

## Chapter 17 – Student Solutions Manual

5. Let  $t_f$  be the time for the stone to fall to the water and  $t_s$  be the time for the sound of the splash to travel from the water to the top of the well. Then, the total time elapsed from dropping the stone to hearing the splash is  $t = t_f + t_s$ . If  $d$  is the depth of the well, then the kinematics of free fall gives  $d = \frac{1}{2}gt_f^2$ , or  $t_f = \sqrt{2d/g}$ . The sound travels at a constant speed  $v_s$ , so  $d = v_s t_s$ , or  $t_s = d/v_s$ . Thus the total time is  $t = \sqrt{2d/g} + d/v_s$ . This equation is to be solved for  $d$ . Rewrite it as  $\sqrt{2d/g} = t - d/v_s$  and square both sides to obtain

$$2d/g = t^2 - 2(t/v_s)d + (1 + v_s^2/g)d^2.$$

Now multiply by  $g v_s^2$  and rearrange to get

$$gd^2 - 2v_s(gt + v_s)d + g v_s^2 t^2 = 0.$$

This is a quadratic equation for  $d$ . Its solutions are

$$d = \frac{2v_s(gt + v_s) \pm \sqrt{4v_s^2(gt + v_s)^2 - 4g^2v_s^2t^2}}{2g}.$$

The physical solution must yield  $d = 0$  for  $t = 0$ , so we take the solution with the negative sign in front of the square root. Once values are substituted the result  $d = 40.7$  m is obtained.

7. If  $d$  is the distance from the location of the earthquake to the seismograph and  $v_s$  is the speed of the S waves then the time for these waves to reach the seismograph is  $t_s = d/v_s$ . Similarly, the time for P waves to reach the seismograph is  $t_p = d/v_p$ . The time delay is

$$\Delta t = (d/v_s) - (d/v_p) = d(v_p - v_s)/v_s v_p,$$

so

$$d = \frac{v_s v_p \Delta t}{(v_p - v_s)} = \frac{(4.5 \text{ km/s})(8.0 \text{ km/s})(3.0 \text{ min})(60 \text{ s/min})}{8.0 \text{ km/s} - 4.5 \text{ km/s}} = 1.9 \times 10^3 \text{ km}.$$

We note that values for the speeds were substituted as given, in km/s, but that the value for the time delay was converted from minutes to seconds.

9. (a) Using  $\lambda = v/f$ , where  $v$  is the speed of sound in air and  $f$  is the frequency, we find

$$\lambda = \frac{343 \text{ m/s}}{4.50 \times 10^6 \text{ Hz}} = 7.62 \times 10^{-5} \text{ m}.$$

(b) Now,  $\lambda = v/f$ , where  $v$  is the speed of sound in tissue. The frequency is the same for air and tissue. Thus

$$\lambda = (1500 \text{ m/s})/(4.50 \times 10^6 \text{ Hz}) = 3.33 \times 10^{-4} \text{ m}.$$

19. Let  $L_1$  be the distance from the closer speaker to the listener. The distance from the other speaker to the listener is  $L_2 = \sqrt{L_1^2 + d^2}$ , where  $d$  is the distance between the speakers. The phase difference at the listener is  $\phi = 2\pi(L_2 - L_1)/\lambda$ , where  $\lambda$  is the wavelength.

For a minimum in intensity at the listener,  $\phi = (2n + 1)\pi$ , where  $n$  is an integer. Thus  $\lambda = 2(L_2 - L_1)/(2n + 1)$ . The frequency is

$$f = \frac{v}{\lambda} = \frac{(2n + 1)v}{2(\sqrt{L_1^2 + d^2} - L_1)} = \frac{(2n + 1)(343 \text{ m/s})}{2(\sqrt{(3.75 \text{ m})^2 + (2.00 \text{ m})^2} - 3.75 \text{ m})} = (2n + 1)(343 \text{ Hz}).$$

Now  $20,000/343 = 58.3$ , so  $2n + 1$  must range from 0 to 57 for the frequency to be in the audible range. This means  $n$  ranges from 0 to 28.

(a) The lowest frequency that gives minimum signal is ( $n = 0$ )  $f_{\min,1} = 343 \text{ Hz}$ .

(b) The second lowest frequency is ( $n = 1$ )  $f_{\min,2} = [2(1) + 1]343 \text{ Hz} = 1029 \text{ Hz} = 3 f_{\min,1}$ . Thus, the factor is 3.

