15 Sound Waves

Sound waves are the most common examples of *longitudinal waves*. The speed of sound waves in a particular medium depends on the properties of that medium and the temperature. As discussed in Chap. 14, sound waves travel through air when air elements vibrate to produce changes in density and pressure along the direction of the wave's motion.

Sound waves can be classified into three frequency ranges:

(1) **Audible waves**: *within the range* of human ear sensitivity and can be generated by a variety of ways such as human vocal cords, etc.

(2) **Infrasonic waves**: *below the audible range* but perhaps within the range of elephant-ear sensitivity.

(3) **Ultrasonic waves**: *above the audible range* and lie partly within the range of dog-ear sensitivity.

15.1 Speed of Sound Waves

The motion of a one-dimensional, longitudinal pulse through a long tube containing undisturbed gas is shown in Fig. 15.1. When the piston is suddenly pushed to the right, the compressed gas (or the change in pressure) travels as a pulse from one region to another toward the right along the pipe with a speed v.

The speed of sound waves depends on the compressibility and density of the medium. We can apply equation $v = \sqrt{\tau/\mu}$, which gives the speed of a transverse wave along a stretched string, to the speed of longitudinal sound waves in fluids or

H. A. Radi and J. O. Rasmussen, *Principles of Physics*,
Undergraduate Lecture Notes in Physics, DOI: 10.1007/978-3-642-23026-4_15,

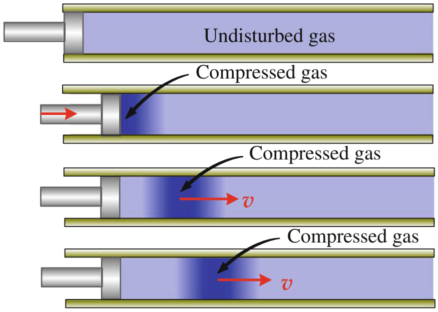


Fig. 15.1 Motion of a longitudinal sound pulse in a gas-filled tube

rods. In fluids we replace τ with the bulk modulus B, and in rods we replace τ with Young's modulus Y. In both, we replace μ with the density ρ. Then:

$$v = \sqrt{\frac{\text{elastic property}}{\text{medium property}}} = \begin{cases} \sqrt{B/\rho} & \text{(In fluids)} \\ \sqrt{Y/\rho} & \text{(In solid rods)} \end{cases} \tag{15.1}$$

Table 15.1 depicts the speed of sound in several different materials.

Table 15.1 The speed of sound in different materials

Medium	v(m/s)	Medium	v(m/s)
Gases		*Solids*	
Oxygen (0 °C)	317	Rubber	1,600
Air (0 °C)	331	Lead	1,960
Air (20 °C)	343	Lucite	2,680
Helium (0 °C)	972	Gold	3,240
Hydrogen (0 °C)	1,286	Brass	4,700
Liquids at (25 °C)		Copper	5,010
Kerosene	1,324	Pyrex	5,640
Mercury	1,450	Iron	5,950
Water	1,493	Granite	6,000
Sea water	1,533	Aluminum	6,420

For sound traveling through air, the relation between the speed and the temperature of the medium is given by the following relation:

$$v = (331\ \text{m/s})\sqrt{1 + \frac{T_C}{273\,°\text{C}}} \tag{15.2}$$

where 331 m/s is the speed of sound at 0 °C, and T_C is the temperature of the medium in degrees Celsius.

Example 15.1

Water at 20 °C has an approximate bulk modulus B of 2.1×10^9 N/m^2 and density ρ of 10^3 kg/m^3. (a) Find the speed of sound in water. (b) Dolphins use sound waves to locate distant food targets by estimating the time Δt between the moment of emitting a sound pulse toward the food and the moment of receiving its reflection, see Fig. 15.2. Calculate such a Δt when the food is 100 m away from the dolphin.

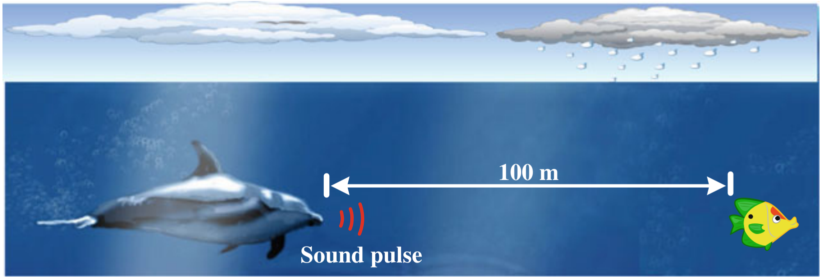


Fig. 15.2

Solution: (a) Using Eq. 15.1, we find that:

$$v = \sqrt{\frac{B}{\rho}} = \sqrt{\frac{2.1 \times 10^9\ \text{N/m}^2}{10^3\ \text{kg/m}^3}} = 1{,}449\ \text{m/s}$$

(b) The total distance traveled by the sound pulse from the dolphin to the food and back to the dolphin is $\Delta x = 2 \times 100\ \text{m} = 200\ \text{m}$. Thus:

$$\Delta t = \frac{\Delta x}{v} = \frac{200\ \text{m}}{1{,}449\ \text{m/s}} = 0.138\ \text{s}$$

15.2 Periodic Sound Waves

As a result of continuous push and pull of a piston in a gas tube, continuous regions of **compressions** and **expansions** (or called **rarefactions**) are generated, see Fig. 15.3a. The darker-colored areas in the figure represent regions where the gas is compressed, and thus the pressure and density are above their equilibrium values. The lighter-colored areas in the same figure represent regions of expansions, where the pressure and density are below their equilibrium values.

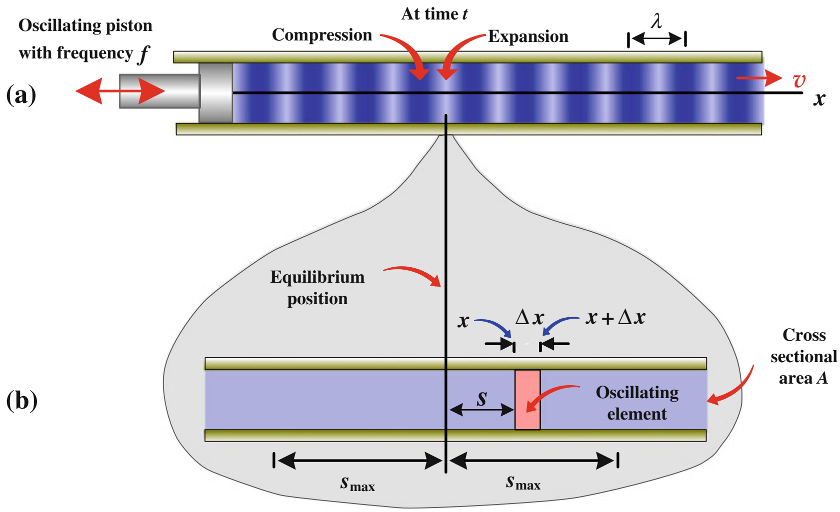


Fig. 15.3 (a) A longitudinal, sinusoidal sound wave is traveling through a long gas-filled tube with a speed v. The wave consists of a moving pattern of compressions and expansions. The wave is shown at an arbitrary time t. (b) An element of thickness Δx is displaced at a distance s to the right from its equilibrium position. Its maximum displacement, either right or left, is s_{max}, where $s_{max} \ll \lambda$

Consider a thin element of air of thickness Δx located at a position x along the tube. As the wave passes through the tube, this element oscillates back and forth in simple harmonic motion about its equilibrium position, see Fig. 15.3b. To describe this element from its equilibrium position, we can use either a sine function or a cosine function. In this book, we use a cosine function of the form:

$$s(x,t) = s_{max}\cos(kx - \omega t) \tag{15.3}$$

where s_{max} is the maximum displacement of the air element to either side of the equilibrium position, see Fig. 15.3b, and is called the **displacement amplitude** of the wave. For this longitudinal sound wave, the wave number k, wavelength λ, angular frequency ω, frequency f, speed v, and period T are all defined and interrelated exactly as for the transverse waves on strings in Sect. 14.3, except that λ is now along the direction of the wave.

For the sinusoidal longitudinal sound wave shown in Fig. 15.4a, the displacement $s(x, t)$ of Eq. 15.3 at $t = 0$ is displayed in Fig. 15.4b. Accordingly, the variation in the gas pressure ΔP about the equilibrium value must also be periodic, see Fig. 15.4c, and based on Eq. 15.3 it must be in the form:

$$\Delta P = \Delta P_{max} \sin(kx - \omega t) \tag{15.4}$$

where ΔP_{max} is the maximum change in pressure from the equilibrium value and is called the **pressure-variation amplitude**, as shown in Fig. 15.4c.

