the audible range for humans.

Comparison between light waves and sound waves

[redacted]	[redacted]
1. These are electromagnetic waves and can pass through vacuum also.	1. These are mechanical waves and cannot pass through vacuum.
2. The velocity of light waves is not affected by temperature, humidity etc.	2. The velocity of sound in air changes with temperature, humidity.
3. These waves excite the retina and produce the sense of vision.	3. These waves excite the ear drum and produce the sense of hearing.
4. These are produced due to transition of electrons from the excited state to the normal state.	4. These are produced by bodies that vibrate.
5. These waves are transverse in nature.	5. These waves can be either transverse or longitudinal in nature depending on the medium in which they propagate.
6. The value of velocity of light in air is 3×10^8 m s^{-1}.	6. The value of velocity of sound in air at normal temperature and pressure is 330 m s^{-1}.

Transmission of sound

Sound can be transmitted from one place to another in the form of mechanical waves. It can be transmitted through solids and surface of liquids in the form of transverse or longitudinal waves but through gases only in the form of longitudinal waves.

Velocity of sound

Velocity of sound in different media is different; but in a given medium its value is constant and depends mainly on two properties, namely, elasticity and density of the medium.

If the medium is homogeneous, its density and elasticity do not change with direction and so the velocity of sound in it remains constant. In solids, the velocity of longitudinal waves is greater than that of transverse waves. This is evident from the fact that primary shock waves produced during an earthquake which are longitudinal in nature reach the seismic station first and the secondary shock waves which are transverse in nature reach the seismic station later.

Sir Issac Newton gave a mathematical expression for the velocity of waves in an elastic medium, as $v = \sqrt{\frac{E}{d}}$; where 'v', 'E' and 'd' are velocity of the wave in the medium, elasticity and density of the medium respectively.

In case of solids, the elasticity is measured by its Young's modulus (Y) and so velocity of sound in solids is given by $v = \sqrt{\frac{Y}{d}}$.

When solids, liquids and gases are compared, the density is maximum in solids, comparatively less in liquids and least in gases. Yet, the velocity of sound in solids is maximum, less in liquids and then least in gases. This is due to the fact that even though the density of solids is greater than that of liquids and gases, the elasticity of solids is many more times larger than that of liquids and gases.

Thus, the ratio of elasticity to density is largest in solids, less in liquids and least in gases and so the decreasing order of velocity of sound is $v_s > v_\ell > v_g$ where v_s, v_ℓ and v_g are velocity of sound in solids, liquids and gases respectively.

In case of gases, the elasticity factor for gases is its pressure and hence the expression for velocity of waves in a given medium was derived by Newton as $v = \sqrt{\frac{P}{d}}$; where 'P' and 'd' are pressure and density of a given gas and 'v' is velocity of sound in the gas.

Sir Isaac Newton assumed that when a sound wave propagates through gas, the changes that take place in volume were isothermal (changes that take place at constant temperature), but it was proved to be wrong. The value of velocity of sound in a gas as presumed by Newton and calculated from his formula was found to be 280 m s^{-1} whereas the observed value by experimentation was about 330 m s^{-1}.

The expression given by Newton for the velocity of sound in a gas was modified by Laplace as $v = \sqrt{\frac{\gamma P}{d}}$; where '$\gamma$' is a constant for a given gas and it is defined as the ratio of the specific heat capacity of the gas at constant pressure to its specific heat capacity at constant volume.

The modification was done as the changes that take place during the propagation of sound in a gas are found to be 'adiabatic' (changes that take place without any transfer of heat). The value of velocity of sound in air calculated using the Laplace correction was coinciding with the observed value obtained by experimentation.

Factors on which the velocity of sound in a gas depends

1. **Temperature:** The velocity of sound in a gas is directly proportional to the square root of its absolute or kelvin temperature.

   Mathematically, $v \propto \sqrt{T}$; where v and T are the velocity of sound in a gas and its absolute temperature respectively.

   If v_1 and v_2 are the velocities of sound in a gas at absolute temperatures T_1 and T_2 respectively then $v_1 \propto \sqrt{T_1}$ and $v_2 \propto \sqrt{T_2}$.

So $\frac{v_1}{v_2} = \sqrt{\frac{d_2}{d_1}}$

2. **Molecular weight:** The velocity of sound in a gas is inversely proportional to the square root of its molecular weight.

