Chapter 3
Sound waves

Lesson No 7:

Objectives:

Student will be able to:

- Define the speed of the sound waves
- Understand the hearing mechanism.
- Understand some applications on sound.

Sound waves are the most common example of longitudinal waves. They travel through any material medium with a speed that depends on the properties of the medium.

Sound waves are divided into three categories that cover different frequency ranges.

(1) *Audible waves* lie within the range of sensitivity of the human ear. They can be generated in a variety of ways, such as by musical instruments, human voices, or loudspeakers.

(2) *Infrasonic waves* have frequencies below the audible range. Elephants can use infrasonic waves to communicate with each other, even when separated by many kilometers.

(3) *Ultrasonic waves* have frequencies above the audible range. The ultrasonic sound it emits is easily heard by dogs, although humans cannot detect it at all. Ultrasonic waves are also used in medical imaging.

3.1 Speed of Sound Waves

The speed of sound waves in a medium depends on the compressibility and density of the medium. If the medium is a liquid or a gas and has a bulk modulus B and density ρ, the speed of sound waves in that medium is

$$v = \sqrt{\frac{B}{\rho}} \qquad (3.1)$$

It is interesting to compare this expression for the speed of transverse waves on a string, $v = \sqrt{T/\mu}$. In both cases, the wave speed depends on an elastic property of the medium bulk modulus B or string tension T and on an inertial property of the medium ρ or μ. In fact, the *speed of all mechanical waves* follows an expression of the general form

$$v = \sqrt{\frac{\text{elastic property}}{\text{inertial property}}}$$

For longitudinal sound waves in a solid rod of material, for example, the speed of sound depends on Young's modulus Y and the density ρ. Table provides the speed of sound in several different materials. The speed of sound also depends on the temperature of the medium. For sound traveling through air, the relationship between wave speed and medium temperature is

$$v = (331 m/s)\sqrt{1 + \frac{T_C}{273°C}}$$

Table 1

Speed of Sound in Various Media

Medium	v (m/s)
Gases	
Hydrogen (0°C)	1 286
Helium (0°C)	972
Air (20°C)	343
Air (0°C)	331
Oxygen (0°C)	317
Liquids at 25°C	
Glycerol	1 904
Seawater	1 533
Water	1 493
Mercury	1 450
Kerosene	1 324
Methyl alcohol	1 143
Carbon tetrachloride	926
Solids[a]	
Pyrex glass	5 640
Iron	5 950
Aluminum	6 420
Brass	4 700
Copper	5 010
Gold	3 240
Lucite	2 680
Lead	1 960
Rubber	1 600

Values given are for propagation of longitudinal waves in bulk media. Speeds for longitudinal waves in thin rods are smaller, and speeds of transverse waves in bulk are smaller yet.

where 331 m/s is the speed of sound in air at 0°C, and T_C is the air temperature in degrees Celsius. Using this equation, one finds that at 20°C the speed of sound in air is approximately 343 m/s.

3.2 Periodic Sound Waves

In this section will help you better comprehend the nature of sound waves. An important fact for understanding how our ears work is that *pressure variations control what we hear*.

One can produce a one-dimensional periodic sound wave in a long, narrow tube containing a gas by means of an oscillating piston at one end, as shown in Figure 3.1. The darker parts of the colored areas in this figure represent regions where the gas is compressed and thus the density and pressure are above their equilibrium values. A compressed region is formed whenever the piston is pushed into the tube. This compressed region, called a compression, moves through the tube as a pulse, continuously compressing the region just in front of itself. When the piston is pulled back, the gas in front of it expands, and the pressure and density in this region fall below their equilibrium values (represented by the lighter parts of the colored areas in Figure 3.1.

