UNIT 3 SOUND

Structure

3.1 INTRODUCTION

In Unit 2, you studied thermal energy and its transfer from one place to another. You may recall that the thermal energy can be transported either by physical transport of material particles (as in the process of convection) or by waves (as in the process of radiation). This holds true for any form of energy; that is, energy can be carried either by matter or by waves. In the present unit, you will study one of the very common examples of transport of energy by waves called sound. *Sound is a mechanical wave which causes auditory sensation*.

You are familiar with a variety of wave phenomena in nature : water waves in a pond; light (electromagnetic wave) which carries energy from the sun to the earth and the sound produced by musical instruments like tabla, shehnai, sitar etc. and the vocal chord of a person. In Section 3.2, you will learn about the different types of waves and their common characteristics.

We describe some sounds as pleasant and some as unpleasant. The sound produced by musical instruments like guitar, piano, violin, tabla or organ pipes are pleasant to our ears. On the other hand, murmuring of students in a classroom, barking of dogs, roaring of lion etc. are recognised as unpleasant sounds (or noise). Would not you like to know what makes a sound pleasant or unpleasant? This happens because of certain characteristics of sound waves which you will learn in Section 3.3.

Sound is associated with waves. However, the speed of propagation of sound waves depends on the medium of propagation. In Section 3.4, you will learn about the speed of sound waves in different media and discover that the parameters like density, pressure, temperature, humidity, etc. of the medium affect the speed of sound. You will also learn in this section how we can determine the speed of sound on the basis of the vibrations of air columns in the resonance tube apparatus.

Objectives

After studying this unit, you should be able to

- understand the difference between a longitudinal wave and a transverse wave,
- describe the perceptual characteristics of sound in terms of its physical parameters,
- discuss the relations for speed of sound in different media,
- explain the effect of various atmospheric factors on the speed of sound, and
- determine the speed of sound on the basis of the vibrations of air columns in organ pipes.

3.2 WAVES

You must have seen waves on the water surface of a pond or a river or the sea. However, if you are asked what is a wave, you may find the question a bit uncomfortable! To find an answer, let us *look* at the water waves little more carefully. When we drop a piece of stone in a pond, we observe that the ripples, constituting a wave, travel on the surface of water. On the basis of this observation, we can define a wave as a **disturbance** which travels at a definite speed. You may ask : **What causes the disturbance (ripples) to propagate on the surface of water**? The stone dropped in the pond forces the particles of the medium (water) to oscillate about their mean position. Mechanical forces arising due to elasticity of the medium (water in the present case) and acting on the adjacent particles of the medium enables this disturbance to travel at a definite speed.

Thus, in a wave motion, disturbances travel through a medium (having properties of elasticity and inertia) due to the oscillatory motion of the particles of the medium. You must, however, note that the particles of the medium do not travel along with the disturbance. *Thus, wave is a means to transfer energy and momentum from one point to another without the particles of the medium being shifted from one point to another*. **The waves which can be produced or propagated only in a material medium are known as elastic waves or mechanical waves**. The examples of mechanical waves are waves on water surface, waves on strings, sound waves etc.

[**Note :** There is another kind of wave, known as electromagnetic wave, which can propagate even through vacuum. The examples of electromagnetic waves are radio waves, microwaves, x-rays and gamma rays. In the present unit, we will confine ourselves only to the mechanical waves.]

Depending upon the direction of oscillation of the particles during the propagation of mechanical waves in a medium, the wave motion is classified into the following two categories :

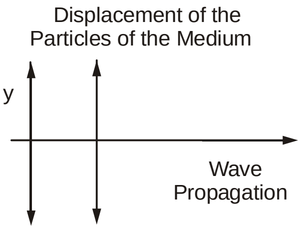
(a) Transverse wave motion, and

(b) Longitudinal wave motion.

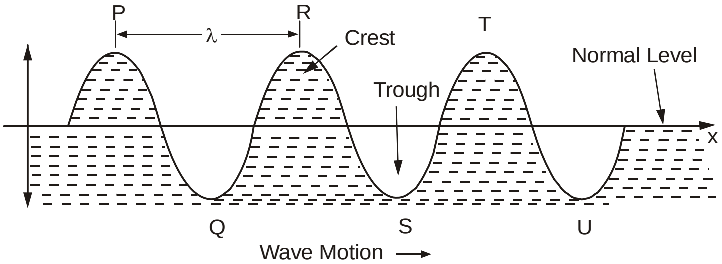
Let us now discuss these wave motions.

Transverse Wave Motion

In the transverse wave motion, displacements of the particles of the medium are in a direction perpendicular to the direction of propagation of wave as shown in Figure 3.1(a).



(a)



(b)

Figure 3.1 : (a) Directions of Particle Displacement and Wave Propagation for Transverse Wave; and (b) Crests and Troughs of a Transverse Wave

A transverse wave travels through a medium in the form of crests and troughs as shown in Figure 3.1(b). A crest is a portion of the medium which is raised temporarily above the normal position of the particles of the medium. The points *P*, *R* and *T* denote the centres of successive crests. Therefore, the centre of crest is the position of maximum displacement in the positive direction. A trough is a portion of the medium which is depressed temporarily below the normal position of the particles of the medium when a transverse wave passes through it. The points *Q*, *S* and *U* denote the centres of successive troughs. Therefore, the centre of trough is the position of maximum displacement in the negative direction (below the normal level). Some examples of transverse wave motion are given below :

(a) Wave traveling along a string tied at one end and other end is move up and down; particles of the string vibrate along a direction perpendicular to the direction along which the disturbance travels.

(b) Movement of string of a sitar or violin.

(c) Waves set up on the surface of water.

(d) Movement of the membrane of a *tabla* or a *dholak*.

Longitudinal Wave Motion

In the longitudinal wave motion, the direction of displacements of the particles of the medium about their mean position is along the direction of wave propagation (Figure 3.2(a)).

