# Sound Waves and Acoustics of Buildings

**Learning Objectives**

*After reading this chapter you will be able to*

- **LO1** Know about audible, ultrasonic, and infrasonic waves
- **LO2** Learn about Production of ultrasonic waves, magnetostriction method, Piezoelectric method, ultrasonic transducer, Galton Whistle method
- **LO3** Understand the absorption, dispersion, and detection of ultrasonic waves
- **LO4** Analyse the applications of ultrasonic waves
- **LO5** Explain the types of acoustics
- **LO6** Discuss on acoustics of buildings
- **LO7** Evaluate the factors affecting the architectural acoustics

## Introduction

A vibration refers to the oscillating motion of any medium and sound is a vibration in an elastic medium. These vibrations transmitting through a solid, liquid, or gas, are composed of frequencies within the range of hearing and are of a level sufficiently strong to be heard. In the case of human hearing it is the vibrations in air that simulate our hearing organs and give a sensation of sound. When sound enters a new medium, it is reflected, transmitted, or absorbed. This scientific study of the propagation, absorption, and reflection of sound waves is called *acoustics*.

Acoustics is the interdisciplinary science that deals with the study of sound, ultrasound and infrasound (all mechanical waves in gases, liquids, and solids). In a broad sense, acoustics may be defined as generation, transmission and reception of energy in the form of vibration waves in matter.

## 9.1 AUDIBLE, ULTRASONIC AND INFRASONIC WAVES — LO1

The simplest form of sound waves is sinusoidal waves of definite frequency, wavelength and amplitude. The frequency range of waves from 20 Hz to 20,000 Hz are said to be audible waves for which range human ears are sensitive but the waves of frequency above the audible range are called ultrasonic waves and below the audible range are known as infrasonic waves.

Ultrasonics is the study and application of the energy of sound waves vibrating at frequencies greater than 20,000 Hz, i.e., beyond the range of human hearing. The application of sound energy in the audible range is limited almost entirely to communications, since increasing the pressure, or intensity, of sound waves increases loudness and therefore causes discomfort to human beings. Ultrasonic waves, however, being inaudible, have little or no effect on the ear even at high intensities. They are produced, commonly, by a transducer containing a piezoelectric substance, e.g. a quartz-crystal oscillator that converts high-frequency electric current into vibrating ultrasonic waves.

Sound waves, particularly in the atmosphere, whose frequencies are below the audible range, i.e., lower than about 20 Hz are called infrasonic waves. Earthquake and seismic waves are elastic waves which occur at infrasonic frequencies in the Earth's crust and in the oceans and seas. The physical laws of propagation in the atmosphere are essentially the same as for audible sound. The local speed of infrasound in air at ambient temperatures near 20°C is about 340 m/s, the same as for audible sound.

## 9.2 PRODUCTION OF ULTRASONIC WAVES  LO2

In most applications, ultrasonic waves are generated by applying an electric current to a special kind of crystal known as a piezoelectric crystal. The crystal converts electrical energy into mechanical energy, which, in turn, causes the crystal to vibrate at a high frequency. In another technique, a magnetic field is applied to a crystal, causing it to emit ultrasonic waves. Although the bulk attention is given to more popular types of transducers which are based on magnetostriction and piezoelectric effect, there are other means of generating ultrasonic waves some of which exhibit great promise.

### 9.2.1 Magnetostriction Method

Before discussing this method for the generation of ultrasonic waves, we shall talk about the magnetostriction effect.

#### *9.2.1.1 Magnetostriction Effect*

When a rod of ferromagnetic material such as iron, nickel or cobalt is placed in a magnetic field keeping its length parallel to the direction of magnetic field, the rod experiences a small change in its length. This effect is termed as magnetostriction effect. The change in length of the rod depends on the intensity of the applied magnetic field and nature of the ferromagnetic material. However, the change in the length is independent of the direction of the field. Since the change is not so great in the other dimensions of the rod, the rod is generally put with its length parallel to the direction of the magnetic field. The cause of change in material's dimensions can be understood as follows. Actually ferromagnetic materials have a structure that is divided into domains, each of which is a region of uniform magnetic polarisation. Under the application of an external magnetic field, the boundaries between the domains shift and the domains rotate. These two effects lead to a change in the dimensions of the materials.

#### *9.2.1.2 Principle Involved*

The general principle involved in producing ultrasonic waves is to cause ferromagnetic materials to vibrate very rapidly. These vibrations cause surrounding air to vibrate with the same frequency, which spreads out in the form of ultrasonic waves.

When the rod is placed inside a magnetic coil carrying alternating current, it suffers a change in length for each half of the alternating current. It means the rod vibrates at a frequency twice that of the frequency of the alternating current. Usually the amplitudes of vibrations are small, but these can be enhanced by achieving the resonance condition, i.e., by matching the frequency of the alternating current with the natural frequency of the material of the rod.

### 9.2.1.3 Construction and Working

In Fig. 9.1, a rod (ferromagnetic material) with its ends $A$ and $B$ is winded by the coils $L_1$ and $L_2$. The coil $L_2$ is connected to the collector of the transistor whereas the coil $L_1$ is connected to its base. In view of an $LC$ circuit, we can adjust the frequency of the oscillatory circuit $\left(\frac{1}{2\pi\sqrt{L_2C}}\right)$ by adjusting the value of the capacitor $C$. The current flowing in the circuit can be determined by the milliammeter connected across the coil $L_2$. A necessary biasing, i.e., the emitter as forward biased and the collector as reverse biased for the $NPN$ transistor, is achieved by the battery (current) connected between the emitter and the collector of the transistor. The alternating current passing through the coil $L_2$ causes a corresponding change in the magnetization of the rod and hence the rod starts vibrating due to the magnetostriction effect.

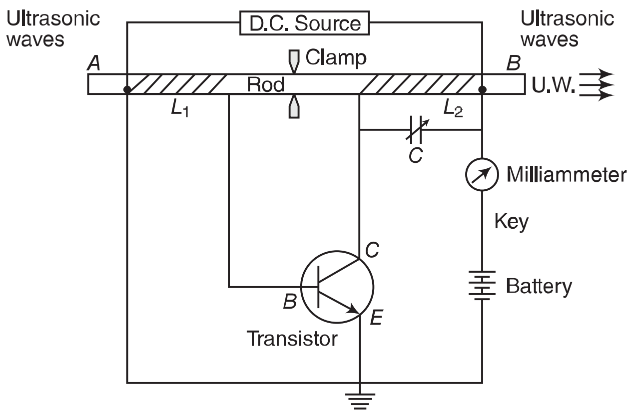


**FIGURE 9.1**

In the above situation, an emf is also induced in the coil which is called as converse magnetostriction effect. Due to this effect an emf is induced in the coil $L_1$. This induced emf is fed to the base of the transistor, which acts as a feed back continuously. This way the current is built up in the transistor and the vibrations of the rod are maintained for the generation of ultrasonic waves. When the frequency of the oscillatory circuit matches with the natural frequency of the vibrating rod, the resonance occurs. At the resonance, the rod vibrates longitudinally with larger amplitude and produces ultrasonic waves of high frequency along both the ends of the rod.

If the Young's modulus of the material of the rod is $Y$, its density is $\rho$ and the length of the rod is $l$, then the frequency of vibrations of the rod is given by $\frac{1}{2l}\sqrt{\frac{Y}{\rho}}$. When this frequency matches with the frequency of the oscillatory circuit $\frac{1}{2\pi\sqrt{L_2C}}$, the resonance occurs. Based on this we get

$$\frac{1}{2\pi\sqrt{L_2C}} = \frac{1}{2l}\sqrt{\frac{Y}{\rho}}.$$

### 9.2.1.4 Advantages and Limitations

There are several advantages of magnetostriction method of generating ultrasonic waves. For example, magnetostrictive or ferromagnetic materials are easily available and inexpensive. The design of the oscillatory circuit is simple and it involves low cost of the materials. Moreover, at low ultrasonic frequencies, the large power output can be produced without any risk of damage of the oscillatory circuit.

On the other hand, this method has some limitations also. For example, through this method we cannot achieve ultrasonic waves of frequencies larger than about 3 MHz. The frequency of oscillations also depends on the temperature and degree of magnetization. So hearing effect may change the frequency of ultrasonic waves and there will be losses of energy due to hystersis and eddy current. Finally the condition of resonance shows that we need to reduce the length of the rod in order to produce higher frequency ultrasonic waves, which is not practically feasible.

### 9.2.2 Piezoelectric Method

LO2

Before discussing this method for the generation of ultrasonic waves, we shall talk about the piezoelectric effect.

#### *9.2.2.1 Piezoelectric Effect*

In 1880, the brothers *Pierre* and *Jacques Curie* discovered in an experiment the fact that certain crystals can develop an electric charge when a mechanical pressure or tension is applied. This phenomenon was later named as Piezoelectric effect. They showed that there was a direct proportion between the mechanical pressure and the resultant charge, and sign of the charge changed when pressure changed to tension or vice versa. This may take the form of a separation of electric charge across the crystal lattice. If the material is not short-circuited, the applied charge induces a voltage across the material. The crystals which acquire a charge when compressed, twisted or distorted are said to be piezoelectric. The effect is present in many crystals but it is useful in *Quartz* and *6*.

In addition, certain ceramics and biological matter such as DNA, bone and various proteins show the piezoelectric effect or the piezoelectricity in response to applied mechanical stress. The word piezoelectricity, which means electricity resulting from pressure, was derived from the Greek words *piezō* or *piezein* that means to squeeze or press and *ēlektron* that means amber (an ancient source of electric charge). Piezoelectric effect finds useful applications such as the production and detection of sound, generation of high voltages, electronic frequency generation, microbalances, and ultrasonic focusing of optical assemblies.

