CHAPTER 12

SOUND

OBJECTIVES

After studying the material of this chapter, the student should be able to:

- determine the speed of sound in air at one atmosphere of pressure at different temperatures.
- distinguish between the following terms: pitch, frequency, wavelength, sound intensity, and loudness.
- determine intensity level in decibels of a sound if the intensity of the sound is given in W/m^2.
- explain how a standing wave can be produced in a wind instrument open at both ends or closed at one end and calculate the frequencies produced by different harmonics of pipes of given length.
- determine the beat frequency produced by two tuning forks of different frequencies.
- explain how an interference pattern can be produced by two sources of sound of the same wavelength separated by a distance d.
- solve problems involving two sources for m, d, λ, and the angular separation (θ) when the other quantities are given.
- solve for the frequency of the sound heard by a listener and the wavelength of the sound between a source and the listener when the frequency of the sound produced by the source and the velocity of both the source and the listener are given.
- explain how a shock wave can be produced and what is meant by the term sonic boom.

KEY TERMS AND PHRASES

sound is a longitudinal wave produced by a vibration which travels away from the source through solids, liquids, or gases, but not through a vacuum. Since a sound wave is a longitudinal wave there are regions of compression (condensation) and expansion (rarefaction) as the wave moves through the medium that transports it.

pitch refers to the frequency of a sound wave and is measured in hertz (Hz).

intensity level of sound is the energy transported by a wave per unit time per unit area. Intensity level of sound is measured in bels; however, the decibel (dB) is more commonly used.

open pipe is a wind instrument that is open to the air at both ends. The first harmonic standing wave that produces resonance has an antinode near each end and one node in the middle of the air column.

closed pipe is a wind instrument that is open to the air at one end but closed at the other end. The first harmonic standing wave that produces resonance in the pipe has an antinode near the open end and a node at the closed end.

sound quality depends on the presence of overtones, their number, and relative amplitudes. The result gives each musical instrument its characteristic quality and timbre.

beats are regular pulsations in the loudness of a sound due to two waves of equal amplitude but slightly different frequencies traveling in the same direction. The number of beats per second is equal to the difference between the frequencies of the component waves and is known as the **beat frequency.**

Doppler effect refers to the perceived change of frequency of a wave when there is relative motion between the source and the listener.

shock waves and **sonic booms** are produced when the speed of the source of sound exceeds the speed of sound. The sound waves in front of the source tend to overlap and constructively interfere. The superposition of the waves produce an extremely large amplitude, high energy wave called a shock wave. When the shock wave passes a listener, this energy is heard as a sonic boom.

SUMMARY OF MATHEMATICAL FORMULAS

speed of sound in air measured in meters per second	$v = 331 + 0.6\,T$ m/s	The speed of sound (v) in air changes with temperature. 331 m/s is the speed of sound in air at 0°C and T is the temperature of air in degrees centigrade.
sound intensity level	$\beta(\text{in dB}) = 10 \log I/I_o$	β is the intensity level in decibels. I is the intensity of the sound in W/m^2. The threshold of hearing $I_o = 1.0 \times 10^{-12}\ W/m^2$.
harmonic frequency produced by an open pipe	$f_n = v/\lambda_n = v/(2L/n)$	The harmonic frequency produced by an open pipe depends on the speed of sound (v) and the length of the pipe (L). The frequencies of successive harmonics are consecutive whole number multiples of the first harmonic, i.e., n = 1, 2, 3, etc.
harmonic frequency produced by a pipe closed at one end	$f_n = v/\lambda_n$ $f_n = v/[4L/(2n - 1)]$	The harmonic frequency produced by a closed pipe depends on the speed of sound (v) and the length of the pipe (L). The frequencies of successive harmonics are consecutive odd whole number multiples of the first harmonic, i.e., n = 1, 3, 5, 7, etc.

sound interference pattern produced by two sources of sound which are in phase and have the same wavelength	constructive interference $\sin \theta = m\lambda/d$ destructive interference $\sin \theta = (m + ½)\lambda/d$	angular displacement (θ) of maxima and minima produced by two sources of sound which are in phase and have the same wavelength (λ). m = 1, 2, 3, etc.
beat frequency	$f_b = f_1 - f_2$	The beat frequency equals the difference between the two frequencies.
Doppler effect source moving toward a stationary listener source moving away from a stationary listener listener moving toward a stationary source listener moving toward a stationary source	$f' = [1/(1 - v_s/v)]\ f$ $f' = [1/(1 + v_s/v)]\ f$ $f' = [1 + (v_o)/(v)]\ f$ $f' = [1 - (v_o)/(v)]\ f$	The frequency (f ') heard by the listener depends on the speed of sound (v), the frequency of the sound emitted by the source (f), speed of the source (v_s) or the speed of the listener (v_o), and the direction of motion of the source (or listener).

CONCEPT SUMMARY

Sound Waves

Sound is a longitudinal wave produced by a vibration which travels away from the source through solids, liquids, or gases, but not through a vacuum. Since a sound wave is a longitudinal wave there are regions of compression (condensation) and expansion (rarefaction) as the wave moves through the medium that transports it.

The speed is independent of the barometric pressure, frequency, and wavelength of the sound. However, the speed of sound in a gas is proportional to the temperature. Use the following equation to determine the speed of sound in air:

$$v = 331 + 0.6\ T \text{ m/s}$$

where v is the speed of sound in meters per second, 331 is the speed of sound in m/s at 0°C, and T is the temperature in degrees centigrade.

Pitch

Pitch refers to the frequency of a sound wave and is measured in hertz (Hz). The range of human hearing is from 20 Hz to 20,000 Hz. This is called the audible range. This range is considered to be the limits of human hearing. The actual range that can be heard varies from person to person. As a person ages, the ear becomes less responsive to higher frequencies.