Longitudinal waves travel through a medium in the form of compressions (*C*) and rarefactions (*R*) as shown in Figure 3.2(b). *In the compression region, the particles of the medium come closer and the separation between*

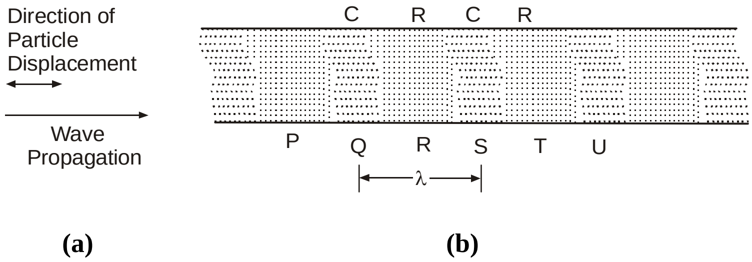


Figure 3.2 : (a) Directions of Particle Displacements and Wave Propagation for Longitudinal Wave; and (b) Compressions and Rarefactions of the Medium Constituting a Longitudinal Wave

the particles become less than the normal separation between them. This causes a decrease in volume and consequent increase in density of the medium in this region. The centres of compressions are *Q*, *S* and *U* shown in Figure 3.2(b). *A rarefaction is a region of the medium in which particles are separated from each other by a distance greater than their normal separation*. Thus, there is an increase in volume and consequent decrease in density of the medium in this region. The centre of rarefactions are *P*, *R* and *T* shown in Figure 3.2(b). Some common examples of longitudinal wave propagation are given below.

(a) When one end of a long spring is tied to a hook in a wall and the other end is moved forward and backward, the variations in the spacing between the terms of the spring constitute the longitudinal waves which move along the length of the spring.

(b) Sound waves in air are longitudinal waves; the ‘disturbance’ which travels in this wave are the variations in the air pressure.

(c) Vibrations of air column above the surface of water in the tube of a resonance apparatus are longitudinal.

There are certain physical quantities which can be associated with all kinds of periodic waves – mechanical as well as electromagnetic. These quantities are very helpful in the analysis of wave motion. To define these quantities, we shall consider the simplest kind of wave motion : periodic wave on a string (Figure 3.3). **The wavelength λ of a wave is defined as the distance between two successive peaks**. For the wave in Figure 3.3, distance *AB* is its wavelength.

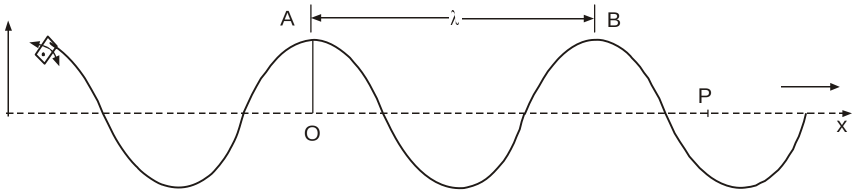


Figure 3.3 : A Periodic Wave Produced on a String by an Oscillating Lever

Another quantity associated with waves is called frequency, *f*. **It is defined as the number of waves passing through a point per second**. Frequency of a wave is a measure of the rate of oscillation of the body producing the wave. In our example of an oscillating lever producing the wave, faster the oscillation of the lever, more number of waves will pass through any point, say *P*, per second. **Time period of a wave is defined as the time taken by two successive crests (or troughs) to pass through a point**. Therefore, time period, *T*, and frequency, *f*, of a wave are related to each other as :

$$T = \frac{1}{f} \qquad \ldots (3.1)$$

Yet another quantity associated with waves is called amplitude. **It is defined as the magnitude of maximum displacement**. In Figure 3.3, amplitude of the wave is *OA*. On the basis of these definitions, we can write the velocity of a wave, as :

$$v = \lambda f \qquad \ldots (3.2)$$

Till now you studied the general features of mechanical waves and the physical parameters associated with them. This might have given you a fairly good idea as to what is a wave, how is it produced and what are its defining features. You are now sufficiently informed to study the sound waves in detail.

But, before that, pause for a moment and think : **How is sound produced when you speak**? While speaking, you essentially apply pressure on the air column in your throat. The resulting succession of compressed and rarified air, after passing through mouth, come out as variety of sounds. *In fact, whenever a material medium – solid, liquid or gas – is disturbed mechanically, waves are produced. When the frequency of this mechanical wave is in the audible range* (*20 Hz – 20000 Hz*), *we perceive it as sound*.

In sound waves, the molecules of air or any other substance oscillate about their mean position and collide with other molecules. In this process, they transfer energy to the adjacent molecule. *The oscillation of the air molecules is along the direction of propagation of the wave and hence sound waves are longitudinal waves*. It comprises compressions and rarefactions within the air. In compressions, air molecules come close to each other (compressed) whereas in the rarefaction they are separated from each other as shown in Figure 3.4. *The compressions are the regions of high air pressure while the rarefactions are the region of low air pressure*. Thus, when sound wave moves through a medium, we have repeating regions of high pressure and low pressure. **Therefore, sound waves are also known as pressure waves**. Figure 3.5 shows the correspondence between the pressure-time fluctuations and the resulting (longitudinal) sound wave.

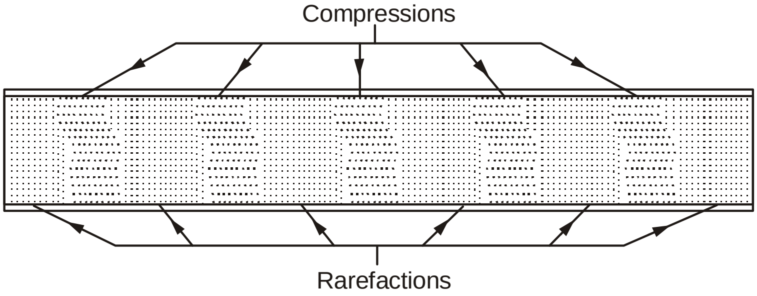


Figure 3.4 : Propagation of Sound in Air through Compressions and Rarefactions of Air Molecules

Note that the pressure-time plot (Figure 3.5) is a periodic wave similar to the wave on the string. Compressions correspond to crests; rarefactions correspond to troughs and “zero point” (horizontal line) correspond to the pressure which the air would have in the absence of disturbance through the medium (air).