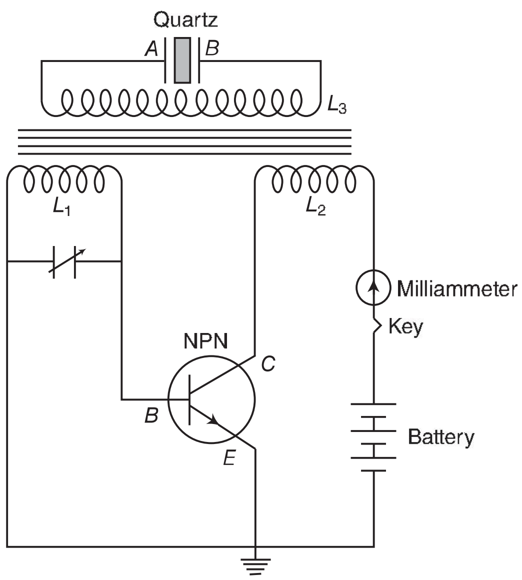


**FIGURE 9.2**

#### 9.2.2.2 Principle Involved

When a slab of a piezoelectric crystal such as quartz is placed between two metal plates and resonant mechanical vibrations are produced in the crystal due to the linear expansion and contraction, elastic waves are propagated in the metallic plates which generate ultrasonic waves. An efficient generation of ultrasonic waves takes place when the crystal oscillates at the maximum amplitude. This happens when the frequency of the oscillatory circuit matches with the natural frequency of one of the modes of vibrations of the crystal. The frequency of the generated ultrasonic waves depends on the Young's modulus and the density of the piezoelectric material.

#### 9.2.2.3 Construction and Working

Piezoelectric generator that works on the piezoelectric effect is used for generating ultrasonic waves of high frequency of about 50 MHz. For this a slice of quartz crystal is placed between two metal plates *A* and *B* in order to form a parallel plate capacitor having the quartz crystal as a dielectric medium. Quartz is preferred because it possesses rare physical and chemical properties. The metal plates are connected to the terminals of a coil which is inductively coupled to the oscillating circuit, as shown in Figure 9.2. Due to this electrical circuit, an alternating potential difference is developed across the plates of the capacitor because of which a tensile pressure appears on the crystal. This produces alternate contraction and expansion of the crystal and the opposite charges are generated on the faces of the crystal lying towards *A* and *B*. Through piezoelectric effect the crystal produces sound waves and when the frequency of electrical oscillations is in the ultrasonic range then ultrasonic waves are generated.

As shown in Fig. 9.2, the variable capacitor *C* is adjusted in order to match the frequency of the oscillatory circuit with the natural frequency of one of the modes of vibrations of the crystal. This way we are able to produce resonant mechanical vibrations in the crystal due to the linear expansion and contraction. If one or both the faces of the crystal are placed in contact with some medium in which elastic waves can be propagated, ultrasonic waves are generated. The *LC* circuit having a variable capacitor *C* and an inductor $L_2$ decides the frequency of the electrical oscillations. When the circuit is closed, the current flows through the *LC* circuit and the capacitor is charged. The current stops flowing when the capacitor is fully charged. After that the capacitor is made to discharge through the inductor so that the electric energy is stored in the form of electric and magnetic fields associated with the capacitor and the inductor, respectively. This way we get electrical oscillations in the circuit and with the help of the other electronic components including a transistor, electrical oscillations are produced continuously. This is fed to the secondary circuit and the crystal vibrates, as it is continuously subjected to alternating electric field.

### 9.2.3 Ultrasonic Transducer

LO2

A transducer is a device which is used to convert one form of energy to another. Ultrasonic transducers convert electrical energy to mechanical energy and vice versa. Ultrasonic sound can be produced by transducers which operate either by the piezoelectric effect or the magnetostrictive effect. The magnetostrictive transducers can be used to produce high intensity ultrasonic sound in the 20–40 kHz range for ultrasonic cleaning and other mechanical applications. Ultrasonic transducers are constructed by incorporating one or more piezoelectric vibrators which are electrically connected to pulsing-receiving system. An ultrasonic transducer includes an ultrasonic transmitting/receiving element typically consisting of piezoelectric element connected to electrodes. The piezoelectric elements typically are made of material such as lead zirconate titanate (PZT), with a plurality of elements being arranged to form a transducer assembly. The transducer assembly is then further assembled into a housing possibly including control electronics, in the form of electronic circuit boards, the combination of which forms an ultrasonic probe.

The active element is the heart of the transducer as it converts the electrical energy to acoustic energy, and vice versa. The active element is basically a piece of polarised material (i.e., some parts of the molecule are positively charged, while other parts of the molecule are negatively charged) with electrodes attached to two of its opposite faces. When an electric field is applied across the material, the polarised molecules will align themselves with the electric field, resulting in induced dipoles within the molecular or crystal structure of the material. This alignment of molecules will cause the material to change dimensions. This phenomenon is known as *electrostriction.* In addition, a permanently-polarised material such as quartz ($SiO_2$) or barium titanate ($BaTiO_3$) will produce an electric field when the material changes dimensions as a result of an imposed mechanical force.

The thickness of the active element is determined by the desired frequency of the transducer. A thin wafer element vibrates with a wavelength that is twice its thickness. Therefore, piezoelectric crystals are cut to a thickness that is half the desired radiated wavelength. The higher the frequency of the transducer, the thinner is the active element. The primary reason that high frequency contact transducers are not produced is because the element is very thin and too fragile.

#### 9.2.3.1 Uses of Ultrasonic Transducers

Ultrasonic transducers are useful for various applications. Ultrasonic testing equipment is used in a variety of applications such as for measuring flow, determining flaws, measuring thickness, and gauging corrosion. Ultrasonic diagnostic imaging systems are in widespread use for performing ultrasonic imaging and measurements of the human body through the use of probes which are used to view the internal structure of a body by creating a scan plane.

### 9.2.4 Galton Whistle Method

LO2

Galton's whistle was invented in 1876 by Francis Galton and is mentioned in his book named *Inquiries into Human Faculty and its Development*. In this book, he described experiments to test the range of frequencies that could be heard by various animals. This whistle most commonly known as dog whistle or silent whistle is a type of whistle that emits sound in the ultrasonic range, which people cannot hear but some other animals can, including dogs and domestic cats.

Galton and subsequent researchers used these whistles to create increasingly higher frequency tones to test research subjects as well as animal abilities to hear different tones, Galton was able to determine that the normal upper limit of human hearing was about 18 kHz. He also noted that the ability to hear higher frequencies declined with age.

Below we discuss the principle involved and the construction and working of the Galton's whistle with regard to the production of ultrasonic waves.

#### 9.2.4.1 Principle Involved

Galton whistle works on the principle of organ pipe, where the distance of annular nozzle from the edge of a pipe and the pressure of air blast are suitably adjusted in order to set the pipe into resonant vibrations at the ultrasonic frequency with the help of the length and the diameter of the pipe.

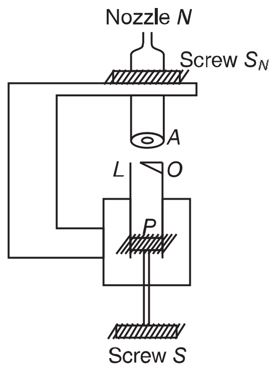

**FIGURE 9.3**

#### 9.2.4.2 Construction and Working

As shown in Fig. 9.3, Galton whistle consists of a closed end air column whose length can be adjusted with the help of a movable piston *P*. A screw *S* is connected to this piston which can move the piston to the desired position. The open end of the pipe $O$ is fitted with a lip $L$, and the gap between the ends $O$ and $A$ can be adjusted with the help of another screw $S_N$ which can move the pipe $A$ up or down. A nozzle $N$ is fitted on the top through which an air blast is blow towards lip $L$. When the blast of air strikes against the lip $L$, the column of air in the pipe is set into vibration. The resonant position is achieved in order to produce the ultrasonic waves by adjusting the length of the air column in $O$. Clearly the resonance frequency depends on the size of the pipe, i.e., its length and diameter.

The wavelength $\lambda$ of the sound wave depends on the length $l$ of the air column in $O$ and the end correction $x$. This is given by

$$\lambda = 4(L + x)$$

From this we can calculate the frequency of the sound or ultrasonic wave as

$$f = \frac{V}{\lambda} = \frac{V}{4(l + x)}$$

Here $V$ is the velocity of the waves produced by Galton's whistle. This whistle can produce ultrasonic waves of low frequencies up to 100 kHz and interestingly the micrometer screw $S$ can be calibrated to give directly this frequency.

## 9.3 ABSORPTION AND DISPERSION OF ULTRASONIC WAVES LO3

When an ultrasonic wave passes through a medium, a part of its energy is converted into heat due to the alternative compression and rarefaction taken place in the wave phenomenon and hence its intensity goes down. The compressions produce the heat that increases the temperature of the medium whereas the rarefactions reduce the temperature, leading to the absorption of these waves in the medium and the wave is said to be attenuated. Two main mechanisms namely absorption and scattering (dispersion) are responsible for the ultrasound attenuation. Different mechanisms such as thermal conductance effects, chemical effects, viscous effects and nonlinearity are responsible for the absorption phenomenon. The phenomena responsible for the ultrasound absorption in biological tissues have not been so far completely understood. In liquids the viscous forces between neighbouring particles moving with different velocities are the major sources of the wave absorption, whereas viscoelastic forces are the main contributors to the wave absorption in homogeneous solids. For example, viscous losses may explain well the sound wave absorption in water where attenuation varies with the square of the frequency. However, this model of viscosity does not explain the experimental measurements of the absorption of the ultrasonic waves in soft biological tissues and bone in the diagnostic frequency range. We can say that the absorption and dispersion of ultrasonic waves generally focus on the influence of ultrasonics on molecular processes in liquids and gases, including hydrodynamics, energy exchange, and chemical reactions.