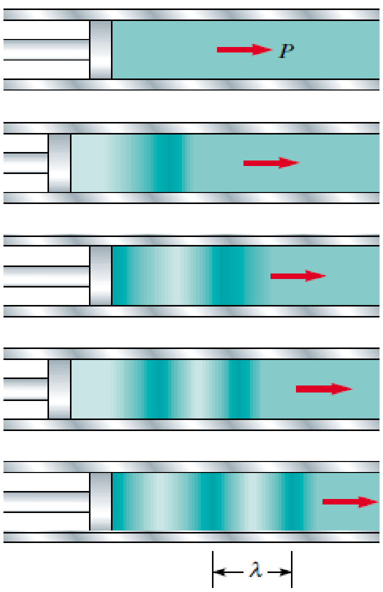


Fig. 3.1 A longitudinal wave propagating through a gas filled tube. The source of the wave is an oscillating piston at the left.

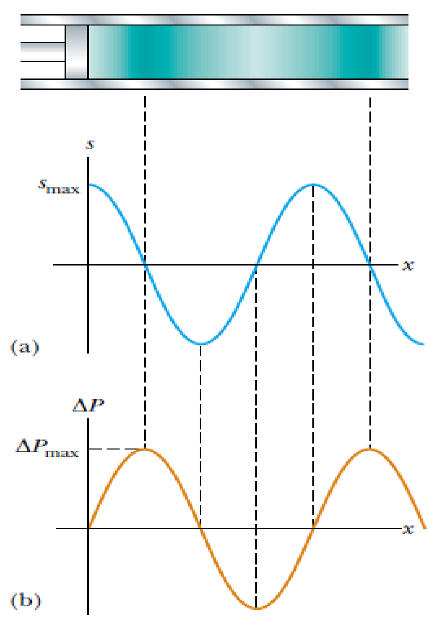


Fig. 3.2 (a) Displacement amplitude and (b) pressure amplitude versus position for a sinusoidal longitudinal wave.

These low pressure regions, called rarefactions, also propagate along the tube, following the compressions. Both regions move with a speed equal to the speed of sound in the medium. As the piston oscillates sinusoidally, regions of compression and rarefaction are continuously set up. The distance between two successive compressions (or two successive rarefactions) equals the wavelength λ. As these regions travel through the tube, any small element of the medium moves with simple harmonic motion parallel to the direction of the wave.

If $s(x, t)$ is the position of a small element relative to its equilibrium position, we can express this harmonic position function as

$$s(x,t) = s_{max}\cos(kx - \omega t) \qquad 3.2$$

where $\mathbf{s_{max}}$ is the maximum position of the element relative to equilibrium. This is often called the displacement amplitude of the wave. The parameter ***k*** is the wave number and ω is the angular frequency of the piston. Note that the displacement of the element is along x, in the direction of propagation of the sound wave, which means we are describing a **longitudinal wave.**

The variation in the gas pressure ΔP measured from the equilibrium value is also periodic. For the position function in Equation 3.1, ΔP is given by

$$\Delta P = \Delta P_{max}\sin(kx - \omega t) \qquad 3.3$$

where the pressure amplitude ΔP_{max} which is the maximum change in pressure from the equilibrium value is given by

$$\Delta P = \rho v \omega s_{max} \qquad 3.4$$

Thus, we see that a sound wave may be considered as either a displacement wave or a pressure wave .A comparison of Equations 3.2 and 3.3 shows that the pressure wave is 90° out of phase with the displacement wave. Graphs of these functions are shown in Figure 3.2. Note that the pressure variation is a maximum when the displacement from equilibrium is zero, and the displacement from equilibrium is a maximum when the pressure variation is zero.

Lesson 8:
Objectives:
- Define the intensity of the sound wave.
- Define the Doppler effect.

3.3 Intensity of Periodic Sound Waves

In the preceding chapter, we showed that a wave traveling on a taut string transports energy. The same concept applies to sound waves. Consider an element of air of mass Δm and width Δx in front of a piston oscillating with a frequency ω, as shown in Fig. 3.3.