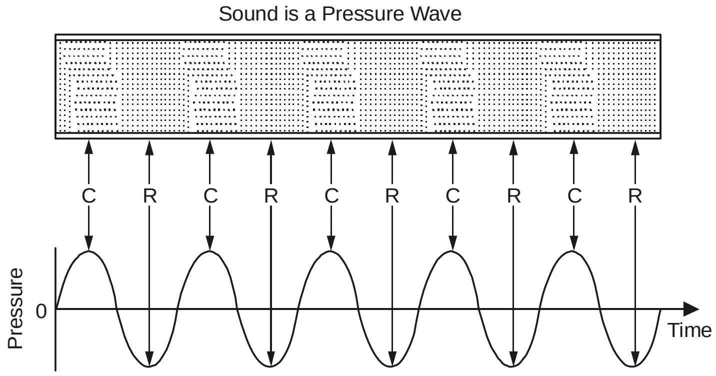


Figure 3.5 : Sound Waves and Corresponding Pressure-Time Curve

Production of Sound

Let us now discuss how sound is produced by a common laboratory apparatus called **tuning fork**. As shown in Figure 3.6, the tuning fork is a metal object. It consists of two tines. When these two tines are struck to a rubber pad, they start vibrating back and forth and disturb the air molecules in its vicinity and the air molecules start oscillating. These oscillations are transferred to the surrounding air molecules by the process of particle-particle collision. Thus, the disturbances which travel through the air molecules (Figure 3.6) constitute the sound waves.

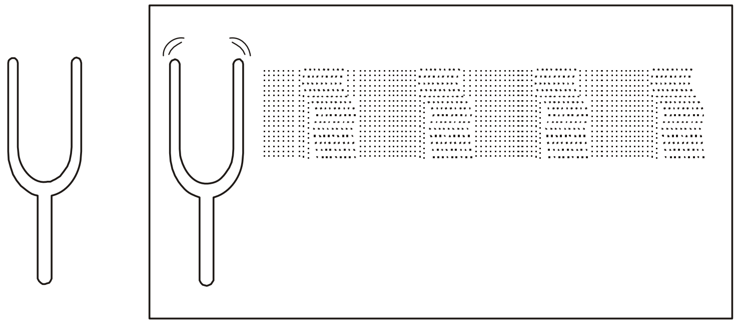


Figure 3.6 : A Tuning Fork; and Propagation of Sound Waves Produced by the Vibrating Tuning Fork

When you strike a tuning fork, it generates sound waves in the surrounding air. The intensity of sound is, however, very small because it depends on the volume of the air disturbed by the vibrating tuning fork. Owing to smaller area of the vibrating portion of the tuning fork, the resulting sound cannot be heard from a distance.

There is a variety of man-made and natural sources of sound. Generally, a source of sound such as sitar and human voice consists of two components : a mechanisms to produce vibrations and a sounding box (also called a resonant structure). To appreciate the role of these components, let us consider the production of sound by a tuning fork mounted on a sounding box (Figure 3.7).

The sounding box is a hollow wooden box whose one side is open. When the tuning fork is struck, we find that the sound can be heard even from a very large distance! You may ask : **How does it happen**? *The sounding box enhances the coupling between the vibrations of the tuning fork and the sound wave. That is, the vibrations of the tuning fork is transferred to the wooden box which disturbs much more air and hence intensity of the resulting sound is enhanced.*

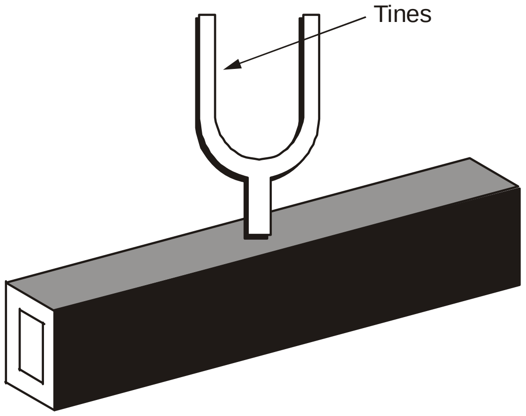


Figure 3.7 : A Tuning Fork Mounted on a Hollow Wooden Box

In fact, when the frequencies of the tuning fork and the standing wave of sound in the sounding box are almost the same, the intensity of the sound is enhanced dramatically due to resonance. You may ask : **What are standing (or stationary) sound waves and how are they created in the sounding box**?

The creation of standing sound waves in the sounding box or any other air column is similar to the creation of standing waves on a string. Suppose a string is fixed at one end and other end is moved up and down periodically. The periodic waves generated on the string is reflected back from the fixed end (boundary) of the string. The incident and reflected waves on the string combine and form standing (stationary) wave. As in the case of strings, incident and reflected sound (pressure) waves in the sounding box also produce standing waves. *One of the important characteristics of the standing waves is that it can have only certain values of wavelength* (*or frequency*) *which is determined by the boundary conditions* (*or the dimensions of the string or the sounding box*).

Now, with this background understanding about the basic components of a source of sound and their functions, you will appreciate why each musical instrument such as sitar or violin consists of strings and some kind of a sounding box or a resonant structure. The strings of these instruments can vibrate with many frequencies. However, only those frequencies will be amplified which are almost same as the allowed frequencies of the standing sound waves in the corresponding sounding box.

Musical instruments like sitar, veena, guitar, violin etc. use strings whose end points are tightly fixed. When such strings are set into vibrations, stationary waves are produced due to superposition of incident and reflected waves. The end points act as nodes and between any pair of nodes, there is an anti-node as shown in Figure 3.8.