   Mathematically, $v \propto \frac{1}{\sqrt{M}}$; where 'v' is the velocity of sound in a gas and 'M' is its molecular weight.

   If v_1 and v_2 are the velocities of sound in two gases whose molecular weights are M_1 and M_2 respectively at a constant temperature, then $\frac{v_1}{v_2} = \sqrt{\frac{M_2}{M_1}}$.

3. **Density:** The velocity of sound in gas is inversely proportional to the square root of its density.

   Mathematically, $v \propto \frac{1}{\sqrt{d}}$; where 'v' and 'd' are the velocity of sound in a gas and its density respectively.

   If 'v_1' and 'v_2' are the velocities of sound in two gases whose densities are 'd_1' and 'd_2' respectively, at a constant temperature, then $\frac{v_1}{v_2} = \sqrt{\frac{d_2}{d_1}}$

Factors that affect velocity of sound in air

1. **Temperature:** The velocity of sound in air is directly proportional to the square root of its absolute temperature.

   Mathematically, $v \propto \sqrt{T}$. So if v_1 and v_2 are the velocities of sound in air at T_1 and T_2 temperatures, then $\frac{v_1}{v_2} = \sqrt{\frac{T_1}{T_2}}$.

   On simplification, we get $v_t = v_0\left(1 + \frac{t}{546}\right)$; where v_o and v_t are the velocities of sound in air at 0°C and at t°C respectively. Thus the velocity of sound in air increases by approximately 0.61 m s^{-1} for 1°C rise in temperature.

2. **Density:** The velocity of sound in air varies inversely as the square root of its density.

   Mathematically, $v \propto \frac{1}{\sqrt{d}}$; So if v_1 and v_2 are the velocities of sound in air at densities 'd_1' and 'd_2' respectively, then $\frac{v_1}{v_2} = \sqrt{\frac{d_2}{d_1}}$

3. **Humidity:** Humidity is the percentage of water vapour present in air. As the humidity increases, the percentage of water vapour in air increases and this decreases the density of air resulting in the increase of velocity of sound. So, increase in the humidity of air increases the velocity of sound in air.

4. **Wind:** Air in motion is called wind. So depending on the direction of wind the velocity of sound would either increase or decrease. If wind blows in the direction of sound propagation, the velocity of sound increases. If the wind blows opposite to sound propagation, the velocity of sound decreases.

Factors that do not affect the velocity of sound in air

1. **Amplitude:** Velocity of sound does not depend on the amplitude of the vibrations.
2. **Frequency (n):** Velocity of sound in air or any other medium does not depend on its frequency. We know that $v = n\lambda$. As the frequency (n) increases, its wavelength (λ) decreases but does not affect the velocity of the wave.
3. **Wavelength (λ):** The velocity of sound in air or any other medium does not depend on its wavelength (λ)

4. **Pressure:** The velocity of sound in air or any gas in given by $v = \sqrt{\frac{\gamma P}{d}}$; where '$\gamma$' is a constant, 'P' is the pressure and 'd' is the density. When the pressure of a gas is changed, its density also changes such that the ratio $\frac{'P'}{d}$ is always a constant. Hence, the variation of pressure of a gas does not affect the velocity of sound in it.

4. Doppler Effect

When a train approaches a station at high speed while blowing the horn, for a person standing on the platform the frequency of the horn would appear to be different from the real frequency. The pitch of the sound appears to increase when the train approaches an observer, and appears to be lower than its true pitch when the train passes by and moves away from the observer.

Similarly, while traveling in a vehicle towards a factory blowing the siren, changes in the frequency of the sound produced can be observed. This phenomenon of apparent change in the frequency of sound whenever there is a relative motion between the source of sound and the observer, is called Doppler Effect.

Mach number and Sonic boom

From the concept of Doppler effect, we understand that the speed of a moving object as compared to the speed of sound in the surrounding medium is important. The speed of sound at sea level at 15° C is about 340.3 m s^{-1} (1225 km h^{-1}). Generally, vehicles moving on land have speeds much less than this value. The fastest French TGV recorded a speed of 574.8 km h^{-1} (160 m s^{-1}). The Japanese maglev trains too have claimed speeds in this range.

However an aircraft can travel at much higher speeds.