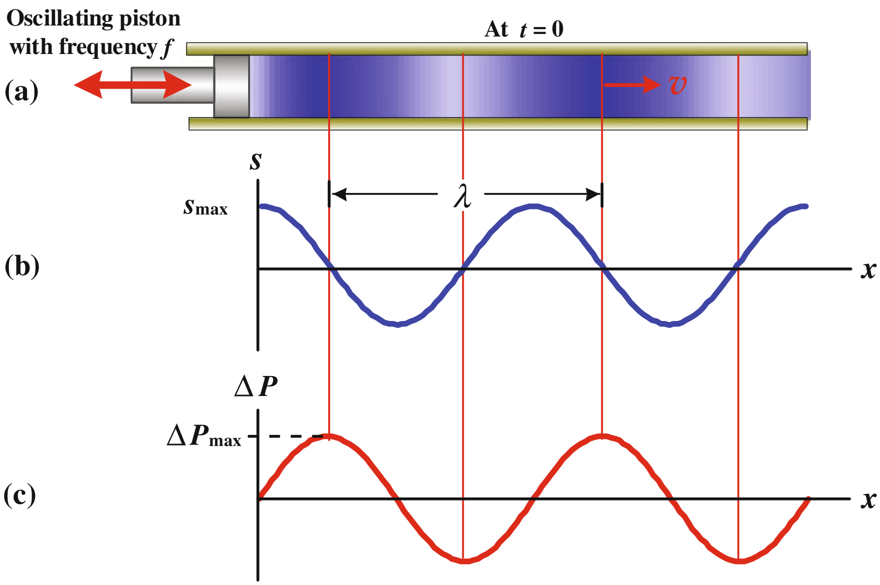


Fig. 15.4 (a) A snapshot at $t = 0$ of a longitudinal sinusoidal sound wave traveling through a long gas-filled tube with a speed v. The variation of both: (b) the displacement amplitude s and (c) the pressure difference ΔP as a function of position

* To find ΔP_{max} in Eq. 15.4, we start with the definition of bulk modulus B, given by Eq. 10.14, and express the change in pressure at any time t as follows:

$$\Delta P = -B\frac{\Delta V}{V} \tag{15.5}$$

The quantity V is the volume element, given by:

$$V = A\ \Delta x \tag{15.6}$$

The quantity ΔV is the change in volume that arises from the difference Δs between the displacements of the two faces of the element in Fig. 15.3. That is, $\Delta s = s(x + \Delta x, t) - s(x, t)$. Thus:

$$\Delta V = A \Delta s \tag{15.7}$$

Substituting Eqs. 15.6 and 15.7 into Eq. 15.5 we get:

$$\Delta P = -B\frac{\Delta s}{\Delta x}$$

Allowing for the differential limit, $\Delta x \to 0$ at any time t, we get:

$$\Delta P = -B\frac{\partial s}{\partial x} \tag{15.8}$$

The partial derivative $\partial s/\partial x$ indicates how s changes with x at any time t. Using Eq. 15.3, and treating t as a constant, we find:

$$\frac{\partial s}{\partial x} = \frac{\partial}{\partial x}[s_{\max}\cos(kx - \omega\, t)] = -ks_{\max}\sin(kx - \omega\, t) \tag{15.9}$$

Thus:
$$\boxed{\Delta P = B\, k\, s_{\max}\sin(kx - \omega\, t)} \tag{15.10}$$

Comparing the two Eqs. 15.4 and 15.10, we find that:

$$\Delta P_{\max} = B\, k\, s_{\max} \tag{15.11}$$

Using Eq. 15.1 allows us to eliminate the bulk modulus B and get the following relation:

$$\Delta P_{\max} = \rho v^2 k\, s_{\max} \tag{15.12}$$

Also, we can eliminate k by using $v = \omega/k$, Eq. 14.38, to find:

$$\boxed{\Delta P_{\max} = \rho v \omega\, s_{\max}} \tag{15.13}$$

Example 15.2

The human ear can tolerate the loudest sound which has a pressure-variation amplitude $\Delta P_{\max} = 28\,\text{Pa}$ (the *threshold of pain*), and can detect the faintest sound which has $\Delta P_{\max} = 2.8 \times 10^{-5}\,\text{Pa}$ (the *threshold of hearing*). For a sound of frequency 1,000 Hz traveling with a speed $v = 343\,\text{m/s}$ in air of density $\rho = 1.21\,\text{kg/m}^3$, calculate the displacement amplitude $s_{\max}$ for the loudest and the faintest sounds.

Solution: From Eq. 15.13, we can find the displacement amplitude $s_{\max}$ for the loudest sound wave as follows:

$$\begin{aligned} s_{\max} &= \frac{\Delta P_{\max}}{\rho v \omega} = \frac{\Delta P_{\max}}{\rho v (2\pi f)} \\ &= \frac{28\,\text{Pa}}{(1.21\,\text{kg/m}^3)(343\,\text{m/s})(2\pi \times 1{,}000\,\text{Hz})} \\ &= 1.1 \times 10^{-5}\,\text{m} \simeq 11\,\mu\text{m} \qquad \text{(Loudest; threshold of pain)} \end{aligned}$$

The displacement amplitude for the loudest sound that can be tolerated by the human ear is about one-tenth the thickness of this page.

Also, from Eq. 15.13, we find the following for the faintest sound wave:

$$\begin{aligned} s_{\max} &= \frac{\Delta P_{\max}}{\rho v \omega} = \frac{\Delta P_{\max}}{\rho v (2\pi f)} \\ &= \frac{2.8 \times 10^{-5}\,\text{Pa}}{(1.21\,\text{kg/m}^3)(343\,\text{m/s})(2\pi \times 1{,}000\,\text{Hz})} \\ &= 1.1 \times 10^{-11}\,\text{m} \qquad \text{(Faintest; threshold of hearing)} \end{aligned}$$

This is a remarkably small number! This displacement amplitude is about one-tenth the size of a typical atom (diameter $\approx 10^{-10}\,\text{m}$). Indeed, the ear is an extremely sensitive detector for sound waves. On the other hand, the ear can detect a sound-wave pulse whose total energy is about the same as the total energy required to remove an outer electron from a single atom.

15.3 Energy, Power, and Intensity of Sound Waves

In Sect. 14.5, we showed that waves transport kinetic and potential energy when they propagate through a medium. The same concept applies to sound waves. Consider an element of air of mass Δm and length Δx in front of a piston oscillating with a frequency f in *one dimension*, as shown in Fig. 15.5.

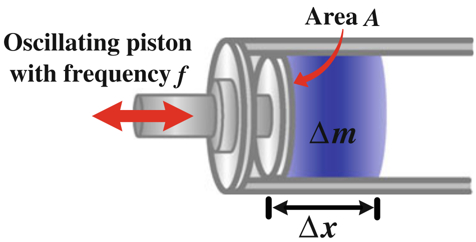


Fig. 15.5 A piston oscillates with frequency f in an air-filled tube. The piston transfers energy to an adjacent air element that has a mass Δm and length Δx, causing it to oscillate with an amplitude s_{max}

The piston transfers energy to this element and hence the energy is propagated away through the tube by the sound wave. As the sound wave propagates away, the displacement of this element with respect to its equilibrium position will be given by Eq. 15.3, i.e.:

$$s(x, t) = s_{max}\cos(kx - \omega t) \tag{15.14}$$

The speed of this element can be found by taking the partial time derivative of s as follows:

$$v(x, t) = \frac{\partial}{\partial t}s(x, t) = \frac{\partial}{\partial t}[s_{max}\cos(kx - \omega t)] = +\omega s_{max}\sin(kx - \omega t) \tag{15.15}$$

* The kinetic energy ΔK associated with the air element of mass $\Delta m = \rho A \Delta x$, where ρ is the air density, will be given by:

$$\Delta K = \tfrac{1}{2}\Delta m\, v^2 = \tfrac{1}{2}\rho A \Delta x\, \omega^2 s_{max}^2 \sin^2(kx - \omega t) \tag{15.16}$$

When we allow Δx to approach zero, this relation becomes a differential relationship and will take the following form:

$$dK = \tfrac{1}{2}\rho A\, \omega^2 s_{max}^2 \sin^2(kx - \omega t)dx \tag{15.17}$$

At a given instant, let us integrate this expression over all the elements in a complete sound wavelength, which will give us the total kinetic energy K_λ in one wavelength:

$$K_\lambda = \int dK = \tfrac{1}{2}\rho A\, \omega^2 s_{max}^2 \int_0^\lambda \sin^2(kx - \omega t)dx \tag{15.18}$$

If we take a snapshot at time $t = 0$, then we can evaluate the above integral by performing the following steps:

$$\begin{aligned}
\int_{x=0}^{x=\lambda} \sin^2(k\,x)dx &= \tfrac{1}{k} \int_{z=0}^{z=k\lambda=2\pi} \sin^2 z\, dz \\
&= \tfrac{1}{k} \int_0^{2\pi} \tfrac{1}{2}[1 - \cos 2z]dz = \tfrac{1}{2k} \left[z - \tfrac{1}{2} \sin 2z\right]_0^{2\pi} \\
&= \tfrac{1}{2k} \left[(2\pi - \tfrac{1}{2} \sin 4\pi) - 0\right] = \frac{\lambda}{4\pi} 2\pi = \frac{\lambda}{2}
\end{aligned} \tag{15.19}$$

where we have used $z = k\,x$, $\sin^2 z = (1 - \cos 2z)/2$ and $k = 2\pi/\lambda$ to arrive to the above result. Of course, we get the same answer if we perform the above steps at any other time different from zero. When we substitute the above result into Eq. 15.18, we get:

$$K_\lambda = \tfrac{1}{4} \rho A \omega^2 s_{max}^2 \lambda \tag{15.20}$$

A similar analysis to the total potential energy U_λ in one wavelength will give exactly the same result. Thus:

$$U_\lambda = \tfrac{1}{4} \rho\, A\, \omega^2 s_{max}^2\, \lambda \tag{15.21}$$

The total energy in one wavelength of the sound wave (E_λ) is the sum of the obtained kinetic and potential energies. Thus:

$$E_\lambda = K_\lambda + U_\lambda = \tfrac{1}{2} \rho\, A\, \omega^2 s_{max}^2\, \lambda \tag{15.22}$$

