UNIT 4 SOUND

Structure

4.1 INTRODUCTION

Sound and music are parts of our everyday sensory experience. Just as humans have eyes for the detection of light and colour, so we are equipped with ears for the detection of sound. The basis for an understanding of sound, music and hearing is the physics of waves. Sound is a wave which is created by vibrating objects and propagated through a medium from one location to another. In this unit, we will investigate the nature, properties and behaviours of sound waves and apply basic wave principles towards an understanding of Doppler effects.

So far, you have come across various forms of energy. Sound is also a form of energy. The sensation known as "Sound" is caused by the vibration of bodies or the source of sound.

A **wave** can be described as a disturbance that travels through a medium, **transporting energy** from one location to another location. The **medium** is simply the material through which the disturbance is moving; it can be thought of as a series of interacting particles. The example of a slinky wave is often used to illustrate the nature of a wave. A disturbance is typically created within the slinky by the back and forth movement of the first coil of the slinky. The first coil becomes disturbed and begins to push or pull on the second coil; this push or pull on the second coil will displace the second coil from its **equilibrium position**. As the second coil becomes displaced, it begins to push or pull on the third coil; the push or pull on the third coil displaces it from its equilibrium position. As the third coil becomes displaced, it begins to push or pull on the fourth coil. This process continues in consecutive fashion, each individual *particle* acting to displace the adjacent particle; subsequently the disturbance travels through the slinky. As the disturbance moves from coil to coil, the energy which was originally introduced into the first coil is transported along the medium from one location to another.

A sound wave is similar in nature to a slinky wave for a variety of reasons. First, there is a medium which carries the disturbance from one location to another. Typically, this medium is air; though it could be **any** materials such as water or steel. The medium is simply a series of interconnected and interacting particles. Second, there is an original source of the wave, some vibrating object capable of disturbing the first particle of the medium. The vibrating object which creates the disturbance could be the vocal chords of a person, the vibrating string and sound board of a guitar or violin, the vibrating times of a tuning fork, or the vibrating diaphragm of a radio speaker. Third, the sound wave is transported from one location to another by means of the particle interaction. If the sound wave is moving through air, then as one air particle is displaced from its equilibrium position, it exerts a push or pull on its nearest neighbours, causing them to be displaced from their equilibrium position. This particle interaction continues throughout the entire medium, with each particle interacting and causing a disturbance of its nearest neighbours. Since a sound wave is a disturbance which is transported through a medium via the mechanism of particle interaction, a sound wave is characterised as a **mechanical wave**.

Wave Motion and its Characteristics

Wave motion is one of the most important methods of transporting energy. It is the disturbance produced in a medium, which travels outwards in all directions. Due to this disturbance, particles of the medium vibrate about their mean positions and energy is handed over from particle to particle.

Thus, wave motion is defined as a disturbance which travels in a material medium and is due to the periodic motion of the particles of the medium about their mean positions, the motion being handed over from particle to particle.

The immediate example that comes to one’s mind is the water waves (ripples) formed in water when a stone is thrown in still water. When the stone touches the water surface, water molecules are pressed. Due to elasticity, water particles try to regain their original positions. In this process, they are set to vibrations about their mean positions. That the particles of the medium only vibrate but do not move is easily noticed when we throw a small piece of paper or cork on to the surface of water.

Characteristics of Wave Motion

(a) It is the disturbance produced in the medium due to the repeated periodic motion of the particles of the medium.

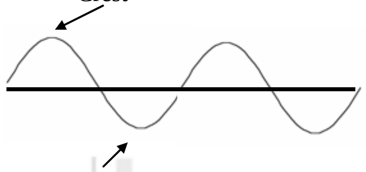
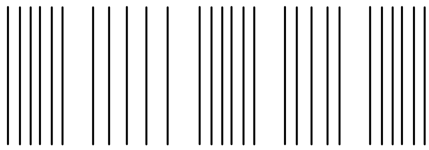
(b) While the wave advances, particles of the medium only vibrate about their mean positions. This is evident from the example given earlier.

(c) There is a phase difference from particle to particle. In other words, a particle ahead gets affected a little later. This is due to the inertia of the medium.

(d) Wave velocity is different from particle velocity. In fact, wave velocity is uniform in all directions in a homogeneous medium. Particle velocity, on the other hand, is maximum when it crosses the mean position and minimum when it reaches the extreme positions. In a way, it is similar to a simple pendulum.

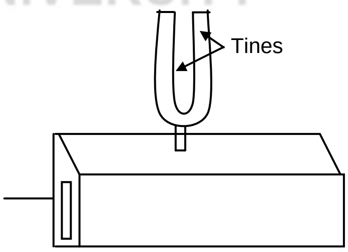
Types of Wave Motion

Based on the nature of vibration, wave motion can be broadly classified into transverse and longitudinal waves. A comparison between the two makes understanding easy.

Transverse Waves	Longitudinal Waves
(a) Particles of the medium vibrate **perpendicular** to the direction in which the wave advances.	(a) Particles of the medium vibrate **parallel** to the direction in which the wave advances.
(b) These waves are characterized by alternate crests and troughs and are normally represented diagrammatically as follows : 	(b) These waves are characterized by alternate compressions (C) and rarefactions (R) and are normally represented as follows : 
Hold one end of a **string** in one hand and tie the other end to a hook. If you give an up and down jerk to the end of the string held by you, you will observe transverse waves.	Hold one end of a **spring** in one hand and tie the other end to a hook. If you give a forward and backward jerk to the end of the spring held by you, you will observe longitudinal waves.
(c) There is no necessity for a medium for the waves to travel and so can travel through vacuum also. Example : Electromagnetic waves.	(c) A material medium is a must. Try and recollect the bell jar experiment which your teacher might have demonstrated when you were in high school classes. Example : Sound waves.
(d) For these waves to advance through a medium, it must possess (i) Elasticity (ii) Inertia (iii) Cohesion Thus, these waves cannot be propagated through gases and are restricted to surface of liquids.	(d) For these waves to advance through a medium, it must possess (i) Elasticity (ii) Inertia Thus, these waves can be propagated through solid, liquid and gaseous medium.
(e) These waves **can be** polarized.	(e) These waves **cannot be** polarized.

Production of Longitudinal Waves

Let us take a tuning fork. On striking it against a pad, it starts vibrating. For example, let us consider the fork when its prong moves towards the right. The air column in the immediate vicinity (on the right) of the fork gets compressed while that on the left gets rarified. Due to elasticity, the prong tries to get back to its normal position. In the bargain, air column on the right of the prong gets rarified and on the left gets compressed. Thus, while a rarefaction follows a compression on the right side, a compression follows a rarefaction on the left. This is the beginning of a train of alternate compressions and rarefactions constituting longitudinal waves.



A Tuning Fork Mounted on a Sound Board

Figure 4.1 : Tuning Fork

Objectives

After studying this unit, you should be able to

- differentiate between transverse wave and longitudinal wave,
- state the Newton's formula for velocity of sound,
- give reasons for the Laplace's correction,
- explain the effects of different parameters on velocity of sound,
- describe the working principle of siren, and
- describe the Doppler effect and its application.

4.2 VELOCITY OF SOUND : NEWTON'S FORMULA FOR VELOCITY OF SOUND AND LAPLACE'S CORRECTION

In this section, you will be introduced to the basic concepts of velocity of sound through different media. You will get to know the effectiveness of water as a medium of communication. That, even a great scientist like Newton is not infallible, is clear from Laplace's correction to Newton's formula for velocity of sound through a gaseous medium.

Before we commence study of velocity of sound and associated facts, it is better to familiarize ourselves with some of the basic terms associated with sound.

Frequency of Vibration (*n*, *f* or *v*)

Frequency is defined as the number of vibrations per second. Unit is cycles per second or vibrations per second or revolutions per second (rps) known as Hertz (Hz).

Time Period (*T*)

This is defined as the time taken to complete one cycle or full vibration. Unit is second. Thus,

$$n = \frac{1}{T} \text{ or } T = \frac{1}{n} \text{ or } nT = 1$$

Wave Velocity (*v*)

It is defined as the distance covered by the waves per second.

Wavelength (λ)

It is defined as the distance between two consecutive particles of the medium in the same phase of vibration. Thus, it is the distance between

(i) two consecutive crests

(ii) two consecutive troughs

(iii) two consecutive compressions

(iv) two consecutive rarefactions

It is measured in metres.

Amplitude (*a*)

The maximum displacement of a particle from its mean position is known as amplitude of vibration.

Relationship linking frequency, wavelength and wave velocity is

$$V = n\,\lambda$$

This is the most fundamental equation in sound.

4.2.1 Velocity of Sound Through Various Media

In general, velocity of sound through any medium is

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

where, *E* is the modulus of elasticity and ρ its density.

In Solids

$$V = \sqrt{\frac{Y}{\rho}}$$

where, *Y* is the Young's modulus and ρ its density.

In Fluids

$$V = \sqrt{\frac{K}{\rho}}$$

where *K* is the bulk modulus of fluids and ρ its density.

4.2.2 Velocity of Sound in Water

As stated earlier,

$$V = \sqrt{\frac{K}{\rho}},$$

where *K* is the bulk modulus of water and ρ its density.