The diminution in intensity of the amplitude of a planar longitudinal wave passing through a liquid is caused by the conversion of the organised collective motion of the sonic pulse into random thermal motion, if we neglect the radiation losses. The total attenuation comprises contributions arising from viscous loss and thermal conductivity. In general, overall attenuation of the ultrasonic waves is characterised by the following exponential decrease of the pressure amplitude $p$ and of the intensity amplitude $I$ with the propagating distance $z$.

$$p = p_0 e^{-\alpha z} \quad \text{and} \quad I = I_0 e^{2-\alpha z}$$

Here $p_0$ and $I_0$ are the pressure and intensity at $z = 0$, i.e., when the wave starts penetrating the medium. The quantity $\alpha$ is called the pressure frequency-dependent attenuation coefficient, which is expressed in cm$^{-1}$. The factor of 2 in the exponential term of the intensity equation results from the transformation of the pressure into intensity, as the intensity is proportional to the square of the pressure. The commonly used units for $\alpha$ in biomedical ultrasonics are dB (decibel).

The dispersion of the ultrasonic wave is referred to the change in its velocity with frequency. In viscous liquids such as glycerine and castor oil the change in velocity with frequency or dispersion cannot be observed in the frequency regime or ultrasonic waves. However, the dispersion of these waves has been observed indirectly by determining the change in wavelength of the waves.

## 9.4 DETECTION OF ULTRASONIC WAVES LO3

There are several methods of detecting the ultrasonic waves, which include Kundt's tube method, sensitive method, and piezoelectric detection method.

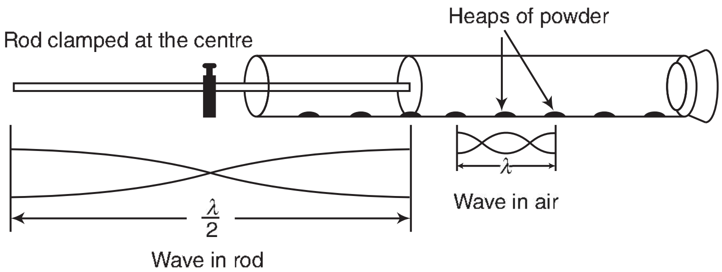


**FIGURE 9.4**

### 9.4.1 Kundt's Tube Method

Kundt's tube has been very efficiently used for the detection of ordinary sound waves and the similar method can be employed for detecting the ultrasonic waves. This tube is a long glass tube supported horizontally with an air column in it. A horizontal rod is clamped at the center of the tube, as shown in Fig. 9.4. This tube contains lycopodium powder scattered in it. When the ultrasonic waves are passed through the tube, the lycopodium powder collects in the form of heaps which are found to be situated at the nodal points whereas the powder is found to be blown off at the antinodal points. The average distance between two adjacent heaps gives rise to the value of half wavelength from which the wavelength of the waves can be calculated. In view of the use of the powder, the method is suitable for the detection of the ultrasonic waves of appreciable wavelengths and it cannot be employed if the wavelength of the waves is very small, i.e., less than few millimeters. However, in the case of liquid medium, powered coke is used in place lycopodium powder to detect the position of nodes and the wavelength of the waves.

If the average distance between the adjacent heaps is $d$ and the frequency of the ultrasonic waves is $f$, then the velocity of the wave is given by $V = 2fd$.

### 9.4.2 Sensitive Flame Method

This method works on the basis of interaction of wave and a sensitive flame, where the change in pressure is noticed. In this method of detection of ultrasonic waves, a narrow sensitive flame is moved along the medium and the change in its intensity is noticed. At the positions of antinodes, the flame is found to be steady (stationary), while the flame is found to flicker at the positions of nodes due to a change taken place in the pressure. The positions of the nodes and antinodes are found out in the medium, and the average distance between the two adjacent nodes gives rise to the value half wavelength. If the value of the frequency of ultrasonic wave is known, the velocity of the wave passing through the medium can be calculated using the same formula as used in the method of Kundt's tube.

### 9.4.3 Piezoelectric Detector

Piezoelectric effect, which is being used in the production of ultrasonic waves based on quartz crystal, can also be used to detect the ultrasonic waves. The underlying principle is as follows. If ultrasonic waves comprising of compressions and rarefactions are allowed to fall upon a quartz crystal, a certain potential difference is developed across the faces of the crystal and varying electric charges are produced. These small charges after amplification by an electronic circuit are used to detect the ultrasonic waves.

## 9.5 APPLICATIONS OF ULTRASONIC WAVES LO4

Ultrasonics have found diverse applications in various fields of medical science or medicine, industry and communication.

### 9.5.1 Medical Applications

After the discovery of $X$-ray imaging in the late 19$^{th}$ century, great advances have been made to diagnosis and treatment equipment based on ultrasonics.

#### *9.5.1.1 Diagnosis*

Scanning of internal organs, vessels and tissues of patient's body based on ultrasonic waves is called ultrasonography. This makes use of high frequency sound waves to produce the images of internal organs and structures for the medical examination and it is possibly the best of all ultrasonic medical applications. The ultrasonic scans are less costly, quicker and easier to use than MRI (magnetic resonance imaging) and CT (computerized tomography) scans. Hence, these are frequently used to monitor and diagnose the condition of organs such as kidneys, liver or gallbladder. In order to diagnose and follow up heart conditions, doctors make efficient use of EVG (echocardiograms) or ultrasonic scans of the heart of the patient.

#### *9.5.1.2 Surgery*

The technology based on ultrasound is increasingly being used in surgery. Here ultrasonic surgical instruments convert an ultrasonic signal into a mechanical vibration by using a transducer. A waveguide is then used to amplify and propagate the vibration to a desired position. The ultrasonic surgical instruments are highly useful in diverse medical procedures, as these can cut bone and other tissue. At the same time reduce bleeding by coagulating tissue. Finally this reduces the average length of surgery and damage to tissue, resulting in fewer complications only.

#### *9.5.1.3 Non-invasive Therapeutic Applications*

Ultrasound energy can be used as non- or minimally invasive high intensity focused ultrasound (HIFU) or high intensity therapeutic ultrasound (HITU). By applying ultrasound energy to heat and destroy diseased tissues, these methods can be used to remove body tissue while treating the cancers and other conditions. Ultrasound imaging systems locate and target liver, kidney or gallbladder stones. These are smashed into pieces by ultrasound pulses and are finally evacuated naturally through urination. Other treatments using ultrasound technology include bone healing and physiotherapy for inflammation caused by joint injuries. Drug delivery is also done based on HIFU/HITU to treat tumours, especially in the brain where it may be difficult to achieve. Cosmetic applications, such as non-invasive liposuction and for a number of therapies to improve skin tone, scars and sun based damage also make use of ultrasound technology.

#### 9.5.1.4 *Dental Care*

Another application of ultrasonics is in dental care as descalers to remove plaque. Ultrasonic descalers have a tip that vibrates at high frequency to break down the bacterial matter to which plaque and calculus stick. The ultrasonic waves have been found quite useful for painless dental cutting. This technology enables a smoother and less painful experience.

#### 9.5.1.5 *Hygiene Safely*

All medical and dental equipment must be absolutely clean before use, otherwise the introduction of pathogenic microbes can lead to infection. It is very important to clean, disinfect and sterlize all multiple use instruments and devices after their use on a patient or surgery. In this direction, ultrasonic cleaning uses a special wash solution to reach and effectively remove organic waste from difficult-to-clean areas, such as equipment or devices with joints and crevices.

### 9.5.2 Industrial Applications

Industrial Applications of ultrasonics include ultrasonic machining, welding, cleaning, etc.

#### 9.5.2.1 *Machining*

Ultrasonic machining is a vibratory process which is now in common use for the mechanical treatment of hard and brittle solids such as glasses, ceramics, precious stones, semiconductors and hard alloys. A glass rod oscillating with ultrasonic frequency can be used to bore holes in steel and other hard metals.

#### 9.5.2.2 *Welding*

With regard to the application of ultrasonics for welding it is believed that practically all metals and plastics can be welded ultrasonic waves of suitable energy. Here the ultrasonic energy converts into heat at the contact area as a result of friction arising between the surfaces. As the temperature of surfaces' layers exceeds the crystallization point, both the layers melt and make a bond together to form a strong joint. Since this process induces negligible stress at the spot of welding, this is quite attractive that the structure of materials remains unchanged.

#### 9.5.2.3 *Cleaning*

Towards the cleaning applications of ultrasound waves, it is worth mentioning that these waves with frequencies 20 kHz to 40 kHz are used for cleaning of jewellery, optical parts, surgical instruments, industrial parts etc. They are used for cleaning clothes and parts of watches. Printing industry used ultrasonic as a method of cleaning complicated and problematic parts has been available for many years with in a wide range of industries. The main advantages are that components of the most complicated shapes can be cleaned efficiently, speedily and comprehensively. Here ultrasonic millions of tiny bubbles within the fluid which act on the surface of the component behave as a brush in many ways. The scrubbing action of this brush can be made as vigorous or gentle as per the requirement.

#### 9.5.2.4 *Structural Composition and Analysis*

Ultrasonic waves are used for producing alloys of uniform composition. Further, these waves are employed to detect cracks or flaws in metal structure.

### 9.5.3 Applications in Food Technology

By tuning frequency, ultrasound can be utilized in food technology. Since ultrasound techniques are relatively cheap, simple and energy saving, these have became an emerging technology for probing and modifying food products. Low power (high frequency) ultrasound is used for monitoring the composition and physiochemical properties of food components and products during processing and storage. However, high power (low frequency) ultrasound induces mechanical, physical and chemical (biochemical) changes through cavitation, which supports many food processing operations such as extraction, freezing, drying, emulsification and inactivation of pathogenic bacteria on food contact surfaces.