Sound waves above 20,000 Hz are called ultrasonic and have found application in medicine and other fields. Those below 20 Hz are called infrasonic waves.

Sound Intensity

The ear transforms the energy of sound waves into electrical signals which are carried to the brain by the nerves. The ear is not equally responsive to all frequencies of sound. It is most sensitive to sounds between 2000 Hz and 3000 Hz.

Loudness is a subjective physiological sensation in a human being that increases with the intensity of a sound. Our subjective sensation of loudness depends not only on **intensity** but also on frequency. A person easily hearing a sound at 1000 Hz may not be able to hear a sound of equal intensity at 50 Hz.

The loudness of a sound is approximately proportional to the common logarithm of the intensity. The intensity level is measured in **bels**, named after Alexander Graham Bell; however, the **decibel** (dB) is more commonly used. The decibel equals one-tenth bel, i.e., 1 dB = 0.1 bel. The formula for the intensity level is

$$\beta(\text{in dB}) = 10 \log I/I_o$$

where β is the intensity level in decibels, I is the intensity of the sound in watt/m^2, and I_o is the minimum intensity audible to the average person and is called the threshold of hearing.

$$I_o = 1.0 \times 10^{-12} \text{ watt/m}^2.$$

The sound levels in dB that are common in everyday life extend from 0 dB (the threshold of hearing) to 140 dB for a jet plane 30 meters away. Ordinary conversation is approximately 65 dB while an indoor rock concert may be 120 dB, which is at the threshold of pain. Exposure to sound levels above 85 dB over an extended period of time may lead to permanent damage to a person's hearing. A table listing intensity levels and intensities of various sounds is given in the textbook.

TEXTBOOK QUESTION 2. What is the evidence that sound is a form of energy?

ANSWER: A source of a sound forces the molecules of the surrounding medium to move in vibratory motion. From chapter 6 in the textbook, a force acting on an object which moves the object through a distance does work. This work equals the change in the object's energy. Evidence of sound energy is apparent to any student who has ever attended a rock concert. If the music is loud enough, the student can feel his chest moving to the beat of the music.

EXAMPLE PROBLEM 1. During an indoor rock concert, sound intensities of 0.15 W/m^2 are produced. Determine the a) intensity levels of these sounds in decibels, and b) amplitude of the sound wave if its frequency is 500 hertz. The density of air is 1.29 kg/m^3 and the speed of sound is 340 m/s.

Part a. Step 1. Apply the formula for the intensity level in decibels.	Solution: (Section 12-2) $I_o = 1.0 \times 10^{-12}$ W/m^2. $\beta = 10 \log (I/I_o)$ $= 10 \log (0.15\ W/m^2/1.0 \times 10^{-12}\ W/m^2) = 10 \log (1.5 \times 10^{11})$ Using your calculator, $\log (1.5 \times 10^{11}) = 11.2$ therefore, $\beta = (10)(11.2)$ dB = 112 dB
Part b. Step 1. Use the equation introduced in chapter 11 of the textbook that relates intensity, frequency, and amplitude to solve for the amplitude.	$I = 2 \pi^2 v \rho f^2 x_o^2$ $0.15\ W/m^2 = 2 \pi^2 (340\ m/s)(1.29\ kg/m^3)(500\ Hz)^2 x_o^2$ $x_o^2 = 6.94 \times 10^{-11}\ m^2$ $x_o = 8.3 \times 10^{-6}$ m or 0.0083 mm Even for very loud sounds, the maximum displacement of air from the equilibrium position is very small.

Sources of Sounds: Musical Instruments

String Instruments

While the theory behind standing waves in stringed instruments was discussed in Chapter 11 of the textbook, it should be noted that the sounds produced by vibrating strings are not very loud. Thus, many stringed instruments make use of a sounding board or box, sometimes called a resonator, to amplify the sounds produced. The strings on a piano are attached to a sounding board while for guitar strings a sound box is used. When the string is plucked and begins to vibrate, the sounding board or box begins to vibrate as well. Since the board or box has a greater area in contact with the air, it tends to amplify the sounds.

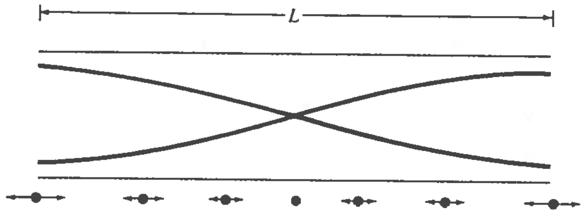
Wind Instruments

The sounds that are produced by a **wind instrument** are the result of standing waves produced in the air contained within the instrument. In some wind instruments, such as woodwinds or brasses, the air is set into vibration by a vibrating reed or the vibrating lip of the musician. In other cases, e.g., the flute or organ, a stream of air is directed against one edge of an opening or mouthpiece. The resulting turbulence produces vibrations within the instrument. The vibrations cover a range of frequencies which are due to longitudinal standing waves which are created in the air column.

Open Pipe

A wind instrument that is open to the air at both ends is known as an **open tube** or **pipe**. The longitudinal standing wave that produces the sound has an antinode at each end and at least one node in the air column. Assuming that the speed of sound is constant, and $v = f\lambda$ for a periodic wave, the frequency produced depends on the length of the tube.