(c) The third lowest frequency is ( $n = 2$ )  $f_{\min,3} = [2(2) + 1]343 \text{ Hz} = 1715 \text{ Hz} = 5 f_{\min,1}$ . Thus, the factor is 5.

For a maximum in intensity at the listener,  $\phi = 2n\pi$ , where  $n$  is any positive integer. Thus  $\lambda = (1/n)(\sqrt{L_1^2 + d^2} - L_1)$  and

$$f = \frac{v}{\lambda} = \frac{nv}{\sqrt{L_1^2 + d^2} - L_1} = \frac{n(343 \text{ m/s})}{\sqrt{(3.75 \text{ m})^2 + (2.00 \text{ m})^2} - 3.75 \text{ m}} = n(686 \text{ Hz}).$$

Since  $20,000/686 = 29.2$ ,  $n$  must be in the range from 1 to 29 for the frequency to be audible.

(d) The lowest frequency that gives maximum signal is ( $n = 1$ )  $f_{\max,1} = 686 \text{ Hz}$ .

(e) The second lowest frequency is ( $n = 2$ )  $f_{\max,2} = 2(686 \text{ Hz}) = 1372 \text{ Hz} = 2 f_{\max,1}$ . Thus, the factor is 2.

(f) The third lowest frequency is ( $n = 3$ )  $f_{\max,3} = 3(686 \text{ Hz}) = 2058 \text{ Hz} = 3 f_{\max,1}$ . Thus, the factor is 3.

25. The intensity is the rate of energy flow per unit area perpendicular to the flow. The rate at which energy flow across every sphere centered at the source is the same, regardless of the sphere radius, and is the same as the power output of the source. If  $P$  is the power output and  $I$  is the intensity a distance  $r$  from the source, then  $P = IA = 4\pi r^2 I$ , where  $A (= 4\pi r^2)$  is the surface area of a sphere of radius  $r$ . Thus

$$P = 4\pi(2.50 \text{ m})^2 (1.91 \times 10^{-4} \text{ W/m}^2) = 1.50 \times 10^{-2} \text{ W}.$$

29. (a) Let  $I_1$  be the original intensity and  $I_2$  be the final intensity. The original sound level is  $\beta_1 = (10 \text{ dB}) \log(I_1/I_0)$  and the final sound level is  $\beta_2 = (10 \text{ dB}) \log(I_2/I_0)$ , where  $I_0$  is the reference intensity. Since  $\beta_2 = \beta_1 + 30 \text{ dB}$  which yields

$$(10 \text{ dB}) \log(I_2/I_0) = (10 \text{ dB}) \log(I_1/I_0) + 30 \text{ dB},$$

or

$$(10 \text{ dB}) \log(I_2/I_0) - (10 \text{ dB}) \log(I_1/I_0) = 30 \text{ dB}.$$

Divide by 10 dB and use  $\log(I_2/I_0) - \log(I_1/I_0) = \log(I_2/I_1)$  to obtain  $\log(I_2/I_1) = 3$ . Now use each side as an exponent of 10 and recognize that  $10^{\log(I_2/I_1)} = I_2 / I_1$ . The result is  $I_2/I_1 = 10^3$ . The intensity is increased by a factor of  $1.0 \times 10^3$ .

(b) The pressure amplitude is proportional to the square root of the intensity so it is increased by a factor of  $\sqrt{1000} = 32$ .

43. (a) When the string (fixed at both ends) is vibrating at its lowest resonant frequency, exactly one-half of a wavelength fits between the ends. Thus,  $\lambda = 2L$ . We obtain

$$v = f\lambda = 2Lf = 2(0.220 \text{ m})(920 \text{ Hz}) = 405 \text{ m/s}.$$

(b) The wave speed is given by  $v = \sqrt{\tau / \mu}$ , where  $\tau$  is the tension in the string and  $\mu$  is the linear mass density of the string. If  $M$  is the mass of the (uniform) string, then  $\mu = M/L$ . Thus

$$\tau = \mu v^2 = (M/L)v^2 = [(800 \times 10^{-6} \text{ kg})/(0.220 \text{ m})] (405 \text{ m/s})^2 = 596 \text{ N}.$$

(c) The wavelength is  $\lambda = 2L = 2(0.220 \text{ m}) = 0.440 \text{ m}$ .