Water is highly incompressible and so allows sound waves without absorbing much of the energy. In fact, sound waves move through fresh water at the rate of 1450 m/s, and at the rate of 1500 m/s through seawater. It is easily seen that these velocities are nearly 4.5 times that of velocity of sound in air. Sound waves can be transmitted much more efficiently through water than through air. This has enabled us developing systems for determining the positions of objects in the ocean and also the distance to the bottom of the ocean by SONAR (**So**und **N**avigation **A**nd **R**anging) devices. Pressure waves are an efficient method of transmitting information through ocean waters. It is no accident that many marine animals communicate taking advantage of this fact.

Determination of Velocity of Sound in Water

Two boats are positioned at a known distance. One lowers a sound source, say a bell. The second lowers a microphone which is connected to the earphone of an observer. When the bell rings, simultaneously a flash occurs. The observer in the second boat switches on a stopwatch on seeing the flash and stops it on hearing the sound. Thus, the time interval for the sound to travel the distance is known.

$$\text{Velocity} = \frac{\text{Distance}}{\text{Time}}$$

This experiment is repeated a few times to minimise errors committed during observations and the mean value is taken.

Use of Sound Waves in Ocean Research

Sound waves are used in many ways in ocean research, such as

(a) For depth measurements with echo sounder. The echo sounder, an electrical device for measuring the depth of water, has since its appearance in 1925 become an important aid to navigation. Short pulses of sound vibration, say of frequency 100/minute, are produced and transmitted vertically from the bottom of the ship to the seabed which reflects these pulses. The reflected pulses are received by the ship after a short interval of time. If *d* is the depth, the pulse has covered a distance $2d = Vt$ where *V* is the velocity of sound in water and t the time interval between transmission and reception. Knowing velocity of sound in water, depth is calculated.

(b) Transmission of information.

4.2.3 Newton's Formula for Velocity of Sound through Gaseous Medium

Newton assumed that the changes taking place in a medium when a sound wave advances through a gaseous medium are isothermal in nature. In other words, according to him, the heat generated in the compression is dissipated to the surrounding and the cooling produced in the rarefaction receives heat from the surrounding atmosphere, thus making the temperature in the region, a constant. We know that

$$V = \sqrt{\frac{K_{iso}}{\rho}}$$

Now,
$$K_{iso} = \frac{\text{Change in pressure}}{\text{Change in volume / Original volume}}$$

$$= -\frac{dp}{\frac{dV}{V}}$$

The negative sign shows that when pressure is increased, volume decreases.

For isothermal change (T = Constant), in a gaseous medium, we have,

$$pV = \text{Constant}$$

Differentiating both side, we get

$$p\,dV + V\,dp = 0$$

or
$$K_{iso} = -\frac{dp}{\frac{dV}{V}} = p$$

Thus, Newton's formula for Velocity of sound is

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

At NTP, for air, $p = 1.013 \times 10^5$ N/m^2 and $\rho = 1.29$ kg/m^3

Hence,
$$V = \sqrt{\frac{1.013 \times 10^5}{1.29}} = 280.23 \text{ m/s}$$

Velocity of sound as per Newton's formula is found to be very much different from the experimental value of 332 m/s.

You may know that physics is an experimental science and so, if the theoretically predicted value does not agree with the experimental value, the theory is not acceptable.

4.2.4 Laplace's Correction

Laplace argued that the changes taking place in a medium when a sound wave advances through the medium are adiabatic in nature and not isothermal as assumed by Newton. A gas under adiabatic condition obeys the equation $p\,V^{\gamma}$ = constant, where p is pressure, V is the volume and $\gamma = \frac{c_p}{c_v}$ the ratio of specific heats. We know that for an adiabatic process

$$pV^{\gamma} = \text{Constant}$$

Differentiating both sides, we get

$$dp V^{\gamma} + p\gamma V^{\gamma-1} dV = 0$$

$\Rightarrow$ $$\gamma\, p\, dV + V\, dp = 0$$

$$K_{\text{adia}} = -\frac{dp}{\frac{dV}{V}} = \gamma\, p$$

Thus, velocity of sound is (γ for air = 1.41),

$$V = \sqrt{\frac{K}{\rho}} = \sqrt{\frac{\gamma\, p}{\rho}}$$

At NTP, $$V = \sqrt{\frac{1.41 \times 1.013 \times 10^5}{1.29}} \quad 332.75 \text{ m/s}$$

We observe that the experimental value is in excellent agreement with the theoretically predicted value after applying Laplace's correction, thus confirming the correction.

Example 4.1

Velocity of sound in fresh water is 1450 m/s. Determine the adiabatic compressibility of water. Take $\rho_{\text{water}} = 1000 \text{ kg/m}^3$.

Solution

$V_{\text{water}} = 1450$ m/s; Adiabatic compressibility = $\frac{1}{K}$ = ?

$\rho_{\text{water}} = 1000 \text{ kg/m}^3$.

$$V = \sqrt{\frac{K_{\text{adia}}}{\rho}} \text{ in a liquid;}$$

$\therefore$ $$V^2 = \frac{K}{\rho}$$

$\therefore$ $$\frac{1}{K} = \frac{1}{V^2 \rho} = \frac{1}{1450^2 \times 1000} = 475 \times 10^{-12} \text{ SI Units}$$

SAQ 1

(a) Density of air at a pressure of 10^5 N/m^2 is 1.21 kg/m^3. If $\gamma = 1.4$, calculate the velocity of sound in air.

(b) Density and pressure of a gas are 1.98 kg/m^3 and 1.013×10^5 N/m^2 respectively. If the adiabatic constant is 1.41, calculate the wavelength of sound of frequency 1000 Hz.

4.3 EFFECT OF DIFFERENT PARAMETERS ON VELOCITY OF SOUND

Velocity of sound varies under different physical conditions. In general, velocity of sound in water increases with increase in pressure, temperature and salinity. In the case of a gaseous medium however, variation with pressure, temperature, density, humidity and wind conditions are not as simple as in the case of water. Study of velocity of sound is incomplete if its variation under different conditions is not studied. Let us now discuss the variation of velocity of sound under different conditions.

4.3.1 Variation of Velocity of Sound in Seawater

With Pressure

In sea water, a depth of 10 m corresponds to a pressure of almost 1 atmosphere. *Thus, at a depth of 10 m of sea water the absolute pressure is 2 atmospheres and at a depth of 100 m, it is 11 atmospheres and so on. Pressure effects dominate in the deeper layers only. Here, the speed of sound increases by about 1.8 m/s for a change of depth of 10 m. This is not a significant change.

With Temperature

Temperature effects dominate in the upper layers where the speed increases by about 3 m/s/°C.

With Salinity

Speed of sound increases with salinity at the rate of 1.3 m/s for a percentage point of salinity. However, salinity changes have no major influence on the speed of sound.

Note : *Pressure $= h \times g \times \rho$

$$= 10 \times 9.81 \times 1025$$

$$= 1.005525 \times 10^5 \text{ N/m}^2$$

(very nearly an atmosphere)

4.3.2 Effect of Pressure, Temperature, Density, Humidity and Wind on Velocity of Sound

Effect of Pressure

We know that the speed of the sound is given by

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

To study the effect of pressure, let us assume that the temperature remains constant. Therefore at constant temperature, we have

$$p\,V = \text{Constant}$$

If V is the volume of one mole of a gas, then density of gas,

$$\rho = \frac{M}{V} \quad \text{or} \quad V = \frac{M}{\rho}$$

where M is molecular weight of the gas.

So, $\dfrac{p\,M}{\rho} = \text{Constant}$

Now, $\dfrac{p}{\rho} = \text{Constant}$, because M is a constant.

Therefore, any change in pressure (p) of a given mass of gas is accompanied by a corresponding change in the density (ρ) of the gas and so $\sqrt{\dfrac{p}{\rho}}$ is a constant.

Since v being equal to $\sqrt{\dfrac{\gamma p}{\rho}}$, any change in pressure has no effect on the velocity of sound.

Effect of Density

We know that $v = \sqrt{\dfrac{\gamma p}{\rho}}$.

For a given gas, γ is a constant and change of pressure has no effect on velocity.

Hence, $$v \propto \sqrt{\frac{1}{\rho}} \text{ i.e. } \frac{v_1}{v_2} = \sqrt{\frac{\rho_2}{\rho_1}}.$$

This shows that at constant pressure, speed of sound in a gas is inversely proportional to the square root of the density of the gas. The speed of the sound in hydrogen gas is greater than that in oxygen for the reason that hydrogen is a lighter gas.

Effect of Moisture

Presence of moisture lowers the density of water.

Thus, $$\rho_{\text{moist air}} < \rho_{\text{dry air}}$$

But $$\frac{v_{\text{moist air}}}{v_{\text{dry air}}} = \sqrt{\frac{\rho_{\text{dry air}}}{\rho_{\text{moist air}}}}$$

Hence, $$v_{\text{moist air}} > v_{\text{dry air}}$$

It is for this reason that sound travels faster after rain than on a dry day.

