$$f_{\text{d}} = \left(\frac{v_{\text{w}}}{v_{\text{w}} - v_{\text{s}}}\right) f_{\text{s}}$$
$$= \left(\frac{v_{\text{w}}}{v_{\text{w}} - v_{\text{w}}}\right) f_{\text{s}}$$
$$= \left(\frac{v_{\text{w}}}{0}\right) f_{\text{s}}$$
$$= \text{undefined}$$

(b) the apparent frequency as the plane moves away from you.

$$f_{\text{d}} = \left(\frac{v_{\text{w}}}{v_{\text{w}} + v_{\text{s}}}\right) f_{\text{s}}$$
$$= \left(\frac{v_{\text{w}}}{v_{\text{w}} + v_{\text{w}}}\right) f_{\text{s}}$$
$$= \left(\frac{v_{\text{w}}}{2v_{\text{w}}}\right) f_{\text{s}}$$
$$= \left(\frac{1}{2}\right) f_{\text{s}}$$

(c) Between these two cases, you hear a sonic boom at the instant of transition from case (a) to case (b).

Paraphrase and Verify

When a plane approaches you at the speed of sound, there is no sound wave preceding the plane. When a plane moves away from you at the speed of sound, the apparent frequency of the sound is one-half the source frequency. Between these two cases, you hear a sonic boom at the instant of transition from case (a) to case (b).

Extension

7. The frequency of red light is less than the frequency of blue light. Thus if the light from a star is shifted from the blue end of the spectrum toward the red end, the frequency of the light has decreased. That means that the star must be moving away from us. If the light from all distant stars shows red shift, then all those stars must be moving away from Earth, proving that the universe must be expanding.

Student Book pages 436–437

Chapter 8 Review

Knowledge

1. **(a)** When a transverse crest of a water wave moves, the water at the top of the crest moves downward. The water below the crest then has to move downward and sideways to make room for the water in the crest and to evacuate a space for the trough.

(b) When an incident wave train is reflected from a barrier, the angle between the incident wave front and the barrier is equal to the angle between the reflected wave front and the barrier. However, the incident wave is moving toward the barrier whereas the reflected wave is moving away from it.

(c) The oscillations of the tuning fork would set up a compression when they moved in the direction of the wave motion and a rarefaction when they moved away from the direction of the wave motion. The compression and rarefactions would move through the medium in ever expanding spheres in a sequence of SHM.

2. **(a)** The speed of a water wave is determined by *g* and the depth of the water.

(b) When a longitudinal wave moves through a medium, the particles of the medium oscillate in sequence, in SHM about their equilibrium position. In the process, they transmit the energy by colliding with a particle next to them, making the wave path parallel to their line of oscillation.

(c) The wavelength varies directly as the speed of the wave. The speed has no influence on the amplitude.

(d) As a wave moves through a medium, each particle of the medium oscillates in SHM either across the direction of motion of the wave (transverse waves) or along the direction of motion (longitudinal waves).

(e) When the speed of the wave is constant, the wavelength varies inversely as the frequency of a wave.

3. **(a)** Interference results when two waves occupy the same position in a medium. If the waves displace the medium in the same direction from the equilibrium, then constructive interference results. If the waves displace the medium in opposite directions from the equilibrium, then destructive interference results.

(b) When two pulses of equal length and amplitude interfere to produce no apparent pulse, destructive interference is taking place. The principle of superposition states that the displacement of the net pulse is the algebraic sum of the displacement of the pulses at each point in the medium. The pulses must have had equal but opposite displacements so that the sum at each point is zero.

(c) A node is the point in an interference pattern where interference produces only total (or nearly total) destruction of the wave. An antinode is the point in an interference pattern where the waves interfere to produce maximum construction. A standing wave results when two waves of equal frequency and amplitude move in opposite directions through a medium. The effect is to produce a series of fixed nodes with antinodes between them.