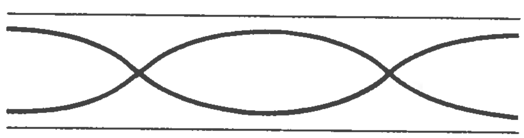
The possible modes of vibration, called harmonics, are similar to those produced in strings. In order to simplify the discussion, the diagrams below show transverse standing waves rather than longitudinal standing waves. The antinodal point in a longitudinal standing wave would actually be a region of alternating compressions and expansions and high pressure variation while at the nodal points the air pressure would remain relatively constant.



First harmonic = fundamental

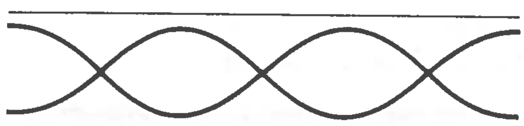
$L = \frac{1}{2}\lambda_1$ $f_1 = v/(2L)$

(actual motion of molecules)



second harmonic

$L = \lambda_1$ $f_2 = v/L$



Third harmonic

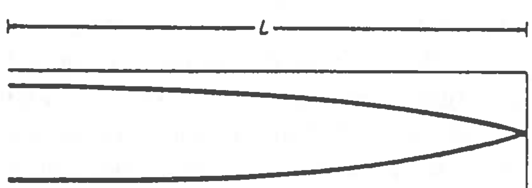
$L = 3/2\ \lambda_3$ $f_3 = (3v)/(2L)$

In general, $\frac{1}{2}\lambda_n = L/n$, where n is an integer and refers to the mode of vibration, e.g., for the 3rd harmonic $n = 3$. The frequency of the particular harmonic can then be determined since $f = v/\lambda_n = v/(2L/n)$. The frequencies of successive harmonics are consecutive whole number multiples of the first harmonic, i.e., 2, 3, 4, etc., times the frequency of the first harmonic.

Closed Pipe

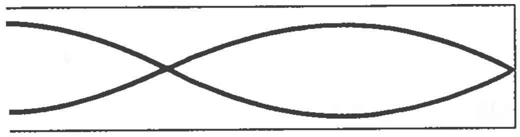
A wind instrument that is open to the air at one end but closed at the other end is known as a **closed tube** or **closed pipe**. The longitudinal standing wave produced in the pipe has an antinode at the open end but a node at the closed end. Assuming the speed of sound is constant, and $v = f\lambda$ for a periodic wave, then the frequency produced depends on the length of the tube.

The diagram shown below represents the first mode of vibration in a closed pipe. The second and third modes of vibration are shown at the top of the next page.



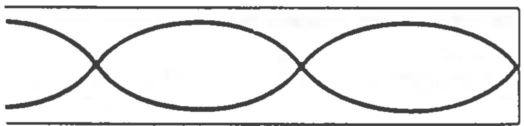
First harmonic = fundamental

$L = \frac{1}{4}\lambda_1$ $f_1 = v/(4L)$



Third harmonic

$L = \frac{3}{4}\lambda_3$ $f_3 = \frac{3}{4}\, v/L$

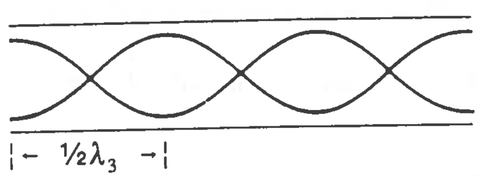
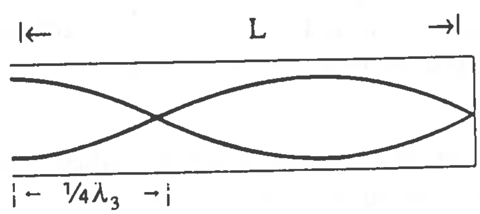


Fifth harmonic

$L = (5/4)\lambda_5$ $f_5 = (5v)/(4L)$

In general, $\frac{1}{4}\lambda_n = L/(2n - 1)$, where n is an integer and refers to the mode of vibration, e.g., for the third harmonic, n = 3. The frequency of the particular harmonic can then be determined, since $f_n = v/\lambda_n = v/[4L/(2n - 1)]$. The frequencies of successive harmonics for a pipe closed at one end are consecutive odd number multiples of the first harmonic, i.e., 3, 5, 7, etc., times the frequency of the first harmonic.

EXAMPLE PROBLEM 2. (a) An open pipe produces a third harmonic standing wave of frequency 1000 Hz on a day when the speed of sound is 340 m/s. Determine the length of the pipe. (b) The pipe is now closed at one end, determine the frequency of the third harmonic.

Part a. Step 1. Determine the wavelength of the sound waves.	Solution: (Section 12-5) $\lambda = v/f$ $= (340\ \text{m/s})/(1000\ \text{Hz})$ $\lambda = 0.340$ meters
Part a. Step 2. Draw an accurate diagram for the 3rd harmonic and determine the length of the pipe.	3rd harmonic  $\frac{1}{2}\lambda_3 = \frac{1}{3}L$ $L = (3/2)\ \lambda_3$ $= (3/2)(0.340\ \text{m})$ $L = 0.510$ m
Part b. Step 1. Draw an accurate diagram for the 3rd harmonic and determine the wavelength of the sound.	3rd harmonic  $\frac{1}{4}\lambda_3 = \frac{1}{3}L$ $\lambda_3 = 3(\frac{1}{4})(0.510\ \text{m})$ $\lambda_3 = 0.383$ m

Part b. Step 2. Determine the frequency of the sound waves.	$f = v/\lambda$ $= (340\ m/s)/(0.383\ m)$ $f = 888\ Hz$

TEXTBOOK QUESTION 7. How will the temperature in a room affect the pitch of organ pipes?