Using ultrasound, full reproducible food processes can now be completed in seconds or minutes. This can be done with high reproducibility, reducing the processing cost, simplifying manipulation and giving higher purity of the final product. This also eliminates post-treatment of waste water and consumes only a fraction of the time and energy normally needed for conventional processes.

### 9.5.4 Applications in Communications

Ultrasonic waves can be produced in the form of beams in the desired direction. These can travel long distances in water before being absorbed. This makes them suitable for the submarine applications. Submarine ultrasonic transmitters have been developed for detecting the presence of iceberg or submarines. These are used for signaling from ship to ship, especially in submerged submarines and also in determination of the depth of sea, position of a ship and submarine. The ship is equipped with the source and receiver of a particular frequency at its bottom. The source is used to transmit the short ultrasound pulses and the reflected pulses are received by the receiver for the detection. Actually the time interval ($t$) between sending and receiving the pulses is measured, which gives rise to the depth of the ocean as

$$d = \frac{Vt}{2}$$

Here $V$ is the velocity of the ultrasonic waves.

### 9.5.5 Detection of Velocity of Sound in Liquid

The stationary wave method is applied to find the velocity of ultrasonic waves in liquid and gases. The velocity of ultrasonic waves in these medium can be calculated from the relation $V = f\lambda_{\text{ult}}$, where $f$ is frequency and $\lambda_{\text{ult}}$ is the wavelength of the ultrasonic waves in the medium. This method is more suitable for finding the velocity of ultrasonics in liquid and gases that are available in small quantity.

In order to find the velocity of sound in a liquid, say kerosene oil, a quartz crystal is placed between two metal plates and the plates are connected to an audio frequency oscillator. The assembly of the crystal and the plates is kept inside the liquid cell. The crystal is made to vibrate in resonance with the oscillator by adjusting the frequency to produce the ultrasonic waves. The reflections of the wave from the sides of the liquid cell form a standing wave pattern with nodes and antinodes at regular intervals. This leads to a particular distribution of the liquid density with maximum density at the nodes and minimum density at the antinodes. Accordingly the refractive index of the liquid is varied and it works as the diffraction grating, known as acoustic grating.

The acoustic grating is mounted on a prism table of spectrometer and a parallel beam of sodium light from collimator is allowed to fall normally on the grating. The diffracted light is found to form a diffraction pattern which is viewed through a telescope. The diffraction pattern consists of central maximum and principal maxima on either sides. The positions of the principal maxima satisfy the following relation

$$\lambda_{\text{ult}} \sin \theta_n = n\lambda$$

Here $\lambda_{ult}$ is the wavelength of sound in the liquid, $\lambda$ is the wavelength of incident sodium light (monochromatic) and $\theta_n$ is the angle of nth other diffraction. We can find the wavelength $\lambda_{ult}$ of the wave in the liquid. If $f$ be the frequency of vibrations of the crysttal, then the velocity of the ultrasonic wave in the liquid can be obtained using the relation $V = f\lambda_{ult}$.

## 9.6 TYPES OF ACOUSTICS LO5

There are various types of the acoustics. These are discussed below.

### 9.6.1 Physical Acoustics

Physical acoustics encompasses propagation and absorption of sound at all frequencies in air and other gases, liquids, semi-solids and solids. It deals with airborne, audible sound, infrasound and ultrasound. Physical acoustics includes both linear processes such as the propagation of sound from traffic, and nonlinear processes such as the shock waves that are generated by planes flying faster than the speed of sound.

### 9.6.2 Engineering Acoustics

Engineering acoustics deals with the development of devices to generate (e.g., loudspeakers), record (e.g., microphones) and analyse (e.g., frequency analysers) sound of all kinds. The field of sound production, recording and reproduction, with all its attendant electronics and measuring instruments, is an important part of engineering acoustics.

### 9.6.3 Architectural Acoustics

Architectural acoustics is concerned with sound in buildings. One aspect of this field is the control of sound within rooms to maximise the acceptability of music or intelligibility of speech. This branch of architectural acoustics deals with sound in lecture theatres, concert halls, meeting rooms and classrooms.

### 9.6.4 Musical Acoustics

Musical acoustics considers the workings of traditional, experimental and electronic musical instruments. The interaction of musicians, instruments, listeners and performance spaces means that many branches of acoustics influence work in this field.

### 9.6.5 Psychological Acoustics

Psychological acoustics studies the brain's signal-processing function, which takes nerve impulses from the ear and interprets them. Physiological acoustics deals with models and theories of the operation of the ear and its anatomy. One practical application of this field is the study of the elements important to achieve a stereophonic effect. Another is the determination of those factors that make one sound unpleasant or annoying and another reverse. There is no direct correlation between loudness and annoyance.

### 9.6.6 Bioacoustics

Bioacoustics studies all aspects of acoustic behaviour in animals and biological media in general. This field includes topics such as sound production by animals, bio-sonar, sound reception by animals, effects of noise on animals and medical diagnostics using acoustics, especially ultrasonics.

## 9.7 ACOUSTICS OF BUILDINGS LO6

The branch of the science which deals with the planning of a building or a hall with a view to provide best audible sound to the audience is called acoustics of building or architectural acoustics. *WC Sabine* in 1911, first of all scientifically tackled the problem of satisfactory speech and music in a hall.

### 9.7.1 Reverberation

When a sound is produced in a building, it lasts too long after its production. It reaches to a listener a number of times. Once it reaches directly from the source and subsequently after reflection from the walls, windows, ceiling and floor of the hall. The listener, therefore, receives series of sounds of diminishing intensity (since part of energy is lost at each reflection); the sound becomes muddy, garbled. The most important factor in the design of an auditorium is reverberation. Reverberation is nothing but the prolonged reflection of sound from the walls, floor and ceiling of a room. It is also defined as the persistence of audible sound after the source has stopped to emit sound. The duration for which the sound persists is called *reverberation time*. The time of reverberation is also defined as the time taken for the sound to fall below the minimum audibility measured from the instant when the source stops sounding. Sabine, using an organ pipe of frequency 512 Hz found that its sound becomes inaudible when its intensity fall to one millionth of its intensity just before stopping the organ pipe. Hence, *Sabine* defines the standard revereberation time as the time taken by sound to fall to one millionth of its intensity just before the source is cut off. Sabine found that the time of reverberation depends upon the size of the hall, loudness of the sound and upon the kind of the music or sound for which hall is to be used. For a sound of frequency 512 Hz, the best time of reverberation was found to be 1 to 1.5 sec and 1.5 to 2 sec for halls of 50,000 and 40,000 cubic feet, respectively.

Based on the range of values of revereberation time for specific purposes, we can determine a relationship between room volume and internal surface area. This assumes the use of standard auditorium construction materials.

### 9.7.2 Basic Requirement for Acoustically Good Halls

Before 1900, the architects and building engineers had no consideration about the acoustical properties of rooms and halls etc. Sometimes, a building was found to be unsatisfactory for the purpose for which it was built. According to Sabine the following essential features are required for the good acoustics.

(i) The sound heard must be sufficiently loud in every part of the hall and no echoes should be present.

(ii) The total quality of the speech and music must be unchanged, i.e., the relative intensities of the several components of a complex sound must be maintained.

(iii) For the sake of clarity, the successive syllables spoken must be clear and distinct, i.e., there must be no confusion due to overlapping of syllables.

(iv) The reverberation should be quite proper, i.e., neither too large nor too small. The reverberation time should be 1 to 2 sec for music and 0.5 to 1 sec for speech.

(v) There should be no concentration of sound in any part of the hall.

(vi) The boundaries should be sufficiently sound proof to exclude extraneous noise.

(vii) There should be no Echelon effect.

(viii) There should be resonance within the building.

### 9.7.3 Transmission of Sound and Transmission Loss

When sound is produced in a hall, it proceeds outward in spherical waves and strikes the boundaries of the hall. The sound waves undergo reflection, absorption and transmission in varying amounts. The amounts of these three processes depend upon the frequency of sound and the characteristics of the wall of the room (i.e., thickness of walls, weight, material, nature of surface). The transmission of sound means the sound energy transmitted through the walls.

The loss of sound energy across a wall or a barrier is defined as transmission loss. So when the sound is transmitted from the source to adjoining room or area, then there is a reduction in the sound intensity. This is known as *transmission loss*. Thus, the transmission loss is numerically equivalent to loss in the intensity of sound. This is expressed in decibels (dB).

(i) If 50 dB and 10 dB are the sound levels measured on either side of a wall, then transmission loss of the wall would be, 50 dB – 10 dB = 40 dB.

(ii) Larger the transmission loss, greater is the sound illusion.

(iii) Transmission loss varies with material used for the construction.

(iv) The methods used for the construction also affect the value of transmission loss.

(v) Transmission loss varies with frequency of sound.

### 9.7.4 Acoustic Environments and Sound Fields

There are two basic environments in which one makes measurements of sound and noise: outdoors and indoors. An outdoor acoustic environment may be quite often referred to as a free field. A sound field is said to be a free field if it is uniform, free from boundaries, and undisturbed by other sources of sound. Anechoic chambers and well-above-the-ground outdoors are free fields. Sound radiated by a source in a free field propagates away from the source and is never reflected back. Sound spreads three-dimensionally from the source such that the intensity falls off as $1/r^2$ (6 dB decrease from source doubles).

The indoors acoustic environment introduces boundaries which reflect sound. If the boundaries completely reflect all incident sound without any absorption then the resulting sound field is termed as diffuse or reverberant. In a diffuse sound field the time average of the mean square sound pressure is the same everywhere through the enclosure. The flow of energy is equally probable in all directions. If the boundaries absorb some of the incident sound and reflect the rest, then the sound field is called semi-reverberant. Energy flows in more than one direction. Semi-reverberant fields are the most widely encountered in the majority of architectural acoustic environments.

