Chapter 17 - Sound Waves

Note Title 8/13/2006

1. Suppose that you hear a clap of thunder 16.2 s after seeing the associated lightning stroke. The speed of sound waves in air is 343 m/s, and the speed of light is 3.00×10^8 m/s. How far are you from the lightning stroke?

$(343\ m/sec)(16.2\ sec) = 5.56 \times 10^3\ m$

Note that light takes $\frac{5.56 \times 10^3}{3.00 \times 10^8} = 1.85 \times 10^{-5}\ sec$, confirming assumption it is instantaneous.

2. Find the speed of sound in mercury, which has a bulk modulus of approximately $2.80 \times 10^{10}\ N/m^2$ and a density of 13 600 kg/m^3.

$v = \sqrt{\frac{B}{\rho}} = \sqrt{\frac{2.8 \times 10^{10}}{1.36 \times 10^4}} = 1.43 \times 10^3\ m/sec$, similar to water

3. A flowerpot is knocked off a balcony 20.0 m above the sidewalk and falls toward an unsuspecting 1.75-m-tall man who is standing below. How close to the sidewalk can the flower pot fall before it is too late for a warning shouted from the balcony to reach the man in time? Assume that the man below requires 0.300 s to respond to the warning.

Time for sound to travel: $\frac{20.0\ m}{343\ m/sec} = 0.0583\ sec.$

$\therefore$ Total warning time $= 0.300 + 0.0583 = 0.358\ sec.$

This represents the minimum flight time for the pot at the end of its flight.

Total flight time for $20 - 1.75 = \frac{1}{2} g T^2$

$$\therefore \quad T = \sqrt{\frac{2(18.25)}{g}}$$

Flight time before escape period is $T - 0.358$, and the distance travelled is $\frac{1}{2} g (\Delta t)^2$

$$= \frac{1}{2} g \left(\sqrt{\frac{2(18.25)}{g}} - 0.358 \right)^2$$

$$= 12.1 \text{ m}$$

$$\therefore \quad 20 - 12.1 = 7.9 \text{ m}$$

4. air 343 m/sec $\leftarrow$

saltwater 1533 m/sec $\leftarrow$

$$343(T + 4.5) = 1553\,T$$

$$\therefore \quad 4.5(343) = 1553T - 343T = 1210T,$$

$$T = 1.28 \text{ sec},$$

$$\therefore \quad 1553\,T = \text{inlet width} = 1553(1.28) = \underline{1981 \text{ m}}$$

5\. The speed of sound in air (in m/s) depends on temperature according to the approximate expression

$$v = 331.5 + 0.607T_C$$

where T_C is the Celsius temperature. In dry air the temperature decreases about 1°C for every 150 m rise in altitude. (a) Assuming this change is constant up to an altitude of 9 000 m, how long will it take the sound from an airplane flying at 9 000 m to reach the ground on a day when the ground temperature is 30°C? (b) **What If?** Compare this to the time interval required if the air were a constant 30°C. Which time interval is longer?

(a) $\Delta T = \frac{\Delta x}{v}$ $\therefore$ sum over little Δx's

$\therefore$ Total time $= \int_0^{9000} \frac{dx}{v}$

$T_c = 30^\circ - \frac{1}{150}x$

$V(T_c) = 331.5 + 0.607 T_c$

$\therefore V(x) = 331.5 + 0.607\left(30 - \frac{x}{150}\right)$

$= 349.7 - 0.00405x$

$\therefore T_{total} = \int_0^{9000} \frac{dx}{349.7 - 0.00405x}$

$= -\frac{1}{0.00405} \ln(349.7 - 00405x) \Big|_0^{9000}$

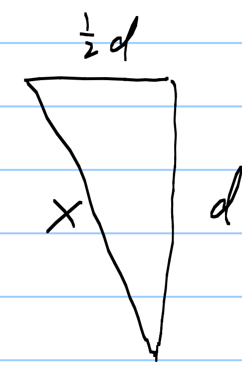
$= -\frac{1}{0.00405}\left[\ln(313.28) - \ln(349.7)\right]$

$= 27.2$ secs.