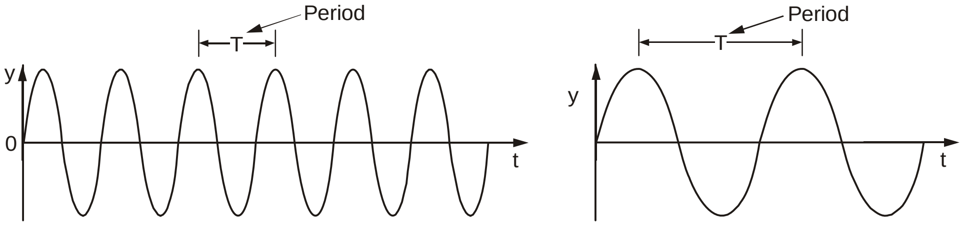


Figure 3.8 : Stationary Waves Formed by a Vibrating String Fixed at Two Ends

The simplest way in which a string fixed at both ends can vibrate is as just one segment (Figure 3.9(a)). *It is then said to execute fundamental mode of vibration*. The length *l* of the string is one-half the wavelength, and the frequency of the fundamental vibration is given by

$$f_0 = \frac{1}{2l}\sqrt{\frac{T}{m}}$$

where T is the tension in the string and m its mass per unit length. You may note here that f_0 is the minimum frequency which the string can produce. In general, the string may vibrate in two or more segments (Figures 3.9(b) and (c)). For n number of segments, the frequency, f_n, of vibration of the string is given by :

$$f_n = \frac{n}{2l}\sqrt{\frac{T}{m}} \quad ; \quad n = 1, 2, 3, \ldots$$

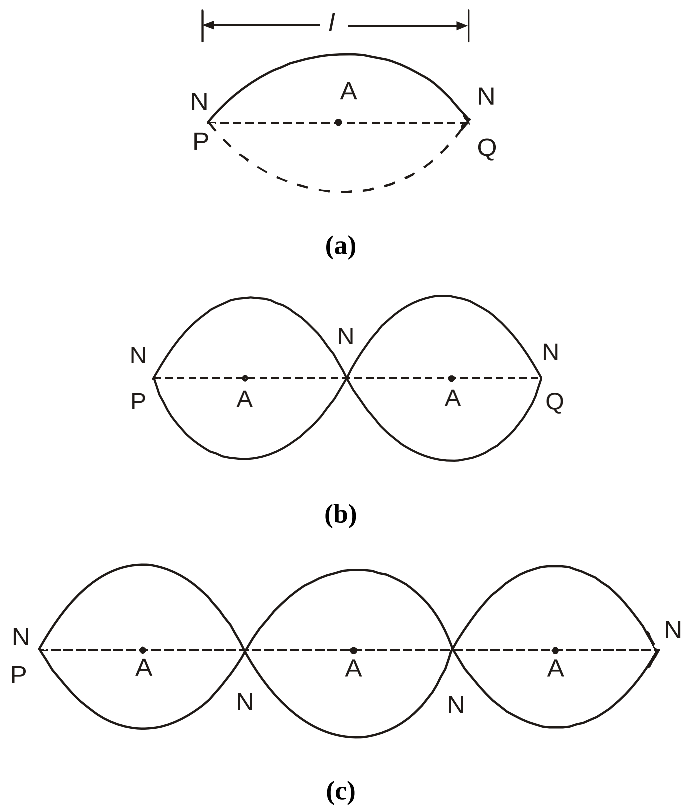


Figure 3.9 : Vibration of String in (a) One; (b) Two; and (c) Three Segments

Regarding propagation of sound, you may ask : **If there are no air molecules (as in vacuum), will propagation of sound wave take place**? The sound wave (in fact, any mechanical wave) cannot travel through a vacuum because the presence of a material medium (air or any other media) is necessary for propagation of sound. To demonstrate this fact, you can do a simple activity. Take a jar and place a ringing bell in the jar as shown in Figure 3.10. You can hear the sound of the bell. Now, if you (somehow) remove the air from the jar, you will not hear the sound of the ringing bell. This happens because the medium (air) required to produce and transport the sound waves has been removed from the jar.

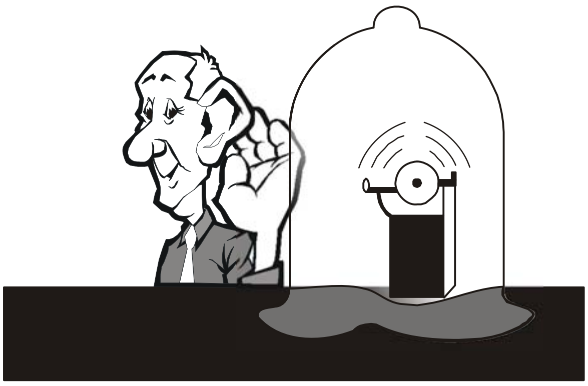


Figure 3.10 : The Sound Produced by the Bell Kept in (Evacuated) Jar cannot be Heard

With this background knowledge about waves in general and sound as longitudinal waves in particular, you can study the perceptual characteristics of sound. You will do it now.

3.3 SOUND AND ITS CHARACTERISTICS

You know that, generally, we are able to distinguish between the voices of a male and a female. The question is : **How do we distinguish between the two voices**? Similarly, what enables us to say that the sound from a musical instrument is different from noise, say the roar of a lion? The uniqueness of the sound produced by a source is described in terms of the three parameters namely pitch, loudness and quality. Each of these characteristics is related to a physical quantities associated with the sound wave.

3.3.1 Pitch

You know that vibrating objects such as the vocal chords of a person, string of a guitar or violin, tines of a tuning fork, etc. introduce sound waves into a medium. This causes the particles of the medium, through which the sound moves, to vibrate at a given frequency. The question is : **When a wave passes through a medium, how frequently the particles of the medium vibrate**?

The frequency at which each particle of the medium vibrates is the same as the frequency of the oscillating object producing the sound wave. **Each source of sound has a characteristic frequency**.

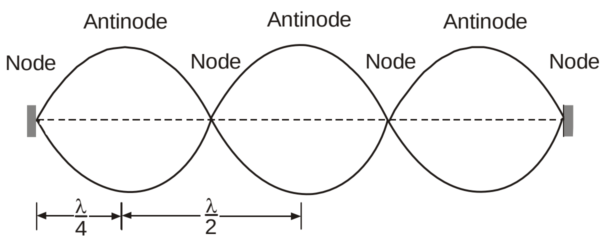


Figure 3.11 : Particle Displacement-Time Plots for (a) High Frequency Wave; and (b) Low Frequency Wave

Mechanical waves having frequency in the frequency range 20 Hz to 20,000 Hz is perceived as sound. If the frequency of the sound is less than 20 Hz (that is, below the audible range of hearing), the sound is known as **infrasound** and when the frequency is more than 20,000 Hz (that is, above the audible range of hearing), it is known as **ultrasound**. Refer to Table 3.1 which shows the audible range of some animals.