(d) In a standing wave in a spring, there is a node at the fixed end of the spring. As you move away from that end of the spring, there are nodes at every one-half wavelength along the spring. This pattern develops by adding the incident wave and the reflected wave (that actually travels backwards and is inverted relative to the incident wave). Between each node there is a region that is one-half a wavelength long with an antinode at the middle.

(e) If the frequency applied to a spring generates a wave such that the length of the spring is not an integral number of half wavelengths, then the waves travelling in one direction along the spring arrive at the other end of the spring out of phase with the waves leaving that end. In this case, the waves interact destructively so that there is no wave pattern established. If, on the other hand, the length of the spring is an integral number of half wavelengths, then the waves arriving at opposite ends of the spring are in-phase with the waves leaving that end. This results in constructive interference and a strengthening of the wave motion in the phenomenon known as resonance.

4. **(a)** The Doppler effect applies to all forms of waves. For light waves, the Doppler effect is used to explain the red-shift in the spectra of light from stars. The Doppler effect is used with radio waves to measure moving objects (cars, planes, etc.). [**NOTE:** Students may not realize that radio waves and light waves are different forms of the same phenomenon.]
   (b) The waves that a source emits in the direction of its motion are decreased in length. Thus observers detect these waves to have a higher frequency than that at which they were generated.

Applications

5. ***Given***

$v = 15.0\ \frac{\text{m}}{\text{s}} \quad l = 2.00\ \text{m}$

Required

time required to generate the pulse (Δt)

explanation of why frequency is not used to describe pulses

Analysis and Solution

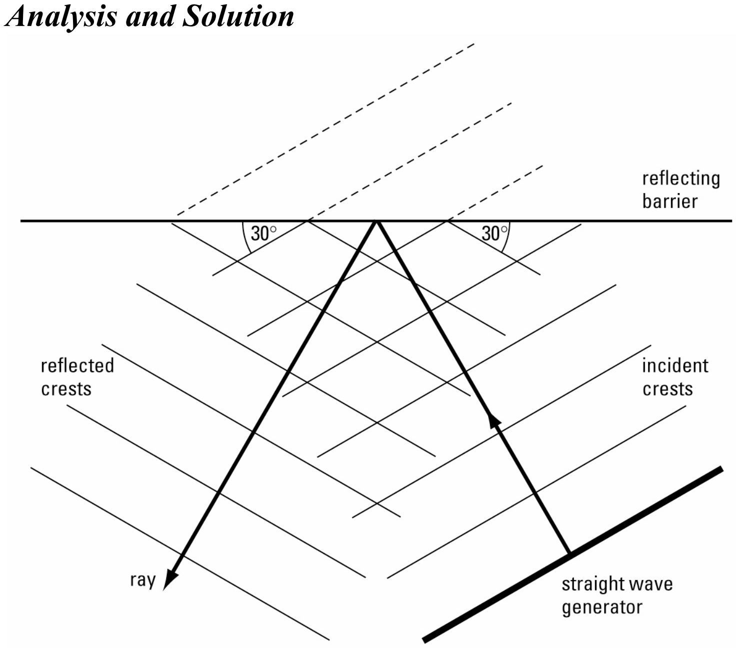
Use the equation for calculating pulse length and solve for time.

$$\begin{aligned} l &= v\Delta t \\ \Delta t &= \frac{l}{v} \\ &= \frac{2.00\ \text{m}}{15.0\ \frac{\text{m}}{\text{s}}} \\ &= 0.133\ \text{s} \end{aligned}$$

Paraphrase and Verify

It required 0.133 s to generate the pulse. Since pulses are single occurrences and frequency implies a repeated occurrence, it makes no sense to convert the time required to generate a pulse into a frequency.

