Sound and Musical Acoustics

Introduction: This unit deals with the properties of longitudinal (compressional) waves traveling through various media. As these waves travel through the medium, the particles in the medium vibrate to produce density and pressure changes along the direction of wave motion. This results in a series of high- and low-pressure regions called condensations and rarefactions, respectively. There are three categories of longitudinal mechanical waves that cover different ranges of frequency: (1) AUDIBLE WAVES lie within the range of sensitivity of the human ear, typically 20 Hz to 20,000 Hz. (2) INFRASONIC WAVES are longitudinal waves with frequencies below the audible range. Earthquake waves are an example. (3) ULTRASONIC WAVES are longitudinal waves with frequencies above the audible range. Sound waves are the most important example of longitudinal waves. We learn much about the world around us by means of sound. Minute amounts of energy carried by sound waves stimulate the sensation of sound. Three stages are necessary in the production of a sensation of sound. The process must be started by a vibrating source - which in its vibration supplies energy to the surrounding medium. The medium transmits this energy from the source to the receiver by means of a sound wave. When the wave arrives at a receiver, energy is transferred to the receiver. If the receiver is the ear, a sensation of sound may be produced.

Sound may be defined psychologically or physically. In the first aspect, it is said to be the sensation produced when the proper disturbance comes to the ear. From the second viewpoint, sound is the stimulus capable of producing the sensation of sound. Whether an observer is necessary for sound to exist depends entirely upon which of the two definitions is used. For our purposes, we shall use the second – or physical definition.

Some four centuries before Christ, the Pythagoreans first established the connection between musical sounds and mathematics. This study continued through the middle ages, and was later developed by Huygens and Galileo. In the eighteenth century, an interest in musical instruments prompted the mathematical study of vibrating bodies and of the propagation of sound though the air. This field of study is called musical acoustics. During the nineteenth century, the study of sound and acoustics had become an integral part of physics. The science of acoustics includes (1) production of sound by various sources, (2) propagation of sound from source to listener, and (3) the perception and judgment of sounds.

Production of Sounds by Various Sources:

All sounds are waves produced by the vibrations of material objects. In pianos and violins, the sound is produced by the vibrating strings; in a clarinet, by a vibrating reed. The human voice results from the vibration of the vocal cords. In each of these cases, a vibrating source sends a disturbance through the surrounding medium, usually air, in the form of longitudinal waves.

Any body that has the properties of inertia and elasticity may be set into vibration. Most bodies can be forced to vibrate at any frequency. This is called forced vibration. All bodies have a natural frequency of vibration. This is the frequency at which the least amount of work is required to produce forced vibrations. Most, but not all, bodies may vibrate in more than one manner and for each of these modes of vibration there is an associated frequency. Only those frequencies of vibration are possible for which standing waves can be set up within the body. The vibration of lowest frequency is called the fundamental. All others are called overtones. The vibrations whose frequencies are integral multiples of the frequency of the fundamental are called harmonics. The fundamental is called the first harmonic.

When the frequency of forced vibrations on a body matches the body's natural frequency or is a sub-multiple of its natural frequency, a dramatic increase in amplitude occurs. This phenomenon is called resonance. For resonance, there is a rapid transfer of energy and a resultant louder sound.

Media That Transmit Sound:

Most sounds we hear are transmitted through air. However, any elastic substance – whether solid, liquid, gas or plasma – can transmit sound. Compared to solids and liquids, air is a relatively poor conductor of sound. The sound of a distant train can be heard more clearly if the ear is placed against the rail. Sound will not travel in a vacuum.

The speed of sound in liquids and solids is much greater than the speed of sound in gases. In water at 25 ˚C, sound travels at about 1500 m/s. In a steel rod, sound travels at about 5200 m/s. In general, speed varies with temperature. The speed of sound in air is 331.5 m/s at 0 ˚C. This speed changes with temperature at 0.607 m/s per ˚C. In gases, the change in speed is large and must be accounted for. In liquids and solids, the change is relatively small and usually neglected.

$$v_{(\text{sound in air})} = 331.5 \text{ m/s} + (0.6^{\text{m/s}}/_{^\circ C})T$$

The Perception and Judgment of Sound:

Most of the sounds we hear are noises. Noise corresponds to an irregular vibration of the eardrum produced by the irregular vibration of some object. The sound of music has a different character, a regular sustained tone. However, the line that separates music and noise is thin and subjective. Musicians usually speak of musical tones in terms of three characteristics – pitch, loudness and quality.