(b) at $30°C$ all altitudes, $v = 331.5 + 0.607(30)$
$= 349.7$ m/sec.

$\therefore \frac{9000}{349.7} = 25.7$ sec.

7. A rescue plane flies horizontally at a constant speed searching for a disabled boat. When the plane is directly above the boat, the boat's crew blows a loud horn. By the time the plane's sound detector perceives the horn's sound, the plane has traveled a distance equal to half its altitude above the ocean. If it takes the sound 2.00 s to reach the plane, determine (a) the speed of the plane and (b) its altitude. Take the speed of sound to be 343 m/s.



$d^2 + \left(\frac{d}{2}\right)^2 = \frac{5}{4}d^2 = x^2$, so $x = \frac{\sqrt{5}}{2} d$

$\therefore \frac{\sqrt{5}}{2} d = (343)(2.00\,\text{sec})$, $d = 613.6$ m

$\therefore \frac{d/2}{2\,\text{sec}} = 153$ m/sec

8. A sound wave in air has a pressure amplitude equal to 4.00×10^{-3} N/m^2. Calculate the displacement amplitude of the wave at a frequency of 10.0 kHz.

$\Delta P_{max} = \rho v \omega s_{max}$, $\omega = 2\pi f$

$$\therefore S_{max} = \frac{\Delta P_{max}}{\rho v 2\pi f} = \frac{4.00 \times 10^{-3}}{(1.20)(343)(6.28)(10 \times 10^{3})}$$

$$= \underline{\underline{1.55 \times 10^{-10}\ m}}$$

9. A sinusoidal sound wave is described by the displacement wave function

$$s(x, t) = (2.00\ \mu\text{m}) \cos[(15.7\ \text{m}^{-1})x - (858\ \text{s}^{-1})t]$$

(a) Find the amplitude, wavelength, and speed of this wave. (b) Determine the instantaneous displacement from equilibrium of the elements of air at the position $x = 0.050\ 0$ m at $t = 3.00$ ms. (c) Determine the maximum speed of the element's oscillatory motion.

(a) Amplitude $= 2.00\ \mu m$

$$K = 15.7\ m^{-1} = \frac{2\pi}{\lambda},\quad \lambda = 0.400\ m$$

$$\omega = \frac{2\pi}{T} = 2\pi f = 858,\quad f = 137\ Hz$$

$$\therefore V = \lambda f = \frac{\omega}{K} = \frac{858}{15.7} = 54.6\ m/sec$$

(b) $S(0.050\,m, 3.00 \times 10^{-3}\,sec) =$

$$2.00\ \mu m \cos(15.7(0.050) - 858(3 \times 10^{-3}))$$

$$= -0.433\ \mu m$$

(c) $V_{max} = \omega(\text{Amplitude}) = (858)(2.0\,\mu m)$
$= 1716\,\mu m/sec = 1.72\,mm/sec$

13. The tensile stress in a thick copper bar is 99.5% of its elastic breaking point of $13.0 \times 10^{10}\ \text{N/m}^2$. If a 500-Hz sound wave is transmitted through the material, (a) what displacement amplitude will cause the bar to break? (b) What is the maximum speed of the elements of copper at this moment? (c) What is the sound intensity in the bar?

The bar is already under stress, so an extra 0.5% will cause it to break.