ANSWER: The frequency the first harmonic of an open pipe is given by $f_1 = v/(2L)$, while for a closed pipe $f_1 = v/(4L)$. Therefore, the frequency is directly proportional to the velocity of sound in air. The velocity of sound in air changes with temperature, i.e., $v = (331 + 0.60\ T)$ m/s where the temperature T is measured in degrees Celsius. As the temperature increases, the velocity increases and the pitch produced by the organ pipe increases.

Quality

The **quality** of a sound depends on the presence of overtones, their number, and relative amplitudes. A piano and a guitar may be playing the same note, with the same frequency and amplitude, yet the sounds are clearly distinguishable. The reason for this is that the relative amplitudes of the harmonics that are produced are different for different instruments and the note which is produced is the result of the superposition of the various harmonics. The result gives each instrument its characteristic quality and timbre.

Even two guitars will sound different because of certain characteristics in the construction of the instrument. These characteristics determine the relative amplitudes of the harmonics.

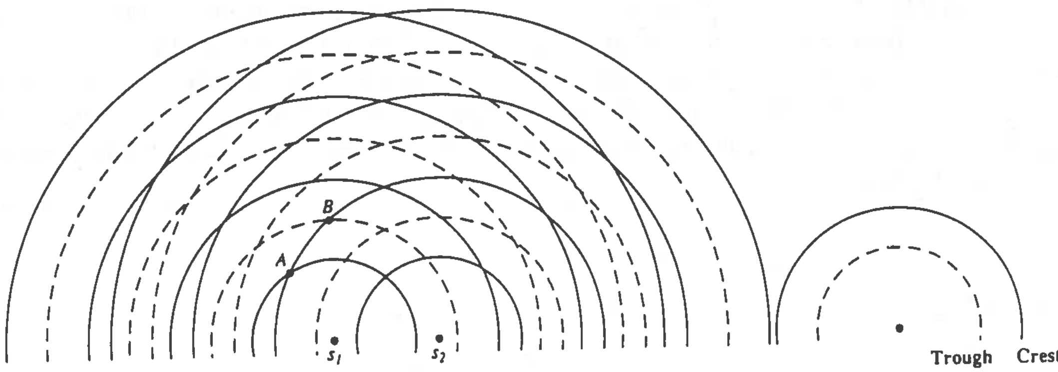
Music Versus Noise

Our minds interpret sounds that include frequencies that are simple multiples of one another as harmonious or pleasing to the ear. Noise is the result of many vibrations of different frequencies and amplitudes with no particular relationship to one another. Oftentimes, the distinction between music and noise is not sharp. The determination must be made by the individual. Thus what is music to the ears of the typical teenager might be considered noise by the typical parent.

Interference of Sound Waves

An **interference pattern** will be produced by two sources of sound waves separated by a certain distance (d) if the sounds produced are of the same frequency and amplitude. The interference pattern represented at the top of the next page is the result of sound produced by two sources, source 1 (s_1) and source 2 (s_2), both of which are in phase. The term "in phase" means that both sources produce compressions at the same moment of time and expansions at the same moment of time.

At locations where the path difference is a whole number multiple of the wavelength, the waves will arrive in phase and constructive interference occurs. Point A in the diagram is such a point. The distance from source 1 to point A is 1λ, while from source 2 the distance is 2λ. The path difference is therefore $2\lambda - 1\lambda = 1\lambda$.



At locations where the path difference is odd multiples of ½λ, the waves arrive out of phase, i.e., a compression is superimposed on a expansion, and destructive interference occurs. Point B in the diagram is such a point. The distance from source 1 to point B is 3/2 λ and from source 2 is 2λ. The path difference is therefore 2λ - 3/2 λ = ½λ.

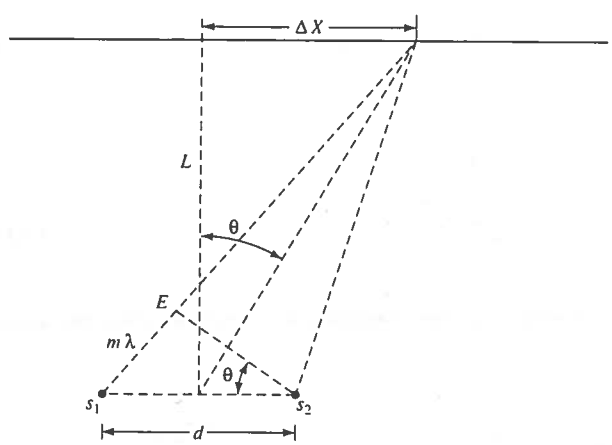
In the diagram shown below, the path difference is represented by the distance from source 1 to E. This distance is mλ for constructive interference and (m + ½)λ for destructive interference, where m = 0, 1, 2, 3, 4, etc.

The following formulas can be used to determine the positions of constructive and destructive interference if the angle θ is relatively small (less than 15°). For small angles, $\tan\theta \approx \sin\theta \approx \theta$, where θ is in radians.

For constructive interference: $\tan\theta = \Delta X/L$ but $\sin\theta = m\lambda/d$ and $\Delta X/L = m\lambda/d$

For destructive interference: $\tan\theta = \Delta X/L$ but $\sin\theta = (m + ½)\lambda/d$ and $\Delta X/L = (m + ½)\lambda/d$

ΔX is the perpendicular distance from the center line to the point in question. L is the length of the center line, mλ or (m + ½)λ is the path difference, and d is the distance between the sources of the sound waves.



EXAMPLE PROBLEM 3. Two point sources of sound are in phase and separated by a distance (d) of 4.0 m. The frequency of the sound is 600 Hz. A listener stands at a point that is 10.0 m along a center line (L) that bisects the line which connects the two speakers. The listener then walks perpendicular to the center line. Determine the distance (ΔX) from the center line to the first two a) nodal points, b) antinodal points that are to the left of the center line. Assume the speed of sound is 340 m/s.