As the sinusoidal sound wave travels along the tube, this amount of energy (E_λ) will cross any given point in the tube during a time interval equal to one period of the oscillation. Thus, the rate of energy (power) transferred by the sound wave through the air is:

$$\mathcal{P} = \frac{\Delta E}{\Delta t} = \frac{E_\lambda}{T}$$

where we used the symbol $\mathcal{P}$ for the power in this section to avoid confusion with the symbol P for pressure. Therefore:

$$\mathcal{P} = \tfrac{1}{2} \rho\, A\, \omega^2 s_{max}^2 \frac{\lambda}{T}$$

Using the relation $v = \lambda/T$, given by Eq. 14.38, we finally reach the following power form:

$$\mathcal{P} = \tfrac{1}{2}\rho A\, v\, \omega^2 s_{\max}^2 \tag{15.23}$$

Thus, the power of a periodic sound wave is proportional to the square of the angular frequency and the square of the displacement amplitude (as in the case of periodic string waves).

For a wave crossing a particular surface, we define its **intensity** I as the power per unit area, or the rate of energy transfer (power $\mathcal{P}$) of the wave through a unit area perpendicular to the direction of the propagation of the wave, i.e. $I = \mathcal{P}/A$. Therefore:

$$I = \frac{\mathcal{P}}{A} \quad \Rightarrow \quad I = \tfrac{1}{2}\rho v \omega^2 s_{\max}^2 \tag{15.24}$$

By using Eq. 15.13, $\Delta P_{\max} = \rho v \omega\, s_{\max}$, the last relation can be written in terms of the pressure amplitude $\Delta P_{\max}$ as:

$$I = \frac{\Delta P_{\max}^2}{2\rho v} \tag{15.25}$$

On the other hand, we can express the pressure amplitude $\Delta P_{\max}$ in terms of the measurable quantities ρ, v, and I as follows:

$$\Delta P_{\max} = \sqrt{2\rho v I} \tag{15.26}$$

In three dimensions, we consider a point source S emitting sound waves uniformly in all directions as **spherical waves**, see Fig. 15.6. When we construct an imaginary sphere of radius r centered at the sound source, the power emitted by this source must be distributed uniformly over this spherical surface, which has an area $4\pi r^2$.

From the definition of the intensity, $I = \mathcal{P}/A$, given by Eq. 15.24, the intensity I at any point on the spherical surface will be given by:

$$I = \frac{\mathcal{P}}{4\pi r^2} \tag{15.27}$$

This equation is known as the **inverse square law** and tells us that the intensity of sound waves emitted from an isotropic point source decreases with the square of the distance r from the source, i.e. the intensity is inversely proportional to the square of the distance r.

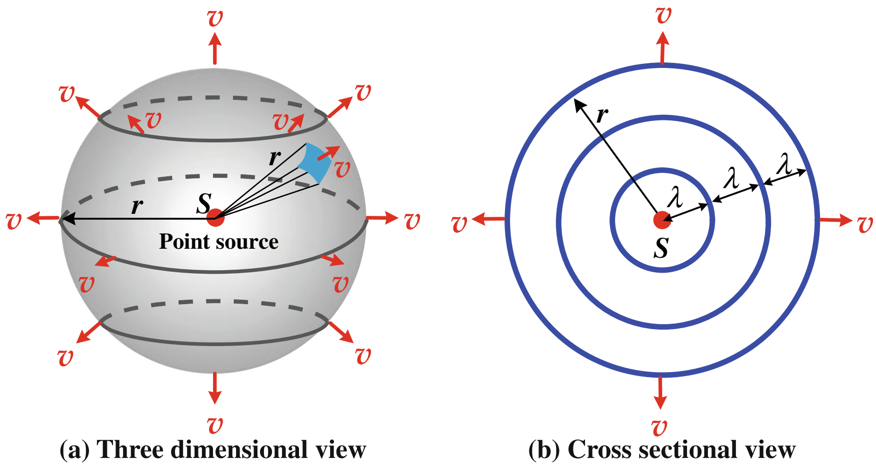


Fig. 15.6 (a) A point source S emitting sound waves uniformly in all directions with the waves passing through an imaginary sphere of radius r. (b) A cross-sectional view showing the wavelength λ between consecutive crests of the sound waves

Example 15.3

At a frequency of 1,000 Hz, the human ear can detect the loudest and faintest sounds with intensities of about $1.0\ \text{W/m}^2$ and $1.0 \times 10^{-12}\ \text{W/m}^2$, respectively. For sound waves traveling with a speed of $v = 343\ \text{m/s}$, find the pressure amplitude ΔP_{max} for the faintest and the loudest sound waves, assuming the air's density is $\rho = 1.21\ \text{kg/m}^3$.

Solution: From Eq. 15.26, we can find the pressure amplitude ΔP_{max} for the loudest sound waves as follows:

$$\Delta P_{max} = \sqrt{2\rho v I} = \sqrt{2(1.21\ \text{kg/m}^3)(343\ \text{m/s})(1\ \text{W/m}^2)}$$
$$= 28.8\ \text{N/m}^2 = 28.8\ \text{Pa} \qquad \text{(Loudest; threshold of pain)}$$

Also, from Eq. 15.26, we find the pressure amplitude ΔP_{max} for the faintest sound waves as follows:

$$\Delta P_{max} = \sqrt{2\rho v I} = \sqrt{2(1.21\ \text{kg/m}^3)(343\ \text{m/s})(1 \times 10^{-12}\ \text{W/m}^2)}$$
$$= 2.88 \times 10^{-5}\ \text{N/m}^2$$
$$= 2.88 \times 10^{-5}\ \text{Pa} \qquad \text{(Faintest; threshold of hearing)}$$

Example 15.4

A point source emits sound waves with a power of 50 W. (a) Find the intensity of the sound waves 2 m away from the source. (b) Find the distance at which the intensity of the sound is 10^{-6} W/m^2.

Solution: (a) The point source S shown in Fig. 15.7. emits energy in the form of spherical sound waves centered at the source. Thus, when using Eq. 15.27 we find that:

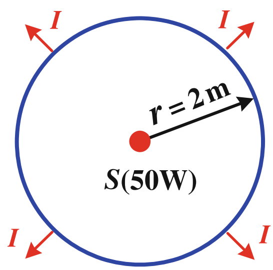
$$I = \frac{\mathcal{P}}{4\pi r^2} = \frac{50\,\text{W}}{4\pi\,(2\,\text{m})^2} = 0.995\,\text{W/m}^2$$

which is close to the intensity of the threshold of pain, see Example 15.3.

(b) Expressing r in Eq. 15.27 in terms of $\mathcal{P}$ and I, we obtain:

$$r = \sqrt{\frac{\mathcal{P}}{4\pi I}} = \sqrt{\frac{50\,\text{W}}{4\pi\,(10^{-6}\,\text{W/m}^2)}} = 1{,}995\,\text{m} \simeq 2\,\text{km}$$

Fig. 15.7



15.4 The Decibel Scale

According to Example 15.2, the displacement amplitude s_{max} for the human ear ranges from about 10^{-5} m for the loudest tolerable sound to about 10^{-11} m for faintest detectable sound, a ratio of 10^6. From Eq. 15.24, we see that the intensity I varies as the square of s_{max}, so the ratio of intensities at these two limits of the human audibility is 10^{12}. This goes to show that the human ear can accommodate an enormous range of intensities.

We can better represent large ranges of I by using logarithms. Now, consider the following logarithmic relation of the base 10:

$$y = \log x$$

It is usual to suppress explicit references to the base 10 (such as $\log_{10} x$) and instead write $\log x$. If x in this equation is multiplied by 10, then y increases by 1, i.e.:

$$y' = \log 10\,x = \log 10 + \log x = 1 + \log x = 1 + y$$

Similarly, if we multiply x by 10^{12}, y increases only by 12.

Consequently, instead of speaking of intensity I of a sound wave, it is much more convenient to speak of its **sound level** β (Greek beta), defined by:

$$\beta = (10\,\text{dB})\log\frac{I}{I_\circ} \tag{15.28}$$

Here dB is the abbreviation for **decibel**, the unit of sound level, a name chosen to recognize the work of Alexander Graham Bell. The constant $I_\circ$ in Eq. 15.28 is the *reference intensity*, taken to be near the threshold of hearing, i.e. $I_\circ = 1.0 \times 10^{-12}\,\text{W/m}^2$. The intensity I in the same equation is measured in watts per square meter.