While studying the aerodynamics of objects moving at higher speeds it would be important to consider the ratio of the speed of the moving object to that of sound in the surrounding air (fluid). This ratio is called the Mach number in honour of an Austrian physicist Ernst Mach.

$$\text{Mach number, } M = \frac{\text{Velocity of the object}}{\text{Velocity of sound in the surrounding medium}}$$

Consider a stationary source A (Mach number, M = 0). The sound waves produced would be concentric spheres as shown in figure (8.15).

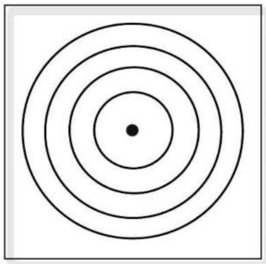


Figure 8.15

Now if the source of sound moves with a velocity V_S less than the velocity of sound V (Mach number M < 1) the spherical wave compressions would be shifted in the direction of motion of the source. (figure 8.16)

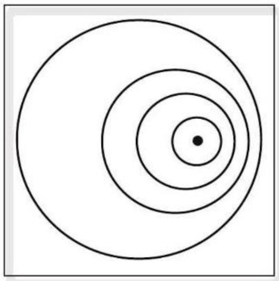


Figure 8.16

However, if the source travels at the speed of sound corresponding to Mach number M = 1, the wavefronts would be bunched together at the object as shown in the figure (8.17).

In this case the sound waves would reach the observer alongwith the source. Thus the sound cannot be heard until the source reaches him.

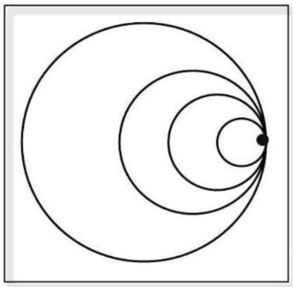


Figure 8.17

If the source travels at a speed greater than the speed of sound, when the corresponding Mach number, M is greater than l, the source precedes the sound produced by it, and the wavefronts lagging behind the source would form a cone as shown in figure (8.18). Thus as the source has passed the observer, wavefronts (compressions) coming from opposite directions would produce an intense thumping sound.

This sound of high intensity is called sonic boom. The thunder is an example of a sonic boom we observe in nature. Such sonic boom would cause the rattling of doors, windows and other objects.

Speeds less than M = 1 are called subsonic, speeds at M = 1 are called transonic and speeds greater than M = 1 are called supersonic.

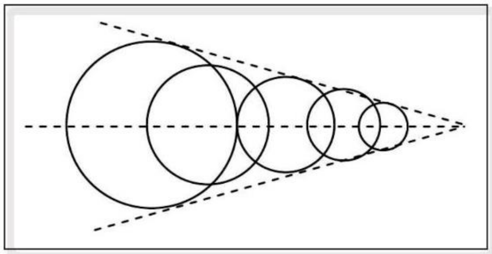


Figure 8.18

Reflection of sound

Sound waves, like other mechanical waves and light waves (electromagnetic waves), undergo reflection when they strike a hard, smooth surface. This reflection of sound obeys the laws of reflection, which is demonstrated in the following activity.

A hard, smooth surface is mounted vertically over a horizontal board on which two tubes P and Q, pointing towards the surface AB are clamped as shown in the figure (8.29). The sound waves from a source, like a ticking clock, are directed to the surface AB through the pipe P inclined at an angle to AB. The tube Q is adjusted such that the listener at L would be able to hear the ticking of the clock clearly. The board CD acts as a screen to prevent the sound waves from the source being heard directly by the listener. By measuring the angles the tubes make with the surface AB, the following can be verified.

(a) Angle of incidence is equal to the angle of reflection.

(b) The incident wave SN and the reflected wave NL are on the same plane.

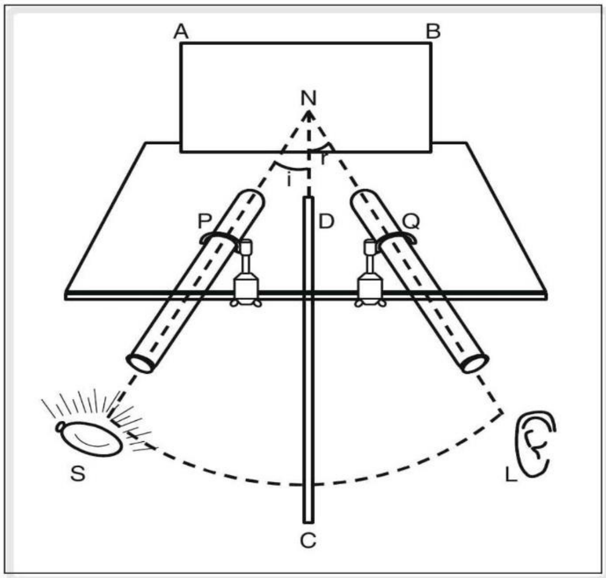


Figure 8.29 Reflection in Sound

Some practical applications of reflection of sound

Mega phone, loud speaker

The main part of the mega phone or the loudspeaker is a horn shaped tube. This tube prevents the spreading of sound waves in all directions. The sound entering in tube undergoes multiple reflections and comes out of the tube with a high directionality and it can propagate longer distances.