Effect of Temperature

Earlier on, we have seen that $\rho_o = \rho_t\,[1 + \gamma\, t]$, where ρ_o is the density at 0°C, ρ_t the density at t°C and γ is the coefficient of cubical expansion of gases.

$$v_t = \sqrt{\frac{\gamma p}{\rho_t}} \text{ and } v_0 = \sqrt{\frac{\gamma p}{\rho_0}}$$

$$\therefore \quad \frac{v_t}{v_0} = \sqrt{\frac{\rho_0}{\rho_t}} = \sqrt{(1 + \gamma t)} = \sqrt{\left(1 + \frac{t}{273}\right)} = \sqrt{\frac{T}{T_0}}$$

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

where T is absolute temperature.

Thus, speed of sound varies directly as the square root of the temperature on the Kelvin scale.

It is for this reason that sound travels faster on a hot day than on a cold day.

Effect of Wind

If the wind direction is favourable, velocity of sound is increased and if it is against, velocity of sound is decreased. Let us consider the case when the wind direction is at an angle θ to the direction of sound wave, as shown in Figure 4.2.

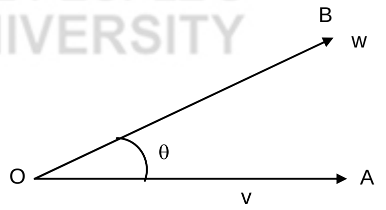


Figure 4.2

The sound travels along OA with a speed of v while the wind is travelling with a velocity w, making an angle of θ with the direction of the velocity of sound. The component of w along the direction of the velocity of sound is w cos θ. This component is added to the velocity of sound and the sound travels in the direction of *OA*, with the resultant speed $V = v + w \cos\theta$. If the wind blows in the direction of the transmission of sound, i.e. $\theta = 0^o$, then $\cos 0^o = 1$, or $V = v + w$. If the wind blows in the direction opposite to that of propagation of sound, i.e. $\theta = 180^o$, then $\cos 180^o = -1$, or $V = v - w$. Thus, we may conclude that, sound travels faster, if θ is acute and slower, if θ is obtuse. The wind will have no effect, on the speed of sound if $\theta = 90^o$.

Example 4.2

Show that the increase in velocity of sound in air for unit degree Celsius rise of temperature is 0.61 m/s, given that the velocity of sound at 0°C is 333 m/s.

Solution

$$V_{273} = 333 \text{ m/s};\ V_{274} = ?$$

$$\frac{V_{274}}{V_{273}} = \sqrt{\frac{274}{273}}$$

$$\therefore \quad V_{274} = V_{273} \times \sqrt{\frac{274}{273}}$$

$$= 333 \times \sqrt{\frac{274}{273}}$$

$$= 333.61 \text{ ms}^{-1}$$

Thus, $V_{274} - V_{273} = 0.61$ m/s

Example 4.3

Wavelength of a note is 27 m in air at 27°C. Find the wavelength when the temperature is increased to 37°C, given that the velocity of sound at 27°C is 340 m/s.

Solution

$$27°\text{C} = 273 + 27 = 300 \text{ K};\ \text{Similarly,}\ 37°\text{C} = 310 \text{ K}$$

$$V_{300} = 340 \text{ m/s};\ \lambda_{300} = 27 \text{ m};\ \lambda_{310} = ?$$

$$\frac{V_{310}}{V_{300}} = \frac{\nu\,\lambda_{310}}{\nu\,\lambda_{300}} = \sqrt{\frac{310}{300}} \quad \text{(Since there is no change in frequency)}$$

$$\therefore \quad \lambda_{310} = \lambda_{300} \times \sqrt{\frac{310}{300}} = 27 \times \sqrt{\frac{310}{300}} = 27.45 \text{ m}$$

Example 4.4

Calculate the velocity of sound in oxygen if the velocity of sound in hydrogen is 1248 m/s at the same temperature, given that the density of oxygen is 16 times density of hydrogen.

Solution

$$\rho_{O_2} = 16\,\rho_{H_2};\ V_{H_2} = 1248 \text{ m/s};\ V_{O_2} = ?$$

$$\frac{V_{O_2}}{V_{H_2}} = \sqrt{\frac{\rho_{H_2}}{\rho_{O_2}}}$$

$$V_{O_2} = V_{H_2} \times \sqrt{\frac{\rho_{H_2}}{\rho_{O_2}}} = 1248 \times \sqrt{\frac{1}{16}} = \frac{1248}{4} = 312 \text{ m/s}$$

Example 4.5

Find the temperature at which sound travels in hydrogen with the same velocity as in oxygen at 1000°C. Assume the ratio of specific heats to be the same for the two gases. Molecular weights of oxygen and hydrogen are 32 and 2 respectively.

Solution

V in H_2 at T K = V in O_2 at 1273 K

$M_{H_2} = 2$ and $M_{O_2} = 32$; T = ?

We know, $pV = RT$

$$\therefore \quad \frac{p}{\rho} = \frac{RT}{M}$$

$$\therefore \quad \sqrt{\frac{\gamma p}{\rho}} = \sqrt{\frac{\gamma RT}{M}}$$

Thus, V in H_2 at T K $= \sqrt{\dfrac{\gamma RT}{2}}$

V in O_2 at 1273 K $= \sqrt{\dfrac{\gamma R \times 1273}{32}}$

But, from the given condition, we can write

$$\sqrt{\frac{\gamma RT}{2}} = \sqrt{\frac{\gamma R \times 1273}{32}}$$

Squaring both sides

$$\frac{T}{2} = \frac{1273}{32}$$

$$\therefore \quad T = 79.5625 \text{ K}$$

SAQ 2

(a) At what temperature is the velocity of sound in nitrogen gas equal to the velocity in oxygen at 20°C? Atomic weights of oxygen and nitrogen are in the ratio 16 : 14. Assume γ to be the same for both the gases.

(b) A hospital uses an ultrasonic scanner to locate tumours in a tissue. What is the wavelength of sound in a tissue, in which the speed of sound is 1.7 km/s^{-1}? The operating frequency of the scanner is 4.2 MHz.

(c) At what temperature will be speed of sound be double its value at 273 K?

(d) The speed of sound of NTP in air is 332 ms^{-1}. Calculate the speed of sound in hydrogen at (i) NTP, (ii) 819^{o}C temperature, and 4 atmospheric pressure, (Air is 16 times heavier than hydrogen).

(e) The velocity of sound in air at 14^{o}C is 340 ms^{-1}. What will it be when the pressure of the gas is doubled and its temperature is raised to 157.5^{o}C?

4.4 CHARACTERISTICS OF SOUND

In our day-to-day life, we come across different types of sound such as deafening noise, loud sound, shrill sound, etc. Let us try to understand the characteristics which differentiate between two different types of sound.

Musical Sound and Noise

In general, sound can be broadly classified into musical sound and noise. A comparison between the two helps better understanding of these.

Musical Sound	Noise
Basically pleasant, since it produces a pleasing effect in the ear	Basically unpleasant since it produces a jarring effect in the ear.
Consists of regular and periodic waves of long duration.	Consists of irregular and aperiodic waves of short duration.
Combination of a number of simple harmonic waves.	Combination of complex wave forms.
There is no sudden change in the amplitude of vibration and so does not involve sudden changes in loudness.	Characterized by sudden changes in loudness.

Characteristics of Musical Sound

The three characteristics of musical sound are :

(a) Pitch

(b) Loudness

(c) Quality or timbre

Let us study these in greater detail.

Pitch

This is the physiological or the acoustic sensation produced in the ear by the frequency. Frequency, as we already know, refers to the number of vibrations per second. High frequency sound corresponds to high pitched or shrill sound and a low frequency sound to low pitched, or dull sound. Very often children and women have a high pitched voice and men have a low pitched voice. Thus, frequency is the cause and pitch is the effect. Frequency is measurable and so is objective, whereas pitch is not measurable and so is subjective. Incidentally, the audio frequency ranges from 20 Hz to 20 kHz.

Loudness

Before we move on to study loudness, good understanding of "intensity" is necessary since loudness is measured in terms of intensity. Intensity of sound (I) is measured as the amount of energy passing through or falling on a unit area, per second normal to the area. It is measured in W/m^2. This depends upon the amplitude of vibration (a), frequency (f), density of the medium (ρ) and velocity of sound through the medium (V).

Thus, $$I = 2\pi^2 f^2 a^2 \rho V$$

The minimum audible sound (I_0) is often referred to as "threshold of audibility". This is taken as the zero of the scale for measurement and is arbitrarily taken as 10^{-12} W/m^2.

Loudness is the physiological or the acoustic sensation produced in the ear by intensity of sound. Thus, intensity is the cause and loudness is the effect. While loudness is subjective, intensity is objective. Loudness is measured in a logarithmic scale.

$$L \propto \log I$$

Bel is the unit of loudness. However, practical unit is "decibel" (dB). One decibel is defined as 10 times the logarithm of an intensity ratio :

$$n = 10 \log\left(\frac{I}{I_0}\right)$$

where n is the loudness or the intensity level in decibels. I is the intensity for which the loudness is to be measured and I_0 is the threshold of audibility.

The above expression can also be written as $I = I_0 \times 10^{n/10}$.

Quality or Timbre

Quality enables us to distinguish between two persons or two instruments even if their frequency and loudness are the same. In the case of wind and string instruments, in addition to the fundamental frequency, many overtones or harmonics of the fundamental frequency are also present with differing intensities. These are responsible for making the music rich. Greater the number of harmonics, richer is the quality of music produced. In fact, no person or instrument can produce a pure tone of a single frequency. The number and the intensity of overtones present in the sound depend upon the size, shape and the mode of vibration.