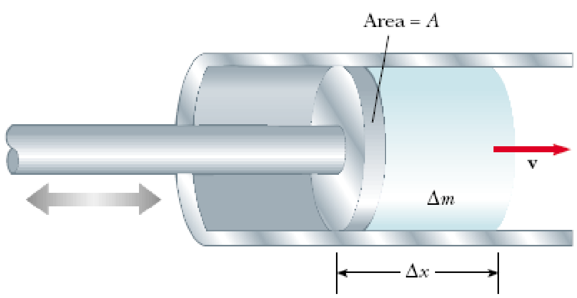


Figure 3.3 An oscillating piston transfers energy to the air in the tube, causing the element of air of width Δx and mass Δm to oscillate with an amplitude s_{max} .

The piston transmits energy to this element of air in the tube, and the energy is propagated away from the piston by the sound wave.
To evaluate **the rate of energy transfer for the sound wave**, we shall define the kinetic energy of this element of air, which is undergoing simple harmonic motion as,

$$K_\lambda = \frac{1}{4}\rho A v(\omega s_{max})^{2}$$

As in the case of the string wave, the total potential energy for one wavelength has the same value as the total kinetic energy; thus, the total mechanical energy for one wavelength is

$$E_\lambda = K_\lambda + U_\lambda = \frac{1}{2}\rho A v(\omega s_{max})^{2}$$

$$\mathcal{P} = \frac{\Delta E}{\Delta t} = \frac{E_\lambda}{T} = \frac{\frac{1}{2}\rho A(\omega s_{\max})^2\lambda}{T} = \frac{1}{2}\rho A(\omega s_{\max})^2\left(\frac{\lambda}{T}\right) = \frac{1}{2}\rho A v(\omega s_{\max})^2 \qquad \textbf{3.5}$$

As the sound wave moves through the air, this amount of energy passes by a given point during one period of oscillation. Hence, the rate of energy transfer is where υ is the speed of sound in air.

We define the intensity I of a wave, or the power per unit area, to be the rate at which the energy being transported by the wave transfers through a unit area A perpendicular to the direction of travel of the wave:

$$I = P/A$$

In the present case, therefore, the intensity is

$$I = P/A = \frac{1}{2}\rho v(\omega s_{max})^2$$

Thus, we see that the **intensity** of a periodic sound wave is proportional to the square of the displacement amplitude and to the square of the angular frequency (as in the case of a periodic string wave). This can also be written in terms of the pressure amplitude ΔP_{max}; in this case, we use Equation 17.4 to obtain

$$I = \frac{\Delta P_{max}^2}{2\rho v} \qquad 3.6$$

Now consider a point source emitting sound waves equally in all directions. From everyday experience, we know that the intensity of sound decreases as we move farther from the source. We identify an imaginary sphere of radius *r* centered on the source. When a source emits sound equally in all directions, we describe the result as a spherical wave. The average power $\mathbf{P_{av}}$ emitted by the source must be distributed uniformly over this spherical surface of area $4\pi r^2$. Hence, the wave intensity at a distance *r* from the source is

$$I = \frac{\mathcal{P}_{av}}{A} = \frac{\mathcal{P}_{av}}{4\pi r^2} \qquad \mathbf{3.7}$$

Sound Levels	
Source of Sound	**β (dB)**
Nearby jet airplane	150
Jackhammer; machine gun	130
Siren; rock concert	120
Subway; power mower	100
Busy traffic	80
Vacuum cleaner	70
Normal conversation	50
Mosquito buzzing	40
Whisper	30
Rustling leaves	10
Threshold of hearing	0

Table3.2

This inverse law which state that the intensity decrease in proportion to the square of the distance from the source

Sound Level in Decibels

Whereas the range of intensities the human ear can detect is so wide, it was convenient to use a logarithmic scale, where the sound level $\boldsymbol{\beta}$ (Greek beta) is defined by the equation

$$\beta = 10 \log \frac{I}{I_0} \qquad 3.8$$

The constant I_o is the *reference intensity*, taken to be at the threshold of hearing (I_o = 1.00 x 10^{-12} W/m^2), and I is the intensity in watts per square meter to which the sound level $\boldsymbol{\beta}$ corresponds, where $\boldsymbol{\beta}$ is measured in decibels (dB). On this scale, the threshold of pain (I = 100 W/m^2) corresponds to a sound level of $\boldsymbol{\beta}$ = 10 log [(1 W/ m^2) / (10^{-12} W/ m^2)] = 120 dB, and the threshold of hearing corresponds to $\boldsymbol{\beta}$ = 10 log [(10^{-12} W/ m^2) / (10^{-12} W/ m^2)] =0 dB.