$\therefore (0.005)(13.0 \times 10^{10}\ N/m^2) = 6.50 \times 10^{8}\ N/m^2$

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

$\therefore s_{max} = \dfrac{6.5 \times 10^8}{(8.92 \times 10^3)(3560)(2\pi)(500)}$

$= 0.00651\ m = 6.5\ mm$

Using $\rho_{cu} = 8.92 \times 10^3$ (p.9, Table 1.5)
$V_{cu} = 3560$ (p.523, Table 17.1)

(b) $s(x,t) = s_{max} \cos(kx - \omega t)$,
$v = \dfrac{\partial s}{\partial t} = s_{max}\omega \sin(kx - \omega t)$,

$$V_{max} = S_{max}\,\omega = (0.00651)(2\pi)(500)$$

$$= 20.5 \text{ m/sec}$$

(c) $I = \frac{1}{2}\rho v(\omega S_{max})^2$

$$= \tfrac{1}{2}(8.92\times 10^{3})(3560)(20.5)^2$$

$$= 6.67\times 10^{9} \text{ Watts/m}^2$$

14. $\Delta P_{max} = \rho v \omega S_{max} = (1.2)(343)(2\pi)(2.0\times10^{3})(2\times10^{-8})$

$$= 1.03\times10^{-1} = 0.103 \text{ Pa}$$

21.] A family ice show is held at an enclosed arena. The skaters perform to music with level 80.0 dB. This is too loud for your baby, who yells at 75.0 dB. (a) What total sound intensity engulfs you? (b) What is the combined sound level?

(a) $80 = 10\log\left(\frac{I_{80}}{10^{-12}}\right)$, $10^{8} = \frac{I_{80}}{10^{-12}}$, $I_{80} = 1.0\times10^{-4}$

$75 = 10\log\left(\frac{I_{75}}{10^{-12}}\right)$ $10^{7.5} = \frac{I_{75}}{10^{-12}}$, $I_{75} = 10^{-4.5}$

$I_{75} = 10^{0.5}\cdot10^{-5} = 3.16\times10^{-5} = 0.316\times10^{-4}$

$\therefore I_{80} + I_{75} = 1.32\times10^{-4}$ Watts/m^2

(b) $\beta = 10 \log\left(\dfrac{1.32\times10^{-4}}{1.0\times10^{-12}}\right)$

$= 10\left(\log 1.32 + 8\right) = 10(0.121 + 8)$

$= 81.2\ dB$

22. Show that the difference between decibel levels β_1 and β_2 of a sound is related to the ratio of the distances r_1 and r_2 from the sound source by

$$\beta_2 - \beta_1 = 20\log\left(\frac{r_1}{r_2}\right)$$

Let $I_{min} =$

$1.0\times10^{-12}\ W/m^2$

$\beta_1 = 10 \log \dfrac{I_1}{I_{min}} = 10 \log \dfrac{P_{av}}{4\pi r_1^2 I_{min}}$

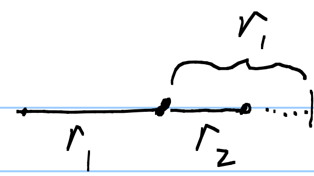
$\beta_2 = 10 \log \dfrac{P_{av}}{4\pi r_2^2 I_{min}}$

$\therefore \beta_2 - \beta_1 = 10\left[\log \dfrac{P_{av}}{4\pi r_2^2 I_{min}} - \log \dfrac{P_{av}}{4\pi r_1^2 I_{min}}\right]$

$= 10 \log\left[\dfrac{P_{av}}{4\pi r_2^2 I_{min}} \Big/ \dfrac{P_{av}}{4\pi r_1^2 I_{min}}\right]$

$= 10 \log\left(\dfrac{r_1}{r_2}\right)^2 = 20 \log\left(\dfrac{r_1}{r_2}\right)$

24. A loudspeaker is placed between two observers who are 110 m apart, along the line connecting them. If one observer records a sound level of 60.0 dB and the other records a sound level of 80.0 dB, how far is the speaker from each observer?



From prob. # 22 above, $\beta_2 - \beta_1 = 20 \log\left(\frac{r_1}{r_2}\right)$

Also, $r_1 + r_2 = 110\text{ m}$, $\beta_2 = 80\text{ dB}$, $\beta_1 = 60\text{ dB}$.