On this scale, the threshold of hearing ($I = 1.0 \times 10^{-12}\,\text{W/m}^2$) corresponds to a sound level of:

$$\begin{aligned}
\beta &= (10\,\text{dB})\log\frac{I}{I_\circ} = (10\,\text{dB})\log\frac{1.0 \times 10^{-12}\,\text{W/m}^2}{1.0 \times 10^{-12}\,\text{W/m}^2} \\
&= (10\,\text{dB})\log 1 \\
&= 0\,\text{dB} \qquad \text{(Threshold of hearing)}
\end{aligned}$$

So our threshold of hearing level corresponds to zero decibel. Also, the threshold of pain ($I = 1.0\,\text{W/m}^2$) corresponds to a sound level of:

$$\begin{aligned}
\beta &= (10\,\text{dB})\log\frac{I}{I_\circ} = (10\,\text{dB})\log\frac{1.0\,\text{W/m}^2}{1.0 \times 10^{-12}\,\text{W/m}^2} \\
&= (10\,\text{dB})\log 10^{12} = (10\,\text{dB}) \times 12 \\
&= 120\,\text{dB} \qquad \text{(Threshold of pain)}
\end{aligned}$$

In general, $\beta = 10 \times n\,\text{dB}$ corresponds to an intensity that is 10^n times the reference intensity, i.e. corresponds to $I = 10^n\, I_\circ = 10^{n-12}\,\text{W/m}^2$. Table 15.2 lists some sound-level values for some environments.

Table 15.2 Approximate sound levels (dB) for several sources

Source of sound	β (dB)	I (W/m^2)
Threshold of hearing in human auditory system	0	10^{-12}
Quiet rustling leaves, calm human breathing	10	10^{-11}
Very calm room	20	10^{-10}
Whispering	30	10^{-9}
Mosquito buzzing	40	10^{-8}
Normal talking (1 m distant)	50	10^{-7}
TV set—typical home level, 1 m distant	60	10^{-6}
Vacuum cleaner	70	10^{-5}
Traffic noise for a main road, 10 m distant	80	10^{-4}
Machine gun	90	10^{-3}
Jack hammer, 1 m distant	100	10^{-2}
Jet engine, 100 m distant	110	10^{-1}
Threshold of pain in human auditory system	120	1

Example 15.5

(a) Find the sound level in decibels for a sound wave of intensity 1.59×10^{-5} W/m^2.
(b) Find the sound intensity of a source rated at a 35 dB sound level.

Solution: (a) From Eq. 15.28, we find that:

$$\begin{aligned}\beta &= (10\,\text{dB})\log\frac{I}{I_\circ}\\ &= (10\,\text{dB})\log\frac{1.59\times10^{-5}\ \text{W/m}^2}{1.0\times10^{-12}\ \text{W/m}^2}\\ &= (10\,\text{dB})\log 1.59\times10^{7}\\ &= 72\,\text{dB}\end{aligned}$$

(b) Substituting in Eq. 15.28 with $\beta = 35$ dB, dividing both sides by 10, and taking the antilog of both sides, we can find I by performing the following steps:

$$\beta = (10\,\text{dB})\log\frac{I}{I_\circ}$$

$$35\,\text{dB} = (10\,\text{dB})\log\frac{I}{I_\circ}$$

$$3.5 = \log\frac{I}{I_\circ}$$

$$\text{antilog}(3.5) = \text{antilog}\left(\log\frac{I}{I_\circ}\right)$$

$$10^{3.5} = \frac{I}{I_\circ}$$

$$I = 10^{3.5} \times I_\circ$$

Thus, with the reference intensity $I_\circ = 1.0 \times 10^{-12}$ W/m^2, we find that:

$$I = 10^{3.5} \times 1.0 \times 10^{-12}\ \text{W/m}^2$$
$$= 3.16 \times 10^{-9}\ \text{W/m}^2$$

Example 15.6

Two identical point sources, S_1 and S_2, have the same power and driven by one oscillator. The positions of the two sources relative to an observer is depicted in Fig. 15.8. The sound intensity at the observer's location from S_2 is found to be $I_2 = 3.0 \times 10^{-6}$ W/m^2. (a) Find the total intensity of the combined sound waves that is received by the observer from the two sources. (b) Find the difference in sound level when the two sources operate simultaneously and when only the second source operates.

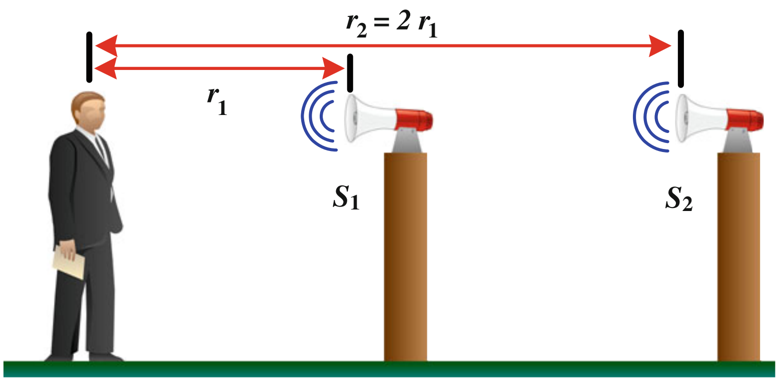


Fig. 15.8

Solution: (a) If I_1 and I_2 are the intensities received by the observer from the point sources S_1 and S_2, respectively, then their ratio will be:

$$\frac{I_1}{I_2} = \left[\frac{\mathcal{P}}{4\pi r_1^2}\right] \Big/ \left[\frac{\mathcal{P}}{4\pi r_2^2}\right] = \frac{r_2^2}{r_1^2} = \frac{(2r_1)^2}{r_1^2} = 4 \quad \Rightarrow \quad I_1 = 4\, I_2$$

This means that the intensity I_1 from S_1 is four times the intensity I_2 from S_2. Thus, the total intensity becomes:

$$I_{\text{tot}} = I_1 + I_2 = 4I_2 + I_2 = 5I_2 = 5(3.0 \times 10^{-6}\,\text{W/m}^2) = 1.5 \times 10^{-5}\,\text{W/m}^2$$

(b) If β_2 is the sound level when only the second source operates and β_{tot} is the sound level when both sources operate together, then:

$$\beta_2 = (10\,\text{dB})\log\frac{I_2}{I_\circ} \quad \text{and} \quad \beta_{\text{tot}} = (10\,\text{dB})\log\frac{I_{\text{tot}}}{I_\circ} = (10\,\text{dB})\log\frac{5I_2}{I_\circ}$$

Then: $\Delta\beta = \beta_{\text{tot}} - \beta_2 = (10\,\text{dB})\log\frac{5I_2}{I_\circ} - (10\,\text{dB})\log\frac{I_2}{I_\circ} = (10\,\text{dB})\log\frac{5I_2}{I_2} = 7\,\text{dB}$

15.5 Hearing Response to Intensity and Frequency

The threshold of hearing in the human auditory system depends on the intensity of the sound (or the sound level in dB) and its frequency. We learned in the previous section that the threshold of hearing at 1,000 Hz requires an intensity of $10^{-12}\,\text{W/m}^2$ and corresponds to a sound level of 0 dB. Conversely, at 100 Hz sound must have an intensity level of about 30 dB to be barely audible.

Figure 15.9 maps the sound regions that humans can respond to for a range of sound levels β (or intensity I) and sound frequencies f. Tentatively, the figure also overlays some sample sources. The lower blue curve of the white area shows the dependence of the threshold of hearing β on the frequency. This curve indicates that humans are sensitive to frequencies ranging from about 20 to 20,000 Hz. The upper bound to the white area is the threshold of pain, and does not depend much on frequency. The lower left region of the white area shows that our ears are particularly insensitive to low frequencies and low intensity levels.

15.6 The Doppler Effect

We move to a different phenomenon that applies to all kinds of waves, not only sound waves. You most probably have noticed that when a car *moves toward* you with a high speed and horns, you hear the horn with a *higher frequency* than when the car is at rest. Contrary wise, when the car *moves away*, you hear the horn with a *lower frequency*. This phenomenon is called the *Doppler effect*.