Pitch corresponds to the vibration frequency of the origin of the sound. High frequency vibrations of the sound source with produce shrill high notes. Low frequency vibrations of the sound source produce deep low notes. A tuning fork vibrating at 256 Hz corresponds approximately to middle C on the piano.

Loudness is a physiological sensation. It depends on the intensity of the sound wave but in a complicated way. Sound intensity is a purely objective and physical attribute of a wave. It is proportional to the square of the amplitude of the wave. We can not measure loudness, however we can measure intensity. We speak of relative loudness in terms of relative intensity by comparing the intensity of the sound to the intensity at the threshold of hearing for a common frequency. The relative intensity of the sound the ear hears is called the noise level and is measure in decibels - a unit named for Alexander Graham Bell. The decibel scale is a logarithmic scale.

Being exposed to loud and sustained sounds is a relatively recent phenomenon of the human experience. We have not yet adapted to the noise pollution we are exposed to every day. Many modern humans have ruined their sense of hearing and destroyed the fine tuning in their ears by exposing themselves willingly to loud sounds for sustained periods of time.

Quality of a tone is determined by the presence and relative intensity of the various overtones. We have no trouble distinguishing between the one from a piano and a like-pitched tone from a clarinet. Each of these tones has a characteristic sound that differs in quality or timbre as it is called by musicians.

Musical Instruments:

Conventional musical instruments can be grouped into one of three classes: those in which the sound is produced by vibrating strings, those in which the sound is produced by a vibrating column of air, and those in which the sound is produced by percussion – the vibrating of a two-dimensional surface.

Stringed instruments: If a stretched string is plucked, waves travel along the string and are reflected at the ends. This sets up a standing wave in the string. Many sets of standing waves can be established; in fact, all standing waves are possible for which the two ends are nodes. The length of the string determines the wavelengths of the standing waves that can be set up in it. $L = n\lambda/2$ – where L is the length of the string and n is any whole number. A string usually vibrates in several different modes simultaneously. The relative amplitudes of the various modes depend upon the stiffness of the string, the point at which it is set into vibration and what is used to cause the vibration.

The vibration of the string is transferred to the sounding board and then to the air – with a considerable dissipation of energy. Stringed instruments are low-efficiency producers of sound - so to compensate for this - we find the string sections of orchestras relatively large.

Wind instruments: Sound is emitted directly by the vibrations of air columns in the instrument. Such a column may be open at one end and closed at the other or it may be open at both ends. Organ pipes fall into this category also. For a column closed at one end, only odd harmonics are possible and the first overtone is the third harmonic. For an air column that is open at both ends, as in the case of the vibrating string, a lowest frequency and all its multiples are possible. There are various ways to set the air column into vibration. In brass instruments such as Trumpets, French Horns, and Trombones, vibrations of the player's lips interact with standing waves that are set up. The length of the column is varied by valves which add or subtract segments. In woodwind instruments such as Clarinets, oboes, and Saxophones, a stream of air produced by the musician set a reed vibrating; where as in Fifes, Flutes, and Piccolos, the musician blows air against the edge of a hole to produce a fluttering stream that sets the air column into vibration.

Percussion Instruments like drums and cymbals have a two-dimensional membrane or elastic surface which is struck to produce sound. The fundamental tone produced depends on the geometry, the elasticity, and in some cases, the tension in the vibrating surface.

Performance Objectives: Upon completion of the readings and activities of this unit and when asked to respond either orally or on a written test, you will be able to:

- ✓ Demonstrate knowledge of the nature of sound waves and the properties sound shares with other waves.
- ✓ Describe the origin of sound in general and in various musical instruments in particular.
- ✓ Solve problems relating the frequency, wavelength and velocity of sound.
- ✓ Relate physical properties of sound waves to perceived pitch and loudness. Use the decibel scale. Solve problems involving intensity and loudness.
- ✓ Define the Doppler Effect. Identify some of its applications. Solve problems using the Doppler Equation.
- ✓ Show an understanding of resonance – especially applied to an air column and a stretched string. Sketch a standing wave. Solve problems involving standing waves.
- ✓ Define harmonics and their origins. Solve problems involving harmonics. Define timbre.
- ✓ Recognize the origin of and solve problems involving beats.