6. ***Analysis and Solution***



7. Given

$v_1 = 15.0\ \frac{\text{cm}}{\text{s}}$ $v_2 = 10.0\ \frac{\text{cm}}{\text{s}}$

$f = 12.0\ \text{Hz}$

Required

changes in the waves as they move into shallow water

Analysis and Solution

Since the waves slow down but the frequency is unchanged, the wavelengths will decrease.

$$v = f\lambda$$

$$\begin{aligned}\lambda_1 &= \frac{v_1}{f}\\ &= \frac{15.0\ \frac{\text{cm}}{\text{s}}}{12.0\ \frac{1}{\text{s}}}\\ &= 1.25\ \text{cm}\end{aligned}$$

Similarly,

$$\begin{aligned}\lambda_2 &= \frac{v_2}{f}\\ &= \frac{10.0\ \frac{\text{cm}}{\text{s}}}{12.0\ \frac{1}{\text{s}}}\\ &= 0.833\ \text{cm}\end{aligned}$$

Paraphrase and Verify

When the waves pass from the deep water to the shallow water, their speed is reduced from 15.0 cm/s to 10.0 cm/s. Because the frequency is constant, the decrease in speed results in a corresponding decrease in wavelengths from 1.25 cm to 0.833 cm. Since the wave fronts are parallel to the line between the deep and shallow water they do not change direction.

8. Given

$v_1 = 12.0\ \frac{\text{cm}}{\text{s}}$ $v_2 = 9.0\ \frac{\text{cm}}{\text{s}}$

$\lambda_1 = 11.5\ \text{cm}$

Required

wavelength in the shallow water (λ_2)

Analysis and Solution

Since the frequency is constant, the wavelength varies directly as the speed. Express this relationship as a ratio and solve for the final wavelength.

$\lambda \propto v$

$\frac{\lambda_2}{\lambda_1} = \frac{v_2}{v_1}$

$\lambda_2 = \lambda_1 \frac{v_2}{v_1}$

$= 11.5 \text{ cm} \left(\frac{9.0 \ \frac{\text{cm}}{\text{s}}}{12.0 \ \frac{\text{cm}}{\text{s}}} \right)$

$= 8.6 \text{ cm}$

Paraphrase

When the wave moves from the deep to the shallow water, the wavelength decreases from 11.5 cm to 8.6 cm.

9. ***Given***

$f = 22 \text{ kHz} = 2.2 \times 10^4 \text{ Hz}$

$v = 350 \ \frac{\text{m}}{\text{s}}$

Required

wavelength (λ)

Analysis and Solution

Use the universal wave equation to solve for wavelength.

$v = f\lambda$

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

$= \frac{350 \ \frac{\text{m}}{\text{s}}}{2.2 \times 10^4 \ \frac{1}{\text{s}}}$

$= 1.6 \times 10^{-2} \text{ m}$

Paraphrase

The wavelength of the ultrasound is 1.6×10^{-2} m.

10. ***Given***

$l = 7.0 \text{ m} \quad f = 2.0 \text{ Hz}$

$l = \frac{5\lambda}{2}$

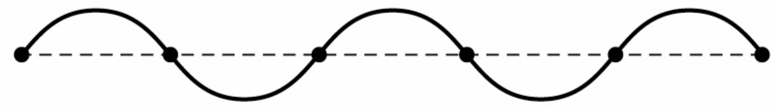
Required

(a) wave pattern for this system

(b) velocity of the wave (v)

Analysis and Solution

(a) The standing wave has 6 nodes and 5 antinodes, which means that it is five half-wavelengths or 2½ λ long.



(b) Use the length of the spring to calculate one wavelength; then use the frequency and wavelength to calculate wave velocity.