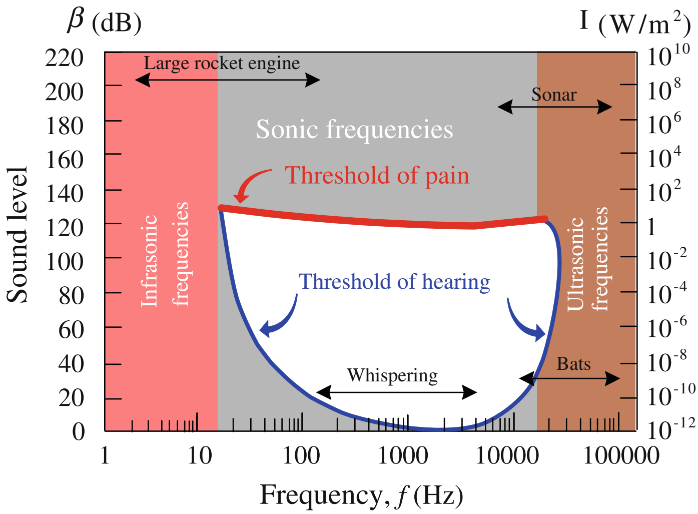


Fig. 15.9 The dependence of the sound level β on the frequency f for normal human hearing (the *white area*) and various sources

Let us now examine this phenomenon quantitatively. First, we consider a point source that emits sound waves radially in all directions in a uniform medium. It is useful to represent the emitted waves using a series of concentric spheres with the source located at their centers. Each sphere represents a wave **crest**, and it moves away from the source with the speed of sound. We call such a sphere of constant phase a **wave front**. Therefore, the distance between any two successive wave fronts equals the wavelength λ of the sound wave and has a frequency f and speed v. In our analyses that follow, we restrict ourselves to the motion of a sound source S and observer O along the line joining them.

Moving Observer and Stationary Source

Figure 15.10 shows an observer O (represented by an ear) moving with a speed v_o toward a stationary source S that emits spherical sound waves of speed $v (v > v_o)$, wavelength λ, and frequency f. The frequency detected by the observer O is the rate at which O intercepts successive wave fronts (or wavelengths).

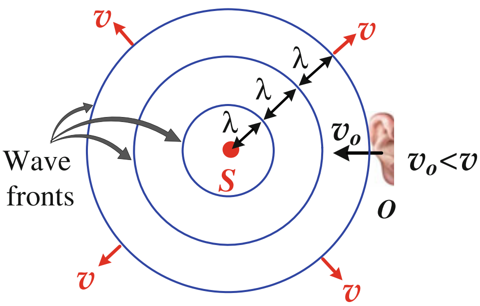


Fig. 15.10 A stationary sound source S emits spherical wave fronts (each is one wavelength λ from the next) with a speed v. An observer O (represented by an ear) moves with a speed v_O towards the source

If the observer O were stationary, the interception rate of wave fronts would be f. But if the observer O is moving toward the source S, then the interception rate f' is greater than f.

When the observer O moves with a speed v_O *toward* a stationary source S, the speed of the wave fronts *relative* to O is not v, but $v' = v + v_O$, while the wavelength λ is unchanged. When we apply the general relation $v = \lambda f$ to this case, i.e. $v' = \lambda f'$, we find that the frequency f heard by the observer has the following relation:

$$f' = \frac{v'}{\lambda} = \frac{v + v_O}{\lambda} = \frac{v + v_O}{v/f} \tag{15.29}$$

This relation can be rewritten as:

$$\boxed{f' = \left(1 + \frac{v_O}{v}\right) f} \qquad (O \text{ is moving towards } S) \tag{15.30}$$

When the observer O moves with a speed v_O *away* from a stationary source S, the speed of the wave fronts *relative* to O is not v, but $v' = v - v_O$, while the wavelength λ is unchanged. Steps similar to those above lead to the frequency heard by the observer as:

$$\boxed{f' = \left(1 - \frac{v_O}{v}\right) f} \qquad (O \text{ is moving away from } S) \tag{15.31}$$

Generally, for an observer O moving with a speed v_O relative to a stationary source S, a *positive sign* is used when O moves *toward* S and a *negative sign* is used when O moves *away from* S. Thus:

$$\boxed{f' = \left(1 \pm \frac{v_O}{v}\right) f} \quad \left\{ \begin{array}{l} + \text{ when } O \text{ is moving towards } S \\ - \text{ when } O \text{ is moving away from } S \end{array} \right\} \tag{15.32}$$

Moving Source and Stationary Observer

Figure 15.11 shows a source S moving with a speed v_S toward an observer O while emitting spherical sound waves of speed v, wavelength λ, and frequency f. The figure indicates that the wave fronts detected by the observer O are closer together than they would be if the source S was not moving. Thus, the wavelength λ' measured by the observer O is shorter than the wavelength λ of the source S.

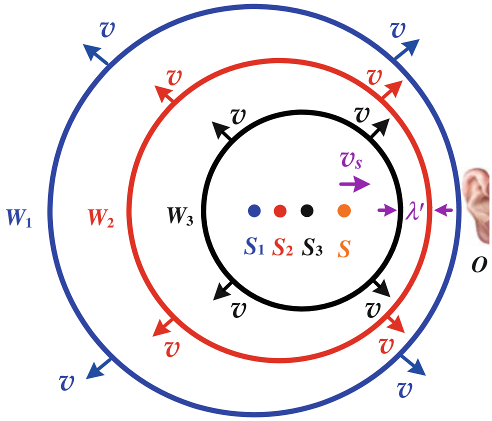


Fig. 15.11 A moving sound source S emits spherical wave fronts with a speed v and wavelength λ, while moving with a speed $v_S < v$ towards a stationary observer O. The wave front W_1 that arises from the source when it was at point S_1..., etc is shown

During a period T, the source S emits a wave front that moves a distance λ with a speed v, while the source itself moves a distance $v_S\, T$ before emitting the next wave front. Thus, the wavelength λ is shortened by $v_S\, T$. Then, the observed wavelength λ' will be:

$$\lambda' = \lambda - v_S\, T = \frac{v}{f} - \frac{v_S}{f} \tag{15.33}$$

Using $v = \lambda\, f$ in this case, i.e. $v = \lambda' f'$, we find that the frequency f' that is heard by the observer O is related to f as follows:

$$\frac{v}{f'} = \frac{v}{f} - \frac{v_S}{f} = \frac{1}{f}\,(v - v_S) \tag{15.34}$$

This relation can be rewritten as:

$$f' = \left(\frac{1}{1 - v_S/v}\right) f \qquad (S \text{ is moving towards } O) \tag{15.35}$$

When the source S is moving with a speed v_S *away* from a stationary observer O, the wavelength λ is increased by $v_S\, T$. Therefore, the observed wavelength λ' will be given by:

$$\lambda' = \lambda + v_S\, T = \frac{v}{f} + \frac{v_S}{f} \tag{15.36}$$

With similar steps to those of Eqs. 15.33–15.35, we get:

$$f' = \left(\frac{1}{1 + v_S/v}\right) f \qquad (S \text{ is moving away from } O) \tag{15.37}$$

Generally, for a source S moving with a speed v_S relative to a stationary observer O, a *negative sign* is used when S moves *toward* O and a *positive sign* is used when S moves *away from* O. Thus:

$$f' = \left(\frac{1}{1 \mp v_S/v}\right) f \qquad \left\{ \begin{array}{l} - \text{ when } S \text{ is moving towards } O \\ + \text{ when S is moving away from } O \end{array} \right\} \tag{15.38}$$

One can find a generalized relation that includes all collinear motion of a source with speed v_S and an observer with speed v_o to be:

$$f' = \left(\frac{1 \pm v_o/v}{1 \mp v_S/v}\right) f \qquad (\text{General Doppler effect}) \tag{15.39}$$

The upper signs in the numerator and denominator ($+v_o/v$ and $-v_S/v$) refer to motion of one *toward* the other, while the lower signs ($-v_o/v$ and $+v_S/v$) refer to motion of one *away from* the other.

Spotlight

You can determine the signs in Eq. 15.39 by remembering that: the word *toward* is associated with an *increase* in observed frequency, while the word *away from* is associated with a *decrease* in observed frequency.

Example 15.7

A car moves on a straight road with a speed of 20 m/s. Its siren emits a sound with a frequency of 500 Hz. Find the frequencies heard by a stationary person on the sidewalk when the car approaches him (Fig. 15.12a) and then when it recedes from him (Fig. 15.12b). Assume collinear motion of the source and observer.

Solution: When the car *approaches* the observer, we use the upper signs in the numerator and denominator of the general formula of Doppler effect given by Eq. 15.39. In this formula, we take $v_o = 0$ for the stationary observer, $v_S = 20$ m/s for the speed of the car, $v = 343$ m/s for the speed of sound in air, and $f = 500$ Hz for the siren frequency. Thus, the frequency f' heard by the observer will be:

$$f' = \left(\frac{1 + v_O/v}{1 - v_S/v}\right) f = \left(\frac{1 + 0}{1 - (20\,\text{m/s})/(343\,\text{m/s})}\right) \times 500\,\text{Hz}$$
$$= 531\,\text{Hz}$$

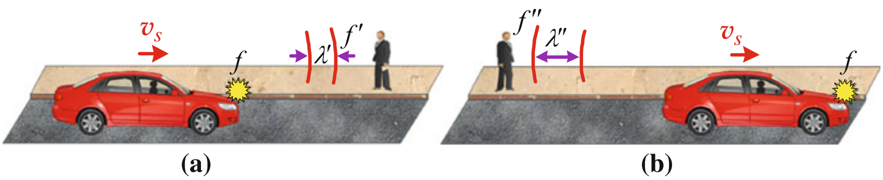


Fig. 15.12

When the car recedes from the observer, we use the lower signs in the numerator and denominator of Eq. 15.39. Thus:

$$f'' = \left(\frac{1 - v_O/v}{1 + v_S/v}\right) f = \left(\frac{1 - 0}{1 + (20\,\text{m/s})/(343\,\text{m/s})}\right) \times 500\,\text{Hz}$$
$$= 473\,\text{Hz}$$

The change in frequency detected by the stationary observer is:

$$\Delta f = f' - f'' = 531\,\text{Hz} - 473\,\text{Hz} = 58\,\text{Hz}$$

This is about 8.6% of the actual frequency emitted from the siren.