Textbook Reference: Hecht Physics: Chapter 11

"Music hath charms to sooth the savage breast. To soften rocks, or bend a knotted oak." *-Congreve*

Exercises and Questions:

The Speed of Sound Waves:

1.) A sound wave produced by a clock chime 515 m away is heard 1.50 seconds later. a.) What is the speed of sound in air? b.) The sound wave has a frequency of 436 Hz. What is its period? c.) What is its wavelength?
343 m/s 0.00229 s 0.787 m

2.) A hiker shouts toward a vertical cliff 685 m away. The echo is heard 4.0 seconds later. a.) What is the speed of sound in air? b.) The wavelength of the sound is 0.75 m. What is its frequency? c.) What is the period of the wave? *343 m/s 457 Hz 0.00219 s*

3.) Sound with a frequency of 261.6 Hz travels through water at a speed of 1435 m/s. Find its wavelength in water. *5.485 m*

4.) The speed of sound at 0 °C is 331.5 m/s. For each degree change in temperature, the speed changes 0.6 m/s. What is the speed of sound on a day when the temperature is 20 °C? *343.5 m/s*

5.) Ultrasound with a frequency of 4.25 MHz can be used to produce images of the human body. If the speed of sound in the body is the same as in salt water, 150 km/s, what is the wavelength in the body? *3.53×10^{-2} m*

6.) What is the temperature of the air on a day when the speed of sound is 347 m/s? *25.8 °C*

7.) If the wavelength of a 440 Hz sound in fresh water is 3.30 m, what is the speed of sound in fresh water?
1452 m/s

8.) A physics student drops a stone into a well 122.5 m deep. How soon after she drops the stone does she hear it hit the water surface at the bottom of the well? The temperature is 20 °C. *5.36 s*

9.) What time is required for sound to travel 5.00 km if the temperature of the air is 10.0 °C? *14.8 s*

10.) What is the wavelength in meters of the sound produced by a tuning fork that has a frequency of 320 Hz? The temperature of the air is 15 °C. *1.06 m*

Intensity and Loudness of Sound Waves: Intensity (I) = Power (P) / Area (a)

The faintest sounds the human ear can detect at a frequency of 1000 Hz correspond to an intensity of about 10^{-12} W/m^2 (the threshold of hearing). The pressure amplitude associated with this intensity is 2.87×10^{-5} N/m^2. Since atmospheric pressure is 10^5 N/m^2, the ear can discern pressure fluctuations as small as 3 parts per 10 billion. The corresponding displacement amplitude is 1.11×10^{-11} m (ten times smaller that the diameter of a molecule). Likewise, the loudest sounds that the ear can tolerate correspond to an intensity of about 1 W/m^2 (the threshold of pain). This corresponds to a pressure amplitude of about 30 N/m^2 and a maximum displacement of 1.1×10^{-5} m. We see that the human ear is an extremely sensitive detector of sound.

Since the human ear is sensitive to the wide range of pressure intensities, it is convenient to use a logarithmic intensity scale when discussing the loudness of sound. Where intensity (I) is the time average rate at which energy is transported by a wave per unit area across a surface normal to the direction of propagation. Intensity has dimensions of power / area and units of watts / meter^2. I_o is the intensity of the threshold of hearing (10^{-12} W/m^2) for a mid-range frequency. β is the relative intensity (loudness) of the sound waves in decibels.

$$\beta = 10 \log (I / I_o)$$

11.) What is the relative intensity in decibels of a sound if the intensity of the wave is 10^{-7} W/m^2? *50 dB*

12.) A source emits sound energy at a rate of 10.0 watts. a.) What is the intensity of the sound wave at a distance of 20.0 m? b.) What is the relative intensity of the sound at the listener's position? *2.0×10^{-7} W/cm^2* *93 dB*