Prolonged exposure to high sound levels may seriously damage the ear. Ear plugs are recommended whenever sound levels exceed 90 dB. Recent evidence suggests that “noise pollution” may be a contributing factor to high blood pressure, anxiety, and nervousness. Table 3.2 gives some typical sound-level values.

3.4 The Doppler Effect

Perhaps you have noticed how the sound of a vehicle’s horn changes as the vehicle moves past you. The frequency of the sound you hear as the vehicle approaches you is higher than the frequency you hear as it moves away from you. This is one example of the Doppler Effect.

To see what causes this apparent frequency change, imagine you are in a boat that is lying at anchor on a gentle sea where the waves have a period of T = 3.0 s. This means that every 3.0 s a crest hits your boat. Fig. 3.5a shows this situation, with the water waves moving toward the left. If you set your watch to t # 0 just as one crest hits, the watch reads 3.0 s when the next crest hits, 6.0 s when the third crest hits, and so on.

From these observations you conclude that the wave frequency is f = 1 / T = 1 / (3.0 s) = 0.33 Hz. Now suppose you start your motor and head directly into the oncoming waves, as in Figure 3.5b. Again you set your watch to t = 0 as a crest hits the front of your boat. Now, however, because you are moving toward the next wave crest as it moves toward you, it hits you less than 3.0 s after the first hit. In other words, the period you observe is shorter than the 3.0 s period you observed when you were stationary. Because f = 1 / T, you observe a higher wave frequency than when you were at rest.

If you turn around and move in the same direction as the waves (see Fig. 3.5c), you observe the opposite effect. You set your watch to $t = 0$ as a crest hits the back of the boat. Because you are now moving away from the next crest, more than 3.0 s has elapsed on your watch by the time that crests catches you. Thus, you observe a lower frequency than when you were at rest.