Part a. Step 1. Determine the wavelength of the sound waves.	Solution: (Section 12-7) $\lambda = v/f = (340\text{ m/s})/(600\text{ Hz})$ $\lambda = 0.567$ m
Part a. Step 2. Draw an accurate diagram and list each of the quantities given.	d = 4.0 m L = 10.0 m $\lambda = 0.567$ m $\Delta X = ?$
Part a. Step 3. Apply the formula for destructive interference to determine the positions of the first two nodal points, m = 0 and m = 1.	first nodal point (m = 0); $\Delta X/L = (0 + ½)\lambda/d$ $\Delta X/(10.0\text{ m}) = (½)(0.567\text{ m})/(4.0\text{ m})$ $\Delta X = 0.71$ m second nodal point (m = 1); $\Delta X/L = (1 + ½)\lambda/d$ $\Delta X/(10.0\text{ m}) = (3/2)(0.567\text{ m})/(4.0\text{ m})$ $\Delta X = 2.13$ m
Part b. Step 1. Apply the formula for constructive interference to determine the positions of the first two antinodal points to the left of the center line, m = 1 and m = 2.	The sources are in phase and therefore an antinodal point occurs along the center line (m = 0). The first two antinodal points to the the left of the center line occur at m = 1 and m = 2. $\Delta X/L = m\lambda/d$ where m = 1 for the 1st nodal point $\Delta X/(10.0\text{ m}) = 1(0.567\text{ m})/(4.0\text{ m})$ $\Delta X = 1.42$ m $\Delta X/(10.0\text{ m}) = 2(0.567\text{ m})/(4.0\text{ m})$ and m = 2 for 2nd nodal point: $\Delta X = 2.84$ m

Beats

Two waves of equal amplitude but slightly different frequencies traveling in the same direction give rise to pulsations of maximum and minimum sound known as **beats**. The number of beats per second is equal to the difference between the frequencies of the component waves and is known as the beat frequency, $f_b = f_1 - f_2$. For example, if waves of 600 hertz and 610 hertz interfere to produce beats, the beat frequency would be 610 Hz - 600 Hz = 10 Hz, i.e., 10 beats per second would be heard.

EXAMPLE PROBLEM 4. A student strikes two tuning forks and hears 2 beats per second. He notes that 440 Hz is printed on one tuning fork. Determine the frequency of the other fork.

Part a. Step 1.	Solution: (Section 12-7)
Determine the frequency of the second tuning fork.	This problem has two possible answers. The difference between the two frequencies must be 2 Hz; however, we cannot be sure which tuning fork has the higher frequency.
	Let f_1 = 440 Hz and f_2 = ?,
	then either $f_1 - f_2$ = 1 Hz
	440 Hz - f_2 = 2 Hz and f_2 = 438 Hz
	or $f_2 - f_1$ = 2 Hz
	f_2 - 440 Hz = 2 Hz and f_2 = 442 Hz
	Therefore, the frequency of the second tuning fork may either be 438 Hz or 440 Hz.

Doppler Effect

When a source of sound waves and a listener approach one another, the pitch of the sound is increased as compared to the frequency heard if they remain at rest. If the source and the listener recede from one another, the frequency is decreased. This phenomena is known as the **Doppler effect**. The pitch heard by the listener is given by the following equations:

$f' = [1/(1 - v_s/v)]\, f$

source moving toward a stationary listener

$f' = [1/(1 + v_s/v)]\, f$

source moving away from a stationary listener

$f' = (1 + v_o/v)\, f$

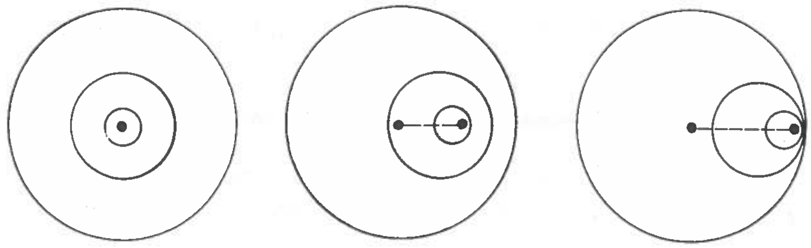
listener moving toward a stationary source

$f' = (1 - v_o/v)\, f$

listener moving away from a stationary source

f' is the frequency of the sound heard by the listener (observer), f is the frequency of the sound emitted by the source, v is the speed of sound in air, v_s is the velocity of the source, and v_o is the velocity of the listener (observer).

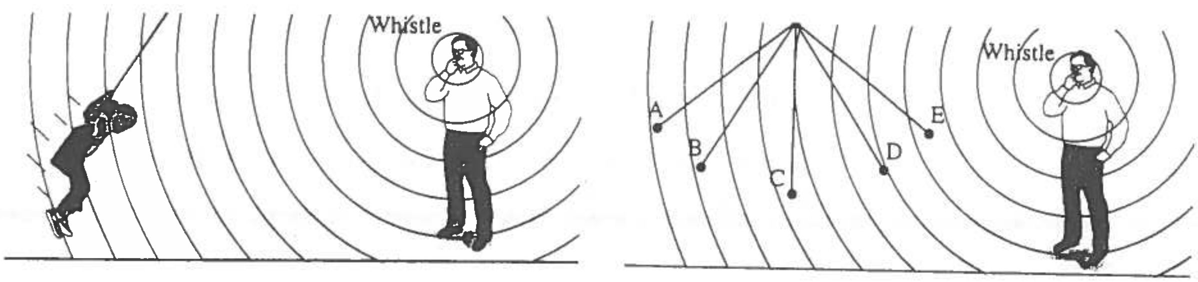
Common examples of the Doppler effect include the change in pitch of the siren of a police car or ambulance as it passes at high speed, as well as the change in pitch of the whistle of a passing train.