$\therefore 80 - 60 = 20 \log\left(\frac{r_1}{r_2}\right)$

$\therefore 1 = \log\left(\frac{r_1}{r_2}\right)$, $10 r_2 = r_1$

$\therefore 11 r_2 = 110\text{ m}$, $\underline{r_2 = 10\text{ m}}$, $\underline{r_1 = 100\text{ m}}$

25. Two small speakers emit sound waves of different frequencies. Speaker *A* has an output of 1.00 mW, and speaker *B* has an output of 1.50 mW. Determine the sound level (in dB) at point *C* (Fig. P17.31) if (a) only speaker *A* emits sound, (b) only speaker *B* emits sound, and (c) both speakers emit sound.

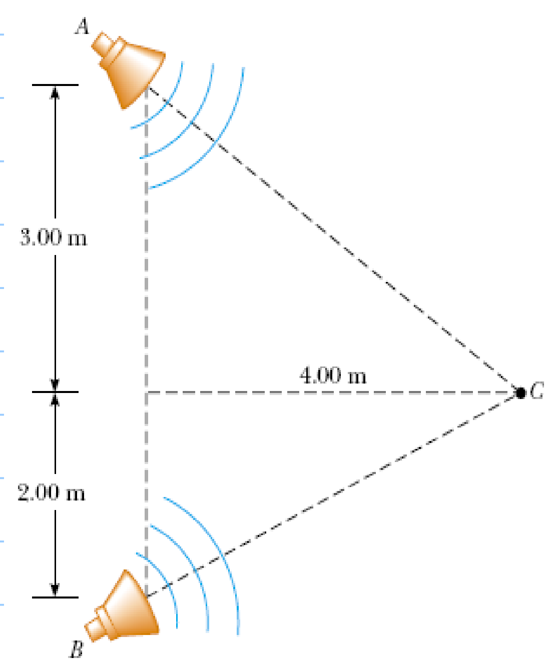


Figure P17.31

(a) A is 5.00 m from C

$\therefore I = \dfrac{1.00\times10^{-3}\text{ W}}{4\pi(5.00)^2} =$

$= 3.18\times10^{-6}\text{ W/m}^2$

$\therefore \text{dB} = 10 \log\left(\dfrac{3.18\times10^{-6}}{1.0\times10^{-12}}\right)$

$= 65.0 \, dB$

(b) B is $\sqrt{16+4} = 4.47 \, m$ from C

$\therefore I = \dfrac{1.50 \times 10^{-3} W}{4\pi (4.47)^2} = 5.97 \times 10^{-6} \, W/m^2$

$\therefore dB = 10 \log \left(\dfrac{5.97 \times 10^{-6}}{1.0 \times 10^{-12}} \right) = 67.8 \, dB$

(c) Add intensities

$$dB = 10 \log \left(\frac{5.97 \times 10^{-6} + 3.18 \times 10^{-6}}{1.0 \times 10^{-12}} \right)$$

$$= 69.6 \, dB$$

27. $dB = 10 \log \dfrac{I}{1.0 \times 10^{-12}} = 40.0$, $I = 1.0 \times 10^{-8} \, W/m^2$

At 3.0 m, $I = \dfrac{P}{A} = \dfrac{P_{av}}{4\pi (3.0)^2}$

$\therefore P_{av} = 36\pi \times 10^{-8} W = \underline{1.13 \times 10^{-6} W}$

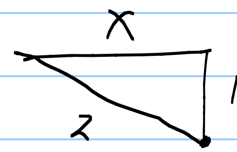
27. A jackhammer, operated continuously at a construction site, behaves as a point source of spherical sound waves. A construction supervisor stands 50.0 m due north of this sound source and begins to walk due west. How far does she have to walk in order for the amplitude of the wave function to drop by a factor of 2.00?

$$\frac{I_1}{I_2} = \frac{r_2^2}{r_1^2} . \quad I = \frac{1}{2}\rho v(\omega s_{max})^2$$

$$\therefore \frac{S_{1max}^2}{S_{2max}^2} = \frac{r_2^2}{r_1^2}, \text{ so } \frac{S_{1max}}{S_{2max}} = \frac{r_2}{r_1}$$

Here, $S_{2max} = \frac{1}{2} S_{1max}$

$$\therefore 2 = \frac{r_2}{r_1}, \text{ so}$$



$x = \sqrt{3}$

$\therefore 50(\sqrt{3}) = x = \underline{86.6\ m}$ = distance to walk.