$$l = \frac{5\lambda}{2}$$

$$\lambda = \frac{2}{5}l$$

$$= \frac{2}{5}(7.0\,\text{m})$$

$$= 2.8\text{ m}$$

$$v = f\lambda$$

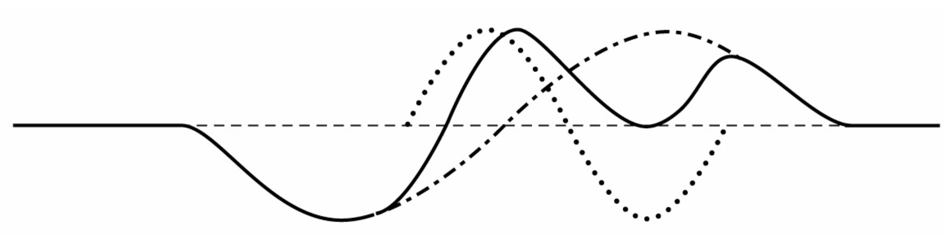
$$= \left(2.0\ \frac{1}{\text{s}}\right)(2.8\text{ m})$$

$$= 5.6\ \frac{\text{m}}{\text{s}}$$

Paraphrase

The wavelength as determined from the standing wave pattern is 2.8 m. This produces a wave velocity of 5.6 m/s.

11. ***Analysis and Solution***



Paraphrase

The solid line indicates the result of the interference of the two dotted waves.

12. ***Given***

$f_1 = 1.5\text{ Hz}$ $\lambda_1 = \frac{2l}{3}$

$\lambda_2 = \frac{2l}{5}$ $\lambda_3 = 2l$

Required

(a) frequency that produces the second standing wave pattern (f_2)

(b) fundamental frequency for the system (f_3)

Analysis and Solution

(a) Since the speed of the wave in the spring is constant, the frequency varies inversely as the wavelength. Use the ratio to calculate the frequency for the second standing wave pattern.

$$f \propto \frac{1}{\lambda}$$

$$\frac{f_2}{f_1} = \frac{\lambda_1}{\lambda_2}$$

$$f_2 = f_1 \frac{\lambda_1}{\lambda_2}$$

$$= \left(1.5\frac{1}{\text{s}}\right)\left(\frac{\frac{2l}{3}}{\frac{2l}{5}}\right)$$

$$= \left(1.5\frac{1}{\text{s}}\right)\left(\frac{5}{3}\right)$$

$$= 2.5\ \frac{1}{\text{s}}$$

$$= 2.5 \text{ Hz}$$

(b) Similarly, calculate the frequency for the third standing wave pattern. This is the fundamental frequency where the length of the spring equals one-half a wavelength.

$$\frac{f_3}{f_1} = \frac{\lambda_1}{\lambda_3}$$

$$f_3 = f_1 \frac{\lambda_1}{\lambda_3}$$

$$= \left(1.5\frac{1}{\text{s}}\right)\left(\frac{\frac{2l}{3}}{2l}\right)$$

$$= \left(1.5\frac{1}{\text{s}}\right)\left(\frac{1}{3}\right)$$

$$= 0.50\ \frac{1}{\text{s}}$$

$$= 0.50 \text{ Hz}$$

Paraphrase

(a) The frequency that produces a standing wave with 5 antinodes is 2.5 Hz.
(b) The fundamental frequency for the spring is 0.50 Hz.

13. ***Given***

$l_1 = 33.0 \text{ cm} \quad f_1 = 659 \text{ Hz}$

$\lambda_1 = 2l_1 \quad l_2 = 28.0 \text{ cm}$

$\lambda_2 = 2l_2$

Required

(a) speed of waves in the string (v)
(b) frequency when the length of the string is shortened (f_2)

Analysis and Solution

(a) Use the universal wave equation to calculate the speed from frequency and wavelength.

$$\begin{aligned}\lambda_1 &= 2l_1\\ &= 2(33.0\text{ cm})\\ &= 66.0\text{ cm}\\ &= 0.660\text{ m}\end{aligned}$$

$$\begin{aligned}v &= f_1\lambda_1\\ &= \left(659\ \frac{1}{\text{s}}\right)(0.660\text{ m})\\ &= 434.9\ \frac{\text{m}}{\text{s}}\\ &= 435\ \frac{\text{m}}{\text{s}}\end{aligned}$$

(b) Since the tension is unchanged, the speed is the same as in part (a). Use the speed and wavelength to calculate the frequency.

$$\begin{aligned}\lambda_2 &= 2l_2\\ &= 2(28.0\text{ cm})\\ &= 56.0\text{ cm}\\ &= 0.560\text{ m}\end{aligned}$$

$$v = f_2\lambda_2$$

$$\begin{aligned}f_2 &= \frac{v}{\lambda_2}\\ &= \frac{434.9\ \frac{\text{m}}{\text{s}}}{0.560\text{ m}}\\ &= 777\ \frac{1}{\text{s}}\\ &= 777\text{ Hz}\end{aligned}$$

Paraphrase

(a) The speed of the wave in the string is 435 m/s.