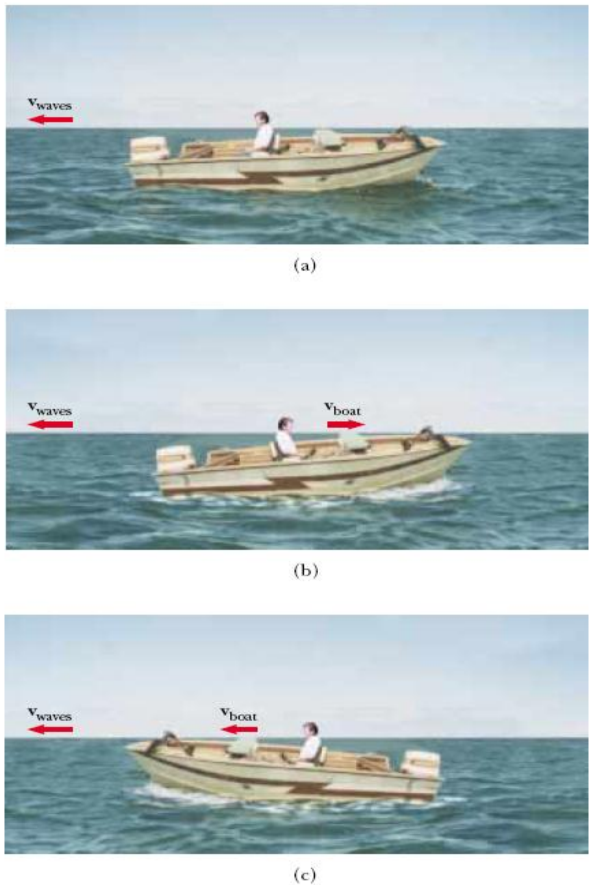


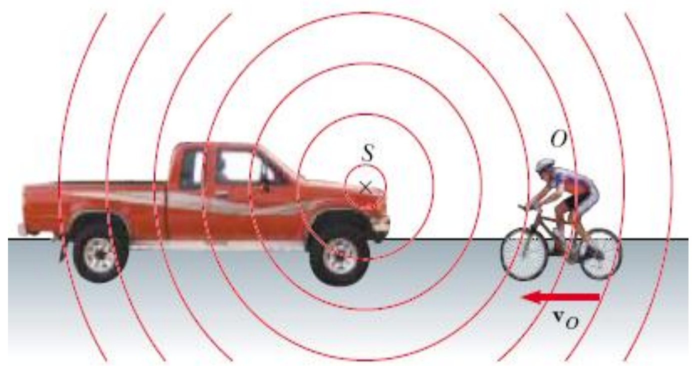
Fig. 3.5 (a) Waves moving toward a stationary boat. The waves travel to the left, and their source is far to the right of the boat, out of the frame of the photograph. (b) The boat moving toward the wave source. (c) The boat moving away from the wave source.

These effects occur because the *relative* speed between your boat and the waves depends on the direction of travel and on the speed of your boat. When you are moving toward the right in Figure 3.5b, this relative speed is higher than that of the wave speed, which leads to the observation of an increased frequency. When you turn around and move to the left, the relative speed is lower, as is the observed frequency of the water waves.

Let us now examine an analogous situation with sound waves, in which the water waves become sound waves, the water becomes the air, and the person on the boat becomes an observer listening to the sound. In this case, an observer O is moving and a sound source S is stationary. For simplicity, we assume that the air is also stationary and that the observer moves directly toward the source (Fig. 3.6). The observer moves with a speed υ_O toward a stationary point source ($\upsilon_s = 0$), where stationary means at rest with respect to the medium, air.

If a point source emits sound waves and the medium is uniform, the waves move at the same speed in all directions radially away from the source; this is a spherical wave. It is useful to represent these waves with a series of circular arcs concentric with the source, as in Figure 3.6. Each arc represents a surface over which the phase of the wave is constant. For example, the surface could pass through the crests of all waves. We call such a surface of constant phase a wave front. The distance between adjacent wave fronts equals the wavelength. In Figure 3.6, the circles are the intersections of these three dimensional wave fronts with the two dimensional paper.

Figure 3.6 An observer *O* (the cyclist) moves with a speed υ_o toward a stationary point source *S*, the horn of a parked truck. The observer hears a frequency *f*. that is greater than the source



We take the frequency of the source in Figure 3.6 to be *f*, the wavelength to be λ, and the speed of sound to be υ. If the observer were also stationary, he or she would detect wave fronts at a rate *f*. (That is, when $\upsilon_o = 0$ and $\upsilon_S = 0$, the observed frequency equals the source frequency). When the observer moves toward the source, the speed of the waves relative to the observer is $\upsilon' = \upsilon_o + \upsilon$, as in the case of the boat, but the wavelength λ is unchanged. Hence, $\upsilon = \lambda f$, we can say that the frequency f' heard by the observer is increased and is given by

$$f' = \frac{\upsilon'}{\lambda} = \frac{\upsilon + \upsilon_o}{\lambda} \qquad 3.9$$

Because $\lambda = \upsilon / f$, we can express f' as

$$f' = \left(\frac{\upsilon + \upsilon_o}{\upsilon}\right) f \qquad \text{(observer moving toward source)} \qquad 3.10$$