Example 4.6

A certain loudspeaker has a circular opening with a diameter of 15 cm. Assume the sound that it emits to be uniform and outward through the entire opening. If the sound intensity at the opening is 100 μW/m^2, how much power is being radiated as sound by the loudspeaker?

Solution

$$I = 100\ \mu\ \text{W/m}^2 = 100 \times 10^{-6}\ \text{W/m}^2;$$

$$d = 15\ \text{cm} = 15 \times 10^{-2}\ \text{m}; \quad P = ?$$

$$A = \pi r^2 = \pi \times \left(\frac{15}{2} \times 10^{-2}\right)^2;$$

$$\text{Power} = I \times A = \frac{10^{-4} \times \pi \times 0.15^2}{4} = 1.77\ \mu\text{W}$$

Example 4.7

A loud symphonic passage produces an intensity level of 70 dB. A person speaking normally produces a sound level of 40 dB. Compare their intensities.

Solution

$$n_1 = 70\ \text{dB and } n_2 = 40\ \text{dB}; \ \frac{I_1}{I_2} = ?$$

$$I_1 = I_0 \times 10^{n_1/10} \qquad \ldots (1)$$

Similarly,

$$I_2 = I_0 \times 10^{n_2/10} \qquad \ldots (2)$$

From Eq. (1) and (2),

$$\frac{I_1}{I_2} = 10^{(n_1 - n_2)/10} = 10^{(70-40)/10} = 10^3$$

Thus, I_1 is 1000 times I_2.

Example 4.8

A sound intensity of about 1.2 W/m^2 can produce pain in the ear. What is its equivalent in decibels?

Solution

$$I = 1.2\ \text{W/m}^2$$

I_0 = threshold of intensity = 10^{-12} W/m^2

$$n = 10\log\left(\frac{I}{I_0}\right) = 10\log\left(\frac{1.2}{10^{-12}}\right) = 120.79 \text{ dB}$$

Example 4.9

What is the amplitude of motion of a wave in the path of a 60 dB, 800 Hz sound wave. Assume that density of air is 1.29 kg/m^3 and velocity of sound is 330 m/s.

Solution

n = 60 dB; ρ = 1.29 kg/m^3; f = 800 Hz; v = 330 m/s; a = ?

$$I = 2\pi^2 f^2 a^2 \rho V$$

$$60 = 10\log\frac{I}{I_0} \Rightarrow I = 10^6 \times 10^{-12} = 10^{-6} \text{ W/m}^2$$

$$\therefore \quad a = \sqrt{\frac{I}{2\pi^2 f^2 \rho v}}$$

$$= \sqrt{\frac{10^{-6}}{2\pi^2 \times 800^2 \times 1.29 \times 330}} = 1.36 \times 10^{-8} \text{ m} = 13.6 \text{ nm}$$

SAQ 3

(a) What is the intensity of a 60 dB sound? If this sound is close to a speaker that has an area 120 cm^2, what is the acoustic output of the speaker?

(b) About how many times more intense will the normal ear perceive a sound of 10^{-6} W/m^2 than one of 10^{-9} W/m^2?

(c) Assume that the average sound level in a certain room due to one person speaking is 40 dB. What will be the sound level when 20 people speak, assuming that all of them speak simultaneously at the same level as did the single person?

(d) A rock band gives rise to an average sound level of 105 dB at a distance of 20 m from the centre of the band. As an approximation, assume that the band radiates sound equally into a hemisphere. What is the acoustic output of the band?

(e) The intensity of sound in normal conversation at home is about 3×10^{-6} W/m^2 and the frequency of normal human voice is about 1000 Hz. Find the amplitude of the waves assuming that the air has a density 1.29 kg/m^3 and velocity of sound in air is 332.5 m/s.

(f) How many decibels is the sound of intensity 10^{-8} W/m^2 more than that of 5×10^{-10} W/m^2?

(g) Intensity of sound of a barking dog is 10^{-3} W/m^2. If the frequency is 1000 Hz, calculate the amplitude of the sound waves at standard conditions. Values of density and velocity of sound at standard conditions are as given in (e) above.

(h) Calculate the amplitude of the sound wave in the above numerical if the temperature of the air is 35°C.

(i) What would be the sound level of a sinusoidal wave of frequency 3000 Hz, in air with an amplitude of 0.2 mm? Assume the density to be 1.29 kg/m^3 and velocity of sound as 330 m/s.

4.5 SIREN

In this section, you will get to know as to how siren is used for measuring unknown frequency.

Description

Siren consists of a wind chest (*W*) into which air can be pumped. Upper disc *D* is capable of rotation about its spindle and is above *A* as shown in Figure 4.3. Disc *A* is fixed and has the same number of holes '*h*' as in *D* near its circumference. Holes in *D* are slanting in just the opposite direction to those in *A*. C_1 and C_2 are counters meant for measuring the number of rotations made by *D*.

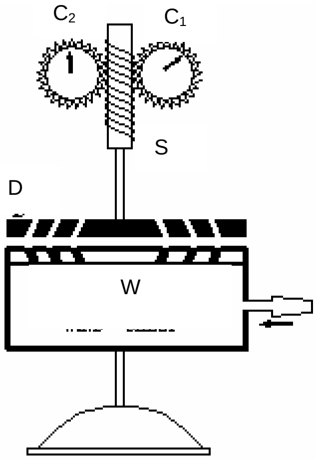


Figure 4.3

Working

Air is pumped into the wind chest *W* with the help of a pump. Each puff of air that escapes through the holes in *A* rotates the upper disc *D*. When the holes in *A* and *D* are aligned, air escapes producing sound of a particular frequency. (You may recall, the sound produced by a flute or for that matter any wind instrument). Frequency of sound produced $\boldsymbol{N = nh}$**,** where '*n*' is the number of rotations made by disc *D* per second and '*h*' is the number of holes. As the pressure inside *W* changes, frequency *N* of sound produced also changes since *n* changes.

Determination of Unknown Frequency

The given note for which the frequency is to be measured is sounded continuously. Pressure of air entering the wind chest *W* is gradually increased. Pitch of sound produced by the air escaping through holes also gradually increases. When the two are nearly equal, beats are heard. Let '*x*' be the number of beats. **If '*n*' is the number of rotations made by the disc *D* per seconds at that time,** $\boldsymbol{N = (n \times h) \pm x}$.

(Beats can be heard both before and after crossing the actual frequency.) In other words, beats can be heard both when the pitch of siren is lower and higher than the actual frequency.

Example 4.10

The disc of a siren has 32 holes. What must be the speed of rotation per minute of the siren disc so that the note emitted by it may be in unison with the tuning fork of frequency 256 Hz?

Solution

$h = 32$; $N = 256$ Hz; n in rpm = ?

$N = nh$,

$\therefore \quad n = 256/32 = 8$ rotations/s $= 8 \times 60 =$ **480 rpm**.

Example 4.11

Disc of a siren is rotating at an angular speed of 7π rad/s. Determine the frequency of sound generated by it if it has 60 holes.

Solution

$n = 7\pi$ rad/s $= 7\pi/2\pi = 3.5$ rotations/s; $h = 60$

$N = nh = 3.5 \times 60 =$ **210 Hz**

SAQ 4

(a) The number of holes in the rotating disc of a siren is 36. If the frequency of sound emitted by the siren is in unison with the frequency of a tuning fork of 512 Hz, calculate the rate of rotation of the disc.

(b) Number of holes in a disc of siren is 46. Frequency of sound generated by the siren is 450 Hz. Determine the rotation per minute of the disc.

(c) Disc of a siren has 46 holes. If the frequency of sound emitted by it is 360 Hz, what is the rate of rotation of the disc? Also determine the wavelength of the sound produced, given velocity of sound is 340 m/s.

(d) Disc of a siren has 45 holes. If the frequency of sound emitted by the siren is 950 Hz, what is the rate of rotation of the disc? Also determine the wavelength of the sound, given velocity of sound is 342 m/s.

(e) Disc of a siren with 60 holes is rotating at an angular speed of 4π rad/s. What is the frequency of sound generated by it?

(f) Disc of a siren has 40 holes and rotates 500 times in 1 minute and 36 seconds. Find the frequency of the note emitted and also the wavelength in air if velocity of sound in air is 342 m/s.

4.6 DOPPLER EFFECT AND ITS APPLICATIONS

Very often we fail to notice the fact that the pitch of sound, when a car blowing its horn or a train sounding its whistle crossing us, the pitch of the sound appears to change. However, this might have aroused the curiosity of those who have a scientific temperament and might have even prompted them to know the why of it. This section highlights this aspect. Doppler log and the transit satellite position fixing system, which are applications of Doppler Effect, form part of your professional course and so a study of Doppler effect is essential.

As early as 1843, Doppler observed that colour of light emitted by a star approaching the earth seemed to be different from that of the one going away. A year later, Buys Ballot proved experimentally that the pitch of sound due to an approaching source was higher than when it was stationary. He named the phenomenon “Doppler effect”.