Table 3.1 : Range of Frequencies of Sound Detected by Some Animals

Animals/Birds	Range of Frequencies which can be Detected	
	As low as (Hz)	As high as (Hz)
Dogs	50	45,000
Cats	45	85,000
Bats	–	1,20,000
Dolphin	–	2,00,000
Elephant	5	10,000

The auditory sensation or perceptual characteristic corresponding to frequency is known as ***pitch*** *of a sound*. A high pitch sound corresponds to *higher frequencies* and a low pitch sound corresponds to lower frequencies. **Therefore, pitch of sound enables us to distinguish between a sharp sound and a dull sound**. For example, the buzzing of a bee or humming of a mosquito has high pitch but the roar of lion has low pitch. Also, the frequency of a female voice is usually higher than the male voice. Therefore, female voice is usually sharper than male voice. Pitch of a sound depends on the :

(a) frequency of the sound waves, and

(b) relative motion between the source of the sound and the listener.

3.3.2 Loudness

Do you know why the sound due to a jet engine is louder than the sound from sitar? It is because the intensity of the sound of a jet engine is more than that of the sound from a sitar. *Intensity of sound is a physical parameter which determines its loudness*.

You may ask : **How do we define the intensity of sound**? It is defined as the amount of energy passing through a point per unit time per unit area in a direction perpendicular to the area. Mathematically, it is expressed as :

$$\text{Intensity} = \frac{\text{Energy}}{\text{Time} \times \text{Area}}$$

or
$$\text{Intensity} = \frac{\text{Power}}{\text{Area}} \qquad \text{. . . (3.3)}$$

because $\text{Power} = \dfrac{\text{Energy}}{\text{Time}}$. The SI unit of Intensity is Watts m^{-2}. Further, the rate of energy transported by a wave is a function of its amplitude : *higher the value of amplitude of the wave, faster is the rate of energy transfer*. Equivalently, we can say that the intensity of the sound wave at a point is a function of its amplitude at the point. The exact dependence of intensity I on the amplitude A is given as

$$I \propto (A)^2 \qquad \text{. . . (3.4)}$$

Now, you may argue : **Why is it that the sound of a jet engine far away from us is not louder than, say, a musical instrument played nearby**? The answer to this question lies in the intensity-distance relation for the sound waves. To find the exact form of this relation, let us consider a point source of sound, S, as shown in Figure 3.12. The sound waves emanating from S spreads out in the form of spherical waves. Let us consider the intensity of sound at points P and Q at

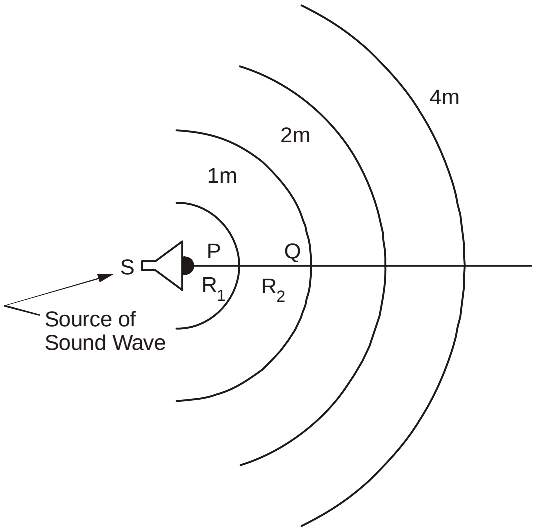


Figure 3.12 : Two-dimensional View of the Spread of Sound Waves in the Form of Circular Waves

distances R_1 and R_2 respectively from the source S. At points P and Q, the energy associated with the sound wave is respectively spread over surface areas $4\pi R_1^2$ and $4\pi R_2^2$ (because surface area of the sphere is $4\pi R^2$). Since energy has to be conserved, energy per unit area at Q is less than its value at P because $R_1 < R_2$. This implies that the intensity (energy per unit area per unit time) of sound at point Q is less than P. The nature of variation of intensity with distance can be obtained by using Eq. (3.3) :

$$\text{Intensity } (I) = \frac{\text{Power}}{\text{Area}}$$

or

$$= \frac{\text{Power}}{4\pi R^2}$$

$$I \propto \frac{1}{R^2} \qquad \ldots (3.5)$$

Eq. (3.5) shows that the intensity varies inversely with the square of the distance from the source.

Humans are equipped with very sensitive ears capable of detecting sound waves of extremely low intensity. The faintest sound which a typical human ear can detect has an intensity of the order of 10^{-12} Wm^{-2}. On the other hand, highest intensity a typical human can safely detect without suffering any physical damage of the ear is of the order of 10^2 Wm^{-2}.

Due to the wide range (10^{-12} Wm^{-2} – 10^2 Wm^{-2}) of intensity a human ear can perceive, it is convenient to use **logarithmic scale** to measure the intensity of sound. To measure the intensity of sound on this scale, the threshold of hearing is assigned a sound level of 0 decibels (abbreviated dB); this sound corresponds to an intensity of 1×10^{-12} Wm^{-2}. A sound which is 10 times more intense (that is, 1×10^{-11} Wm^{-2}) is assigned a sound level of 10 dB. A sound which is 10×10 that is, 100 times more intense (1×10^{-10} W/m^2) is assigned a sound level of $10 \times 2 = 20$ dB. Observe that this scale is based on powers or multiples of 10. **If**

one sound is 10^x times more intense than another sound (reference sound), then it has a sound level which is ($10 \times x$) more decibels than the reference sound.