(a) $v_{obj} = 0$ (b) $v_{obj} < v_{snd}$ (c) $v_{obj} = v_{snd}$

Light waves also exhibit the Doppler effect. The spectra of stars that are receding from us is shifted toward the longer wavelengths of light. This is known as the **red shift**. Measurement of the red shift allows astronomers to calculate the speed at which stars are moving away. Since almost all stars and galaxies exhibit a red shift, it is believed that the universe is expanding.

TEXTBOOK QUESTION 17. Figure 12-32 shows the various positions of a child in motion on a swing. A monitor is blowing a whistle in front of the child on the ground. At which position will the child hear the highest frequency for the sound of the whistle? Explain your reasoning.



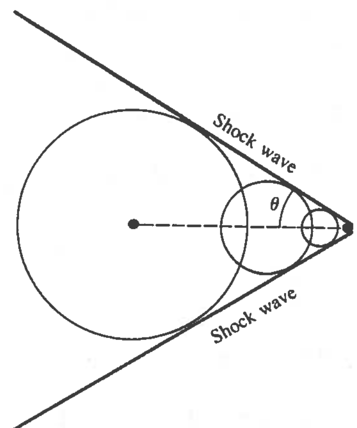
ANSWER: A child's speed on a swing is greatest at the bottom of the arc, i.e., at point C. The Doppler effect predicts that the frequency heard by the child will be greatest when the child's speed approaching the whistle is greatest. This occurs at point C as the child approaches the whistle. The lowest frequency heard by the child also occurs at point C as the child is traveling away from the whistle.

EXAMPLE PROBLEM 5. A stationary source emits sound of frequency 500 Hz on a day when the speed of sound is 340 m/s. A listener moves toward the source of sound at 40 m/s. Determine the a) frequency heard by the listener, b) wavelength of the sound between the source and the listener, and c) answer parts a and b if the listener was moving away from the source.

Part a. Step 1.	Solution: (Section 12-8)
Determine the frequency heard by the listener.	This problem involves the Doppler effect. Apply the formula for a moving listener approaching a stationary source.
	$f' = [1 + (v_o)/(v)]\, f$
	$f' = [1 + (40\text{ m/s})/(340\text{ m/s})](500\text{ Hz}) = 560\text{ Hz}$

Part b. Step 1. Determine the wavelength of the sound between the source and the listener.	The source of the sound is not moving; therefore, the wavelength of the sound remains the same regardless of the listener's speed. $\lambda = v/f$ $\lambda = (340 \text{ m/s})/(500 \text{ Hz}) = 0.68 \text{ m}$
Part c. Step 1. Solve for the listener moving away.	The wavelength of the sound will not change whether the listener is moving toward or away from the source; however, the frequency heard will change. Apply the formula for a listener moving away from the source. $f' = [1 - (v_o)/(v)]\, f = [1 - (40 \text{ m/s})/(340 \text{ m/s})]\,(500 \text{ Hz})$ $f' = 441 \text{ Hz}$

Shock Waves and the Sonic Boom



(d) $v_{obj} > v_{snd}$

When the speed of a source of sound exceeds the speed of sound, the sound waves in front of the source tend to overlap and constructively interfere. The superposition of the waves produce an extremely large amplitude wave called a **shock wave**.

The shock wave contains a great deal of energy. When the shock wave passes a listener, this energy is heard as a **sonic boom**. The sonic boom is heard only for a fraction of a second; however, it sounds as if an explosion has occurred and can cause damage.

PROBLEM SOLVING SKILLS

For problems involving the sound intensity:

1. Complete a data table noting the intensity level of the sound, the intensity of the threshold of hearing, frequency of the sound, the density of air, and the speed of sound.
2. Solve for the sound intensity in decibels and the amplitude of the sound wave.

For problems involving harmonics produced in pipes:

1. If necessary, solve for the speed of sound in the pipe.
2. Note whether the problem involves an open or closed pipe. Draw an accurate diagram locating the nodes and antinodes for the harmonic(s) requested.

3. Determine the wavelength of the waves producing the particular harmonic.
4. Solve for the frequency of the particular harmonic. If the frequency is given use the above steps to solve for the length of the pipe.

For problems involving an interference pattern produced by two sources of sound of the same frequency and amplitude which are separated by a distance d:

1. Draw an accurate diagram labeling d, ΔX, L, m, $m\lambda$, and λ.
2. Complete a data table listing the information given in the problem and the information requested in the solution.
3. Note whether the problem involves constructive interference or destructive interference.
4. Choose the appropriate formula(s) and solve the problem.

For problems involving the Doppler effect:

1. Complete a data table listing information both given and implied in the problem.
2. Note whether the source or the listener is moving; also note whether the source and listener are approaching each other or moving away from each other.
3. Select the appropriate formula and solve for frequency heard by the listener.
4. Solve for the wavelength of the sound between the source and the listener.

SOLUTIONS TO SELECTED TEXTBOOK PROBLEMS

TEXTBOOK PROBLEM 8. What is the intensity of sound at the pain level of 120 dB? Compare it to a whisper at 20 db.

