4.11 SOUND

Sound is a mechanical wave responsible for the sensory experience of hearing. We can hear the mechanical waves in air that have frequencies between 20 Hz and 20 kHz, called the audible range. The mechanical waves of frequencies above 20 kHz are called **ultrasound**, and those below 20 Hz the **infrasound**. Sound waves are created by vibrating objects, such as a vocal chord, a guitar string, a drum, etc., and propagate through a medium, most commonly air, from one location to another. Since sound is a mechanical wave, it has all the properties of mechanical waves we have described in the this chapter.

4.11.1 General Properties of Sound Waves

As pointed out above, sound waves are a type of mechanical waves. But unlike waves on a rope, sound waves in air are **longitudinal**, which means that the particles of the medium (air) vibrate along the same line as that of wave travel (Fig. 4.22). As a matter of fact sound wave in all fluids are longitudinal since fluids cannot provide restoring force to a shear stress generated when a sound wave traveling in the medium. Sound waves in solids can be both longitudinal and transverse.

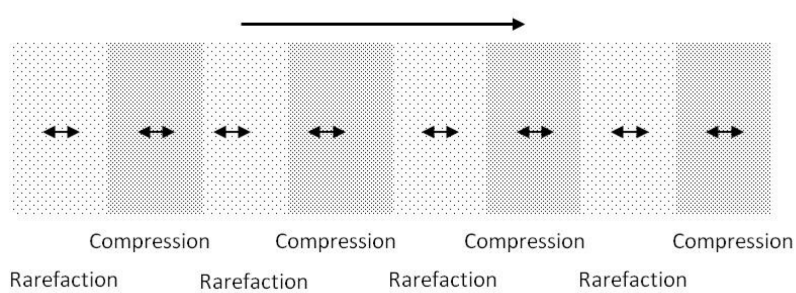

Figure 4.22: As sound passes in air, it creates regions of high pressure, called compressions, and regions of low pressure, called rarefactions.

When sound travels through air, particles of air vibrating in the forward direction press against other particles of air creating a higher pressure than when the wave was not there. Thus, as sound wave propagates through air we obtain regions of compressed air and rarified air. The phenomena are called **compression** and **rarefaction** of air. Hence, the difference of pressure from the ambient pressure gives us an equivalent description of the disturbance or the wave function.

A simple planar wave can be generated by vibrating a planar surface back and forth sinusoidally. The wave function for the pressure wave will be denoted by Δp to distinguish it from the wave function ψ which will be used for the particle displacement wave. For the sake of continuity in our discussion we postpone deriving the relation between the two equivalent representations of the wave function for sound. The plane wave is a cosine or sine function of position and time as discussed in the last chapter.

$$\Delta p(x,t) = p(x,t) - p_0 = A\cos(kx - \omega t + \phi_p) \quad \text{(Planar sound wave)} \tag{4.59}$$

Here A is the amplitude of the wave, k the wave number, ω the angular frequency, and ϕ_p the phase constant for the pressure wave. The amplitude A is the maximum deviation of absolute pressure p at a point with the coordinate x at time t from the ambient pressure p_0. The actual frequency f is related to the angular frequency ω as

$$\omega = 2\pi f.$$

The wave number k is related to the wavelength λ inversely as it gives the number of waves that can fit in 2π meters if the wavelength is expressed in meters.

$$\lambda = \frac{2\pi}{k}.$$

The speed v of the plane sound wave comes from the ratio of the distance traveled over time taken, or wavelength divided by one time period T, which is the same as wavelength multiplied by frequency.

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

By analyzing the vibration of the particles of the medium, we can show that the speed of mechanical waves, including sound wave, through a medium comes from a competition between two opposite tendencies - a restoring force whose tendency is to bring the particle to equilibrium and an inertia whose tendency is to maintain the motion. In a one-dimensional system such as a string, the restoring force is provided by the tension in the string (F_T) and the inertia is provided by mass per unit length of the string (μ). The speed of mechanical wave in a string was stated in the last chapter to be

$$v = \sqrt{\frac{F_T}{\mu}}.$$

The speed of sound in air is similarly related to the properties of air. The restoring force is provided by the bulk modulus B and the inertia is provided by mass per unit volume ρ. The speed of sound in air is therefore given in terms of properties of air by the following.

$$v = \sqrt{\frac{B}{\rho}}.$$

The density of air is not constant. It depends on the temperature and pressure. We quote here experimental relation of dependence of speed on temperature. At 1 atm and $0°C$, the speed of sound in air is found to be 331 m/s and at another temperature t°C, the speed of sound in air at 1 atm is given by the following approximate formula.

$$v \approx 331\left(1 + 1.8 \times 10^{-3} t\right)\ \text{m/s}.$$

Thus at room temperature of 20°C, the speed of sound in air is approximately 343 m/s. Speed of sound is different in different materials depending upon their bulk moduli and densities. Table 4.1 gives the speed of sound in some common materials of interest.