### 9.7.5 Indoor Acoustics

When a sound source is enclosed, the radiated sound energy is retained within the enclosure. If the boundaries are perfectly reflective then the sound energy inside the enclosure could theoretically grow until a pressure is reached that would be explosive. Fortunately, most realistic boundaries are at least partly absorbing (air also absorbs sound) and the kinds of sound sources usually encountered in a room (for example, human speech) are not extremely powerful. For example, the sound power produced by human speech is very small. Typical male and female speakers generate 34 $\mu$W and 18 $\mu$W, respectively, at a distance of 3.28 ft. So, common sound sources are not excessively powerful, the sound energy in the enclosure travels about the enclosure and slowly decays as it is absorbed by the boundaries and the medium.

### 9.7.6 Sabine's Formula for Reverberation Time

Consider a source of the sound in an enclosure. We shall assume that

(i) The rate of emission of energy from the source is constant.

(ii) The energy is transmitted equally in all directions and its distribution is uniform throughout the enclosure.

(iii) The dissipation of energy in the air is negligible and that it is confined only to the boundary walls.

(iv) The power of absorption of the absorbent material is independent of the intensity of the sound.

(v) The effect of superposition is negligible.

The reverberation time can be measured by producing white noise in the enclosure at a level 60 dB above background, switching it off, and measuring the time it takes to drop back to background. The drawbacks to this method are that it takes a high power source and the noise produced is unpleasantly loud. Measuring the time required for a smaller intensity drop and extrapolating to the 60 dB time is the usual procedure. This requires some calculation and a mathematical model for the decay curve of the sound in the enclosure.

If a sound source of intensity $I_0$ is switched off at time $t = 0$, then the sound starts to die away and will be 60 dB down (or $10^{-6}\, I_0$) after one reverberation time later, i.e., at $t = T$, where $T$ is the revereberation time (sometimes called $RT_{60}$ as a mnemonic for its defintion). To evaluate the scaling constant $a$, note that

$$e^{-at/T} = 10^{-6} \qquad \text{at } t = T \tag{i}$$

where $a$ is called scaling constant.

Taking the natural logarithm of both sides, we get

$$-a = -6 \text{ In } (10) = -13.82$$

This evaluation will permit a calculation of the reverberation time $T$ if any two intensities $I_0$ and $I$ are measured along with the time interval $t$ between the two measurements. From Eq. (i), the relationship for $T$ is

$$T = \frac{13.28t}{\text{In } (I_0/I)} \tag{ii}$$

It is found that rather than the intensity, the voltage is displayed from the microphone and the intensity is proportional to the square of the voltage. In terms of the measured voltages, the reverberation time relationship is obtained as

$$T = \frac{13.28t}{\text{In } (V_0^2/V^2)} \tag{iii}$$

This is the relationship which is to be used in the experiment to determine the reverberation time of the room. It could then be compared with the approximate relationship

$$T = \frac{0.161\,\text{V}}{aS} \tag{iv}$$

where $V$ is room volume in cubic meters, $S$ is surface area in square meters, and $a$ is average absorption coefficient. The rough absorption coefficient obtained in this manner could help to evaluate the change, which might be made in the reverberation time by changing the surfaces (carpet, curtains, etc.).

Absorption coefficient for standard building materials is given by Sabine's formula

$$T = \frac{0.161\,\text{V}}{\Sigma aS}$$

where $\Sigma aS$ is the total acoustic absorption in the enclosure.

### 9.7.7 Absorption Coefficient and Its Measurement

What are the essential parameters of a typical room necessary to determine its acoustical behaviour? First, an enclosed space that has an internal volume $V$. Second, it has a total boundary surface area $S$. Third, each of the individual surface areas has an absorption coefficient. The average absorption coefficient for all surfaces together is given by the individual surface areas and are the individual absorption coefficients of the individual surface areas. Since the boundaries of the room reflect incident sound energy, the sound signal received by a listener at some location in the room will consist of sound which arrives directly from the source, sound which arrives after reflecting from one surface, and sound which has undergone several reflections. The average distance between reflections in such a space is called the *mean free path* and is related to the dimensions of the room. This is because each time the sound interacts with a surface in the room it loses some of its energy due to absorption. The absorption coefficient of the material of a surface is $a$, then a fraction $(1 - a)$ of the sound energy incident upon the surface is returned to the side from which it came. The absorption coefficient of sound is essentially the dissipation of energy into heat, and in so far as it is affected by a bounding surface it is mainly due to one of two causes, porosity and flexural vibrations. The absorption coefficient of any material, as originally defined by Sabine, is the ratio of the sound absorbed by that material to that absorbed by an equivalent area of open window. Thus, a perfectly absorbent material would have an absorption coefficient of 1.

**Measurement** Two audio frequency sources of powers $P_1$ and $P_2$ are employed in the test chamber. The actual value of $P_1$ and $P_2$ need not be known, but their ratio must be known. Then

$$A = \frac{4V}{c}\frac{\log(P_1/P_2)}{T_1 - T_2}$$

where $T_1$ and $T_2$ are the respective times of decay to the threshold of audibility. From this relation mean coefficient of absorption can be obtained since $A - aS$, where $S$ is the area of the absorbing surface is the measure of mean coefficient of absorption. The test chamber for the experiment exclude all extraneous and must have a long time of reverberation when empty.

Another reverberation method employed by Sabine was to measure the absorbing power of a room in terms of that of an open window. Let $aS$ and $(aS + w)$ be the total absorption of the room with windows closed and open, respectively and $t_0$ and $t_c$ are the time taken for the sound to decay to the threshold of audibility in the two cases, respectively. Then for same intensity of sound in both the cases,

$$\frac{w}{aS} = \left(\frac{t_0}{t_c} - 1\right)$$

and for same energy $P$ of source

$$\log\left(1 + \frac{w}{aS}\right) = \frac{c}{4V}(aS(t_c - t_0) - wt_0)$$

From the above relation $aS$ can be calculated in terms of $w$.

## 9.8 FACTORS AFFECTING THE ARCHITECTURAL ACOUSTICS LO7

By an acoustically good hall we mean that in which every syllable or musical note reaches an audible level of loudness at every point of the hall and then quickly dies away to make room for the next syllable or group of notes. The departure from this makes the hall defective acoustically. Following factors affect the architectural acoustics:

(i) **Reverberation**: The reverberation can be controlled by the following factors:
   (a) By providing windows and ventilators which can be opened and closed in order to optimise the value of the time of reverberation optimum.
   (b) By covering the floor with carpets.
   (c) By heavy curtains with folds.
   (d) By full capacity of audience.

(ii) **Adequate Loudness:** It can be reduced by using large sounding boards behind the speaker and facing the audience. Large polished wooden reflecting surfaces immediately above the speakers are also helpful. Low ceiling are also of great help in reflecting the sound energy towards the audience by providing additional sound energy with the help of equipment like loudspeakers.

(iii) **Focusing due to Walls and Ceiling**: For uniform distribution of sound energy in the hall, there should be curved surfaces. If such surfaces are present, they should be covered with absorbent material. Ceiling should be low. A paraboloidal reflected surface arranged with the speaker at the focus is also helpful in sending a uniform reflected beam of sound in the hall.

(iv) **Echoes**

(v) **Resonance**

(vi) **Echelon Effect**

(vii) **Extraneous Noise and Sound Insulation**: Generally, there are three types of noises, which are very troublesome. These are Air Borne Noise, Structure Borne Noise and Inside Noise.

*Air Borne Noise:*

The noises are transmitted through the air. Sound insulation for the reduction of air borne noise can be achieved by the following methods:

(a) By avoiding opening for pipes and ventilators.
(b) By allotting proper places for doors and windows.
(c) Using double doors and windows with separate frames and having insulating material between them.
(d) By making arrangements for perfectly shutting doors and windows.
(e) Using heavy glass in doors, windows and ventilators.
(f) By providing double wall construction, floating floor construction, suspended ceiling construction, box type construction, etc.

*Structure Borne Noise:*

The most common sources of this type of sound are footsteps, street traffic, hammering, drilling, operating machinery, moving of furniture, etc. Sound insulation for the reducing of structure borne noise is done by the following ways:

(a) By breaking the continuity by interposing layers of some acoustical insulator.

(b) By using double walls with air space between them.

(c) By using anti-vibrations mounts.

(d) By soft floor finishing (carpet, rubber, etc.)

(e) By insulating the machinery, as the mechanical equipments like refrigerators, lifts, fans etc., produce vibrations in the structure.

*Inside Noise:*

The following methods are used for sound insulation of inside noise.

(a) The machinery (like typewriters) should be placed on absorbent pads.

(b) Any engine inside the hall should be fitted on the floor with a layer of wood.

(c) The floor should be covered with carpet.

(d) The wall, floors and ceiling should be provided with sound absorbing materials.

(e) The sound absorbing materials should be mounted on the surface near the source of noise.

### 9.8.1 Sound Absorbing Materials

Special materials used to increase absorption of sound waves or to reduce the reflection of sound waves in a room or hall are known as sound absorbing material. The material should have the following requirements:

(a) It should have good resistance to fire.

(b) It should be efficient over a wide range of frequencies.

(c) It should have high sound absorbing efficiency.

(d) It should be cheap, easily available, easy to fix, good looking, light in weight and waterproof and should have economical maintenance and sufficient structural strength. The sound absorbing materials are broadly classified into the following four categories, namely porous absorbents, cavity resonators, composite types of absorbents, and resonant absorbents or panel absorbers.

## SUMMARY

The main topics covered in this chapter are summarised below.