4.6.1 Doppler Effect in Sound

Apparent change in the pitch of sound due to relative motion between a source and an observer or a listener is Doppler effect. Doppler frequency shift is the difference between the actual frequency (n) and the apparent frequency (n_1) when there is relative motion between a source and an observer or listener.

Doppler effect is the phenomenon of change in apparent pitch of the sound due to relative motion between the source of the sound and the listener.

Relative Motion

In all cases, except when the source and the observer or the listener move in the same direction as the source with the same velocity, there is relative motion between the two. In other words, a change in the gap between the two is indicative of relative motion between the two. Doppler effect in sound is applicable when the velocities of the source and the listener or observer are much less than the velocity of sound. Let us now consider all the cases.

Case 1 : Source in Motion, While Listener is at Rest

Source approaching a stationary listener

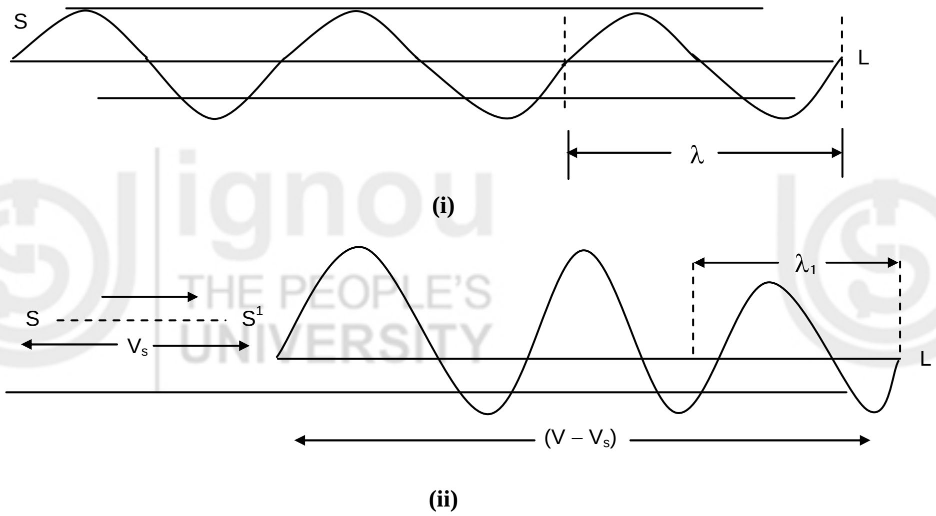


Figure 4.4 : Diagrams of Waves being Compressed or being Spaced Out

Let us consider a source (S) with a velocity V_S approaching a stationary listener (L). For convenience, let us take the distance between the source and listener as V metres, where V is the velocity of sound. This means that the two are separated by a time interval of one second. Thus, a sound emitted at a particular moment by S reaches L at the end of one second. If λ is the wave length and n the frequency of sound emitted, when the first wave reaches L, the n^{th} wave will just be emitted by the source. Thus, n waves, each of wave length λ, will occupy the space between S and L.

Hence, $$V = n\,\lambda \qquad \text{. . . (A)}$$

If now, the source approaches the listener with a velocity V_S, at the end of one second when the first wave approaches L, n^{th} wave will just be emitted from its new position S' in such a way that $SS' = V_S$. At this stage, it appears as though the n waves are compressed in the region $S'L$. Apparently, there is a reduction in the wave length to λ_1 or an increase in the frequency to n_1 in such a way that

$$V = n_1\,\lambda_1 \qquad \text{. . . (B)}$$

$$\lambda_1 = \frac{S'L}{n} = \frac{V - V_S}{n}$$

$$\therefore \qquad n_1 = \frac{V}{\lambda_1} = \frac{V}{\dfrac{(V - V_S)}{n}} = n\left(\frac{V}{V - V_S}\right) \qquad \text{. . . (1)}$$

It is evident from this expression that $n_1 > n$. This is what we observe when a car blowing its horn or an engine sounding its whistle approaches a stationary listener.

Case 2 : Source Receding from Stationary Listener

If we substitute – V_S for V_S in the expression (1) above, we get

$$n_2 = n\left(\frac{V}{V-(-V_s)}\right) = n\left(\frac{V}{V+V_s}\right) \qquad \text{. . . (2)}$$

In other words, $n_2 < n$. This is what we observe when a car blowing its horn or an engine sounding its whistle recedes.

Case 3 : Listener Approaching a Stationary Source

When both the source and the listener are at rest, n waves will cross the listener L in one second in such a way that $V = n\,\lambda$.

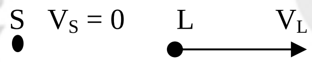
If now the listener approaches the source with a velocity V_L, during the one second interval, he would have advanced through a distance V_L metres and so would have heard the waves present in that region also. Thus, the number of additional waves heard by him is V_L / λ where λ is the wavelength. So, total number of waves heard by him per second is $n + (V_L / \lambda)$.

$$\therefore \qquad n_3 = \left(n + \frac{V_L}{\lambda}\right) = \left(\frac{V}{\lambda} + \frac{V_L}{\lambda}\right) = \left(\frac{V+V_L}{\lambda}\right)$$

$$n_3 = \left(\frac{(V+V_L)}{\frac{V}{n}}\right) = \left(\frac{(V+V_L)}{V}\right) n \qquad \text{. . . (3)}$$

Thus, $n_3 > n$.

Case 4 : Listener Receding from a Stationary Source



By substituting – V_L for V_L in (3) above,

$$n_4 = \left(\frac{V+(-V_L)}{V}\right) n = \left(\frac{(V-V_L)}{V}\right) n \qquad \text{. . . (4)}$$

Thus, $n_4 < n$.

Case 5 : Both in Motion

Source chasing listener with a velocity V_S while listener moves away with velocity V_L

To start with, let us keep the listener at rest ($V_L = 0$) and let the source approach the listener with a velocity V_S. This is the same as case (1). Thus, the apparent frequency

$$n_1 = \left(\frac{V}{V-V_s}\right) n$$

If now the listener moves away from the source with a velocity V_L, apparent frequency

$$n_5 = \left(\frac{V - V_L}{V}\right) n_1$$

Substituting for n_1,

$$n_5 = \left(\frac{V - V_L}{V}\right) \times \left(\frac{V}{V - V_s}\right) n = \left(\frac{V - V_L}{V - V_s}\right) n \qquad \ldots (5)$$

If $V_L = V_S$, there is no Doppler effect. Substituting V_L for V_S, we get

$$n_5 = \left(\frac{V - V_s}{V - V_s}\right) n$$

$$n_5 = n$$

This confirms the correctness of the expression.

Case 6

Source receding from the listener with a velocity V_S, while the listener chases the source with a Velocity V_L

By substituting – V_L for V_L and – V_S for V_S in expression (5) above, apparent frequency

$$n_6 = \left(\frac{V - (-V_L)}{V - (-V_s)}\right) \times n = \left(\frac{V + V_L}{V + V_s}\right) n \qquad \ldots (6)$$

Case 7

Both approaching each other

To start with, let the listener be at rest and let the source approach the listener with a velocity V_S. This is case (1).

$$\therefore \qquad n_1 = \left(\frac{V}{V - V_s}\right) n$$

If now the listener approaches the source with a velocity V_L, apparent frequency

$$n_7 = \left(\frac{V + V_L}{V}\right) n_1 = \left(\frac{V + V_L}{V}\right)\left(\frac{V}{V - V_s}\right) n$$

$$= \left(\frac{V + V_L}{V - V_s}\right) n \qquad \ldots (7)$$

Case 8

Both receding from each other

By substituting – V_S for V_S and – V_L for V_L in expression (7), we get

$$n_8 = \left(\frac{V + (-V_L)}{V - (-V_s)}\right) n = \left(\frac{V - V_L}{V + V_s}\right) n \qquad \text{. . . (8)}$$

4.6.2 Applications of Doppler Principle

In Estimating the Speed of Distant Stars and Planets

When a star approaches the earth, frequency increases or the wavelength of light received decreases, i.e. the spectral line in the spectrum shifts towards blue. Similarly, when it recedes, frequency decreases or the wavelength increases, i.e. the spectral line shifts towards red. Thus, when the star approaches,

$$n' = n\left(\frac{C}{C - V_s}\right)$$

where n' is the apparent frequency, n is the actual frequency, C is the velocity of light and V_S the relative velocity between the star and the earth.

$$\therefore \qquad \frac{C}{\lambda'} = \frac{C}{\lambda}\left(\frac{C}{C - V_s}\right)$$

$$\frac{\lambda}{\lambda'} = \frac{C}{C - V_s}$$

$$\frac{\lambda'}{\lambda} = \frac{C}{C} - \frac{V_s}{C}$$

$$\frac{\lambda'}{\lambda} = 1 - \frac{V_s}{C}$$

$$1 - \frac{\lambda'}{\lambda} = \frac{V_s}{C}$$

$$\frac{d\lambda}{\lambda} = \frac{V_s}{C}$$

or,
$$V_s = C \times \frac{d\lambda}{\lambda}$$

Knowing the change in wavelength $d\lambda$, original wavelength λ and the velocity of light C, V_S can be calculated.

To Estimate the Velocities of Moving Planes or Submarines

Here also the apparent frequency as measured by the source helps in measuring velocities of planes or submarines. In the case of submarines, V is the velocity of sound under water which is of the order of 1500 m/s and in the case of planes it is the velocity of light $c = 3 \times 10^8$ m/s.

