14. SOUND

Key words: Sound, Hearing, Pitch, Audible Range, Ultrasonic, Infrasonic, Human Ear, Intensity, Sound Intensity, Loudness, Spherical Wave, Sound Level, Decibels, Intensity Level (or Sound Level), Reflection of Sound Waves, Interference of Sound Waves, Echo, Principle of Superposition, Constructive Interference, Destructive Interference, Beats, Sonar Standing Wave, Nodes, Antinodes, Fundamental Frequency, Harmonics, Natural Frequencies or Resonant Frequencies, Doppler Effect, Red Shift.

14.1 Sound and Hearing

Sound is a mechanical longitudinal wave that travels in air and other materials. We perceive the sound waves by Hearing. The Pitch of a sound is determined by the frequency - the higher the frequency, the higher the pitch. The Audible Range of frequencies for humans is roughly from 20Hz to 20,000Hz. Sound waves whose frequency is outside the audible range may reach the ear but we are not generally aware of them. We also use the term sound for similar waves with frequencies above (Ultrasonic) and below (Infrasonic) the range of human hearing. Many animals can hear ultrasonic frequencies; dogs for example, can hear sounds as high as 50,000Hz, and bats can detect frequencies as high as 100,000Hz.

The Human Ear is a marvelous instrument for detecting the vibrations caused by sound waves. The sound waves enter the auditory canal and cause the eardrum to vibrate. Typically, the radius of this membrane is 4.2mm. The vibration is then transmitted through the three small bones to the fluid-filled cochlea (the spiraled part of the inner ear which receives sound vibrations and converts them to nerve impulses).

14.2 Sound Intensity

The Loudness, or intensity, of a sound is related to the amplitude of the sound wave. Like all other waves, sound waves transfer energy from one region to another. The intensity is the physical quantity that characterizes this transfer. The Intensity of a wave $I$ is the energy transported by a wave per unit time across a unit area perpendicular to the energy flow.
\[ I = \frac{E}{A \cdot t} \quad (14-1) \]

It is proportional to the square of the wave amplitude. From (14-1) we can deduce that \( I = \frac{1}{A} \frac{E}{t} = \frac{P_{av}}{A} \) where \( P_{av} \) is the average power. Because of this, intensity has units of power per unit area, or watts/meter^2 \( \frac{W}{m^2} \). That is, the intensity \( I \) is the average power transmitted per unit area. If a wave flows out from the source in all directions, it is a three-dimensional wave. In an isotropic medium, the wave is said to be a **Spherical Wave**. As the wave moves outward, the energy it carries is spread over a larger and larger area since the surface area of a sphere of radius \( r \) is \( 4\pi r^2 \). Thus, the intensity of a spherical wave is:

\[ I = \frac{P_{av}}{A} = \frac{P_{av}}{4\pi r^2} \quad (14-2) \]

Therefore, if \( P_{av} = \text{constant} \), then the intensity decreases as the inverse square of the distance from the source.

\[ I \propto \frac{1}{r^2} \quad (14-3) \]

If we consider two points at distances \( r_1 \) and \( r_2 \), then \( I_1 = \frac{P}{4\pi r_1^2} \) and \( I_2 = \frac{P}{4\pi r_2^2} \) so

\[ \frac{I_2}{I_1} = \frac{r_1^2}{r_2^2} \quad (14-4) \]

This inverse-square relationship also holds for various other energy-flow situations involving a point source such as light emitted by a point source.

### 14.3 Sound Level: Decibels

**Loudness** is a sensation in the consciousness of a human being. It is related to a physically measurable quantity, intensity, introduced in the previous
section. The human ear can detect sounds with an intensity as low as $10^{-12} \text{W/m}^2$ and as high as 1 W/m$^2$ (and even higher, but it is painful above the level 1 W/m$^2$). This is an incredibly wide range of intensity, spanning a factor of $10^{12}$ from the lowest to the highest. Presumably because of this wide range, what we perceive as loudness is not directly proportional to its intensity. To produce a sound that sounds about twice as loud requires a sound wave that has about 10 times greater intensity. Because of this, relationship between the subjective sensation of loudness and the physically measurable intensity, sound intensity levels are usually specified on a logarithmic scale. The unit of this scale is called the bel, after the American inventor of the telephone, Alexander Bell, or much more commonly, the Decibel (dB), which is 0.1bel. (10dB=1B.) The Intensity Level (or Sound Level) $\beta$ of a sound wave is defined by the equation:

$$\beta = (10 \text{dB}) \log_{10} \left( \frac{I}{I_0} \right)$$  \hspace{1cm} (14-5)

In this equation, $I_0$ is reference intensity, chosen to be $I_0 = 10^{-12} \text{W/m}^2$ and “log” denotes the logarithm to the base 10. A sound wave with intensity $I=I_0$ has an intensity level of 0dB. This level corresponds roughly to the faintest sound that can be heard by a person with normal hearing. The intensity of an elevated train is 90dB. The intensity at the pain threshold, $W=1\text{W/m}^2$, corresponds to an intensity level of 120dB.