Table 4.1: Speed of sound in various material at 25°C and 1 atm Source: Kaye & Laby, Table of physical and chemical constants 16th edition (published 1995).

Medium	Speed of longitudinal wave (m/s)	Speed of transverse w (m/s)
Isotropic Solids		
Aluminum, rolled	6374	3111
Brass	4372	2100
Polycarbonate	2220	910
Pyrex Glass	5640	3280
Steel, Stainless	5980	3297
Liquids		
Blood	1584	
Glycerin (Glycol)	1920	
Mercury	1449	
Water, Distilled	1496	
Water, Sea (3.5% salinity)	1534	
Gases		
Air	343	
Helium ($0°C$)	972	
Hydrogen ($0°C$)	1286	

Most waves encountered in life are not plane waves. For example sound coming from a conical speaker is not plane but more like spherical (Fig. 4.23). At large distances from a conical speaker the curvature of the wave fronts become small enough that the waves can be approximated to be planar.

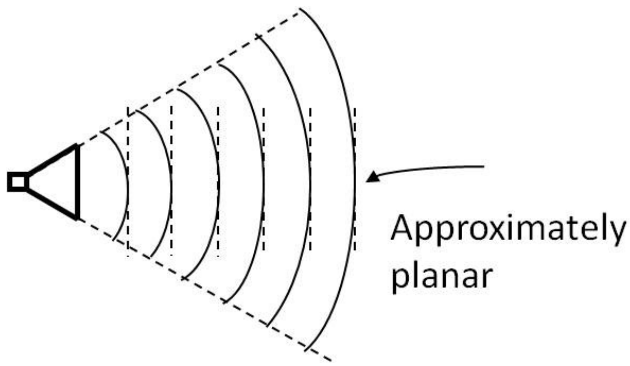

Figure 4.23: Conical speakers. Far away from the speaker, the waves become almost planar and could be approximated by plane waves.

4.11.2 Intensity of Sound - Decibel

The SI-unit of intensity is W/m^2. The intensity of sound that a human ear can hear ranges from approximately 10^{-12} W/m^2 to 1 W/m^2. This is a very wide range of values. When values of interest are spread over a large range, we use logarithm to collapse the values to smaller range of values. In the case of sound, we introduce a logarithm scale called **decibel(dB)** to capture the exponent of 10 in the absolute intensity I compared to a reference intensity I_0 by base-10 logarithm.

$$I(\text{in dB}) \equiv 10 \log \left[\frac{I}{I_0}\right] \tag{4.60}$$

Thus if the intensity is 1,000-times the reference, then it will have a decibel of 30, and if it is 1,000,000-times the reference then it has a decibel of 60. The reference intensity for sound wave is 10^{-12} W/m^2, approximately the threshold of normal human hearing at 1000 Hz of frequency. Therefore, human hearing covers 0 to 120 decibels! A useful information is that a 3-dB drop intensity corresponds to halving the signal.

Since absolute intensity is proportional to the square of the amplitude of the wave, the intensity in dB can be also written in terms of amplitude A of the wave to the amplitude A_0 of the reference wave, but this time the factor would be 20 since replacing $I \sim A^2$ leads to a factor of 2 from the logarithm using $log\ (a^n) = n\ log\ a$.

$$I(\text{in dB}) \equiv 20 \log \left[\frac{A}{A_0}\right]. \tag{4.61}$$

4.11.3 Sources and Quality of Sound

Figure 4.24: Tuning forks of frequencies 256 Hz, 512 Hz and 1024 Hz, from left to right.

Any vibrating object will be a source of sound. If an object vibrates at a single frequency, it will produce a pure tone of that frequency. For instance, a tuning fork can be constructed that produces a single-frequency sound when struck. Smaller tuning forks produce higher frequencies than the larger ones (Fig. 4.24).

Musical instruments produce discrete set of frequencies, the fundamental and overtones, whose frequencies are integral multiples of the fundamental frequency. When a particular key is played on an instrument, it generally produces both the fundamental frequency and the overtones. You may have noticed that the same key, for instance the middle C of piano, played on different instruments, sound different to our ears. The physical reason for the difference is the different mixture of overtones and their relative amplitudes produced in each. Different mixtures of overtones give the sound its **quality or tone color or timber**.