Example 15.8

Submarines use sound propagation under water to navigate, communicate, or detect other objects; this technique is known as sonar (**SO**und **NA**vigation and **R**anging). A submarine 1 (sub 1) moves with a speed $v_1 = 10$ m/s and emits a sonar wave of frequency $f = 1{,}500$ Hz. A second submarine 2 (sub 2) moves directly towards the first one with a speed $v_2 = 8$ m/s. See Fig. 15.13, and take the speed of sound in water to be 1,533 m/s. (a) Find the frequency detected by an observer in sub 2. (b) Find the reflected frequency detected by an observer in sub 1. (c) Find the frequency detected by an observer in sub 2 when the two submarines miss each other and pass.

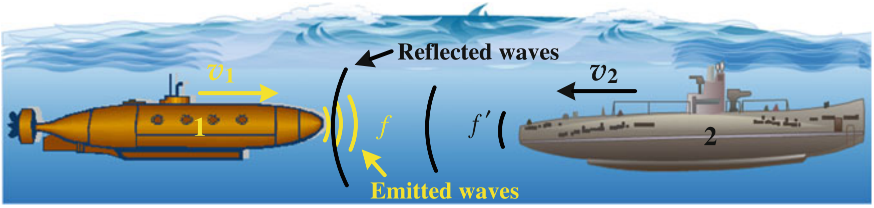


Fig. 15.13

Solution: (a) When the submarines move *toward* each other, we use the *upper signs* in the numerator and denominator of Eq. 15.39. Then we take:

$$\begin{aligned} v_o &= v_2 = 8\,\text{m/s for observer (sub 2)} \\ v_S &= v_1 = 10\,\text{m/s for the speed of the source (sub 1)} \\ v &= 1{,}533\,\text{m/s for the speed of sound in water,} \\ f &= 1{,}500\,\text{Hz for the emitted frequency from the source (sub 1)} \end{aligned}$$

Thus, the frequency f' received by an observer in sub 2 will be:

$$\begin{aligned} f' &= \left(\frac{1 + v_o/v}{1 - v_S/v}\right) f \\ &= \left(\frac{1 + (8\,\text{m/s})/(1{,}533\,\text{m/s})}{1 - (10\,\text{m/s})/(1{,}533\,\text{m/s})}\right) \times 1{,}500\,\text{Hz} = 1{,}518\,\text{Hz} \end{aligned}$$

(b) The frequency calculated in part (a) will be reflected from sub 2 (which acts as a moving source) and then be detected by sub 1 (the moving observer). In this case we take:

$$\begin{aligned} v_o &= v_1 = 10\,\text{m/s for observer (sub 1)} \\ v_S &= v_2 = 8\,\text{m/s for the speed of the source (sub 2)} \\ v &= 1{,}533\,\text{m/s for the speed of sound in water,} \\ f' &= 1{,}518\,\text{Hz for the emitted frequency from the source (sub 2)} \end{aligned}$$

Thus, the frequency f'' received by an observer in sub 1 will be:

$$f'' = \left(\frac{1 + v_o/v}{1 - v_S/v}\right) f' = \left(\frac{1 + (10\,\text{m/s})/(1{,}533\,\text{m/s})}{1 - (8\,\text{m/s})/(1{,}533\,\text{m/s})}\right) \times 1{,}518\,\text{Hz} = 1{,}536\,\text{Hz}$$

(c) When the submarines move *away from* each other, we use the *lower signs* in the numerator and denominator of Eq. 15.39. All the parameters used in this equation will be identical to the one in part (a). Thus, the frequency f' received by an observer in sub 2 will be:

$$f' = \left(\frac{1 - v_o/v}{1 + v_S/v}\right) f = \left(\frac{1 - (8\,\text{m/s})/(1{,}533\,\text{m/s})}{1 + (10\,\text{m/s})/(1{,}533\,\text{m/s})}\right) \times 1{,}500\,\text{Hz} = 1{,}483\,\text{Hz}$$

15.7 Supersonic Speeds and Shock Waves

When a source moves toward a stationary object with a speed equal to the speed of sound, i.e. when $v_o = 0$ and $v_S = v$, Eq. 15.39 predicts that $f' = (1+0)/(1-1)f = \infty$, which means that f' will be infinitely great. This also means that the source is moving as fast as its generated spherical wave fronts, as suggested by Fig. 15.14. Then the gas molecules pile up at what is called the shock front.

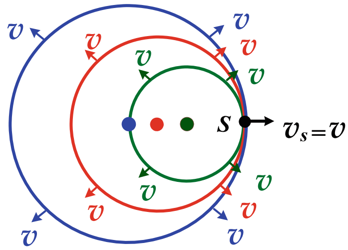


Fig. 15.14 A source of sound that moves at the speed of sound

Now what happens when v_S exceeds v? For such supersonic speeds, Eq. 15.39 predicts a negative f' and hence no longer applies. In such case, the speed of the source is faster than the speed of the wave fronts as shown in Fig. 15.15 for various source positions.

At $t = 0$, the source is at point S_0 and at a later time t, the source is at point S_t, see Fig. 15.15. At that instant, the radius of the wave front W_0 which originated when the source was at point S_0 is vt. In the same time interval, the source travels a greater distance $v_S\ t$ to the point S_t. The radius of any wave front is v multiplied by the elapsed time since the source emitted the wave front. The tangent line drawn from point S_t to the wave front centered at point S_0 is the tangent of all other wave fronts generated at intermediate times. The envelope to all of these wave fronts is a cone called the **Mach cone**. This conical wave front is known as a **shock wave** because it is the accumulation of all wave fronts and hence is causing an abrupt increase followed by a decrease of air pressure and then back to normal. The loud sound produced by this shock wave is known as a **sonic boom**.

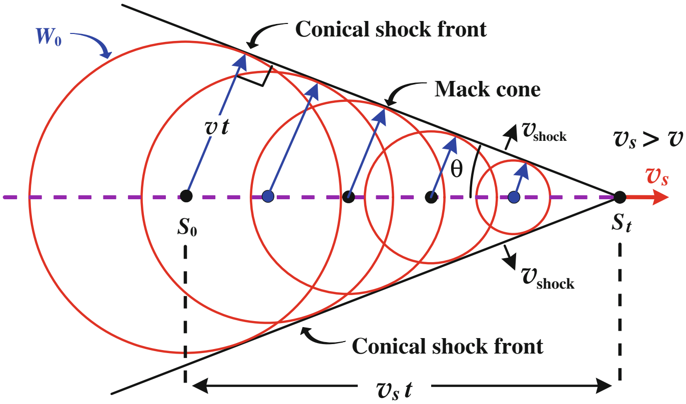


Fig. 15.15 A source of sound that moves with a speed v_S greater than the speed of sound v. All the spherical wave fronts expand at the speed of sound v and assemble along the surface of a cone called the Mach cone, forming a shock wave

The Mach cone has an apex half-angle θ (called the *Mach angle*):

$$\sin\theta = \frac{vt}{v_S\,t} = \frac{v}{v_S} \qquad \text{(Mach cone half-angle)} \qquad (15.40)$$

The ratio v_S/v is called the Mach number. When you hear that a jet plane has flown at Mach 3, it means that its speed v_S was 3 times the speed of sound ($v = 343$ m/s). With this supersonic speed, the jet plane generates a shock wave which produces a loud sound (*sonic boom*).

Example 15.9

A supersonic jet travels horizontally at Mach 2.5. At time $t = 0$, the jet is over a person's head at an altitude $h = 10$ km. (a) Where will the jet be before the ground observer hears the boom of the shock wave? (b) How long will the person wait before hearing that boom?

Solution: Figure 15.16 shows a sketch of the Mach cone at time $t = 0$, when the jet is just above the person's head. In addition, the figure shows the instant at time t when the person hears the *sonic boom*.

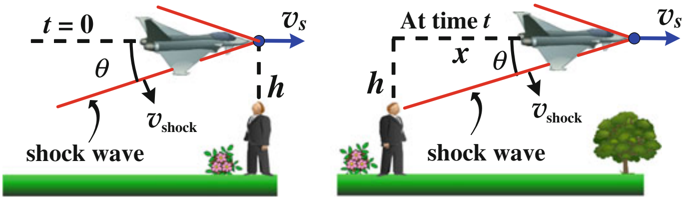


Fig. 15.16

(a) The half-angle of the shock wave cone can be obtained as follows:

$$\sin\theta = \frac{v}{v_S} = \frac{1}{2.5} = 0.4 \quad \Rightarrow \quad \theta = \sin^{-1} 0.4 \simeq 23.6°$$

From the figure's geometry, we can find the distance x as follows:

$$\tan\theta = \frac{h}{x} \quad \Rightarrow \quad x = \frac{h}{\tan\theta} = \frac{10{,}000\,\text{m}}{\tan 23.6\,°} = 22{,}889\,\text{m} = 22.9\,\text{km}$$

(b) The time the person will wait before hearing the sonic boom is:

$$t = \frac{x}{v_S} = \frac{x}{2.5v} = \frac{22{,}889\,\text{m}}{2.5 \times (343\,\text{m/s})} = 26.7\,\text{s}$$

15.8 Exercises

Section 15.1 Speed of Sound Waves

(1) Find the speed of sound in air when the temperature is 35 °C.