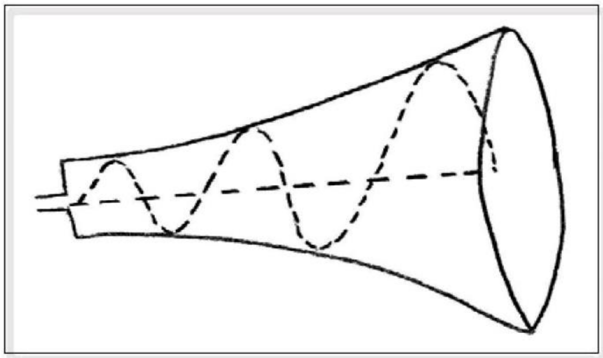


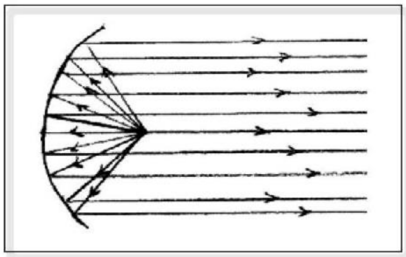
Figure 8.30 Mega phone

Hearing aid

The hearing aid used by the persons who are hard of hearing is also called ear trumpet. The sound enter hearing aid or the trumpet through a narrow opening and undergoes multiple reflections and comes out from the wide end with a large amplitude.

Sound boards

These boards are very useful for the uniform spreading of sound in big audiotoria etc. If any sound is produced at the focus of concave reflector it can be reflected back as parallel waves and thus the sound distributes uniformly.



Whispering gallery

Whispering gallery is a big circular hall. Around a big round pillar a dome is constructed. If a person whispers near the pillar, the sound undergoes multiple reflections and can be heard throughout the hall.

Sonar

It is an abbreviation for 'Sound Navigation and Ranging'. It is a special technique which is used in ships to calculate the depth of ocean beds and several other purposes. The main principle used in SONAR is reflection of sound.

At the bottom of a ship two devices, one for the production of ultrasonics and one for the detection of the reflected ultrasonics from the ocean bed are fixed as shown in figure (8.32). If 'v' is the velocity of ultrasonics in the ocean water and 't' is the time taken to receive the reflected ultrasonics from the ocean bed; the depth of the ocean bed can be found by $d = \frac{vt}{2}$.

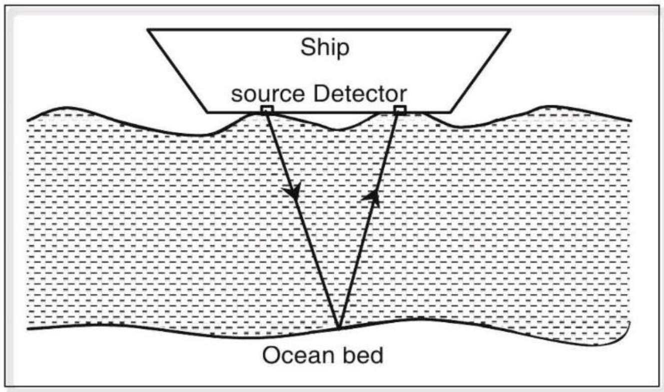


Figure 8.32 Working of sonar

Echo

When a sound wave strikes a smooth, hard surface it is reflected back to the listener and the repetition of sound a short time after it is produced is called an 'echo'. When a person claps standing in front of a reflecting surface like a big wall, he will hear two sounds; viz, one produced by him and the other one which is reflected from the surface. In order to distinguish between these two sounds a time gap of atleast 0.1 second (which is known as **persistence of hearing**) is required. If the time gap is less than 0.1 second, the person will not be able to hear the echo. If 'v' is the velocity of sound in air at a given temperature, 'd' is the distance between the source of sound (the person) 'P', and the reflector 'R' of sound (figure 8.33), the time taken to hear the echo is 't' seconds, then from figure (8.33),