33. (a) $f' = \left(\frac{1}{1 - \frac{V_s}{V}}\right) f = \left(\frac{1}{1 - \frac{40.0}{343}}\right) 320 = 362\ Hz$

= approaching

Passing by: $\left(\frac{1}{1 + \frac{40}{343}}\right) 320 = 287\ Hz$

$\therefore \Delta f = 75.7\ Hz$

(b) $343 = \lambda'(362\ Hz)$, $\lambda' = 0.948\ m$

36. Expectant parents are thrilled to hear their unborn baby's heartbeat, revealed by an ultrasonic motion detector. Suppose the fetus's ventricular wall moves in simple harmonic motion with an amplitude of 1.80 mm and a frequency of 115 per minute. (a) Find the maximum linear speed of the heart wall. Suppose the motion detector in contact with the mother's abdomen produces sound at 2 000 000.0 Hz, which travels through tissue at 1.50 km/s. (b) Find the maximum frequency at which sound arrives at the wall of the baby's heart. (c) Find the maximum frequency at which reflected sound is received by the motion detector. By electronically "listening" for echoes at a frequency different from the broadcast frequency, the motion detector can produce beeps of audible sound in synchronization with the fetal heartbeat.

(a) Max speed from simple harmonic motion is ωA. Here, $A = 0.0018\ m$, $\omega = 2\pi f = 2\pi(115/\text{min})$

$$= 2\pi\left(\frac{115 \text{ beats}}{\text{min}} \cdot \frac{1 \text{ min}}{60 \text{ sec}}\right) = 12.0 \frac{\text{beats}}{\text{sec}}$$

$$\therefore v = \omega A = (12.0)(0.0018) = 0.0217 \text{ m/sec}$$

(b) Wall acts as a moving source

$$\therefore f' = \left(1 + \frac{V_0}{V}\right) f = \left(1 + \frac{0.0217}{1500}\right)(2{,}000{,}000 \text{ Hz})$$

$$= 2{,}000{,}029 \text{ Hz}$$

(c) Heart wall sees waves coming in at freq in (b), but reflects, or generates, waves even faster because it is moving as a source.
i.e., because it is moving as an observer, it meets each incoming wave at frequency f', which is reflected and leaves at 1500 m/sec.

and f', but then for the next wave, acting as a moving source, generates (reflects) the next wave, and is closer to the wave front of the previously generated wave, and so the effective frequency is even higher.

$$\therefore f'' = \left(\frac{1}{1-\frac{v_s}{v}}\right) f' = \left(\frac{1}{1-\frac{0.0217}{1500}}\right)(2{,}000{,}029)$$

$$= 2{,}000{,}058 \text{ Hz}$$

37. A tuning fork vibrating at 512 Hz falls from rest and accelerates at 9.80 m/s². How far below the point of release is the tuning fork when waves of frequency 485 Hz reach the release point? Take the speed of sound in air to be 340 m/s.

$$485 = \left(\frac{1}{1+\frac{V_s}{340}}\right) 512, \quad 485 = \frac{(340)(512)}{340+V_s},$$

$$340 + V_s = \frac{(340)(512)}{485}, \quad V_s = \frac{(340)(512)}{485} - 340$$

$$V_s = 18.9 \text{ m/sec}$$

$$V_s^2 = 2gd, \quad d = \frac{(18.9)^2}{2(9.8)} = \underline{\underline{18.3 \text{ m}}}$$

38. A block with a speaker bolted to it is connected to a spring having spring constant $k = 20.0$ N/m as in Figure P17.40. The total mass of the block and speaker is 5.00 kg, and the amplitude of this unit's motion is 0.500 m. (a) If the speaker emits sound waves of frequency 440 Hz, determine the highest and lowest frequencies heard by the person to the right of the speaker. (b) If the maximum sound level heard by the person is 60.0 dB when he is closest to the speaker, 1.00 m away, what is the minimum sound level heard by the observer? Assume that the speed of sound is 343 m/s.