- Scientific study of the propagation, absorption, and reflection of sound waves is called acoustics. Acoustics is the interdisciplinary science that deals with the study of sound, ultrasound and infrasound (all mechanical waves in gases, liquids, and solids). In a broad sense, acoustics may be defined as generation, transmission and reception of energy in the form of vibration waves in matter.
- Various types of acoustics, namely physical acoustics, engineering acoustics, architectural acoustics, musical acoustics, psychological acoustics, bioacoustics, were discussed.
- Description of audible waves, ultrasonic waves, and infrasonic waves were given.
- Certain crystals can develop an electric charge when a mechanical pressure or tension is applied. This phenomenon is named as Piezoelectric effect.

- A transducer is a device which is used to convert one form of energy to another. Ultrasonic transducers convert electrical energy to mechanical energy and vice versa. Ultrasonic sound can be produced by transducers which operate either by the piezoelectric effect or by the magnetostrictive effect. The magnetostrictive transducers can be used to produce high intensity ultrasonic sound in the 20–40 kHz range for ultrasonic cleaning and other mechanical applications.
- Principle of ultrasonic transducer was discussed.
- It was discussed how ultrasonic waves are produced. Their applications were talked about.
- Acoustics of buildings was discussed in detail. Reverberation was introduced and it was said that the reverberation is nothing but the prolonged reflection of sound from the walls, floor and ceiling of a room. It is also defined as the persistence of audible sound after the source has stopped to emit sound. The duration for which the sound persists is called reverberation time. The time of reverberation is also defined as the time taken for the sound to fall below the minimum audibility measured from the instant when the source stops sounding.
- Basic requirement for the acoustically good halls were discussed. These are the following.
  - (a) The sound heard must be sufficiently loud in every part of the hall and no echoes should be present.
  - (b) The total quality of the speech and music must be unchanged, i.e., the relative intensities of the several components of a complex sound must be maintained.
  - (c) For the sake of clarity, the successive syllables spoken must be clear and distinct, i.e., there must be no confusion due to overlapping of syllables.
  - (d) The reverberation should be quite proper, i.e., neither too large nor too small. The reverberation time should be 1 to 2 seconds for music and 0.5 to 1 second for speech.
  - (e) There should be no concentration of sound in any part of the hall.
  - (f) The boundaries should be sufficiently sound proof to exclude extraneous noise.
  - (g) There should be no Echelon effect.
  - (h) There should be resonance within the building.
- Transmission of sound and transmission loss were discussed in detail.
- Sabine's formula for reverberation time was derived and its theoretical as well as physical aspects were talked about.
- Finally, the absorption coefficient was introduced and methods were talked about for its measurement.
- Factors affecting the architectural acoustics were discussed in detail and the methods of its removal were talked about.

## SOLVED EXAMPLES

**EXAMPLE 1** The frequency limits of the range of human hearing ear is from about 20 Hz to 20 kHz. The speed of sound is about 34,500 cm/sec. What is the wavelength of the wave in cm?

**SOLUTION** The frequency range is given as 20 Hz to 20 kHz.

The speed of sound = 34500 cm/sec = 345 m/sec

We know that the frequency of sound wave is related to its wavelength by $v = f\lambda$

$$\therefore \qquad \lambda = \frac{345}{20}$$

So for the frequency of 20 Hz, wavelength $\lambda = \frac{345}{20}$ m $= 17.25$ m $= 1725$ cm

For the frequency of 20 kHz, wavelength $\lambda = \frac{345}{20 \times 10^3}$ m $= 17.25 \times 10^{-3}$ m $=$ **1.725 cm**

Therefore, wavelength range of the sound wave is 1.725 cm to 1725 cm.

**Example 2** Calculate the velocity of the sound in air in cm per sec at 100°C if the density of air at S.T.P. is 0.001293 g/cm$^3$, the density of the mercury at 0°C is 13.60 g/cm$^3$, the specific heat of air at constant pressure is 0.2417 and the specific heat of air at constant volume is 0.1715.

**Solution** The velocity of sound in air is given by

$$v = \sqrt{\frac{\gamma p}{\rho}} \quad \text{with usual notation.}$$

The quantity $\rho$ of the air is 0.001293 g/cm$^3$

The pressure $p$ is given by

$$p = h\rho g = 76 \times 13.6 \times 980 \text{ dynes/cm}^3$$

Now
$$\gamma = \frac{C_p}{C_v} = \frac{0.2417}{0.1715}$$

$$\therefore \qquad v = \sqrt{\frac{0.2417 \times 76 \times 13.6 \times 980}{0.1715 \times 0.001293}}$$

The velocity $v$ is proportional to $\sqrt{T}$, where $T$ is the temperature of the air. Thus, if $v'$ be the velocity at 100°C and $v$ at 0°C, then

$$\frac{v'}{v} = \sqrt{\frac{273+100}{273}} = \sqrt{\frac{373}{273}}$$

$$v' = \sqrt{\frac{373}{273}}v$$

$$= \sqrt{\frac{373 \times 0.2417 \times 76 \times 13.6 \times 980}{273 \times 0.1715 \times 0.001293}} = 38839.12 \text{ cm/sec}$$

$=$ **38839 cm/sec**

**Example 3** The wavelength of the gas emitted by a tuning fork of frequency 512 vibration/sec in air at 17°C is 66.5 cm. If the density of air at S.T.P. is 1.293 mg/cm$^3$, calculate the ratio of two principal specific heats of air. Assume that the density of mercury is 13.6 g/cm$^3$.

**Solution** Since $v = f\lambda$, the velocity of sound at 17°C is given by

$$v = 512 \times 66.5 \text{ cm per sec}$$

Now,
$$v_0 = \sqrt{\frac{\gamma p}{\rho}}$$

Here $p$ = 76 cm of mercury = 76 × 13.6× 980 dynes/cm$^3$. The density of air $\rho = \frac{1.293}{1000}$ g/cm$^3$. If $v_0$ be the velocity at 0°C and since the velocity is proportional to $\sqrt{T}$,

$$v_0 = \sqrt{\frac{273}{290}}v = \sqrt{\frac{273}{290}} \times 512 \times 66.5$$

Now, $$v_0 = \sqrt{\frac{\gamma p}{\rho}}$$

∴ $$\gamma = \frac{v_0^2 \rho}{p} = \frac{273 \times (512 \times 66.5)^2 \times 1.293}{290 \times 1000 \times 76 \times 13.6 \times 980} = \mathbf{1.39}$$

**Example 4** A hall of floors is 15 × 30 m$^2$ along with height of 6 m, in which 500 people occupy upholstered seat and the remainder sit on wooden chairs. Optimum reverberation time for orchestral music is 1.36 sec and absorption coefficient per person is 0.44.

(a) Calculate the coefficient of absorption to be provided by the walls, floor and ceiling when the hall is fully occupied.

(b) Calculate the reverberation time if only the half upholstered seats are occupied.

**Solution**

(a) The optimum reverberation time is $T$ = 1.36 sec

Using Sabine's formula equation of SI unit

$$T = 0.161\frac{V}{aS}$$

$$1.36 = \frac{0.161 \times (15 \times 30 \times 6)}{aS}$$

$aS$ = 319 SI units

Absorption due to audience = 500 × 0.44

= 220 SI units

Therefore, the absorption provided by the walls, floor and ceiling is

319 – 220 = **99 SI unit**

(b) When the hall is only half filled the absorption will also be provided by vacant seats in addition to the absortion by the audience.

250 × 0.44 = 110 SI unit

The absorption by vacant wooden seats = 250 × 0.02 = 5 SI unit

So the total absorption of the hall = 99 + 110 + 5 = **214 SI unit**

Here the reverberation time, given by Sabine's formula, is now

$$T = \frac{0.161 \times (15 \times 30 \times 6)}{214} = \frac{0.161 \times (15 \times 30 \times 6)}{214}$$

**= 2.03 sec**

**Example 5** Calculate the total absorption coefficient of cinema hall, whose volume is 8000 m$^3$ and reverberation time required is 1.8 sec.

**Solution**

The reverberation time is given by

$$T = \frac{0.161V}{aS} = \frac{0.161V}{\text{Total absorption in hall}}$$

$\therefore$ $$\text{Total absorption in hall} = \frac{0.161V}{T} = \frac{0.161 \times 8000}{1.8}$$

$$= \mathbf{715.55\ O.W.U.}$$

**EXAMPLE 6** Find out reverberation time of empty hall of volume 1700 m$^3$ having a seating capacity for 150 persons with following data

| *Surface* | *Area* | *Coefficient of absorption in O. W. U.* |
|---|---|---|
| Plastered wall | 98 m$^2$ | 0.03 |
| Plastered ceiling | 144 m$^2$ | 0.04 |
| Wooden door | 15 m$^2$ | 0.06 |
| Cushioned chairs | 88 m$^2$ | 1.0 |

**SOLUTION** Given $V$ = 1700 m$^3$

Based on the given data, the absorption by

Plastered wall = 98 × 0.03 = 2.94

Plastered ceiling = 144 × 0.04 = 5.76

Wooden door = 15 × 0.06 = 0.90

Cushioned chairs = 88 × 1.0 = 88.0

$\therefore$ Total absorption = 97.6

$$\text{Reverberation time } T = \frac{0.161V}{aS} = \frac{0.161 \times 1700}{97.6}$$

or **T = 2.80 sec**

**EXAMPLE 7** Calculate the reverberation time for a hall of volume 1400 m$^3$, which has seating capacity of 110 persons with full capacity of audience and when audience are occupying only cushioned seats. Relevant data may be taken from Ex. 6.