Part a. Step 1. Apply the formula for intensity level in decibels and determine the intensity level for the 120 dB sound.	Solution: (Section 12-2) $\beta = 10 \log (I/I_o)$ where $I_o = 1.0 \times 10^{-12}$ W/m^2. 120 dB = 10 log (I/1.0 x 10^{-12} W/m^2) 12 = log (I/1.0 x 10^{-12} W/m^2) From algebra, if A = log B, then B = 10^A; therefore, I/1.0 x 10^{-12} W/m^2 = 10^{12} I = (1.0 x 10^{12})(1.0 x 10^{-12} W/m^2) = 1.0 W/m^2
Part a. Step 2. Apply the same formula and determine the intensity level for the 20 dB sound.	$\beta = 10 \log (I/I_o)$ 20 dB = 10 log (I/1.0 x 10^{-12} W/m^2) 2 = log (I/1.0 x 10^{-12} W/m^2) I/1.0 x 10^{-12} W/m^2 = 10^2 I = (1.0 x 10^2)(1.0 x 10^{-12} W/m^2) = 1.0 x 10^{-10} W/m^2

Part a. Step 3.

Determine the ratio of the sound intensity levels.

$(1.0\ W/m^2)/(1.0 \times 10^{-10}\ W/m^2) = 1.0 \times 10^{10}$

The intensity level for the sound at the level of pain is 10 billion times greater than that of a whisper.

TEXTBOOK PROBLEM 20. What would be the sound level (in dB) of a sound wave in air that corresponds to a displacement amplitude of vibrating air molecules of 0.13 mm at 300 Hz?

Part a. Step 1.

Use the equation from chapter 11 of the textbook to determine the intensity.

Solution: (Section 12-2)

$I = 2\ \pi^2\ v\ \rho\ f^2\ x_o^2$

$I = 2\ \pi^2(343\ m/s)(1.29\ kg/m^3)(300\ Hz)^2(1.3 \times 10^{-4}\ m)^2$

$I = 13.28\ W/m^2$

Part a. Step 2.

Solve for the intensity level in decibels.

$\beta = 10 \log (I/I_o)$ where $I_o = 1.0 \times 10^{-12}\ W/m^2$

$= 10 \log [(13.28\ W/m^2)/(1.0 \times 10^{-12}\ W/m^2)]$

$= 10 \log (1.328 \times 10^{13})$

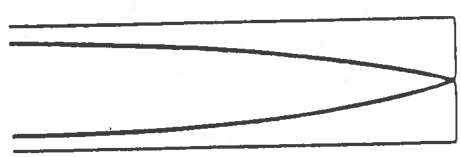
$\beta = (10)(13.1) \approx 130\ dB$

TEXTBOOK PROBLEM 25. An organ pipe is 112 cm long. What are the fundamental and first three audible overtones if the pipe is (a) closed at one end, and (b) open at both ends.

Part a. Step 1.

Draw a diagram of the fundamental frequency of the pipe closed at one end.

Solution: (Section 12-5)



First harmonic = fundamental

$L = \frac{1}{4}\lambda_1 \qquad f_1 = v/(4L)$

Part a. Step 2.

Determine the wavelength of the sound waves.

The distance between adjacent nodes and antinodes is $\frac{1}{4}\lambda$. Based on the diagram, the length of the pipe equals $\frac{1}{4}\lambda$.

$1.12\ m = \frac{1}{4}\lambda$; therefore, $\lambda = 4.48\ m$

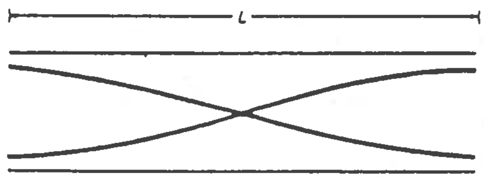
Part a. Step 3.

Determine the fundamental frequency of the waves. Assume that the speed of sound is 343 m/s.

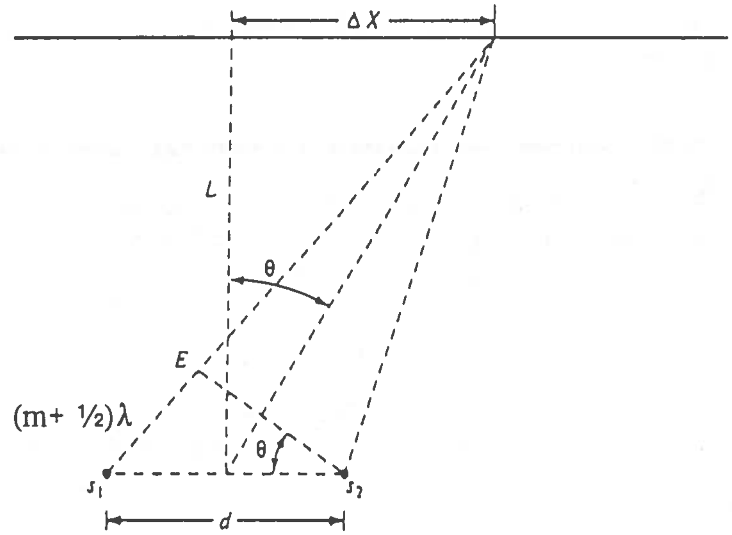
$v = f\ \lambda$

$343\ m/s = f_1\ (4.48\ m)$

$f_1 = 76.6\ Hz$

Part a. Step 4. Determine the wavelength of the first three audible overtones.	For a pipe closed at one end, the frequencies heard are consecutive odd multiples of the fundamental, i.e., 3, 5, 7, etc. times the fundamental frequency. f_3 = 3(76.6 Hz) = 230 Hz f_5 = 5(76.6 Hz) = 383 Hz f_7 = 7(76.6 Hz) = 536 Hz
Part b. Step 1. Draw a diagram of the fundamental frequency of the pipe open at both ends.	 First harmonic = fundamental $L = \frac{1}{2}\lambda_1$ $f_1 = v/(2L)$
Part b. Step 2. Determine the wavelength of the sound waves.	The distance between adjacent nodes is ½λ. Based on the diagram, the length of the pipe equals ½λ. 1.12 m = ½λ; therefore, λ = 2.24 m
Part a. Step 3. Determine the fundamental frequency of the sound.	$v = f\lambda$ 343 m/s = f_1 (2.24 m) f_1 = 153 Hz
Part a. Step 4. Determine the wavelength of the first three audible overtones.	For a pipe open at both ends, the frequencies heard are consecutive whole number multiples of the fundamental, i.e., 2, 3, 4 etc. times the fundamental frequency. f_2 = 2(153 Hz) = 306 Hz f_3 = 3(153 Hz) = 459 Hz f_4 = 4(153 Hz) = 612 Hz