You know that some sounds appear loud whereas others appear faint to the ear. *The sensations produced in the ear which enable us to distinguish between a loud and a faint sound is called loudness*. The loudness (L) or the intensity level of a sound is related with the intensity I of sound as :

$$L = \log_{10}\left(\frac{I}{I_0}\right) \qquad \text{. . . (3.6)}$$

where I_0 is the threshold of hearing given as :

$$I_0 = 10^{-12}\,\mathrm{Wm}^{-2}$$

If $I = 10\,I_0$, then $L = \log_{10}(10\,I_0 / I_0) = 1$ bel. *Thus, the loudness of a sound is said to be 1 bel, if its intensity is 10 times that of the threshold of hearing.* A smaller unit, called decibel (dB), is defined as :

$$1\ \text{decibal}\,(\text{dB}) = \left(\frac{1}{10}\right)\text{bel}$$

The **loudness** of a sound is a subjective perception (perception which varies from person to person) and it depends on a number of factors including the intensity of sound. Age is one of the factors which affects the human ear’s response to a sound. Despite the distinction between intensity (a well defined physical quantity) and loudness (a subjective perception of intensity of sound), we can say that the more intense sound will be perceived to be louder sound. Factors on which intensity or loudness of a sound depends are :

- Amplitude of the sound wave,
- Surface area of the vibrating body,
- Distance of the source from the listener,
- Density of the medium between source and listener, and
- Frequency of the sound wave.

3.3.3 Quality

You know that when two or more different musical instruments play the same note, the difference in their sounds can be easily distinguished. For example, a piano and a trumpet both may be playing exactly the same note having the same frequency and the same loudness, still the difference between the two sounds can be felt. Similarly, you recognize your friends’ voices because each one of them have a distinctly different voice from others. The question is : **What makes two sounds distinct from each other despite the fact that their physical parameters such as amplitudes, and frequencies are the same**? It is made possible due to a perceptual parameter called **quality of sound**.

The quality of a sound refers to the characteristic of the musical sound that distinguishes between two sounds of same pitch and loudness from one another. The next logical question is : **What determines the quality of a sound**? The quality of the sound is mainly determined by harmonic content of the sound. To understand the meaning of harmonic content of a sound, you may recall that a vibrating object producing sound has a natural frequency of vibration determined by its physical parameters. *A harmonic is defined as an integer multiple of the natural or fundamental frequency. Thus, if the sound produced by an object consists of waves having frequencies equal to its harmonics, the harmonic content of the sound is high*. The number and magnitude of harmonics present in a sound gives it a distinctive character called the quality.

Till now, you have studied the perceptual, characteristics of sound and their relation with the associated physical parameters. You have learnt that the sound wave travels through a medium by means of interactions among the particles of the medium. Now, you may be interested to know : **How fast a sound wave travels? Does the speed of sound depend on the physical properties of the medium of travel**? In the following section you will discover answers to these and other related questions.

To fix your ideas about the pitch and measurement of intensity of sound on the decibels scale, solve the following SAQs.

SAQ 1

(a) Velocity of sound in air is 330 ms^{-1}. Calculate the frequency of sound of wavelength 16.5 m.

(b) We the humans beings can detect frequencies as high as 20,000 Hz. Assuming that the speed of sound in air is 345 ms^{-1}, determine the wavelength of the sound corresponding to the upper limit of the audible range of frequencies.

(c) The intensity of sound from a loudspeaker is 10^3 times more than the intensity of human voice. If the intensity of human voice is 10^{-8} Wm^{-2}, calculate the sound level of the loudspeaker in decibels with respect to the human voice.

3.4 SPEED OF SOUND : NEWTON'S FORMULA

You have learnt earlier in this unit that for the generation and propagation of sound waves, material medium is necessary. It is, therefore, logical to assume that the speed of sound wave depends on the physical properties such as density and elasticity of the medium in which it travels. Newton proposed that the speed of sound in any media – solid, liquid or gas – is a function of the elasticity and density of the media. Written mathematically, Newton's formula for the speed of sound v is :

$$v = \sqrt{\frac{E}{\rho}} \qquad \ldots (3.7)$$

where E is the coefficient of elasticity of the medium and ρ is the density of the medium. For the propagation of sound waves in solids, Newton's formula reduces to :

$$v = \sqrt{\frac{Y}{\rho}} \qquad \ldots (3.8)$$

where Y is the Young's modulus. As the sound waves propagate in a solid rod, small deformations are produced in it (solid rod). Since the extent of deformation in the rod is affected by its elasticity (Young's modulus), the velocity of sound also depends on Y.

Similarly, Newton's formula for the fluid (liquids and gases) medium is written as :

$$v = \sqrt{\frac{K}{\rho}} \qquad \text{. . . (3.9)}$$

where K is the bulk modulus of elasticity. *The bulk modulus of a fluid is a measure of compressibility of a fluid*. When we apply pressure on an enclosed fluid, its volume decreases. This causes increase in density of the fluid. The bulk modulus, therefore, is a measure of the fractional change in density of a fluid due to change in pressure; that is :

$$K = \frac{dP}{\left(\frac{d\rho}{\rho}\right)} \qquad \text{. . . (3.10)}$$

The value of the speed of sound in air predicted by Newton's formula was at variance with the experimental value. It was so because speed of sound in air also depends on the other physical parameters of the atmosphere.

The genesis of the difference between the Newton's prediction and experimental observations lies in the assumption about the thermodynamic considerations. Newton was of the opinion that the changes in pressure and volume of a gas, responsible for the propagation of sound waves in a gaseous medium, are isothermal in nature. *That is, the temperature of the gaseous medium remains constant*. The amount of heat produced during compression is lost to the surroundings and heat lost during rarefactions is gained from the surroundings. Therefore, Newton's formula can be written as :

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

where K_i is the *coefficient of isothermal elasticity*. Under isothermal conditions, K_i is found to be equal to pressure. Therefore, the speed of sound can be written as :

$$v = \sqrt{\frac{P}{\rho}} \qquad \text{. . . (3.11)}$$

To estimate the speed of sound in air at NTP, we can write this equation as

$$v = \sqrt{\frac{hdg}{\rho}} \qquad \text{. . . (3.12)}$$

Substituting h = 0.76 m of Hg column; d (density of mercury) = 13.6×10^3 kg m^{-3}; g = 9.8 ms^{-2} and density of air, ρ = 1.293 kg m^{-3}, in Eq. (3.12), we get :

$$v = \sqrt{\frac{0.76 \times 13.6 \times 10^3 \times 9.8}{1.293}}$$

$$= 280 \text{ ms}^{-1}.$$

However, experimental value of the speed of sound in air at STP is estimated to be 332 ms^{-1}. Thus, we find that the experimentally determinated value is 16% higher than the Newton's prediction. The discrepancy was explained by Laplace, a French mathematician. *He pointed out that it was wrong to assume that the pressure and volume changes in a gaseous medium causing propagation of sound were isothermal*; rather, the changes are **adiabatic** because of the following reasons :

(a) The numerical value of the speed of sound in a gas is quite large. Therefore, the pulses of compression and rarefaction follow one another so rapidly that there is no time left for any exchange of heat amongst themselves or with the surroundings, and

(b) The exchange of heat is restrained because gases are bad conductors of heat.