(b) When the string is shortened to 28.0 cm, the frequency increases to 777 Hz.

14. ***Given***

$f = 426\text{ Hz}$ $v = 335\ \frac{\text{m}}{\text{s}}$

(a) $l_1 = \frac{\lambda}{4}$ (b) $l_2 = \frac{3\lambda}{4}$

Required

(a) length of the shortest closed pipe that can produce resonance (l_1)

(b) length of the next longest closed pipe that can produce resonance (l_2)

Analysis and Solution

(a) The shortest closed pipe for which resonance occurs is 0.25 wavelengths long. Calculate the wavelength using the universal wave equation; then calculate the length of the pipe.

$$v = f\lambda$$

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

$$= \frac{335\ \frac{\text{m}}{\text{s}}}{426\ \frac{1}{\text{s}}}$$

$$= 0.7864\ \text{m}$$

$$l_1 = \frac{\lambda}{4}$$

$$= \frac{0.7864\ \text{m}}{4}$$

$$= 0.197\ \text{m}$$

$$= 19.7\ \text{cm}$$

(b) Use the same wavelength to calculate the length of the second-shortest pipe, which would be 0.75 wavelengths long.

$$l_2 = \frac{3\lambda}{4}$$

$$= \frac{3(0.7864\ \text{m})}{4}$$

$$= 0.590\ \text{m}$$

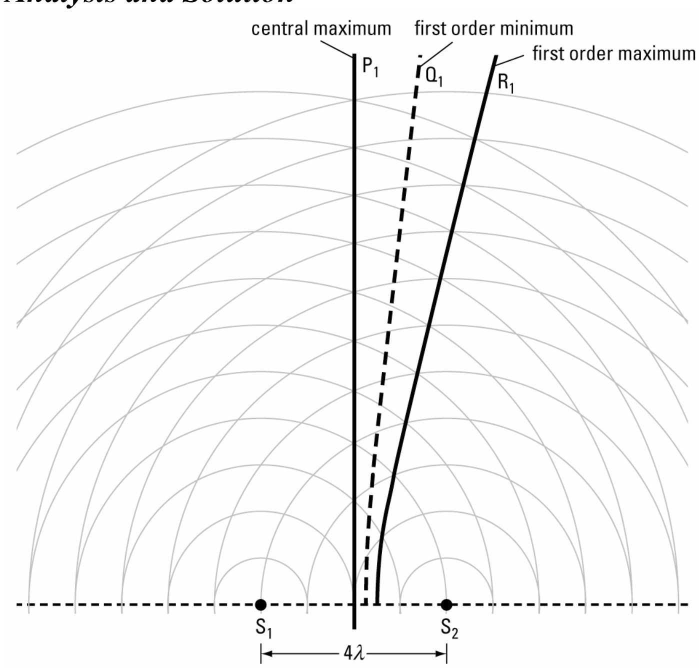
$$= 59.0\ \text{cm}$$

Paraphrase

(a) The shortest closed pipe that will produce resonance for this frequency is 19.7 cm long.

(b) The second-shortest closed pipe that will produce resonance for this frequency is 59.0 cm long.