**EXAMPLE 14-1. Sound Level on the Street.**

On a busy street, the sound is 70dB. What is the intensity of the sound level on the street?

$$\beta = 10 \log \frac{I}{I_0}$$

$$I_0 = 1.0 \cdot 10^{-12} \frac{\text{W}}{\text{m}^2}$$

$$\log \frac{I}{I_0} = \frac{\beta}{10}$$

$$\frac{I}{I_0} = 10 \frac{\beta}{10}$$

$$I = I_0 \cdot 10^{\frac{\beta}{10}} = 1.0 \cdot 10^{-12} \cdot 10^{\frac{70}{10}} \cdot \frac{\text{W}}{\text{m}^2}$$
Recall that \( x = \log y \) is the same as \( y = 10^x \) because \( \log y = \log 10^x = x \log 10 = 1 \times x \)

14.4 **Reflection and Interference of Sound Waves**

Waves reflect off objects in their path. When a wave strikes an obstacle, or comes to the end of the medium it is traveling in, at least a part of the wave is reflected. Example: you may have heard a shout reflected from a distant cliff—which we call an **Echo**.

When two waves pass through the same region of space at the same time, they **interfere**. In this case, the displacement at any given point will be the vector sum of the displacements of the separate waves. This is the **Principle of Superposition**. According to this principle, if two periodic waves are in step at a point, then their amplitudes add together. This phenomenon is called **Constructive Interference**. If the waves are a half-cycle out of step at a point, the resulting amplitude is smaller and the phenomenon is called **Destructive Interference**. Two sound waves with slightly different frequencies, \( f_1 \) and \( f_2 \), interfere in time; the sound level at a given position alternately rises and falls. Alternating constructive and destructive interference produces **Beats**. The beat frequency is

\[
    f_{\text{beat}} = f_1 - f_2 \quad (14-6)
\]

Reflection of the sound waves has a lot of applications. One of them is **Sonar** (from the initial letters of SOund NAvigation Ranging). Sonar is an apparatus, which locates a submerged object by emitting high-frequency sound waves and registering the reflected vibrations. It is used for detecting submarines, shoals of fish, etc., and for finding ocean depths. The principles of work of the sonar can be illustrated by the following example.

**EXAMPLE 14-2.** The echo of the sound reflected from the ocean floor directly below the ship comes 2.5 s later. How deep is the ocean at this point? Assume that the speed of sound in seawater is \( 1560 \frac{m}{s} \) and it does not vary significantly with depth.

\[
    t_{\text{tot}} = 2.5 \text{s} \\
    v = 1560 \frac{m}{s} \\
    d = ?
\]
The round trip time for sound is 2.5s, so the time for the sound to travel the distance from the surface to the ocean floor is: \( t = 1.25 \text{s} \).

\[
d = v \cdot t = 1950 \text{m} \approx 2.0 \cdot 10^3 \text{m}
\]

Several animals use sound the same way for navigation. Bats depend primarily on sound rather than sight for guidance during flight. That’s how they can fly in the total darkness of a cave. Dolphins use an analogous system for underwater navigation.

Acoustical phenomena have many important medical applications. Ultrasonic imaging (the reflection of ultrasound waves from regions in the interior of the body) is used for prenatal examinations, the detection of anomalous conditions such as tumors, the study of heart-valve action and so on. Registration of an acoustic emission is widely used in technology for monitoring the behavior of constructions, bridges and so on under operating conditions. Acoustic measurements are very effective in the location of earthquakes, underground atomic weapon tests and so on.

When a sinusoidal wave is reflected at a stationary or free end, the original and reflected wave continue to make a **Standing Wave**. At the **Nodes** of a standing wave, the displacement is always zero; the **Antinodes** are the points of maximum displacement. Fixed string ends are nodes; ends that are free to move transversely are antinodes. Standing waves on a string of length \( L \) can have only certain specific frequencies. When both ends are held stationary, the allowed frequencies \( f_n \) are:

\[
f_n = n \cdot \frac{v}{2L} = nf_1 (n = 1, 2, 3, \ldots)
\]

(14-7)

where \( f_1 = \frac{v}{2L} \) is called the **Fundamental Frequency**. All integer multiples of \( f_1 \) are called **Harmonics**. The fundamental frequency of a vibrating string with length \( L \), held at both ends, is

\[
f_1 = \frac{1}{2L} \sqrt{\frac{F_i}{\mu}}
\]

(14-8)

where string tension is \( F_i \) and the mass per unit length is \( \mu \).