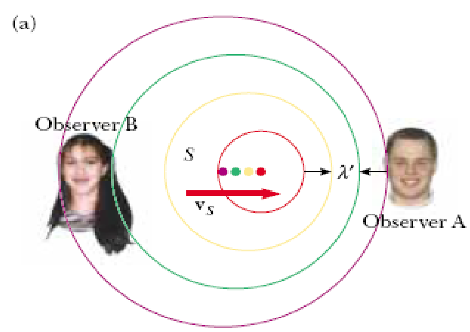
If the observer is moving away from the source, the speed of the wave relative to the observer is $\upsilon' = \upsilon - \upsilon_o$. The frequency heard by the observer in this case is decreased and is given by

$$f'' = \left(\frac{\upsilon - \upsilon_o}{\upsilon}\right) f \qquad \text{(observer moving away from source)} \qquad 3.11$$

In general, whenever an observer moves with a speed υ_o relative to a stationary source, the frequency heard by the observer is given by Equation 3.9, with a sign convention: **a positive** value is substituted for υ_o when the observer moves toward the source and **a negative** value is substituted when the observer moves away from the source.

Now consider the situation in which the source is in motion and the observer is at rest. If the source moves directly toward observer A in Figure 3.9a, the wave fronts heard by the observer are closer together than they would be if the source were not moving. As a result, the wavelength $\lambda^`$ measured by observer A is shorter than the wavelength λ of the source. During each vibration, which lasts for a time interval T (the period), the source moves a distance $\upsilon_s T = \upsilon_s / f$ and the wavelength is shortened by this amount. Therefore, the observed wavelength $\lambda^`$ is

$$\lambda^` = \lambda - \Delta\lambda = \lambda - \upsilon_s / f$$



(b)

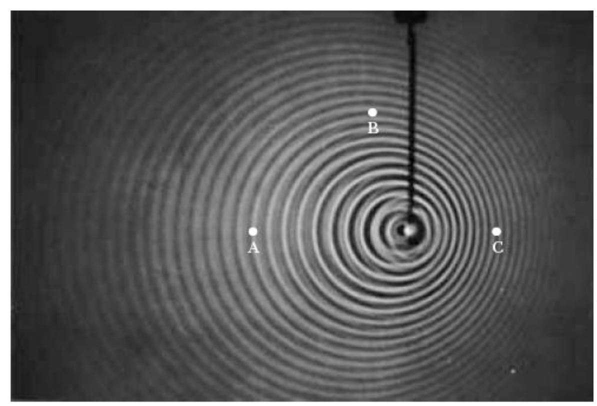


Figure 3.7 (a) A source *S* moving with a speed υ_s toward a stationary observer A and away from a stationary observer B. Observer A hears an increased frequency, and observer B hears a decreased frequency. (b) The Doppler Effect in water, observed in a ripple tank. A point source is moving to the right with speed υ_s .

Because $\lambda = \upsilon_s / f$, the frequency $f^`$ heard by observer A is

$$f\,\frac{\upsilon}{\lambda} = \frac{\upsilon}{\lambda - \left(\upsilon_s/f\right)} = \frac{\upsilon}{\left(\upsilon/f\right) - \left(\upsilon_s/f\right)}$$

$$f'' = \left(\frac{\upsilon}{\upsilon - \upsilon_s}\right) f \qquad \text{(source moving toward observer)} \quad 3.11$$

That is, the observed frequency is *increased* whenever the source is moving toward the observer. When the source moves away from a stationary observer, as is the case for observer B in Figure 3.7a, the observer measures a wavelength λ' that is greater than λ and hears a decreased frequency:

$$f'' = \left(\frac{\upsilon}{\upsilon + \upsilon_s}\right) f$$

We can express the general relationship for the observed frequency when a source is moving and an observer is at rest as Equation 3.11, with the same sign convention applied to υ_s as was applied to υ_o: a positive value is substituted for υ_s when the source moves toward the observer and a negative value is substituted when the source moves away from the observer. Finally, we find the following general relationship for the observed frequency:

$$f'' = \left(\frac{\upsilon + \upsilon_o}{\upsilon + \upsilon_s}\right) f$$

In this expression, the signs for the values substituted for υ_o and υ_s depend on the direction of the velocity. A positive value is used for motion of the observer or the source toward the other, and a negative sign for motion of one away from the other.