15. ***Analysis and Solution***



16. ***Given***

$2\lambda = 2.8 \text{ cm}$

Required

wavelength (λ)

Analysis and Solution

On a second order maximum, the points are 2λ farther from one source than the other. Thus the given distance equals 2λ. Use this relationship to calculate λ.

$$2\lambda = 2.8 \text{ cm}$$

$$\lambda = \frac{2.8 \text{ cm}}{2}$$

$$= 1.4 \text{ cm}$$

Paraphrase

The wavelength of the interference pattern is 1.4 cm.

17. ***Given***

$f_s = 290 \text{ Hz} \quad v_w = 340 \ \frac{\text{m}}{\text{s}}$

$v_s = 72.0 \ \frac{\text{km}}{\text{h}} = 20.0 \ \frac{\text{m}}{\text{s}}$

Required

apparent frequency of the sound (f_d)

Analysis and Solution

Use the Doppler effect equation for a source moving toward the observer.

$$f_d = \left(\frac{v_w}{v_w - v_s} \right) f_s$$

$$= \left(\frac{340 \ \frac{\text{m}}{\text{s}}}{340 \ \frac{\text{m}}{\text{s}} - 20.0 \ \frac{\text{m}}{\text{s}}} \right) (290 \text{ Hz})$$

$$= 308 \text{ Hz}$$

Paraphrase

The apparent frequency of the approaching car horn has increased to 308 Hz.

18. ***Given***

$f_d = 580 \text{ Hz} \quad f_s = 540 \text{ Hz}$

$v_w = 350 \ \frac{\text{m}}{\text{s}}$

Required

speed of the source (v_s)

Analysis and Solution

Use the Doppler equation for a sound moving away from the observer and solve for the speed of the source.

$$f_d = \left(\frac{v_w}{v_w - v_s}\right) f_s$$

$$v_s = \left(\frac{f_d - f_s}{f_d}\right) v_w$$

$$= \left(\frac{580\text{ Hz} - 540\text{ Hz}}{580\text{ Hz}}\right)\left(350\ \frac{\text{m}}{\text{s}}\right)$$

$$= 24.1\ \frac{\text{m}}{\text{s}}$$

$$= 86.9\ \frac{\text{km}}{\text{h}}$$

Paraphrase

In order to produce the increase in the apparent frequency, the sound must be moving toward you at a speed of 24.1 m/s or 86.9 km/h.

19. ***Given***

$$v_w = 350\ \frac{\text{m}}{\text{s}}$$

$$f_d = \tfrac{1}{2} f_s$$

Required

speed of the source (v_s)

Analysis and Solution

Use the Doppler equation for a source moving away from the observer. Calculate the speed of the source.

$$f_d = \left(\frac{v_w}{v_w + v_s}\right) f_s$$

$$v_s = \left(\frac{f_s - f_d}{f_d}\right) v_w$$

$$= \left(\frac{f_s - \frac{1}{2} f_s}{\frac{1}{2} f_s}\right)\left(350\ \frac{\text{m}}{\text{s}}\right)$$

$$= \left(\frac{\frac{1}{2} f_s}{\frac{1}{2} f_s}\right)\left(350\ \frac{\text{m}}{\text{s}}\right)$$

$$= 350\ \frac{\text{m}}{\text{s}}$$

$$= 1260\ \frac{\text{km}}{\text{h}} \text{ or } 1.26 \times 10^3\ \frac{\text{km}}{\text{h}}$$

A source moving toward you at the speed of sound would not be heard until it produced a sonic boom.

Paraphrase and Verify

For the frequency that you hear to be one half of the true frequency, the speed of the source would need to be 350 m/s or 1.26×10^3 km/h. The source is moving away from you at the speed of sound. If the source had been moving toward you, you would not hear it until it passed you and you heard a sonic boom.