we get $v = \frac{2d}{t}$ or $d = \frac{vt}{2}$

If $t = 0{\cdot}1$ second, then $d = \frac{v \times 0.1}{2} = \frac{v}{20}$

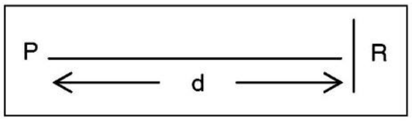


Figure 8.33 Echo

Thus, the minimum distance required to hear an echo is $\frac{1}{20}$th part of the magnitude of the velocity of sound in air. If we take the velocity of sound as 330 m s^{-1}, this minimum distance would be 16.5 m.

Determination of velocity of sound using an echo

Consider a person standing at P in front of a hill or a big wall and producing a sound (figure 8.34). Let 't_1' be the time taken to hear an echo. Now the person moves towards the reflector by a distance 'd' to a position Q and again produces a sound. Now the echo is heard after 't_2' time. From the figure (8.34), we have, $v = \frac{2(d+x)}{t_1}$ and $v = \frac{2x}{t_2}$

$\therefore 2(d+x) = vt_1$ and $2x = vt_2$

$\therefore 2d + 2x = vt_1$

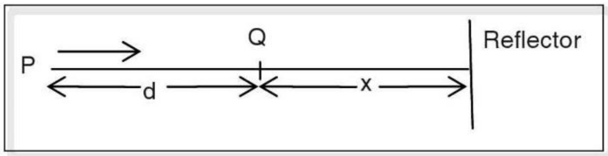


Figure 8.34

Eliminating x, we have $2d + vt_2 = vt_1$

$\therefore vt_1 - vt_2 = 2d$

or $v = \frac{2d}{t_2 - t_1}$

If the initial and final positions of the person are 'Q' and 'P' and 't_1' and 't_2' are the time intervals to hear the echo at these positions respectively, then $v = \frac{2d}{t_2 - t_1}$.

Reverberation

If sound is produced by a source 'S' in a closed enclosure as shown in the figure (8.35), the observer of sound 'O', can hear the sound directly coming from the source and also reflected from the roof or walls of the enclosure. If the reflections are multiple, the observer continues to hear the sound even after the source of sound has stopped producing the sound.

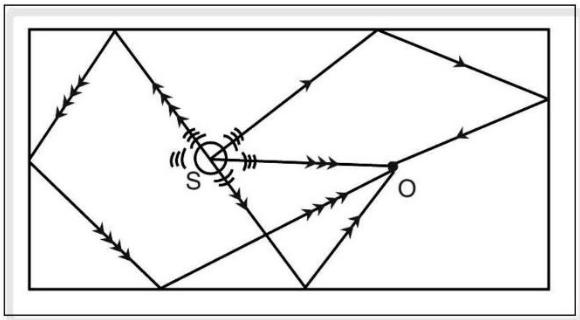


Figure 8.35 Reverberation

This persistence of sound in a closed enclosure, due to continuous reflections at the walls or the floor or the ceiling of the enclosure, even after the source has stopped producing sound is known as 'reverberation'.

Acoustics of buildings

In theatres, auditoria, big halls etc the reverberation of sound is a common problem. Due to this the music or the speech rendered becomes uninteresting or unintelligible. The reverberation of sound can be optimised by taking certain precautions while the theatres are being constructed.

1. The wall of the hall should be covered with some absorbing material like wallpaper or the walls should be painted to make it rough.
2. There should not be any concave reflectors in the halls.
3. The stairs, seats should be covered with absorbing materials.
4. The windows, doors etc., should be provided with thick curtains, or windows should be provided with double or triple doors.

Playback of the sound track

Light passing through the part of the film corresponding to the sound track is detected by a high sensitive electrical device and is converted into an electric signal which is converted into sound in a loudspeaker.

Human ear

Like the human eye gives us the sensation of vision or sight, the human ear is a sense organ enabling us to hear the sounds produced in the surroundings. Just as the optical images produced on the retina are conveyed to the brain by the optic nerve, the sound waves are sensed by the delicate parts in the ear and is conveyed to the brain by the auditory nerve. To understand the process involved in hearing let us study the internal structure of the ear.