TEXTBOOK PROBLEM 46. Two loud speakers are 1.80 m apart. A person stands 3.00 m from one speaker and 3.50 m from the other speaker. (a) What is the lowest frequency at which destructive interference will occur at this point? (b) Calculate two other frequencies that also result in destructive interference at this point (give the next two highest). Let T = 20°C.

Part a. Step 1. Draw an accurate diagram showing the path difference from the sources to the point in question.	Solution: (Section 12-6) 
Part a. Step 2. Determine the wavelength of the lowest frequency.	The path difference from the two sources to the point in question equals 3.50 meters - 3.00 meters = 0.50 meter. For destructive interference to occur, the waves must arrive out of phase. For destructive interference, the path difference 0.50 meter = $(m + \frac{1}{2})\lambda$ where m = 0, 1, 2, etc. The lowest frequency at which destructive interference occurs corresponds to the longest wavelength. The longest wavelength occurs at m = 0. From 0.50 meter = $(m + \frac{1}{2})\lambda$, when m = 0, $\frac{1}{2}\lambda$ = 0.50 meter and λ = 1.0 meter.
Part a. Step 3. Determine the speed of sound at 20°C.	$v = 331 + 0.6\,T$ m/s $v = 331 + (0.6)(20)$ m/s = 343 m/s
Part a. Step 4. Determine the lowest frequency at which destructive interference occurs.	$v = f\lambda$ 343 m/s = f (1.0 m) f = 343 Hz
Part b. Step 1. Determine the wavelength of the next two higher frequencies.	The next possibilities occur at m = 1 and m = 2. At m = 1, then $(3/2)\lambda$ = 0.50 meter and λ = 0.33 meter At m = 2, then $(5/2)\lambda$ = 0.50 meter and λ = 0.20 meter

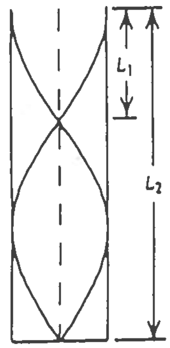
Part b. Step 2. Determine the next two higher frequencies.	$v = f \lambda$ 343 m/s = f (0.33 m), f = 1030 Hz 343 m/s = f (0.20 m), f = 1720 Hz

TEXTBOOK PROBLEM 49. The predominant frequency of a fire engine's siren is 1550 Hz when at rest. What frequency do you detect if you move with a speed of 30.0 m/s (a) toward the fire engine, and (b) away from the fore engine.

Part a. Step 1. Determine the frequency you hear as you approach the car.	Solution: (Section 12-7) This problem involves the Doppler effect. Apply the formula for a moving listener approaching a stationary source. $f' = [1 + (v_o)/(v)]f$ $f' = [1 + (30 \text{ m/s})/(343 \text{ m/s})](1550 \text{ Hz}) = 1690 \text{ Hz}$
Part b. Step 1. Determine the frequency heard as you recede.	$f' = [1 - (v_o)/(v)]\, f$ $f' = [1 - (30 \text{ m/s})/(343 \text{ m/s})](1550 \text{ Hz})$ $f' = 1410 \text{ Hz}$

TEXTBOOK PROBLEM 76. A tuning fork is set into vibration above a vertical open tube filled with water (Fig. 12-35). The water level is allowed to drop slowly . As it does so, the air in the tube above the water level is heard to resonate with the tuning fork when the distance from the tube opening to the water level is 0.125 m and again at 0.395 m. What is the frequency of the tuning fork?

Part a. Step 1. Determine whether the tube acts like a pipe closed at one end or open at both ends.	Solution: (Section 12-5) Sound is free to pass out of the top of the tube. Therefore, the top of the tube is an open end. The sound reflects back up the tube at the water level. Therefore, the water level acts as a closed end. The tube is a pipe closed at one end.
Part a. Step 2 Draw an accurate diagram for the water level at the 1st harmonic and the 3rd harmonic.	The water level is slowly lowered from the top of the pipe until the first resonance occurs. This resonance represents the 1st harmonic. For a pipe closed at one end, the next resonance that occurs is the 3rd harmonic. The diagram for the third harmonic is shown at the top of the next page.



Part a. Step 3. Use the diagrams in step 3 to determine the wavelength of the sound waves.	At the 1st harmonic, $L_1 = \frac{1}{4}\lambda$. At the 3rd harmonic $L_3 = \frac{3}{4}\lambda$. The distance between the node of the 1st harmonic and the node of the 3rd harmonic $\Delta L = L_3 - L_1 = 0.395\ \text{m} - 0.125\ \text{m} = 0.270\ \text{m}$. However, as shown in the diagram, $\Delta L = \frac{3}{4}\lambda - \frac{1}{4}\lambda = \frac{1}{2}\lambda$. $\frac{1}{2}\lambda = 0.270\ \text{m}$ $\lambda = 0.540\ \text{m}$
Part a. Step 4. Determine the frequency of the tuning fork.	$f = v/\lambda$ $f = (343\ \text{m/s})/(0.540\ \text{m}) = 635$ hz