**SOLUTION** We have total absorption in hall (from Ex. 6) = 97.6, $V$ = 1400 m$^3$.

When the hall is with full capacity of 110 person, the absorption due to them

= 110 × 4.7 = 517

Now total absorption = 97.6 + 517 = 614.6

Reverberation time

$$T = \frac{0.161V}{aS} = \frac{0.161 \times 1400}{614.6}$$

$$\boldsymbol{T = 0.367\ \text{sec}}$$

**EXAMPLE 8** The volume of a room is 980 m$^3$. The wall area of the room is 150 m$^2$, ceiling area is 95 m$^2$ and floor area is 90m$^2$. The average sound absorption coefficient (i) for wall is 0.03, (ii) for ceiling is 0.80 and (iii) for the floor is 0.06. Calculate the average sound absorption coefficient and the reverberation time.

**SOLUTION** The average sound absorption coefficient

$$a = \frac{a_1S_1 + a_2S_2 + a_3S_3}{S_1 + S_2 + S_3}$$

$$= \frac{0.03 \times 150 + 0.80 \times 95 + 0.06 \times 90}{150 + 95 + 90}$$

$$= 0.256$$

and total area $S = 150 + 95 + 90 = 335$

Now total absorption of the room

$$= aS$$

$$= 0.256 \times 335 = 85.76 \text{ metric Sabines}$$

Reverberation time

$$T = \frac{0.161V}{aS}$$

$$= \frac{0.161 \times 980}{85.76}$$

$$= \mathbf{1.84\ sec}$$

**EXAMPLE 9** How much acoustic power enters the window of area 1.58 m$^2$, via the sound wave (standard intensity level = $10^{-16}$ W/cm$^2$). The window opens on a street where the street noise results in an intensity level at the window of 60 dB.

**SOLUTION** Given the intensity level at window = 60 dB

Area of the window = 1.58 m$^2$

Standard intensity level $I_0 = 10^{-16}$ W/cm$^2$ = $10^{-12}$ W/m$^2$.

We know that intensity level = 10 $\log_{10}(I/I_0)$ dB

$\therefore$ $60 = 10 \log_{10} (I/10^{-12})$ dB

$I = 9.98 \times 10^{-7}$ W/m$^2$

Acoustic power = intensity × area = $9.98 \times 10^{-7} \times 1.58 = 1.576 \times 10^{-6}$ W = $\mathbf{1.58 \times 10^{-6}}$ **W**

**EXAMPLE 10** Find the frequency to which a piezoelectric oscillator circuit should be turned so that a piezoelectric crystal of 0.1 cm thickness vibrates in its fundamental mode to generate ultrasonic waves. Young's modulus and density of material of the crystal are $8 \times 10^{10}$ Nm$^{-2}$ and $2.654 \times 10^3$ kg m$^{-3}$ respectively.

**SOLUTION** Given, thickness of the crystal $t = 1 \times 10^{-3}$ m, density (D) = $2.654 \times 10^3$ and $Y = 8 \times 10^{10}$ Nm$^{-2}$

From the relation, the fundamental frequency of piezoelectric oscillator

$$f = \frac{p}{2t}\sqrt{\frac{Y}{D}} = \frac{1}{2 \times 0.001}\sqrt{\frac{8 \times 10^{10}}{2.654 \times 10^3}}$$

$$= \mathbf{2.75 \times 10^6\ Hz}$$

**EXAMPLE 11** Calculate the natural frequency of 30 mm of iron rod. The density of iron rod and Young's modulus are $7.25 \times 10^3$ kg/m$^3$ and $115 \times 10^9$ N/m$^2$ respectively. Can you use it in magnetostriction oscillator to produce ultrasonic waves?

**SOLUTION** Given, $l = 3 \times 10^{-2}$ m, $D = 7.25 \times 10^3$ kg/m$^3$ and $Y = 115 \times 10^9$ N/m$^2$

From the relation, the frequency of ultrasonic waves by magnetostriction oscillator is

$$f = \frac{1}{2l}\sqrt{\frac{Y}{D}} = \frac{1}{2\times3\times10^{-2}}\sqrt{\frac{115\times10^{9}}{7.25\times10^{3}}}$$

$$= 66.38\times10^{3}\text{ Hz}$$

$$= \mathbf{66.38\ kHz}$$

**Example 12** Calculate the fundamental frequency of a quartz crystal of $3 \times 10^{-3}$ m thickness. The density of the crystal is 2650 kg m$^{-3}$ and Young's modulus is $7.9 \times 10^{10}$ N/m$^2$.

**Solution** Given, $l = 3 \times 10^{-3}$ m, $Y = 7.9 \times 10^{10}$ N/m$^2$ and $D = 2650$ kg/m$^3$

From the relation, the fundamental frequency of quartz crystal

$$f = \frac{1}{2l}\sqrt{\frac{Y}{D}} = \frac{1}{2\times3\times10^{-3}}\sqrt{\frac{7.9\times10^{10}}{2650}}$$

$$= 9.1\times10^{5}\text{ Hz}$$

$$= \mathbf{0.91\ MHz}$$

**Example 13** Calculate the natural frequency of iron of 0.03 m length, the density of iron is $7.23 \times 10^3$ kg/m$^3$ and Young's modulus $116 \times 10^{10}$ N/m$^2$.

**Solution** Given, $l = 0.03$ m, $D = 7.23 \times 10^3$ kg/m$^3$ and $Y = 116 \times 10^{10}$ N/m$^2$

Formula used is

$$f = \frac{1}{2l}\sqrt{\frac{Y}{D}} = \frac{1}{2\times0.03}\sqrt{\frac{116\times10^{10}}{7.23\times10^{3}}}$$

$$f = 0.211\times10^{6}\text{ Hz}$$

$$= \mathbf{0.21\ MHz}$$

**Example 14** An ultrasonic source of 0.67 MHz sends down a pulse towards sea bed which come back after 1 sec. Find out the depth of sea and the wavelength of pulse. The velocity of sound in sea water is 1690 m/sec.

**Solution** Given, $f = 0.67 \times 10^6$ Hz, $t = 1$ sec and $v = 1690$ m/sec

By using the formula

$2h = vt$ and $v = f\lambda$

where $h$ is depth of the sea, we get

$2 \times h = 1690 \times 1$

$h = 845$ m

and $$\lambda = \frac{v}{f} = \frac{1690}{0.67\times10^{6}} = \mathbf{0.00252\ m}$$

**Example 15** Calculate the capacitance to produce ultrasonic waves of $10^6$ Hz with an inductance of 1 Henry.

**Solution** Given, $f = 10^6$ Hz and $L = 1$ Henry

Formula used is

$$f = \frac{1}{2\pi\sqrt{LC}}$$

or

$$C = \frac{1}{4\pi^2 L f^2}$$

$$C = \frac{1}{4 \times (3.14)^2 \times 1 \times (10^6)^2} = \frac{10^{-12}}{4 \times (3.14)^2}$$

$$\mathbf{= 0.0254\ pF}$$

**Example 16** A quartz crystal of thickness 1 mm is vibrating at resonance. Calculate the fundamental frequency. Given $Y$ for quartz = $7.9 \times 10^{10}$ N/m$^2$ and $\rho$ for quartz = 2650 kg/m$^3$.

**Solution** The fundamental frequency of the vibration is given by

$$f = \frac{1}{2l}\sqrt{\frac{Y}{e}}$$

$$f = \frac{1}{2 \times 0.001}\sqrt{\frac{7.9 \times 10^{10}}{2650}}$$

$$= 2.72998 \times 10^6 \text{ Hz}$$

The fundamental frequency of the quartz crystal = $2.730 \times 10^6$ Hz = **2.73 MHz**

## Objective Type Questions

**Q.1** If the period of a wave is decreased, then
(a) the amplitude of the wave decreases (b) the amplitude of the wave increases
(c) the frequency of the wave decreases (d) the frequency of the wave increases

**Q.2** Which of the following frequency range is audible to the human ear?
(a) 50-100 Hz (b) 500-1000 Hz (c) 5000-10000 Hz (d) all of the above

**Q.3** A property of sound which is most closely associated with the pitch of a musical note is
(a) amplitude (b) frequency (c) wave velocity (d) all of the above

**Q.4** Two tones have the same amplitude. The statement which is true is
(a) the sounds must be equally loud to the ear
(b) the sounds must have the same pitch
(c) the sounds must have the same timbre
(d) none of the above must be true (though they may be true)

**Q.5** When the amplitude of a sound pressure wave is doubled, the sound pressure level (in decibels)
(a) is doubled (b) is halved (c) decreases by 2 dB (d) increases by 6 dB

**Q.6** "This note is higher in pitch than the note" is a statement about
(a) relative pitch (b) absolute pitch (c) binaural hearing (d) none of these

**Q.7** Lying on the floor, you will exert pressure on the floor, compared to standing on the floor
(a) more (b) less (c) the same (d) not known

**Q.8** A mass oscillates on a spring. As the mass passes through the point of equilibrium,
(a) kinetic energy is maximum and potential energy is maximum
(b) kinetic energy is minimum and potential energy is maximum

(c) kinetic energy is maximum and potential energy is minimum
(d) kinetic energy is minimum and potential energy is minimum

**Q.9** The difference between the time each of your ears hears a sound can help you judge of the sound.
(a) direction (b) pitch (c) loudness (d) speed

**Q.10** As the temperature of the air increases, the speed of sound in air
(a) increases (b) decreases (c) does not change (d) none of these

**Q.11** Which of the following is the false statement?
(a) sound waves are longitudinal waves (b) sound can travel through a vacuum
(c) light travels much faster than sound (d) transverse waves in a guitar string are different from sound waves

**Q.12** The Doppler shift explains
(a) why a sound grows quieter as we move away from the source
(b) why the siren on a police car changes pitch as it races past us
(c) the phenomenon of beats
(d) sound diffraction

**Q.13** The two tones of 440 Hz and 444 Hz are played. The beat frequency is
(a) 440Hz (b) 444 Hz (c) 442 Hz (d) 4 Hz

**Q.14** Which of the following will not affect the fundamental frequency of vibration of a string?
(a) changing the amplitude of vibration (b) changing the tension of the string
(c) changing the length of the string (d) changing the density of the string