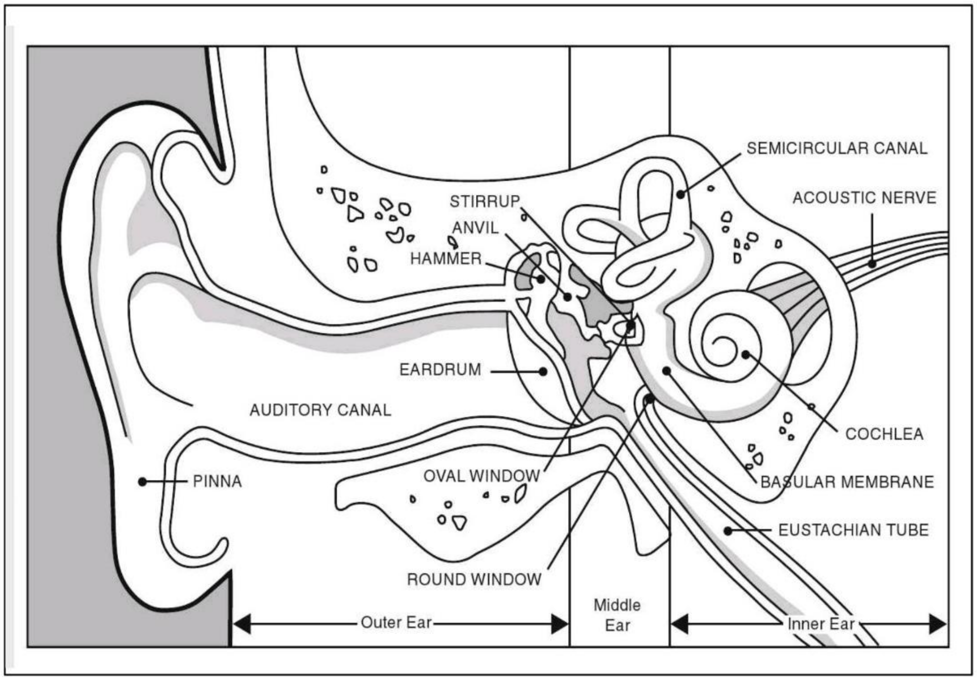


Figure 8.41

The human ear as shown in the figure (41) here is divided into three parts—the outer ear, the middle ear and the inner ear.

As we know sound is transmitted as longitudinal waves consisting of compressions and rarefactions. The pinna of the outer ear helps in diverting these compression/rarefactions to the eardrum through the ear canal or auditory canal which too is a part of the outer ear. The eardrum, also known as tympanic membrane forms the gateway to the middle ear. It is lightly stretched membrane of about 0.8×10^{-4} m thick.

The thin and delicate ear drum has another delicate bone attached to it, which is the first of the three bones constituting the middle ear. The first, called the hammer, is in contact with the eardrum at one end and the anvil, the second bone at the other end.

The compressions and rarefactions of the external sound make the ear drum to vibrate and these vibrations are conveyed through the anvil to the third bone called the stirrup which is in contact with the oval window leading to the inner ear. The middle ear is connected to the throat through the eustachian tube for equalising the pressure on either side of the eardrum.

The inner ear consists of the spiral shaped cochlea containing a fluid. The minute vibrations of the oval window coming from the outer and middle ears agitate this fluid causing the hair-like projections on a membrane in the cochlea to vibrate. The resonant vibrations of the hair-like structures generate signals in the auditory nerve connected to the brain to be interpreted as sounds with corresponding frequencies.

☛ *Examples*

1. A source of longitudinal waves vibrates 320 times in two seconds. If the velocity of this wave in the air is 240 m s^{-1}, find the wavelength of the wave.

Solution

Velocity of wave, $v = 240 \text{ m s}^{-1}$

Frequency of the wave, $n = \frac{320}{2} = 160$ hertz

Velocity of wave, $v = n\lambda$

Wave length, $\lambda = \frac{v}{n} = \frac{240}{160} = 1.5$ m

2. The distance between any two successive antinodes or nodes of a stationary wave is 0.75 m. If the velocity of the wave is 300 m s^{-1}, find the frequency of the wave.

Solution

Wavelength of the wave, $\lambda = 0.75 \text{ m} \times 2$
$= 1.5$ m
Velocity of the wave $= 300 \text{ m s}^{-1}$

frequency, $n = \frac{v}{\lambda} = \frac{300}{1.5} = 200$ hertz