A convenient rule concerning signs for you to remember when working with all Doppler-effect problems are as follows:

The word toward is associated with an increase in observed frequency. The words away from are associated with a decrease in observed frequency.

Although the Doppler Effect is most typically experienced with sound waves, it is a phenomenon that is common to all waves. For example, the relative motion of source and observer produces a frequency shift in light waves. The Doppler Effect is used in police radar systems to measure the speeds of motor vehicles. Likewise, astronomers use the effect to determine the speeds of stars, galaxies, and other celestial objects relative to the Earth.

Shock Waves

Now consider what happens when the speed υ_s of a source *exceeds* the wave speed υ. This situation is depicted graphically in Figure 3.8a. The circles represent spherical wave fronts emitted by the source at various times during its motion. At t = 0, the source is at S_o, and at a later time t, the source is at S_n. At the time t, the wave front centered at S_o reaches a radius of υt.

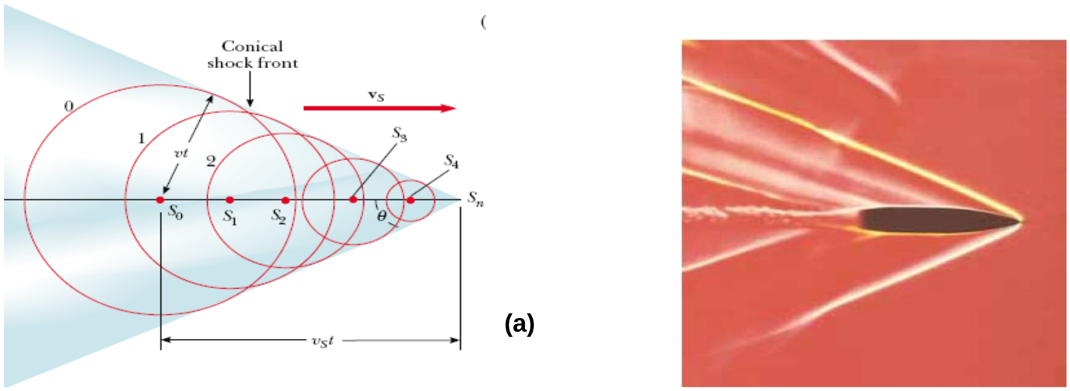


Figure 3.8 (a) A representation of a shock wave produced when a source moves from S_0 to S_n with a speed υ_s , which is greater than the wave speed υ in the medium. The envelope of the wave fronts forms a cone whose apex half-angle is given by $\sin\theta = \upsilon_s/\ \upsilon_s$. (b) A stroboscopic photograph of a bullet moving at supersonic speed through the hot air above a candle. Note the shock wave in the vicinity of the bullet.

In this same time interval, the source travels a distance $\upsilon_s t$ to S_n. At the instant the source is at S_n, waves are just beginning to be generated at this location, and hence the wave front has zero radius at this point. The tangent line drawn from S_n to the wave front centered on S_o is tangent to all other wave fronts generated at intermediate times. Thus, we see that the envelope of these wave fronts is a cone whose apex half-angle 0 (the "Mach angle") is given by

$$\sin\theta = \frac{\upsilon t}{\upsilon_s t} = \frac{\upsilon}{\upsilon_s}$$

Figure 3.9 The **V**-shaped bow wave of a boat is formed because the boat speed is greater than the speed of the water waves it generates. A bow wave is analogous to a shock wave formed by an airplane traveling faster than sound.

The ratio υ_s / υ is referred to as the *Mach number*, and the conical wave front produced when $\upsilon_s > \upsilon$ (supersonic speeds) is known as a *shock wave.* An interesting analogy to shock waves is the **V**-shaped wave fronts produced by a boat (the bow wave) when the boat's speed exceeds the speed of the surface-water waves (Fig. 3.9).