**Q.15** Compared to the velocity of a 400 Hz sound through air, the velocity of a 200 Hz sound through air is
(a) twice as great (b) one-half as great (c) the same (d) times larger

**Q.16** In general, sound travels fastest through
(a) gases (b) liquids (c) solids (d) vacuum

**Q.17** In a sound wave, at a place where there is a node in the air pressure wavy, the air molecule displacement
(a) has a node (b) has an antinode
(c) oscillates between node and antinode (d) none of the above

**Q.18** When a sound wave passes from air into water, it changes direction. This phenomenon is known as
(a) refraction (b) diffraction (c) reflection (d) polarisation

**Q.19** A sound pressure level of 110 decibels would be considered
(a) very loud (b) average for speaking
(c) very soft (d) nothing can be said

**Q.20** In damped harmonic motion, the following quantity decreases.
(a) amplitude (b) frequency (c) period (d) velocity

**Q.21** If the displacement of vibrating particles is perpendicular to the direction of propagation of the wave, the wave is said to be
(a) linear (b) transverse (c) longitudinal (d) standing

**Q.22** There are two organ pipes of the same length. One has one end closed, while the other has both ends open. The one with a closed end will emit sound of
(a) a higher frequency (b) a lower frequency
(c) the same frequency (d) double amplitude

**Q.23** When a stretched wire (fixed at both ends) is vibrating in the second harmonic, there is/are
(a) one node (b) two nodes (c) three nodes (d) infinite nodes

**Q.24** Two pure tones cause resonance in different positions along the basilar of membrane. These tones have different
(a) amplitude (b) frequency (c) timbre (d) intensity

**Q.25** Overtones have wavelengths, compared to the fundamental
(a) longer (b) shorter (c) the same (d) times larger

**Q.26** In order to double the wavelength of a sound wave, you should only
(a) double its amplitude (b) double its frequency
(c) halve its amplitude (d) halve its frequency

**Q.27** When two sine waves that are 180° out of phase are added together, the amplitude of the sum is
(a) always zero (b) always less than the amplitude of either wave
(c) equal to the amplitude of the smaller wave (d) always less than the amplitude of the larger wave
(e) always greater than the amplitude of the smaller wave

**Q.28** A sound wave has sound intensity level SIL = 50 dB. Recall that SIL = 10 log ([$I/10^{-12}$ W/m$^2$)]). The intensity $I$ of this wave, in W/m$^2$, is therefore
(a) 50 (b) 5 (c) $10^{-5}$ (d) $10^{-7}$ (e) $10^{-10}$

**Q.29** A sound wave with SIL = 50 dB is reflected by a cloth-covered wall that absorbs 75% of its intensity. The SIL of the reflected wave is
(a) 75 dB (b) 47 dB (c) 44 dB (d) 25 dB (e) 12.5 dB

**Q.30** Light and sound are both waves; yet we can hear a car that is coming from behind the corner of a building before we can see the car. This is because
(a) sound travels faster than light (b) sound $\lambda_{\text{sound}} > \lambda_{\text{light}}$, sound diffracts more than light
(c) sound is not reflected by buildings (d) sound and light interfere, with sound winning out

**Q.31** A moving locomotive is sounding its horn as it crosses a highway. There are people in all directions from the locomotive – in front, in back, to the right and left. Compared to the "true" pitch, as heard by the engineer, the horn's pitch heard by these people is
(a) higher (b) lower
(c) the same for all of the people (d) higher for some, true for others, and lower for yet others of the people

**Q.32** The frequency of the note B4 is close to 500 Hz. The period of this vibration is
(a) 500 sec (b) 1 sec (c) 0.2 sec (d) 2 msec
(e) none of these

**Q.33** A sine wave and a square wave cannot have the same
(a) loudness (b) wavelength (c) frequency (d) tone quality (e) pitch

**Q.34** An electric bell is operating in a vacuum. We cannot hear the sound of the bell because
(a) air is needed to conduct the electric current to the bell
(b) the bell's metal cannot vibrate in vacuum
(c) there is no air to conduct the vibrations to our ears
(d) the vacuum jar absorbs the sound
(e) the noise of the pump is louder than the noise of the bell

**Q.35** The wavelength of "shortwave" radio waves is smaller than that of standard broadcast (AM) radio waves. They both propagate at the same speed. This allows you to conclude that, compared to AM waves, the "shortwaves" have
(a) lower frequency (b) longer period (c) higher frequency (d) smaller amplitudes

**Q.36** When a sound wave enters from air into a metal, in which the speed of sound is much larger than in air, it does not change its
(a) wavelength (b) frequency (c) speed (d) all of these (a-c) change

**Q.37** Sound moves at 345 m/sec towards a rock wall, reflects, and returns (as an echo). The roundtrip takes 2 sec. How far away is the wall?
(a) 70 m (b) 170 m (c) 340 m (d) 345 m (e) 350 m

**Q.38** Two identical sound sources differ in distance from the listener by $^1/_2$ wavelength. The result will be
(a) no sound at the listener
(b) constructive interference
(c) sound which is twice as loud as one source
(d) beats

**Q.39** Which of the following crystals show piezoelectric effect?
(a) NaCl (b) Barium Titanate (c) Diamond (d) Quartz

**Q.40** The frequency of vibration of the D.C. magnetized rod in the magnetostriction generator is
(a) Equal to the frequency of alternating current
(b) Twice the frequency of alternating current
(c) Half the frequency of alternating current
(d) None

## TRUE OR FALSE

### State whether True or False

**Q.1** A steady tone played on a violin is an almost perfect sine wave.

**Q.2** Different vowel sounds differ mainly in the relative frequency and amplitude of the first two formats.

**Q.3** The threshold of hearing is at 0 phons for all frequencies.

**Q.4** A standing wave remains constant, without any change in time whatever.

**Q.5** The precedence effect enables us to hear the fundamental frequency of a complex wave, even when that frequency is absent in the Fourier spectrum.

**Q.6** In the well-tempered scale, only the octaves are perfect intervals.

**Q.7** Light is a longitudinal wave, whereas sound is transverse.

**Q.8** A triangle wave contains higher-frequency Fourier components than a sine wave of the same periodicity.

**Q.9** In a CD player the disk rotates at a constant linear velocity.

**Q.10** In a dynamic loudspeaker the sound is produced by vibration of a permanent magnet.

**Q.11** In an audio system, AM-FM tuner, tape recorder, and CD player each requires its own separate amplifier and loudspeaker.

**Q.12** To make the acoustics of an auditorium more live, the wall, ceiling, and floor surfaces should be made as sound absorbent as possible.

**Q.13** In white noise all frequencies are present, and all have the same intensity.

**Q.14** Attack transients help determine the tone quality of a musical note.

**Q.15** The sound quality of a violin is due only to the resonances of its strings; the violin body has no resonances of its own.

**Q.16** Percussion instruments have only a single resonance.

**Q.17** For two electrical devices connected to the same voltage, the one with the smaller resistance draws the smaller current.

**Q.18** In order to avoid interference between different AM stations, each station uses a carrier wave that is different from that of any of the other stations.

**Q.19** Magnetostriction oscillator can generate ultrasonic waves of single frequency.

**Q.20** We can generate ultrasonic waves of frequency $f$, $2f$, …, where $f$ is the fundamental frequency.

**Q.21** The magnitude of the Piezoelectric effect of a crystalline material does not depend on direction.

**Q.22** The Piezoelectric effect of a material is something to do with the crystal symmetry.

**Q.23** The Piezoelectric effect of a material depends on its crystal structure.

## Practice Problems

**Q.1** What is piezoelectric effect? Describe the construction of a piezoelectric oscillator for the production of ultrasonic waves.

**Q.2** Give the theoretical treatment of Sabine's law. Define the term 'period of revereberation'.

**Q.3** Sketch a graph of pressure vs time for two sound waves that differ only in pitch. Sketch a graph of pressure vs time for two sound waves that differ only in timbre.

**Q.4** A mass on a spring is found to oscillate naturally at a frequency of 0.5 Hz. This mass-spring system is then driven by an oscillator. Describe what happens as the frequency of the oscillator is varied from 0.2 Hz to 0.8 Hz.

**Q.5** Sketch the first two normal modes of sound pressure in a tube open at one end, closed at the other end. If the fundamental mode has a frequency of 440 Hz, what is the frequency of the other mode? Is it harmonic?

**Q.6** Ram is in a fire truck rushing toward the scene of a fire. Shyam is standing at the scene of the fire. There is no wind. Who hears a higher pitch for the fire truck's siren? Explain why.

**Q.7** Explain what is meant by a restoring force? Why is it necessary for vibrations to occur?

**Q.8** What is the wavelength of a 440 Hz sound in air, if the speed of sound in air is 340 m/s? Would the wavelength be longer or shorter if the sound were passing through water?

**Q.9** A wave pulse travels down the length of a wave machine like the one in the front of the lecture hall. The pulse reflects from the end. Describe the difference you would notice between a wave machine with the end free to move and a wave machine with the end fixed.

**Q.10** Define diffraction. How would you demonstrate diffraction of sound waves?

**Q.11** One sound is made up of equal amplitudes of 110 Hz, 220 Hz, and 440 Hz pure tones. A second sound is made up of equal amplitudes of 110 Hz, 330 Hz, and 550 Hz pure tones. In what way(s) are these two sounds the same? In what way(s) are these two sounds different? What is the term given to this combining of pure tones to get a complex tone?

**Q.12** Two pure tones are played, one at a constant frequency of 550 Hz, the other has a variable frequency. Describe all the phenomena you hear as the frequency of the second tone is varied gradually from 550 Hz to 1100 Hz.

**Q.13** Why not ultrasonics be produced by passing high frequency alternating current through a loud speaker?