(a) $V_{max} = \omega A$, and $\omega^2 = \frac{K}{m}$

$$\therefore \omega = \sqrt{\frac{20.0}{5.0}} = 2.0 \text{ Hz}$$

$$\therefore V_{max} = (2.0)(0.5) = 1.0 \text{ m/sec.}$$

$$\therefore f' = \left(\frac{V}{V \pm V_s}\right) f = \left(\frac{343}{343 \pm 1}\right) 440$$

$$\therefore f = \underline{\underline{441, 439 \text{ Hz}}}$$

(b) $$\frac{I_1}{I_2} = \frac{r_2^2}{r_1^2} \quad \therefore I_2 = \frac{r_1^2 I_1}{r_2^2} = \frac{1}{(1+2A)^2} I_1$$

$$= \frac{1}{4} I_1$$

$$60 = 10 \log \frac{I_1}{10^{-12}}, \quad I_1 = 10^{-6}, \quad \therefore I_2 = 0.25 \times 10^{-6}$$

$$\therefore\ dB_2 = 10 \log \frac{2.5 \times 10^{-7}}{10^{-12}} = 10(0.40 + 5)$$

$$= \underline{54\ dB}$$

39. A train is moving parallel to a highway with a constant speed of 20.0 m/s. A car is traveling in the same direction as the train with a speed of 40.0 m/s. The car horn sounds at a frequency of 510 Hz, and the train whistle sounds at a frequency of 320 Hz. (a) When the car is behind the train, what frequency does an occupant of the car observe for the train whistle? (b) After the car passes and is in front of the train, what frequency does a train passenger observe for the car horn?

Must use $f' = \left(\frac{V \pm V_o}{V \mp V_s}\right) f$ since the medium (the air) is not moving relative to source/observer.

(a) source = train, moving away at 20 m/sec, which decreases frequency.
$\therefore\ V + V_s$

observer = car, moving toward source at 40 m/sec, increasing frequency.
$\therefore\ V + V_o$.

$$\therefore\ f = \left(\frac{343 + V_o}{343 + V_s}\right) f = \left(\frac{343 + 40}{343 + 20}\right) 320 = \underline{338\ Hz}$$

(b) source = car, moving away at 40 m/sec, decreasing freq., $\therefore\ V + V_s$

observer = train, moving toward source at 20 m/sec, increasing freq.

$\therefore V + V_o$

$$\therefore f' = \left(\frac{v+v_o}{v+v_s}\right) f = \left(\frac{343+20}{343+40}\right) 512 = \underline{485 \text{ Hz}}$$

40. At the Winter Olympics, an athlete rides her luge down the track while a bell just above the wall of the chute rings continuously. When her sled passes the bell, she hears the frequency of the bell fall by the musical interval called a minor third. That is, the frequency she hears drops to five sixths of its original value. (a) Find the speed of sound in air at the ambient temperature $-10.0°C$. (b) Find the speed of the athlete.

(a) $V = 331\sqrt{1 + \frac{T_c}{273}} = 331\sqrt{1 + \frac{-10}{273}} = 325$ m/sec.

(b) Moving toward sound, $f' = \left(\frac{V+V_o}{V}\right) f$

Moving away, $f'' = \left(\frac{V-V_o}{V}\right) f$

$$\frac{f''}{f'} = \frac{5}{6} = \frac{V-V_o}{V+V_o} = \frac{325-V_o}{325+V_o}$$

$$\therefore 5(325+V_o) = 6(325-V_o)$$

$$\therefore 11V_o = 325, \quad V_o = \underline{29.5 \text{ m/sec}}$$