The frequencies at which standing waves are produced are called the **Natural Frequencies or Resonant Frequencies**.
EXAMPLE 14-3. Piano String. A piano string is 1.10 m long and has a mass of 9.00 g. (a) How much tension must the string be under if it is to vibrate at a fundamental frequency of 131 Hz? (b) What are the frequencies of the first three harmonics?

\[ L = 1.10 \text{ m} \]
\[ M = 9.00 \text{ g} = 9.00 \times 10^{-3} \text{ kg} \]
\[ f_1 = 131 \text{ Hz} = 131 \text{ s}^{-1} \]

(a) \( F_T \)?

\[ f_1 = \frac{1}{2L} \sqrt{\frac{F_T}{\mu}} \quad \mu = \frac{m}{L} \]

\[ F_T = 4 \left( \frac{m}{L} \right) L^2 f_1^2 \quad F_T = 680 \text{ N} \]

(b) \( f_2, f_3 \)?

\[ f_2 = 2f_1 = 2 \times 131 \text{ Hz} = 262 \text{ Hz} \]
\[ f_3 = 3f_1 = 3 \times 131 \text{ Hz} = 393 \text{ Hz} \]

14.5 Doppler Effect

You may have noticed that you hear the pitch of the siren on a speeding ambulance or a fire truck drop abruptly as it passes you. This phenomenon is called the **Doppler Effect**. This effect refers to the change in the pitch of a sound due to the motion either of the source or of the listener. If the source and the listener are approaching each other, the perceived pitch is higher; if they are moving apart, the perceived pitch is lower. This is because the source that approaches the listener is “chasing” the previously emitted wave and emits each crest closer to the previous one. As a result, the listener in front of the source will detect more wave crests passing per second, so the frequency heard is higher. The waves emitted behind the source, on the other hand, are farther apart than when the source is at rest because it is speeding away from them. Therefore, fewer wave crests per second pass by the listener and perceived pitch is lower. If the source and listener frequencies \( f_S \) and \( f_L \), their velocities \( v_s \) and \( v_L \), and the speed of sound is \( v_1 \), then the relationship between \( f_S \) and \( f_L \) can be written as follows:

\[ f_L = \frac{v + v_L}{v + v_S} f_S \quad \text{(14-9)} \]
The direction from the listener to the source is positive.

**EXAMPLE 14-4.** A moving siren of a police car at rest emits sound at a frequency of 1600Hz. What frequency will you hear if you are at rest and the police car moves at 25.0 m/s (56 mi/h) (a) toward you, and (b) away from you? Suppose that the speed of sound in the air is \( v = 343m/s \).

\[
v = 343 \frac{m}{s}
\]

\[
v_L = 0
\]

\[
|v_S| = 25.0 \frac{m}{s}
\]

\[
f_S = 1600Hz
\]

(a) Source moves toward the listener. \( f_L = \)?

\[
v_L = 0, v_S = -25.0 \frac{m}{s}
\]

then (14-9) can be written as follows:

\[
f_L = \frac{v}{v - v_S} f_S = \frac{1}{1 - \frac{v_S}{v}} f_S
\]

\[
f_L = 1726Hz
\]

(b) Source moves away from the listener. \( f_L = \)?

\[
v_L = 0, v_S = +25.0 \frac{m}{s}
\]

\[
f_L = \frac{v}{v + v_S} = 1491Hz
\]

There is also a Doppler effect for electromagnetic waves such as light waves or radio waves. An application of the Doppler effect with radio waves is, for example, radar (from the initial letters of RAdio Detection And Ranging). The good example is a device used in police cars to check the speed of other cars. The electromagnetic wave emitted by the device is reflected from a moving car, which then acts as a moving source and the wave reflected back to the device with Doppler shift in frequency. The transmitted and reflected signals are combined to produce beats and the speed can be computed from the frequency of the beats. The data of Doppler radar measurements always are demonstrated on TV during weather forecasts.
The Doppler effect for light is of fundamental importance in astronomy. Light emitted by elements in the stars of distant galaxies show shift toward longer wavelength and smaller frequency compared with light from the same elements on the earth. This is called the **Red Shift** since red has the lowest frequency of visible light. The famous American astronomer, Edwin Hubble, discovered that the farther the galaxy is from us, the greater the red shift so the faster these galaxies move away. These observations provide solid evidence for the “Big Bang” theory, which describes a universe that has been expanding for about 14 billion years.