(d) The frequency of the sound wave in air is the same as the frequency of oscillation of the string. The wavelength is different because the wave speed is different. If  $v_a$  is the speed of sound in air the wavelength in air is

$$\lambda_a = v_a/f = (343 \text{ m/s})/(920 \text{ Hz}) = 0.373 \text{ m}.$$

45. (a) Since the pipe is open at both ends there are displacement antinodes at both ends and an integer number of half-wavelengths fit into the length of the pipe. If  $L$  is the pipe length and  $\lambda$  is the wavelength then  $\lambda = 2L/n$ , where  $n$  is an integer. If  $v$  is the speed of sound then the resonant frequencies are given by  $f = v/\lambda = nv/2L$ . Now  $L = 0.457 \text{ m}$ , so

$$f = n(344 \text{ m/s})/2(0.457 \text{ m}) = 376.4n \text{ Hz}.$$

To find the resonant frequencies that lie between 1000 Hz and 2000 Hz, first set  $f = 1000 \text{ Hz}$  and solve for  $n$ , then set  $f = 2000 \text{ Hz}$  and again solve for  $n$ . The results are 2.66 and 5.32, which imply that  $n = 3, 4$ , and  $5$  are the appropriate values of  $n$ . Thus, there are 3 frequencies.

(b) The lowest frequency at which resonance occurs is  $(n = 3) f = 3(376.4 \text{ Hz}) = 1129 \text{ Hz}$ .

(c) The second lowest frequency at which resonance occurs is  $(n = 4)$

$$f = 4(376.4 \text{ Hz}) = 1506 \text{ Hz}.$$

47. The string is fixed at both ends so the resonant wavelengths are given by  $\lambda = 2L/n$ , where  $L$  is the length of the string and  $n$  is an integer. The resonant frequencies are given by  $f = v/\lambda = nv/2L$ , where  $v$  is the wave speed on the string. Now  $v = \sqrt{\tau/\mu}$ , where  $\tau$  is the tension in the string and  $\mu$  is the linear mass density of the string. Thus

$f = (n/2L)\sqrt{\tau/\mu}$ . Suppose the lower frequency is associated with  $n = n_1$  and the higher frequency is associated with  $n = n_1 + 1$ . There are no resonant frequencies between so you know that the integers associated with the given frequencies differ by 1. Thus

$$f_1 = (n_1/2L)\sqrt{\tau/\mu} \text{ and}$$

$$f_2 = \frac{n_1+1}{2L} \sqrt{\frac{\tau}{\mu}} = \frac{n_1}{2L} \sqrt{\frac{\tau}{\mu}} + \frac{1}{2L} \sqrt{\frac{\tau}{\mu}} = f_1 + \frac{1}{2L} \sqrt{\frac{\tau}{\mu}}.$$

This means  $f_2 - f_1 = (1/2L)\sqrt{\tau/\mu}$  and

$$\tau = 4L^2\mu(f_2 - f_1)^2 = 4(0.300 \text{ m})^2(0.650 \times 10^{-3} \text{ kg/m})(1320 \text{ Hz} - 880 \text{ Hz})^2 = 45.3 \text{ N}.$$

53. Each wire is vibrating in its fundamental mode so the wavelength is twice the length of the wire ( $\lambda = 2L$ ) and the frequency is  $f = v/\lambda = (1/2L)\sqrt{\tau/\mu}$ , where  $v = \sqrt{\tau/\mu}$  is the wave speed for the wire,  $\tau$  is the tension in the wire, and  $\mu$  is the linear mass density of the wire. Suppose the tension in one wire is  $\tau$  and the oscillation frequency of that wire is  $f_1$ . The tension in the other wire is  $\tau + \Delta\tau$  and its frequency is  $f_2$ . You want to calculate

$\Delta\tau/\tau$  for  $f_1 = 600$  Hz and  $f_2 = 606$  Hz. Now,  $f_1 = (1/2L)\sqrt{\tau/\mu}$  and  $f_2 = (1/2L)\sqrt{(\tau + \Delta\tau)/\mu}$ , so

$$f_2 / f_1 = \sqrt{(\tau + \Delta\tau)/\tau} = \sqrt{1 + (\Delta\tau/\tau)}.$$

This leads to  $\Delta\tau/\tau = (f_2 / f_1)^2 - 1 = [(606 \text{ Hz}) / (600 \text{ Hz})]^2 - 1 = 0.020$ .