(2) The bulk modulus B and density ρ of mercury at 40 °C are 2.4×10^9 Pa and 13.45×10^3 kg/m^3, respectively. Calculate the speed of sound in mercury at this temperature.

(3) Find the speed of sound in a steel rod that has a Yang's modulus $Y = 2 \times 10^{11}$ N/m^2 and density $\rho = 7.8 \times 10^3$ kg/m^3.

(4) A steel rod that has a Yang's modulus $Y = 2 \times 10^{11}$ N/m^2, density $\rho = 7.8 \times 10^3$ kg/m^3, and length $L = 100$ m is struck at one end. A person at the other end hears two sounds as a result of the propagation of two longitudinal waves, one that traveled through the rod and the other that traveled through the air at 20 °C. What is the time interval between the two sounds?

(5) The speed of a longitudinal wave in an adiabatic process is written as $v = \sqrt{B_{ad}/\rho}$, where $B_{ad} = -V\,dP/dV$ as given by Eq. 10.14. In the case of

an ideal gas, the relation between the pressure P and volume V during an adiabatic process is given by $PV^{\gamma} = \text{constant}$, where γ is the ratio of the heat capacity at constant pressure to the heat capacity at constant volume. (a) Show that $B_{ad} = \gamma P$ for an ideal gas. (b) Show that the speed of a longitudinal wave in the adiabatic process of an ideal gas is given by $v = \sqrt{\gamma RT/M}$, where R is the universal gas constant, T is the Kelvin temperature, and M is the molecular mass of the gas.

(6) Hydrogen is a diatomic gas with molecular mass $M = 2$ kg/kmol and $\gamma = 1.41$. Find the speed of sound in hydrogen gas at 27 °C.

(7) The auto-focusing mechanism of old cameras used to depend on the camera sending a high frequency ultrasonic sound pulse toward the object being photographed. The camera would calculate the time that the pulse would take from the moment it left the camera to the moment it was detected by the camera's sensor. Based on the travel time of such a pulse, the camera would adjust its lens automatically. If the speed of sound in air is 343 m/s, find the travel time of a pulse for an object: (a) 1.5 m away, and (b) 5 m away.

(8) A fishing boat emits an ultrasonic pulse vertically toward the sea bed. Then pulse is received 1.5 s after being reflected from the ocean floor. If the speed of sound in sea water is 1,560 m/s, how far down is the ocean floor from the boat's location?

(9) On a warm summer day (32.3 °C), a boy drops a stone from the top of a cliff. Using his stopwatch, he finds that it took 20.9 s from the moment he dropped that stone until the moment he hears the sound of the splash that the stone makes with the surface of the water below. Take $g = 9.8\ \text{m/s}^2$. How high is the cliff?

Section 15.2 Periodic Sound Waves

(10) The pressure variation in a periodic sound wave is given by:

$$\Delta P = (2\ \text{Pa}) \sin \pi [(2\ \text{m}^{-1})x - (686\ \text{s}^{-1})t]$$

(a) Find the pressure-variation amplitude. (b) Find the wavelength and frequency of the pressure wave. (c) Find the speed of the pressure wave.

(11) A sinusoidal sound wave has the following displacement:

$$s(x, t) = (4\ \mu\text{m}) \cos[(20\ \text{m}^{-1})x - (6860\ \text{s}^{-1})t]$$

(a) Find the displacement amplitude, wavelength, frequency, and speed of the wave. (b) Find the value of the displacement of an element of air at the position $x = 2\,\text{mm}$ at time $t = 2\,\text{ms}$. (c) Find the maximum speed of this oscillating element.

(12) In homogenous air of density $\rho = 1.21\,\text{kg/m}^3$ a sinusoidal periodic sound wave has a wavelength $\lambda = 0.2\,\text{m}$, speed $v = 343\,\text{m/s}$, and pressure-variation amplitude $\Delta P_{\text{max}} = 0.5\,\text{Pa}$. (a) Show that the function that describes the pressure-variation depends on position x and time t according to the following expression:

$$\Delta P = (0.5\,\text{Pa})\sin\pi[(10\,\text{m}^{-1})x - (3{,}430\,\text{s}^{-1})t]$$

(b) Show that the function that describes the displacement of an element of air is governed in position and time by the following expression:

$$s(x,t) = (0.112\,\mu\text{m})\cos\pi[(10\,\text{m}^{-1})x - (3{,}430\,\text{s}^{-1})t]$$

(13) To generate a sound wave of speed $v = 343\,\text{m/s}$ and displacement amplitude $s_{\text{max}} = 5.5\,\mu\text{m}$ in air of density $\rho = 1.2\,\text{kg/m}^3$, one finds that the pressure-variation amplitude ΔP_{max} has to be limited to a maximum value of 0.84 Pa. What is the minimum wavelength that the sound wave can have?

Section 15.3 Energy, Power, and Intensity of Sound Waves

(14) Figure 15.17 depicts a very long open tube of area $A = 5 \times 10^{-3}\,\text{m}^2$ that was filled at normal atmospheric pressure with air that has a density $\rho = 1.2\,\text{kg/m}^3$. When the piston is driven at a frequency of 500 Hz and amplitude of 0.15 cm, a sinusoidal sound wave with a speed $v = 343\,\text{m/s}$ is maintained in the tube. What power must be supplied by the piston to produce this sound wave?

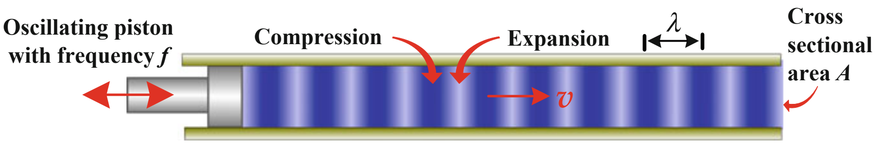


Fig. 15.17 See Exercise (14)

(15) A sound source vibrates at 1 kHz and produces sound waves of intensity $0.5\,\text{W/m}^2$ at a fixed point in space. (a) Find the intensity at this point if

the frequency is doubled while the displacement amplitude is kept constant. (b) Find the intensity at this point if the frequency is halved while the displacement amplitude is tripled.

(16) A loudspeaker emits a sound intensity of 100 μW/m^2 in a circular tube of radius $r = 7.5$ cm. How much power is being radiated as sound by the loudspeaker?

(17) Sound waves propagate with the same intensity I and angular frequency ω in: (1) air of density $\rho_a = 1.29$ kg/m^3 with a speed $v_a = 331$ m/s and, (2) water of density $\rho_w = 1{,}000$ kg/m^3 with a speed $v_w = 1{,}493$ m/s. Find the following for the two media: (a) the ratio of the values of the wavelength, (b) the ratio of the values of the displacement amplitude, and (c) the ratio of the values of the pressure-variation amplitude. (d) When $I = 10^{-6}$ W/m^2 and $\omega = 2{,}000\pi$ rad/s, evaluate the wavelength, displacement amplitude, and the pressure variation amplitude in each medium.

(18) The area of human eardrum is about $A = 5 \times 10^{-5}$ m^2. The intensity of sound at the threshold of hearing is $I = 10^{-12}$ W/m^2 and at the threshold of pain is $I = 1$ W/m^2. Find the sound power incident on the eardrum at both thresholds.

Section 15.4 The Decibel Scale

(19) When the human auditory system experiences a sound intensity of 1.2 W/m^2 it results in pain. Represent this amount in decibels.

(20) When a person speaks loudly, the sound level produced is 70 dB. When that person speaks normally, the sound level generated is at 40 dB. Find the ratio of the intensities of the two sounds.

(21) Two students argue loudly at sound levels of 80 dB and 78 dB. (a) Find the sound intensities for the individual students. (b) Find the combined sound level when the students argue simultaneously.

(22) (a) Show that doubling the intensity of sound will increase its level by 3 dB. (b) Show that halving the intensity of sound will decrease its level by 3 dB.

(23) One stereo amplifier is rated at 80 W and another is rated at 120 W. If the intensity of the sound produced at the maximum level of the first amplifier is taken as a reference, how much louder in dB will the second amplifier be at the maximum level?

(24) An engineer standing in front of an airplane with its four engines running experiences a sound level of 135 dB. What sound level would the engineer

experience if the pilot shut down: (a) only one engine, and (b) only two engines, and (c) only three engines?

(25) The amplitude of a sound wave is increased by a factor of 2.25. (a) By what factor will the intensity increase? (b) By how many dB will the sound level increase?