20. ***Given***

$\lambda_s = 0.550\ \text{m} \quad v_s = 120\ \frac{\text{km}}{\text{h}} = 33.33\ \frac{\text{m}}{\text{s}}$

$v_w = 345\ \frac{\text{m}}{\text{s}}$

Required

apparent frequency of the siren (f_d)

Analysis and Solution

Use the wavelength from the source and the speed of sound to calculate the frequency of the source; then use the Doppler effect equation for a source moving toward the observer to calculate the apparent frequency of the sound.

$$v_w = f_s \lambda_s$$

$$\begin{aligned} f_s &= \frac{v_w}{\lambda_s} \\ &= \frac{345\ \frac{\text{m}}{\text{s}}}{0.550\ \text{m}} \\ &= 627.3\ \frac{1}{\text{s}} \\ &= 627.3\ \text{Hz} \end{aligned}$$

$$\begin{aligned} f_d &= \left(\frac{v_w}{v_w - v_s} \right) f_s \\ &= \left(\frac{345\ \frac{\text{m}}{\text{s}}}{345\ \frac{\text{m}}{\text{s}} - 33.33\ \frac{\text{m}}{\text{s}}} \right) (627.3\ \text{Hz}) \\ &= 694\ \text{Hz} \end{aligned}$$

Paraphrase

The movement of the car toward the observer causes its apparent frequency to increase from 627 Hz to 694 Hz.

21. ***Given***

$v_w = 350\ \frac{\text{m}}{\text{s}} \qquad f_d = 2 f_s$

Required

speed of the source (v_s)

Analysis and Solution

Use the Doppler effect equation for a sound moving toward you and calculate the speed of the source. Then use this calculated speed of the object to calculate the apparent frequency if the source had been moving away from you.

$$f_d = \left(\frac{v_w}{v_w - v_s}\right) f_s$$

$$\begin{aligned} v_s &= \left(\frac{f_d - f_s}{f_d}\right) v_w \\ &= \left(\frac{2f_s - f_s}{2f_s}\right)\left(350\ \frac{\text{m}}{\text{s}}\right) \\ &= \left(\frac{f_s}{2f_s}\right)\left(350\ \frac{\text{m}}{\text{s}}\right) \\ &= 175\ \frac{\text{m}}{\text{s}} \end{aligned}$$

When the source moves away from you:

$$\begin{aligned} f_d &= \left(\frac{v_w}{v_w + v_s}\right) f_s \\ &= \left(\frac{350\ \frac{\text{m}}{\text{s}}}{350\ \frac{\text{m}}{\text{s}} + 175\ \frac{\text{m}}{\text{s}}}\right) f_s \\ &= (0.667) f_s \end{aligned}$$

A more elegant way to state the argument is:

$$\begin{aligned} f_d &= \left(\frac{v_w}{v_w + v_s}\right) f_s \\ &= \left(\frac{v_w}{v_w + \frac{1}{2} v_w}\right) f_s \\ &= \left(\frac{v_w}{\frac{3}{2} v_w}\right) f_s \\ &= \left(\frac{2}{3}\right) f_s \end{aligned}$$

Paraphrase

The object is moving toward you at half the speed of sound or 175 m/s. If the source is moving away from you, the apparent frequency would be 2/3 the source frequency.

Extensions

22. The interference pattern is for two in-phase point sources at a separation of 3 wavelengths. If the speed of sound is 350 m/s, then the wavelength for a source with a frequency of 512 Hz is about 0.683 m. To create this interference pattern in sound would require sources that are 2.05 m apart (3 × 0.683 m). The in-phase sources might be a pair of small speakers connected to an audio frequency generator set at the desired separation. To detect the maxima and minima using just your ears would be very difficult. You would need to use a microphone connected to an oscilloscope or computer. As the requirements to detect this interference pattern are so restricted, it is very unlikely that anyone would detect the pattern unless they had set up a system with the intention to do so.

23. The ratio of the wavelength to the distance between two in-phase point sources affects the interference pattern because the pattern depends on the phase shift produced when the waves from one source travel farther than the waves from the other source. The greatest phase shift occurs on the extension of the line between the sources. Thus if the sources are 4λ apart, then the greatest possible phase shift is 4λ , which occurs on the fourth order maximum. Thus this pattern will contain a central maximum with four maxima and four minima on either side of it.