65. (a) The expression for the Doppler shifted frequency is

$$f' = f \frac{v \pm v_D}{v \mp v_S},$$

where  $f$  is the unshifted frequency,  $v$  is the speed of sound,  $v_D$  is the speed of the detector (the uncle), and  $v_S$  is the speed of the source (the locomotive). All speeds are relative to the air. The uncle is at rest with respect to the air, so  $v_D = 0$ . The speed of the source is  $v_S = 10$  m/s. Since the locomotive is moving away from the uncle the frequency decreases and we use the plus sign in the denominator. Thus

$$f' = f \frac{v}{v + v_S} = (500.0 \text{ Hz}) \left( \frac{343 \text{ m/s}}{343 \text{ m/s} + 10.00 \text{ m/s}} \right) = 485.8 \text{ Hz}.$$

(b) The girl is now the detector. Relative to the air she is moving with speed  $v_D = 10.00$  m/s toward the source. This tends to increase the frequency and we use the plus sign in the numerator. The source is moving at  $v_S = 10.00$  m/s away from the girl. This tends to decrease the frequency and we use the plus sign in the denominator. Thus  $(v + v_D) = (v + v_S)$  and  $f' = f = 500.0$  Hz.

(c) Relative to the air the locomotive is moving at  $v_S = 20.00$  m/s away from the uncle. Use the plus sign in the denominator. Relative to the air the uncle is moving at  $v_D = 10.00$  m/s toward the locomotive. Use the plus sign in the numerator. Thus

$$f' = f \frac{v + v_D}{v + v_S} = (500.0 \text{ Hz}) \left( \frac{343 \text{ m/s} + 10.00 \text{ m/s}}{343 \text{ m/s} + 20.00 \text{ m/s}} \right) = 486.2 \text{ Hz}.$$

(d) Relative to the air the locomotive is moving at  $v_S = 20.00$  m/s away from the girl and the girl is moving at  $v_D = 20.00$  m/s toward the locomotive. Use the plus signs in both the numerator and the denominator. Thus  $(v + v_D) = (v + v_S)$  and  $f' = f = 500.0$  Hz.

77. The siren is between you and the cliff, moving away from you and towards the cliff. Both “detectors” (you and the cliff) are stationary, so  $v_D = 0$  in Eq. 17–47 (and see the discussion in the textbook immediately after that equation regarding the selection of  $\pm$  signs). The source is the siren with  $v_S = 10$  m/s. The problem asks us to use  $v = 330$  m/s for the speed of sound.

(a) With  $f = 1000$  Hz, the frequency  $f_y$  you hear becomes

$$f_y = f \left( \frac{v+0}{v+v_s} \right) = 970.6 \text{ Hz} \approx 9.7 \times 10^2 \text{ Hz}.$$

(b) The frequency heard by an observer at the cliff (and thus the frequency of the sound reflected by the cliff, ultimately reaching your ears at some distance from the cliff) is

$$f_c = f \left( \frac{v+0}{v-v_s} \right) = 1031.3 \text{ Hz} \approx 1.0 \times 10^3 \text{ Hz}.$$

(c) The beat frequency is  $f_c - f_y = 60$  beats/s (which, due to specific features of the human ear, is too large to be perceptible).

81. (a) With  $r = 10$  m in Eq. 17–28, we have

$$I = \frac{P}{4\pi r^2} \Rightarrow P = 10 \text{ W}.$$

(b) Using that value of  $P$  in Eq. 17–28 with a new value for  $r$ , we obtain

$$I = \frac{P}{4\pi (5.0)^2} = 0.032 \frac{\text{W}}{\text{m}^2}.$$

Alternatively, a ratio  $I'/I = (r/r')^2$  could have been used.

(c) Using Eq. 17–29 with  $I = 0.0080 \text{ W/m}^2$ , we have

$$\beta = 10 \log \frac{I}{I_0} = 99 \text{ dB}$$

where  $I_0 = 1.0 \times 10^{-12} \text{ W/m}^2$ .