(26) Two identical point sources, S_1 and S_2, are located from an observer as shown in Fig. 15.18. They are emitting sound waves with the same power from the same oscillator. The sound intensity at the observer's location from S_2 is $I_2 = 4.0 \times 10^{-6}\,\mathrm{W/m^2}$. (a) Find the total intensity of sound waves that is received by the observer from the two sources. (b) Find $\beta_{tot} - \beta_2$, which is the difference in the sound level when the two sources operate together and when the second source operates by itself. (c) Show that $\beta_1 - \beta_2 = (20\,\mathrm{dB})\log(r_2/r_1) = 9.54\,\mathrm{dB}$.

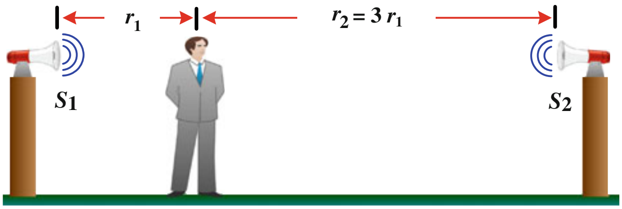


Fig. 15.18 See Exercise (26)

Section 15.5 Hearing Response to Intensity and Frequency

(27) What is the ratio of highest to lowest intensity that our auditory system can accommodate at: (a) 100 Hz, and (b) 1,000 Hz? (Use Fig. 15.9)

(28) What are the lowest and highest frequencies that our auditory system can detect if the sound level for normal talking is 50 dB? (Use Fig. 15.9)

Section 15.6 The Doppler Effect

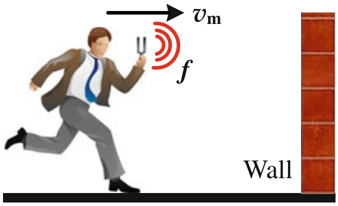
(29) A source emits a 2.5 kHz sound wave. If this source moves toward you at 20 m/s while you stay still, will the observed frequency be the same as if you moved toward the source at 20 m/s while it stays still?

(30) While at rest, a bat sends out ultrasonic sound at 45 kHz. What is the bat's received sound frequency if that sound wave strikes a mouse running away with a speed of 20 m/s?

(31) While a bat is flying toward a wall at a speed of 5 m/s, it emits an ultrasonic sound of 35 kHz. What frequency does the bat receive from the reflected wave?

(32) A man holding an oscillating tuning fork with a frequency $f = 200$ Hz, runs toward a wall with a speed $v_m = 5$ m/s, see Fig. 15.19. The speed of sound in air is 343 m/s. (a) What frequency difference does he observe between the tuning fork and its echo? (b) How fast must he run away from the wall to observe a difference in frequency equal to 5 Hz?

Fig. 15.19 See Exercise (32)



(33) An observer hears a frequency of 530 Hz from the siren of an approaching train; see part (a) of Fig. 15.20. After the train passes, the observer nearly in the path of the train hears a frequency of 470 Hz, see part (b) of Fig. 15.20. The speed of sound is 343 m/s. Find the train's speed.

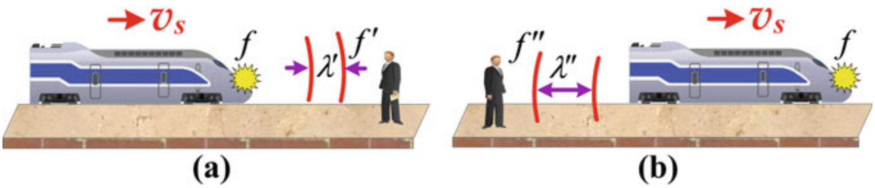


Fig. 15.20 See Exercise (33)

(34) A school bus moving with a speed $v_b = 15$ m/s generates a whistling sound at a frequency $f_b = 300$ Hz, see Fig. 15.21. A truck approaches the bus with a speed $v_t = 30$ m/s while its engine rumbles at a frequency $f_t = 500$ Hz. The speed of sound in air is 343 m/s. Assume approximately collinear paths. (a) What is the frequency detected by the driver in the truck? (b) What is the frequency detected by an observer in the bus? (c) After the truck passes the bus, what is the frequency detected by an observer in the bus?

(35) Two trams, A and B have identical sirens of frequency 500 Hz. Tram A is stationary and Tram B is moving towards the right, away from A at a speed of $v_B = 35$ m/s. An observer between the two sirens moves towards the right with a speed $v_o = 20$ m/s, see Fig. 15.22. Assume the speed of sound in air to be 340 m/s. (a) With what frequency does the observer hear the siren emitted from tram A? (b) With what frequency does the observer hear the siren emitted from tram B? (c) What is the difference in frequency heard by the observer?

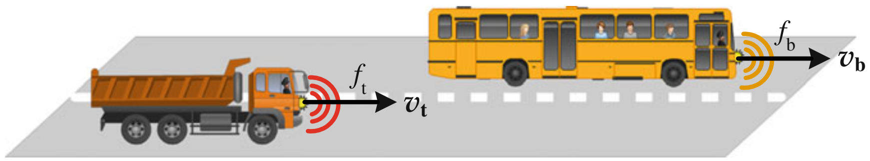


Fig. 15.21 See Exercise (34)

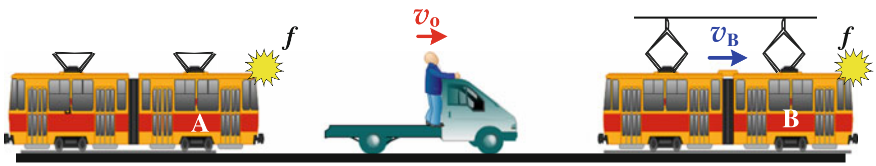


Fig. 15.22 See Exercise (35)

(36) A siren on the top of a stationary fire engine emits sound in all directions at a frequency $f = 900$ Hz. Assume that the speed of sound in calm air is 343 m/s and that a steady wind is blowing towards the East with a speed of 15 m/s. (a) Find the wavelength of the sound East of the siren. (b) Find the wavelength of the sound West of the siren. (c) Find the frequency of the sound heard when a firefighter approaches the siren with a speed of 15 m/s while walking *against* the wind. (d) Find the frequency of the sound heard when a firefighter approaches the siren with a speed of 15 m/s while walking *with* the wind.

Section 15.7 Supersonic Speeds and Shock Waves

(37) The Concorde could fly at Mach 1.5. The speed of sound is 340 m/s. (a) What does Mach 1.5 means? (b) What is the angle between the direction of the propagation of the shock wave front and the direction of the plane's velocity?

(38) A supersonic jet is traveling horizontally at Mach 3. At $t = 0$, the jet is over a person's head at an altitude $h = 15$ km, see the left part of the sketch in Fig. 15.23. (a) Where will the jet be before the person hears the boom of the shock wave, see the right part of the sketch in Fig. 15.23? (b) How long will the person wait before hearing that boom?

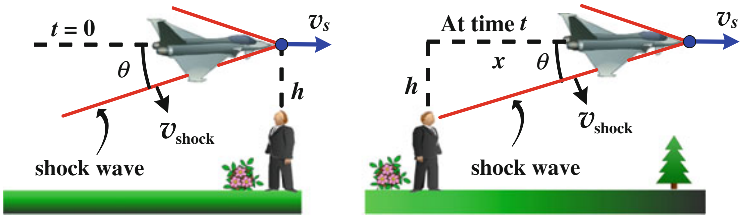


Fig. 15.23 See Exercise (38)

(39) A jet plane travels at Mach 2.5. The speed of sound is 320 m/s. (a) Find the angle of the shock wave compared to the direction of the jet's motion. (b) If the jet is flying $h = 6$ km vertically above a person on the ground, how long will it take for that person to hear the shock wave?

(40) A supersonic rocket travels at a constant speed of 1,190 m/s in a direction making an angle ϕ with the horizontal, see the sketch in Fig. 15.24. As the rocket gains altitude, an observer on the ground hears for the first time the boom of the shock wave when the rocket is directly above him. Assume the speed of sound in air to be 340 m/s. (a) Find the angle ϕ. (b) If the rocket is above the person at an altitude $h = 10$ km, find the time of flight. (c) Find the horizontal displacement of the rocket.

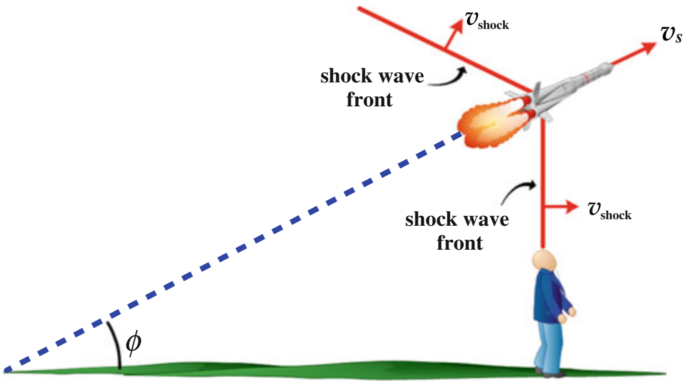


Fig. 15.24 See Exercise (40)