To Calculate the Speed of the Ship

This will be studied in detail by you as part of Functional course.

Used for Berthing

Again, this is a part of the Functional course.

Example 4.12

A stationary car sounds its horn. A child rides away from it at the rate of 2 m/s

(a) If the horn sounds a note of frequency 300 Hz, what frequency does the child hear?

(b) What velocity must the child have to hear a frequency 305 Hz? Assume the velocity of sound to be 340 m/s.

Solution

$$V_S = 0,\ V_L = 2 \text{ m/s},\ n = 300 \text{ Hz},\ V = 340 \text{ m/s}$$

(i) $n' = ?$

(ii) $V_L = ?$ if $n' = 305$ Hz.

(a) $$n' = \left(\frac{V - V_L}{V}\right) n = \left(\frac{340 - 2}{340}\right) \times 300 = \frac{338}{340} \times 300 = 298.24 \text{ Hz}$$

(b) $$305 = \left(\frac{V + V_L}{V}\right) \times 300$$

(because apparent frequency > actual frequency if only the listener approaches)

$$\therefore \quad 305 = \left(\frac{340 + V_L}{340}\right) \times 300$$

$$\frac{305}{300} - 1 = \frac{V_L}{340}$$

$$\therefore \quad \frac{V_L}{340} = \frac{305}{300} - 1$$

i.e. $V_L = 5.67$ m/s

Example 4.13

A locomotive approaches and passes a person standing beside the track at 30 m/s. Its whistle is emitting a note of frequency 2000 Hz. What frequency will the person hear (i) as the train approaches, (ii) as it recedes? Speed of sound in air is 340 m/s.

Solution

$$V_L = 0;\ V_S = 30 \text{ m/s};\ V = 340 \text{ m/s};\ n = 2000 \text{ Hz};\ n_{\text{approach}} = ?\ n_{\text{receding}} = ?$$

$$n_a = \left(\frac{V}{V - V_s}\right) n = \left(\frac{340}{340 - 30}\right) \times 2000 = 2193.55 \text{ Hz}$$

Similarly, $$n_r = \left(\frac{V}{V + V_s}\right) n = \left(\frac{340}{370}\right) \times 2000 = 1837.83 \text{ Hz}$$

Example 4.14

An automobile moving at 30 m/s is approaching a factory whistle that has a frequency 500 Hz. If the speed of sound is 340 m/s, find the apparent frequency of the whistle as heard by the driver.

Solution

$$n = 500 \text{ Hz};\ V_L = 30 \text{ m/s};\ V = 340 \text{ m/s};\ V_S = 0;\ n' = ?$$

$$n' = \left(\frac{V + V_L}{V}\right) n = \left(\frac{340 + 30}{340}\right) 500 = 544.12 \text{ Hz}$$

Example 4.15

A passenger on a railway platform observed that as the train passed through the station at a speed of 72 kmph, the frequency of the whistle appeared to drop by 500 Hz. Calculate the frequency of the whistle, if the velocity of sound in air is 340 m/s.

Solution

$$V_L = 0;\ V_S = 72 \text{ kmph} = 20 \text{ m/s};\ V = 340 \text{ m/s}$$

$$n_a - n_r = 500 \text{ Hz};\ n = ?$$

$$n_a = \left(\frac{V}{V - V_s}\right) n \ ;\ n_r = \left(\frac{V}{V + V_s}\right) n$$

$$\therefore \quad n_a - n_r = n\left(\frac{V}{V - V_s} - \frac{V}{V + V_s}\right) = \left(\frac{V + V_s - V + V_s}{V^2 - V_s^2}\right) nV$$

$$\therefore \quad \frac{2n\,V V_s}{V^2 - V_s^2} = 500$$

$$\text{Thus,} \quad n = 500\left(\frac{V^2 - V_s^2}{2V V_s}\right) = \frac{500 \times (340^2 - 20^2)}{2 \times 340 \times 20} = 4235.29 \text{ Hz}.$$

Example 4.16

Two trains travelling in opposite directions on parallel tracks at 100 kmph each, cross each other. One of them is whistling a note of frequency 800 Hz. Find the apparent pitch as heard by the passenger in the other train (i) before they cross each other, (ii) after they cross each other. Velocity of sound is 340 m/s.

Solution

$$V_s = V_L = 100 \text{ kmh} = \frac{100 \times 1000}{3600} = 27.78 \text{ m/s};\ n = 800 \text{ Hz};\ V = 340 \text{ m/s}$$

$$n_a = ?\ \ n_r = ?$$

$$\text{(a)} \quad n_a = \left(\frac{V + V_L}{V - V_s}\right) n = \left(\frac{340 + 27.78}{340 - 27.78}\right) \times 800 = 942.36 \text{ Hz}$$

$$\text{(b)} \quad n_r = \left(\frac{V - V_L}{V + V_s}\right) n = \left(\frac{340 - 27.78}{340 + 27.78}\right) \times 800 = 679.15 \text{ Hz}$$

Example 4.17

When a car sounding its horn of frequency 500 Hz passes a stationary observer with a speed of 20 m/s, the frequency changes in the ratio 9 : 10. Calculate the velocity of sound.

Solution

$$n = 500 \text{ Hz};\ V_L = 0;\ V_s = 20 \text{ m/s};\ \frac{n_r}{n_a} = \frac{9}{10};\ V = ?$$

$$n_r = \left(\frac{V}{V + V_s}\right) n \text{ and } n_a = \left(\frac{V}{V - V_s}\right) n$$

$$\therefore \quad \frac{n_r}{n_a} = \left(\frac{V}{V + V_s}\right) \times n \times \frac{1}{n}\left(\frac{V - V_s}{V}\right) = \frac{9}{10}$$

$$\frac{V - 20}{V + 20} = \frac{9}{10}$$

or, $10\,V - 200 = 9\,V + 180$

$\therefore$ $V = 380$ m/s

SAQ 5

(a) The siren of two fire engines have a frequency of 600 Hz each. A man hears the siren from the two engines, one approaches him with a speed of 36 km h^{-1} and the other going away from him at a speed of 54 km h^{-1}? What is the difference in frequency of two siren heard by the man? Take speed of sound to be 340 ms^{-1}.

(b) A train standing at the outer signal of a railway station blows a whistle of frequency 400 Hz in still air :

(i) What is the frequency of the whistle for a platform observer, when the train (a) approaches the platform with a speed of 10 ms^{-1}? (b) recedes from the platform with a speed of 10 ms^{-1}?

(ii) What is the wavelength of the sound received by platform observer in each case?

(iii) What is the speed of sound in each case?

Take speed of sound in still air as 340 ms^{-1}.

(c) The siren of a police car emits a pure tone at a frequency of 1175 Hz. Find the frequency that you would perceive in your car under the following circumstances.

(i) Your car at rest, police car moving towards you at 35 m/s.

(ii) Police car at rest, your car moving towards it a 35 m/s.

(iii) You and the police car moving towards one another at 20 m/s.

(iv) You moving at 12 m/s, police car chasing behind you at 40 m/s.

Take velocity of sound = 343 m/s.

(d) Both the source and observer move in the same direction with a velocity equal to half the velocity of sound. Compute the change in frequency of the sound as detected by the observer.

(e) Both the source and observer approach each other with a velocity equal to half the velocity of sound. Compute the change in frequency of the sound as detected by the observer.

(f) A locomotive whistle 256 vib/sec is moving towards you with a velocity of $1/20^{th}$, that of sound. What will be the frequencies of the notes heard by you before and after the engine passes you?

4.7 SUMMARY

Let us summarise what you have learnt in this unit :

- Sound is a form of energy.
- Sound is produced by the vibration of particles in the medium.
- Wave motion is a disturbance created in the medium due to which the particles of the medium vibrate and the energy is transferred.
- Wave motion basically is of two types, i.e. Transverse and Longitudinal.
- Sound travels in the form of longitudinal waves and electromagnetic waves are example of transverse wave.
- Longitudinal wave consists of alternate compressions and rarefactions.