Not every sound produced are like those of musical instruments, such as when you drop a stone or a rubber ball on a concrete floor. Clearly you can tell whether a stone or a rubber ball hit the concrete floor due to the difference in quality of the two sound, but you cannot discern a pitch in either. Such sounds are called noise. The reason

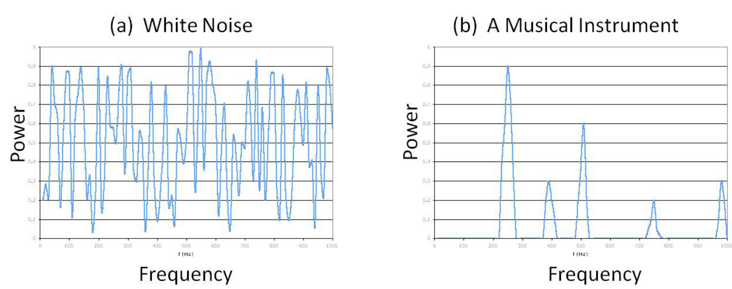

Figure 4.25: (Power spectra of (a) white noise and (b) a musical instrument. Musical instruments produce fundamental and overtones while noise contains almost continuum of frequencies.

you are not able to find a pitch in a noise is that it usually consists of a continuous sound spectrum unlike sound of a musical note which consists of a particular frequency and its overtones. If you plot the intensity versus frequency in a noise, you will get a continuous graph, rather than spikes at the fundamental and overtones in the case of musical notes (Fig. 4.25). The plot of the intensity versus frequency is also called the **power spectrum**.

Perception of sound

Human ears serve as excellent detectors of sound. We perceive several characteristics of sound: loudness, pitch, tone, timbre or tone color. They all have their basis in physical content of the waves impinging upon the eardrums. Loudness has to do with the energy in the wave and is related to the intensity of the wave. Pitch and tone are related with the frequency; a higher pitch or tone generally refers to higher frequency. Timbre or tone color refers to the frequency composition of a musical tone.

4.11.4 Sound through Solid Media

Since sound is a mechanical vibration, it can travel through any material medium. In liquid and gas, only longitudinal sound is possible because fluids do not have a restoring force in tangential direction, they have restoring force only against compression. Solids have restoring force for compression as well as shear forces. Therefore you will find three polarizations of sound waves in solid: one longitudinal, and two transverse modes, one for each perpendicular direction.

The speeds of longitudinal and transverse waves are different since the restoring forces are different for them.

$$v_{\text{sound}} = \sqrt{\frac{\text{Restoring force per unit area}}{\text{Inertia as given by density}}} \tag{4.62}$$

For a uniform isotropic material the two transverse waves have the same speed. Let Y be the Young's modulus, G the shear modulus, and ρ the density of the solid. The speed of longitudinal sound v_L is related to the Elastic modulus E.

$$v_L = \sqrt{\frac{E}{\rho}} \tag{4.63}$$

where $E = Y + \frac{3}{4}B$. Here Y is the Young's modulus and B the bulk modulus. On the other hand, the speed of transverse waves v_T is related to the shear modulus.

$$v_T = \sqrt{\frac{G}{\rho}} \tag{4.64}$$

For instance, steel has $Y \approx 215$ GPa, $B = 166$ MPa, $G \approx 84$ GPa, and density $7,800\ \text{kg/m}^3$, therefore the longitudinal and transverse waves travel at different speeds in steel.

$$\text{In steel: } v_L = 6592\ \text{m/s}; \quad v_T = 3281\ \text{m/s}.$$

The numbers here are a little different than those listed in the table because of the temperature dependence of sound. In general, shear stress G is less than the Young's modulus Y. Hence speed of transverse waves will be less than that of longitudinal wave. Sound waves in solids are used to find defects inside solid materials by non-destructive means. The non-destructive techniques based on propagation of waves in material media have important applications in medical physics and other engineering fields. For instance, in aeronautics, invisible cracks in the wings of air planes can be detected even before they become large enough to cause an accident.

4.11.5 Ultrasound

Ultrasound is the name given to the sound waves having frequencies above 20,000 Hz. Humans can't hear these waves, but many animals such as dogs and bats have sensitivity to these waves. Bats even use ultrasound for navigation at night by producing ultrasound that bounces off obstacles in their flight path. In tissue and water, ultrasound of frequency 5 MHz range have wavelength in the millimeter and sub-millimeter range. Since a wave scatters most strongly from obstacles that have dimensions of the order of their wavelengths, ultrasound sent inside human body is able to reflect off inter-tissue spaces of millimeter dimensions. The returned wave is constructed into image of the reflecting surfaces giving ultrasound imaging of internal organs. Ultrasound machines have become universally accepted as powerful tools for the detection of kidney stones, heart ailments and fetuses. Powerful ultrasound machines are also used for surgery.

Ultrasound also has many industrial uses, including cleaning, and non-destructive technology where one can detect defects in inside metals sheets that otherwise appear normal.