In the light of above arguments, Laplace modified Newton's formula for the speed of sound as :

$$v = \sqrt{\frac{K_a}{\rho}} \qquad \text{. . . (3.13)}$$

where K_a is the coefficient of adiabatic elasticity. In terms of pressure P and γ (the ratio of two principal specific heats of a gas), the adiabatic elasticity is given as

$K_a = \gamma P$. Substituting this value of K_a in Eq. (3.13), we get :

$$v = \sqrt{\frac{\gamma P}{\rho}} \qquad \text{. . . (3.14)}$$

The value of γ depends on the nature of the gas. For air, $\gamma = 1.41$. Thus, the speed of sound in air is given by Eq. (3.14) :

$$v = \sqrt{1.41} \times \sqrt{\frac{P}{\rho}}$$

$$= \sqrt{1.41} \times 280 \text{ ms}^{-1}$$

$$= 332.5 \text{ ms}^{-1}$$

So, we see that by applying the **Laplace correction**, the theoretical value is in close agreement with the experimental value of the speed of sound in air.

3.4.1 Factors Affecting the Speed of Sound in a Gaseous Medium

The speed of sound in a gaseous medium such as air is affected by its temperature, pressure and humidity. Let us discuss these effects briefly.

Effect of Pressure

You know that the Laplace formula for the speed of sound in a gas is given as Eq. (3.14) :

$$v = \sqrt{\frac{\gamma P}{\rho}} \qquad \text{. . . (3.14)}$$

Consider one gram molecule of a gas whose pressure and volume are P and V respectively. If T is the absolute temperature of the gas, then according to the gas equation :

$$PV = RT$$

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

Substituting for P in Eq. (3.14), we get :

$$\therefore \qquad v = \sqrt{\frac{\gamma RT}{V \times \rho}} = \sqrt{\frac{\gamma RT}{M}} \qquad \text{. . . (3.15)}$$

where $M\ (= V \times \rho)$ is the molecular weight of the gas. Now, you know that for a given gas, R, γ and M are constants. If the temperature T of the gas is kept constant, then v is constant. *Hence, at a given temperature, the speed of sound is independent of the pressure of the gas*.

Effect of Temperature

From Eq. (3.15), we have :

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

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

Thus, the speed of sound in a gas is directly proportional to the square-root of its absolute temperature. *It is for this reason that on a hot summer day sound travels faster than on a cold winter day*.

The temperature coefficient of the speed of sound is defined as the change in the speed of sound, when temperature changes by 1^oC. It is found that velocity of sound in air increases approximately by 0.61 ms^{-1} for every 1^oC rise in temperature. Mathematically, it is written as :

$$v = 331\ \text{ms}^{-1} + (0.61\ \text{ms}^{-1}\ {}^oC^{-1}) \times T\ (\text{in}\ {}^oC)$$

Effect of Humidity

The presence of water vapours in air changes its density. When moisture is present in air, the density of air decreases because the density of water vapours is less than that of dry air. To obtain the nature of dependence of the speed of sound on humidity of the air, let ρ_m = density of moist air; ρ_d = density of dry air; v_m = velocity of sound in moist air, and v_d = velocity of sound in dry air. Thus, from Eq. (3.14), we can write :

$$v_m = \sqrt{\frac{\gamma P}{\rho_m}} \qquad \text{. . . (3.16)}$$

and

$$v_d = \sqrt{\frac{\gamma P}{\rho_d}} \qquad \text{. . . (3.17)}$$

On dividing, Eq. (3.16) by Eq. (3.17), we get

$$\frac{v_m}{v_d} = \sqrt{\frac{\rho_d}{\rho_m}}$$

Since the presence of water vapours decreases the density of air, $\rho_m < \rho_d$ and we have $v_m > v_d$. *That is, speed of sound in moist air is greater than the speed of sound in dry air. That is why sound travels faster on a rainy day than on a dry day*.

It is also important to note that the Laplace formula for speed of sound does not involve frequency or wavelength. Hence, sound of any frequency or wavelength travels through a medium with the same speed. Further, the amplitude of sound wave normally does not affect its speed. However, if the amplitude is too large, the speed of sounds increase slightly. All other factors like phase, loudness, pitch, quality etc. have practically no effect on speed of sound.

The study of stationary sound waves in air columns discussed in Section 3.2 is very helpful in experimental determination of the speed of sound in laboratory. The apparatus used for this purpose is called *resonance tube apparatus*. Let us now discuss how we can measure the speed of sound by analyzing the vibrations of air columns in resonance tube or organ pipe.

3.4.2 Measurement of the Speed of Sound : Vibrations of Air Columns

The resonance tube apparatus, shown in Figure 3.13(a), consists of a 100 cm glass tube whose lower end is connected to a water reservoir. It is fixed on a vertical board, which is provided with a heavy base carrying leveling screws. A metre scale is also fixed on the vertical board. The length of air column (that is, the portion of the tube above the free surface of water in the tube) can be adjusted by raising or lowering the water reservoir.