- In any medium, velocity of sound $v = \sqrt{\frac{E}{\rho}}$, where E is the Modulus of Elasticity applicable to the medium and ρ its density.
- Velocity of sound in solids $= \sqrt{\frac{Y}{\rho}}$ where, Y is Young's Modulus and ρ the density of the medium.
- Velocity of sound in fluids $= \sqrt{\frac{K}{\rho}}$ where, K is the Bulk Modulus of Elasticity and ρ the density of the medium.
- Newton's formula for velocity of sound through a gaseous medium is $v = \sqrt{\frac{p}{\rho}}$ where, p is the pressure in the medium and ρ its density.
- Laplace's correction to Newton's formula is $v = \sqrt{\frac{\gamma p}{\rho}}$; where $\gamma = \frac{C_P}{C_V}$.
- Velocity of sound in sea water varies at the rate of :
  - (a) 1.8 m/s for a change of depth of 10 m.
  - (b) 3 m/s/°C
  - (c) 1.3 m/s for every percentage point of salinity.
- Change in pressure does not cause a change in velocity of sound in a gaseous medium as it is accompanied by a proportionate change in density making $\frac{p}{\rho}$ a constant.
- $v \propto \sqrt{T}; \therefore \frac{v_1}{v_2} = \sqrt{\frac{T_1}{T_2}}$
- $v \propto \frac{1}{\sqrt{\rho}}; \therefore \frac{v_1}{v_2} = \sqrt{\frac{\rho_2}{\rho_1}}$
- $\rho_{\text{moist air}} < \rho_{\text{dry air}} \therefore v_{\text{moist air}} > v_{\text{dry air}}$
- $V' = V \pm w$ depending upon the fact whether wind is favourable or otherwise.
- Pitch is the physiological or the acoustic sensation produced in the ear due to frequency. Similarly, loudness is the physiological or the acoustic sensation produced in the ear by intensity of sound.
- Intensity of sound (I) is the energy falling on or passing through unit area normal to the area per second.

$$I = 2\pi^2 f^2 a^2 \rho V$$

- Threshold of audibility (I_0) is the minimum audible sound and is taken as equivalent to 10^{-12} W/m^2.
- (a) $L \propto \log I$.
  - (b) $n = 10 \log \left(\frac{I}{I_0}\right)$ or $I = I_0 \times 10^{n/10}$
  - (c) Unit of loudness is Bel. However, the practical unit is "decibel" which incidentally is defined as ten times the logarithmic ratio of 1.26 : 1.

- Quality of sound is that characteristic which enables us to differentiate between two persons or two instruments even though they have the same frequency and intensity.
- *N* = *nh* where '*N*' is the frequency to be measured, '*n*' the frequency of rotation of the disc *D* and '*h*' the number of holes.
- Case 5 is to be taken as the general case. By comparing the vector diagrams of all the other cases with Case 5 and substituting for V_S and V_L suitably, we obtain the expressions for all the seven cases.

Case	Vector Diagram	Expression for Apparent Frequency
5	S •→ V_S L •→ V_L	$n_5 = \left(\frac{V - V_L}{V - V_S}\right) n$
6	V_S ←• S V_L ←• L	$n_6 = \left(\frac{V - (-V_L)}{V - (-V_S)}\right) n$ $\therefore n_6 = \left(\frac{V + V_L}{V + V_S}\right) n$
7	S •→ V_S V_L ←• L	$n_7 = \left(\frac{V - (-V_L)}{V - V_S}\right) n$ $\therefore n_7 = \left(\frac{V + V_L}{V - V_S}\right) n$
8	V_S ←• S L •→ V_L	$n_8 = \left(\frac{V - V_L)}{V - (-V_S)}\right) n$ $\therefore n_8 = \left(\frac{V - V_L}{V + V_S}\right) n$
1	S •→ V_S L • $V_L = 0$	$n_1 = \left(\frac{V - 0}{V - V_S}\right) n$ $\therefore n_1 = \left(\frac{V}{V - V_S}\right) n$
2	V_S ←• S L • $V_L = 0$	$n_2 = \left(\frac{V - 0}{V - (-V_S)}\right) n$ $\therefore n_2 = \left(\frac{V}{V + V_S}\right) n$
3	$V_S = 0$ S • V_L •→ L	$n_3 = \left(\frac{V - (-V_L)}{V - 0}\right) n$ $\therefore n_3 = \left(\frac{V + V_L}{V}\right) n$
4	$V_S = 0$ S • L •→ V_L	$n_4 = \left(\frac{V - V_L)}{V - 0}\right) n$ $\therefore n_4 = \left(\frac{V - V_L}{V}\right) n$

- Doppler Principle is used in measuring speed of ship, submarines, distant stars, planets, etc.

4.8 KEY WORDS

Wave Motion : A wave motion is defined as a disturbance which is handed over from one part of the medium to the next due to the repeated motion of the medium particle about their mean positions.

Transverse Wave Motion : When the particles of the medium vibrate about their mean positions in a direction perpendicular to the direction of propagation of disturbance, the wave motion is called the transverse wave motion.

Longitudinal Wave Motion : When the particles of the medium vibrate about their mean positions along the direction of propagation of disturbance, the wave motion is called the longitudinal wave motion.

Wave Length (λ) : The distance travelled by the disturbance in the time, the particle of the medium completes once vibration is called wave length.

Pressure Wave : Since a sound wave consists of a repeating pattern of high pressure and low pressure regions moving through a medium, it is sometimes referred to as a pressure wave.

Frequency : The number of vibrations performed by a particle in one second is defined as frequency.

Time Period : This is defined as the time required to complete one vibration.

Amplitude : The maximum displacement of the particle on either side of its mean position is called its amplitude.

Doppler Effect : Doppler effect is the phenomenon of change in apparent pitch (frequency) of the sound due to the relative motion between the source of the sound and the listner.

Musical Sound : A musical sound consists of a series of harmonic waves following each other at a regular interval of time, without sudden changes in their amplitude.

Noise : A noise consists of a series of waves following each other at irregular interval of time, with sudden change in their amplitudes.

Intensity of Sound : The intensity of sound at any point may be defined as the amount of sound energy passing per unit time per unit area around that point in a perpendicular direction.

Pitch : It is the characteristics of musical sound that helps the listner to distinguish a shrill note from a grave (flat or dull) one.

Loudness : The sensation of hearing which enables to distinguish between a laud and a faint sound is called loudness.

4.9 ANSWERS TO SAQs

SAQ 1

(a) We know, velocity of sound in air,

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

Here, $\gamma = 1.4$, $p = 10^5$ Pa, and $\rho = 1.21$ kg/m^3.

So, putting all these values in the above equation, we get

$$v = \sqrt{\frac{1.4 \times 10^5}{1.21}} = 340.15 \text{ m/sec}$$

(b) We know $\quad v = \sqrt{\frac{\gamma p}{\rho}}$

$$= \sqrt{\frac{1.4 \times 1.013 \times 10^5}{1.98}} = 267.63 \text{ ms}^{-1}$$

We also know $\quad v = \lambda \nu$

$\Rightarrow \quad 265.58 = \lambda \times 1000$

$\Rightarrow \quad \lambda = 0.26763$ m

SAQ 2

(a) We know $\quad \frac{v_1}{v_2} = \sqrt{\frac{T_1}{T_2}\frac{M_2}{M_1}} \qquad \left(\because \; v = \sqrt{\frac{\gamma RT}{M}}\right)$

Now, v_1 and v_2 are same.

So, $\quad \frac{T_1}{T_2} = \frac{M_1}{M_2}$

$\Rightarrow \quad T_1 = 273 + 20 = 293$ K

Also, $\quad \frac{M_1}{M_2} = \frac{16}{14}, \quad T_2 = ?$

$\Rightarrow \quad T_2 = T_1 \times \frac{M_2}{M_1} = 293 \times \frac{14}{16} = 256.37$ K

or $\quad = -16.62^\circ$C

(b) Here $\quad v = 1.7 \text{ km s}^{-1} = 1.7 \times 10^3 \text{ ms}^{-1}$

$\nu = 4.2 \text{ MHz} = 4.2 \times 10^6$ Hz

We know $\quad \lambda = \frac{v}{\nu} = \frac{1.7 \times 10^3}{4.2 \times 10^6} = 4.05 \times 10^{-4} \text{ m} = 0.405 \text{ mm}$

(c) We know that $\quad \frac{v_2}{v_1} = \sqrt{\frac{T_2}{T_1}}$

Here, $\quad v_2 = 2\, v_1, \quad T_1 = 273$ K

Therefore, $\quad \frac{2v_1}{v_1} = \sqrt{\frac{T_2}{273}}$

$\Rightarrow \quad T_2 = 1092 \text{ K} \quad \text{or} \quad 819^\circ\text{C}$

(d) (i) We know, $v = \sqrt{\frac{\gamma p}{\rho}}$

So, $\frac{v_a}{v_h} = \sqrt{\frac{\rho_h}{\rho_a}}$

where ρ_h and ρ_a are densities of hydrogen and air, respectively.

Given $\frac{\rho_h}{\rho_a} = \frac{1}{16}$

$\Rightarrow \quad \frac{v_a}{v_h} = \sqrt{\frac{1}{16}} = \frac{1}{4}$

$v_h = 4\, v_a = 4 \times 332 = 1328 \text{ ms}^{-1}$

(ii) We also know that the speed of sound is directly proportional to the square root of absolute temperature of the gas.

So, $\frac{v_{819}}{v_0} = \sqrt{\frac{273 + 819}{273}} = 2$

So, $v_{819} = 2 v_0 = 2 \times 1326 = 2656 \text{ ms}^{-1}$

Note that there is no effect of the change in pressure on the speed of sound.

(e) We know $\frac{v_2}{v_1} = \sqrt{\frac{T_2}{T_1}}$

Note that there is no effect of the change in pressure on the speed of sound.

So, $\frac{v_2}{340} = \sqrt{\frac{430.5}{287}}$

$\Rightarrow \quad V_2 = 416.41 \text{ ms}^{-1}$

[$\because$ Here $T_2 = 273 + 157.7 = 430.7$ K and $T_1 = 273 + 14 = 287$ K].