85. (a) The intensity is given by  $I = \frac{1}{2} \rho v \omega^2 s_m^2$ , where  $\rho$  is the density of the medium,  $v$  is the speed of sound,  $\omega$  is the angular frequency, and  $s_m$  is the displacement amplitude. The displacement and pressure amplitudes are related by  $\Delta p_m = \rho v \omega s_m$ , so  $s_m = \Delta p_m / \rho v \omega$  and  $I = (\Delta p_m)^2 / 2 \rho v$ . For waves of the same frequency the ratio of the intensity for propagation in water to the intensity for propagation in air is

$$\frac{I_w}{I_a} = \left( \frac{\Delta p_{mw}}{\Delta p_{ma}} \right)^2 \frac{\rho_a v_a}{\rho_w v_w},$$

where the subscript  $a$  denotes air and the subscript  $w$  denotes water. Since  $I_a = I_w$ ,

$$\frac{\Delta p_{mw}}{\Delta p_{ma}} = \sqrt{\frac{\rho_w v_w}{\rho_a v_a}} = \sqrt{\frac{(0.998 \times 10^3 \text{ kg/m}^3)(1482 \text{ m/s})}{(1.21 \text{ kg/m}^3)(343 \text{ m/s})}} = 59.7.$$

The speeds of sound are given in Table 17-1 and the densities are given in Table 15-1.

(b) Now,  $\Delta p_{mw} = \Delta p_{ma}$ , so

$$\frac{I_w}{I_a} = \frac{\rho_a v_a}{\rho_w v_w} = \frac{(1.21 \text{ kg/m}^3)(343 \text{ m/s})}{(0.998 \times 10^3 \text{ kg/m}^3)(1482 \text{ m/s})} = 2.81 \times 10^{-4}.$$

87. (a) When the right side of the instrument is pulled out a distance  $d$  the path length for sound waves increases by  $2d$ . Since the interference pattern changes from a minimum to the next maximum, this distance must be half a wavelength of the sound. So  $2d = \lambda/2$ , where  $\lambda$  is the wavelength. Thus  $\lambda = 4d$  and, if  $v$  is the speed of sound, the frequency is

$$f = v/\lambda = v/4d = (343 \text{ m/s})/4(0.0165 \text{ m}) = 5.2 \times 10^3 \text{ Hz}.$$

(b) The displacement amplitude is proportional to the square root of the intensity (see Eq. 17-27). Write  $\sqrt{I} = Cs_m$ , where  $I$  is the intensity,  $s_m$  is the displacement amplitude, and  $C$  is a constant of proportionality. At the minimum, interference is destructive and the displacement amplitude is the difference in the amplitudes of the individual waves:  $s_m = s_{SAD} - s_{SBD}$ , where the subscripts indicate the paths of the waves. At the maximum, the waves interfere constructively and the displacement amplitude is the sum of the amplitudes of the individual waves:  $s_m = s_{SAD} + s_{SBD}$ . Solve

$$\sqrt{100} = C(s_{SAD} - s_{SBD}) \quad \text{and} \quad \sqrt{900} = C(s_{SAD} + s_{SBD})$$

for  $s_{SAD}$  and  $s_{SBD}$ . Add the equations to obtain

$$s_{SAD} = (\sqrt{100} + \sqrt{900})/2C = 20/C,$$

then subtract them to obtain

$$s_{SBD} = (\sqrt{900} - \sqrt{100})/2C = 10/C.$$

The ratio of the amplitudes is  $s_{SAD}/s_{SBD} = 2$ .

(c) Any energy losses, such as might be caused by frictional forces of the walls on the air in the tubes, result in a decrease in the displacement amplitude. Those losses are greater on path B since it is longer than path A.

101. (a) The blood is moving towards the right (towards the detector), because the Doppler shift in frequency is an *increase*:  $\Delta f > 0$ .

(b) The reception of the ultrasound by the blood and the subsequent remitting of the signal by the blood back toward the detector is a two step process which may be compactly written as

$$f + \Delta f = f \left( \frac{v + v_x}{v - v_x} \right) \quad \text{where } v_x = v_{\text{blood}} \cos \theta.$$

If we write the ratio of frequencies as  $R = (f + \Delta f)/f$ , then the solution of the above equation for the speed of the blood is

$$v_{\text{blood}} = \frac{(R-1)v}{(R+1)\cos \theta} = 0.90 \text{ m/s}$$

where  $v = 1540 \text{ m/s}$ ,  $\theta = 20^\circ$ , and  $R = 1 + 5495/5 \times 10^6$ .

(c) We interpret the question as asking how  $\Delta f$  (still taken to be positive, since the detector is in the “forward” direction) changes as the detection angle  $\theta$  changes. Since larger  $\theta$  means smaller horizontal component of velocity  $v_x$  then we expect  $\Delta f$  to decrease towards zero as  $\theta$  is increased towards  $90^\circ$ .