Jet airplanes traveling at supersonic speeds produce shock waves, which are responsible for the loud "sonic boom" one hears. The shock wave carries a great deal of energy concentrated on the surface of the cone, with correspondingly great pressure variations. Such shock waves are unpleasant to hear and can cause damage to buildings when aircraft fly supersonically at low altitudes. In fact, an airplane flying at supersonic speeds produces a double boom because two shock waves are formed, one from the nose of the plane and one from the tail. People near the path of the space shuttle as it glides toward its landing point often report hearing what sounds like two very closely spaced cracks of thunder.

Digital Recording

In digital recording, information is converted to binary code (ones and zeroes), similar to the dots and dashes of Morse code. First, the waveform of the sound is sampled, typically at the rate of 44 100 times per second. Figure 3.10 illustrates this process. The sampling frequency is much higher than the upper range of hearing, about 20 000 Hz, so all frequencies of sound are sampled at this rate. During each sampling, the pressure of the wave is measured and converted to a voltage. Thus, there are 44 100 numbers associated with each second of the sound being sampled, these measurements are then converted to binary numbers. In playback, these binary numbers are read and used to build the original waveform.

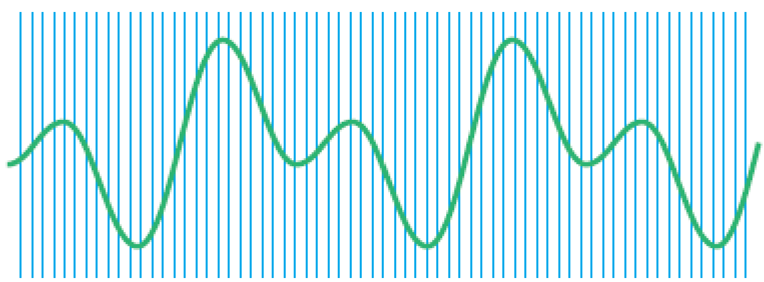


Figure 3.10 Sound is digitized by electronically sampling the sound waveform at periodic intervals. During each time interval between the blue lines, a number is recorded for the average voltage during the interval. The sampling rate shown here is much slower than the actual sampling rate of 44 100 samples per second.

Motion Picture Sound

Another interesting application of digital sound is the soundtrack in a motion picture. Early twentieth-century movies recorded sound on phonograph records, which were synchronized with the action on the screen. Beginning with early newsreel films, the variable area optical soundtrack process was introduced, in which sound was recorded on an optical track on the film. The width of the transparent portion of the track varied according to the sound wave that was recorded. A photocell detecting light passing through the track converted the varying light intensity to a sound wave. As with phonograph recording, there are a number of difficulties with this recording system. For example, dirt or fingerprints on the film cause fluctuations in intensity and loss of fidelity.

SUMMARY

1- sound waves are longitudinal and travel through *a compressible medium with a speed that depends on the elastic and inertial properties o*f that medium. the speed of sound in a liquid or gas having a bulk modulus b and density p is

$$u = \sqrt{\frac{B}{p}}$$

2- For sinusoidal sound waves, the variation in the position of an element of the medium is given by

$$s(x,t) = s_{max} \cos(kx - \omega t)$$

and the variation in pressure from the equilibrium value is

$$\Delta p = \Delta p_{max} \sin(kx - \omega t)$$

Where Δp_{max} is the **pressure amplitude** . the pressure wave is 90^{o} out of phase with the displacement wave. the relationship between s_{max} and Δp_{max} is given by

$$\Delta p_{max} = \rho v \omega_{smax}$$

3- The intensity of a sound wave, which is the power per unit area, is

$$I = \frac{p}{A} = \frac{\Delta p_{max}^2}{2\rho v}$$

4- The sound level of a sound wave , in decibels, is given by

$$\beta = 10 \ \ell og \ (I/I_0)$$

the constant I_0 is reference intensity, usually taken to be at the threshold of hearing $(1.00 \times 10^{-12} W/m^2)$, and $I$is the intensity of sound wave in watts per square meter.the change in frequency heard by an observer whenever there is relative motion between a source of sound waves and the observer is called the **doppler effect.** the observed frequency is

$$f = \left(\frac{v + v_0}{v - v_s}\right)$$