SAQ 3

(a) We know, $I = I_0 \times 10^{\frac{n}{10}}$

Here $I_0 = 10^{-12}\text{ W/m}^2, \quad n = 60 \text{ dB}$

So, $I = 10^{-12} \times 10^{\frac{60}{10}} = 10^{-6}\text{ W/m}^2$

Area $= 120 \text{ cm}^2 = 1.20 \times 10^{-2}\text{ m}^2$

Output $= I \times \text{Area} = 10^{-6} \times 1.20 \times 10^{-2} = 1.20 \times 10^{-8}\text{ W}$

(b) $I_1 = 10^{-6}\text{ W/m}^2$

$I_2 = 10^{-9}\text{ W/m}^2$

Ratio $\frac{I_1}{I_2} = \frac{10^{-6}}{10^{-9}}$

$I_1 = 10^3\, I_2$

(e) Here $I = 3 \times 10^{-6}$ W/m^2 ; f = 1000 Hz, f = 1.29 kg/m^3; v = 332.5 ms^{-1}

We know, $$a = \sqrt{\frac{I}{2\pi^2 \; f^2 \; \rho \; v}}$$

$$= \sqrt{\frac{3 \times 10^{-6}}{2 \times \pi^2 \times 1000^2 \times 1.29 \times 332.5}}$$

$$= 18.8 \times 10^{-9} \text{ m} \quad \text{or} \quad 18.8 \text{ nm}$$

(f) We know, $$\frac{I_1}{I_2} = 10^{\frac{(n_1 - n_2)}{10}}$$

$$\Rightarrow \quad \frac{10^{-8}}{5 \times 10^{-10}} = 10^{\frac{(n_1 - n_2)}{10}}$$

$$\Rightarrow \quad 20 = 10^{\frac{(n_1 - n_2)}{10}}$$

$$\Rightarrow \quad \log 20 = \frac{(n_1 - n_2)}{10}$$

$$\Rightarrow \quad n_1 - n_2 = 13$$

(g) Here $I = 10^{-3}$ W/m^2, f = 1000 Hz, ρ = 1.29 kg/m^3, v = 332.5 m/s.

We know $$a = \sqrt{\frac{I}{2\pi^2 \; f^2 \; \rho \; v}}$$

$$= \sqrt{\frac{10^{-3}}{2\pi^2 \times 1000^2 \times 1.29 \times 332.5}}$$

$$= 343.6 \times 10^{-9} \text{ m} \quad \text{or} \quad 343.6 \text{ nm}$$

(i) Here f = 3000 Hz, a = 0.2 mm or 0.2 × 10^{-3} m, ρ = 1.29 kg/m^3, v = 330 m/s.

We know $$I = 2\pi^2 \; f^2 \; a^2 \; \rho \; v$$

So, $$I = 2\pi^2 \times 3000^2 \times (0.2 \times 10^{-3})^2 \times 1.29 \times 330$$

$$= 3.025 \times 10^3 \text{ W/m}^2$$

SAQ 4

(a) Here h = 36; N = 512 Hz; n in rpm

$N = n\,h$

So, $$n = \frac{512}{36} \text{ rotation per sec}$$

$$= \frac{512}{36} \times 60 \text{ rpm} = 853.33 \text{ rpm}$$

(b) Here h = 46; N = 450 Hz; n is in rpm

We know $N = n\,h$

$$450 = n \times 46$$

$\Rightarrow \quad n = \dfrac{450}{46}$ rotation/s

$= \dfrac{450 \times 60}{46}$ rpm or 586.96 rpm

(c) Here, $h = 46$, $N = 360$ Hz, n = revolution per second.

We know; $N = n\,h$

$\Rightarrow \quad 360 = n \times 46$

$\Rightarrow \quad n = \dfrac{360}{46}$ revolution per second

$= \dfrac{360}{46} \times 60$ rpm

$= 469.56$ rpm

Further, we know $v = \lambda\, N$

$\Rightarrow \quad 340 = \lambda \times 360$

$\Rightarrow \quad \lambda = \dfrac{340}{360} = 0.9444$ m or 94.44 cm

(d) Here $h = 46$, $N = 950$ Hz, n = revolution per second

We know, $N = n\,h$

$\Rightarrow \quad 960 = 46\,n$

$\Rightarrow \quad n = 20.87$ revolution/sec or 1252.17 rpm

Further, we know $v = \lambda\, N$

$\Rightarrow \quad 342 = \lambda \times 960$

$\Rightarrow \quad \lambda = 0.35625$ m or 35.625 cm

(e) Here $h = 60$, $n = \dfrac{4\pi}{2\pi} = 2$ revolution per second

We know, $N = n\,h$

$= 2 \times 60 = 120$ Hz

(f) Here $h = 40$; $n = 500$ times in 1 minute and 36 seconds
$= 5.2083$ revolution per second

We know; $N = n\,h$

$= 40 \times 5.2083 = 208.33$ Hz

Again $v = \lambda\, N$

$\Rightarrow \quad 342 = \lambda \times 208.33$

$\Rightarrow \quad \lambda = 1.64$ m

SAQ 5

(a) Here $v = 340\ \text{ms}^{-1}$, $\nu = 600$ Hz.

For engine approaching the man :

$$U_s = 36\ \text{kmh}^{-1} = 10\ \text{ms}^{-1}$$

$$\nu' = \frac{v}{v - U_s}\,\nu = \frac{340}{340 - 10} \times 600 = 618.18\ \text{Hz}$$

For engine going away from the man :

$$U_s = 54\ \text{kmh}^{-1} = 15\ \text{ms}^{-1}$$

$$\nu'' = \frac{v}{v - U_s}\,\nu = \frac{340}{340 + 15} \times 600 = 574.65\ \text{Hz}$$

$\therefore$ $$\nu' - \nu'' = 618.18 - 574.65 = 43.53\ \text{Hz}$$

(b) Here $v = 340\ \text{ms}^{-1}$, $\nu = 40$ Hz, $U_s = 10\ \text{ms}^{-1}$

When the engine approaches the platform

(i) $$\nu' = \frac{v}{v - U_s}\,\nu = \frac{340}{340 - 10} \times 400 = 412.1\ \text{Hz}$$

When the engine recedes from the platform, then

$$\nu' = \frac{v}{v + U_s}\,\nu = \frac{340}{340 + 10} \times 400 = 388.6\ \text{Hz}$$

(ii) $$\lambda' = \frac{v - U_s}{\nu} = \frac{340 - 10}{400} = 0.825\ \text{m}$$

Wavelength of sound waves received by observer, when engine recedes from the platform,

$$\lambda' = \frac{v + U_s}{v} = \frac{340 + 10}{400} = 0.875\ \text{m}$$

(iii) The relative velocity of sound w.r.t moving engine will remain unaltered in both the cases, i.e. it will be $340\ \text{ms}^{-1}$.

(c) (i) Here $v_0 = 0$, $v_s = 35$ m/s, $v = 343\ \text{ms}^{-1}$ (for the speed of sound in still air).

We know, $$\nu' = \nu\,\frac{v}{v - v_s} = 1175 \times \frac{343}{343 - 35} = 1308.52\ \text{Hz}$$

(ii) In this case, $v_s = 0$, $v_0 = 35$ m/s, $v = 343$ m/s

$$\nu' = \nu\,\frac{v + v_0}{v} = 1175 \times \frac{(343 + 35)}{343} = 1295\ \text{Hz}$$

(iii) In this case, $v_s = 17.5$ m/s, $v_0 = 17.5$ m/s

$$\nu' = \nu\,\frac{v + v_0}{v - v_s} = 1175 \times \frac{(343 + 17.5)}{(343 - 17.5)} = 1301.34\ \text{Hz}$$

(iv) Here, $v_0 = 12$ m/s and $v_s = 37$ m/s

$$\nu' = \nu\,\frac{v - v_0}{v - v_s} = 1175 \times \frac{(343 - 12)}{(343 - 37)} = 1271\ \text{Hz}$$

Note that in all four cases, in the problem, the relative speed between you and the police car is the same, i.e. 35 m/s, but the result for all these four cases are different.

(d) In this case, $\nu' = \left(\dfrac{v - v_0}{v - v_s}\right)\nu$.

Both are moving in the direction of sound

$$\nu' = \left(\frac{v - \frac{v}{2}}{v - \frac{v}{2}}\right)\nu$$

$$\nu' = \nu$$

no change in frequency.

(e) In this case, $\nu' = \left(\dfrac{v - v_0}{v - v_s}\right)\nu$

Observer is moving in the opposite direction of sound

$$\nu' = \left(\frac{v + \frac{v}{2}}{v - \frac{v}{2}}\right)\nu = 3\nu$$

$$\Delta\nu = 3\nu - \nu = 2\nu = 200\%$$

(f) We know that, $\nu' = \nu\left(\dfrac{v - v_0}{v - v_s}\right)$

(i) When locomotive is approaching the stationary observer

$$\nu = 256 \text{ vib./sec}, \; v_s = \frac{v}{20} \text{ and } v = 0.$$

$$\therefore \quad \nu' = 256\,\frac{v - 0}{v - \frac{v}{20}} = 256 \times \frac{20}{19} = 269.5 \text{ vib/sec}$$

(ii) When locomotive passes the stationary observer,

$$v_s = -\frac{v}{20}.$$

$$\nu' = 256\,\frac{v - 0}{v - \left(-\frac{v}{20}\right)} = 256 \times \frac{20}{21} = 243.8 \text{ vib/sec}$$