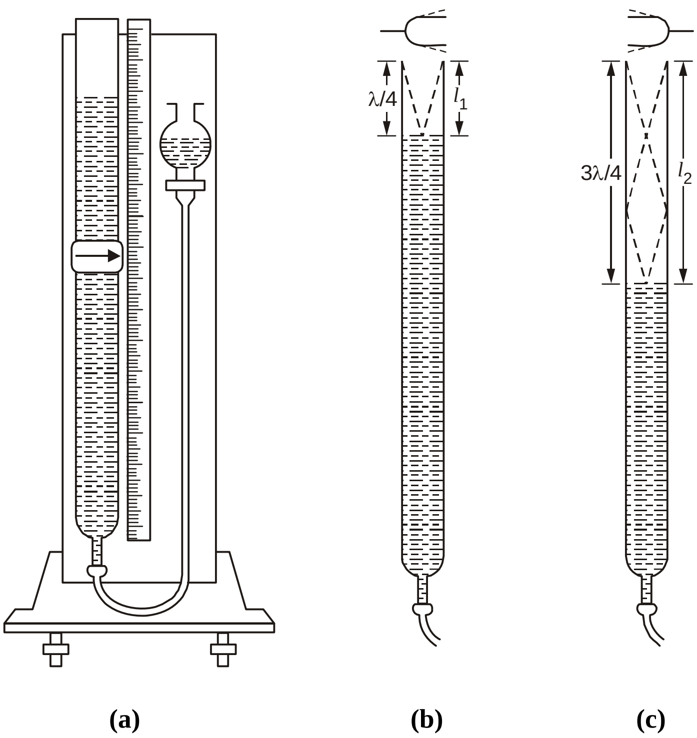


Figure 3.13 : (a) Resonance Tube Apparatus; (b) Vibration of Fundamental Mode; and (c) Vibration of the next Resonance Mode

When a vibrating tuning fork of frequency *f* is held above the upper end of the resonance tube, a sound wave is generated inside the air column. It is reflected from the closed end of the tube. The superposition of incident and reflected waves gives rise to stationary waves. *The closed end of the tube acts as a node whereas the open end acts as an antinode. The position of the water level is so adjusted that we hear the maximum sound*. This is the condition of resonance which happens when the air column is in unison with the given tuning fork. For the *fundamental mode of vibration* (Figure 3.13(b)), we can write (on the basis of the formation of stationary waves on strings as discussed in production of sound in

Section 3.2), the length of the air column, $l_1 = \frac{\lambda}{4}$, where λ is the wavelength of the stationary wave.

Next, the position of the water level is lowered till we get another position of resonance with the same tuning fork (Figure 3.13(c)). Again, on the basis of the discussion in Section 3.2, the length of the air column in this case is given as $l_2 = \frac{3\lambda}{4}$. Thus, it follows that :

$$\lambda = 2(l_2 - l_1).$$

Since the velocity of sound is given as :

$$v = f\lambda$$

we can write :

$$v = 2\,f\,(l_2 - l_1)$$

Thus, using Eq. (3.18), the speed of sound can be determined.

SAQ 2

(a) An air column, disturbed by a tuning fork of frequency 256 Hz, gives resonance at column lengths 33.4 cm and 101.8 cm. Calculate the speed of sound in air.

(b) Using the value of speed of sound obtained in (a) above, calculate the speed of sound wave at temperature of 20^{o}C Celsius at normal atmospheric pressure.

3.5 SUMMARY

- The wave motion is classified into two categories, namely transverse waves and longitudinal waves depending upon the direction of oscillation of the particles with respect to the direction of propagation of mechanical waves in a medium.
- A transverse wave travels through a medium in the form of **crests** and **troughs** and a longitudinal wave travels through a medium in the form of **compressions** and **rarefactions**.
- Pitch, loudness and quality are the perceptual characteristics of sound which enables us to differentiate between the sounds from different persons or instruments.
- The speed of sound waves depend on the inertial as well as elastic properties of a medium.
- The Newton's formula for the velocity of sound under isothermal conditions is given by :

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

where P is the pressure and ρ is the density of the medium.

- The Newton's formula for the velocity of sound in a gaseous medium, after Laplace modification, is given by :

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

where $\gamma \left(= \frac{C_p}{C_v}\right)$ is the ratio of two specific heat capacities of the gas. C_p is the specific heat capacity at constant pressure and C_v is the specific heat capacity at constant volume.

- Pressure, temperature, density and humidity are the factors which affect the speed of sound in a gaseous medium.

- The frequency of fundamental vibration of a string is given by :

$$f_0 = \frac{1}{2l}\sqrt{\frac{T}{m}}$$

where the length l of the string is one-half the wavelength, T is the tension in the string and m is the mass per unit length. For n number of segments, the expression for frequency of vibration is

$$f_n = \frac{n}{2l}\sqrt{\frac{T}{m}}$$

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

- The speed of sound can be determined by using a resonance tube apparatus with the help of the following relation :

$$v = 2f\,(l_2 - l_1)$$

where f is the frequency, l_1 is the length of air column for fundamental vibration and l_2 is the length of air column for the next resonant vibration

3.6 ANSWERS TO SAQs

SAQ 1

(a) As per the problem, the velocity of sound, $\boldsymbol{v}$ = 330 ms^{-1}; and the wavelength of sound, λ = 16.5 m

We know from Eq. (3.2),

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

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

$$= \frac{330\ \text{ms}^{-1}}{16.5\ \text{m}}$$

$$= 20\ \text{Hz}$$

(b) Again, from Eq. (3.2), we can write :

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

$$= \frac{345\ \text{ms}^{-1}}{20,000\ \text{Hz}}$$

$$= 0.0173\ \text{m (approximate)}$$

(c) The intensity of sound from the loudspeaker is 10^3 times the intensity of human voice. Since we have to determine the sound level of the loudspeaker with respect to human voice, we use the definition of decibel. According to the definition (see page 71), the sound level of the loudspeaker is

$$10 \times 3 = 30\ \text{dB}$$

SAQ 2

(a) Let l_1 and l_2 be the lengths of air column for two consecutive resonances. Thus, we have :

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

$$= (101.8 - 33.4)\ \text{cm}$$

$$= 0.684\ \text{m}$$

or, $\lambda = 1.368\ \text{m}$

Using the relation for the speed of sound

$$v = f\ \lambda$$

$$= (256\ \text{Hz}) \times (1.368\ \text{m})$$

$$= 350.2\ \text{ms}^{-1}$$

(b) We know that the correction in the value of speed of sound due to temperature is given as :

$$v = (350.2\ \text{ms}^{-1}) + (0.61\ \text{ms}^{-1}\,\text{C}^{-1}) \times (20\ ^{o}\text{C})$$

$$= 362.4\ \text{ms}^{-1}$$