13.) A jet plane in a landing approach is found to have a noise intensity at ground level of 0.11 W/m^2. Determine the relative intensity (loudness) at this location. *110 dB*

14.) The threshold of pain indicates the upper intensity level for audible sounds. Sounds of greater intensity produce pain rather than hearing. The threshold of pain at 1000 Hz is 1.0 W/m^2. What is the relative intensity for this threshold? *120 dB*

15.) What is the intensity of a sound wave that has a relative intensity (loudness) of 30 dB? What effect on relative intensity is there when this intensity is doubled? *10^{-9} W/m^2* *33 dB*

Doppler Effect:

In general, a Doppler Effect is experienced whenever there is relative motion between the source and the observer. When the source and observer are moving toward each other, the frequency heard by the observer is higher than the frequency of the source. When the source and observer move away from each other, the observer hears a frequency that is lower than the source. According to the equation below - where f is the frequency of the source and f' is the frequency the observer hears. v is the speed of sound; v_o is the speed of the observer and v_s is the speed of the source. The top signs in the numerator and denominator are used when either or both are moving toward the other. The bottom signs are used when they are moving away.

$$f' = f \left[\frac{v \pm v_o}{v \mp v_s} \right]$$

16.) A train engineer blows the train's whistle that has a frequency of 400 Hz as the train approaches a station. If the speed of the train is 25 m/s, what frequency will be heard by a person at the station? The temperature is 20 °C. *430 Hz*

17.) A train traveling at 95 km/hr passes a factory whose whistle is blowing at 288 Hz. The temperature is 20 °C. What frequency does a passenger on the train hear as the train a.) approaches the factory? b.) leaves the factory? *310 Hz* *266 Hz*

18.) The ratio of the speed of a fast moving object to the speed of sound is sometimes expressed as a Mach number: v_s / v = Mach number; where v_s is the speed of the source and v is the speed of sound. A bullet fired from a rifle travels at Mach 1.38 (that is $v_s / v = 1.38$). What is the speed of the bullet on a day when the temperature is 0 °C? *457 m/s*

19.) Standing at a crosswalk, you hear a frequency of 560 Hz from the siren on an approaching police car. After the police car passes, the observed frequency of the siren is 480 Hz. Determine the car's speed from these observations. It's a cold day, use 330 m/s for the speed of sound. *25.4 m/s*

20.) What is the drop in frequency of the sound a listener hears as a train with its horn sounding passes at 145 km/hr? The frequency of the horn is 320 Hz and the temperature is 25.0 °C. *76 Hz*

Standing Waves is a String Fixed at Both Ends:

If a string of length L is fixed at both ends, a standing wave can be set up in the string by a continuous superposition of waves incident on and reflected from the ends. The string has a number of natural patterns of vibration, called normal modes. Each of these has a characteristic frequency which is easily calculated. Where n is the n^{th} mode of vibration, recall that $f = v/\lambda$ and the speed of a wave in a string depends on its elastic and inertial properties. This can be written in equation form, where F is the tension in the string and μ is the linear density in mass/length. Then the natural frequencies of vibration are given by the equation below:

$$v = (F/\mu)^{\frac{1}{2}} \qquad f_n = n/2L\ (F/\mu)^{\frac{1}{2}} \qquad \lambda_n = 2L/n$$

21.) A standing wave is established in a 120 cm long string fixed at both ends. The string vibrates in four segments when driven at 120 Hz. a.) Determine the wavelength. b.) What is the fundamental frequency?
60.0 cm *30.0 Hz*

22.) A piece of string 5.30 m long has a mass of 15.0 g. What must the tension in the string be to make a wave with a wavelength of 120.0 cm and a frequency of 125 Hz. *63.7 N*

23.) A stretched string is 160 cm long and has a linear density of 0.015 g/cm. What tension in the string will result in a second harmonic of 460 Hz? *812 N*

24.) A string 50.0 cm long has a mass per unit length of 2.0×10^{-4} kg/m. To what tension should this string be stretched it its fundamental frequency is to be a.) 20 Hz? b.) 4500 Hz? *0.08 N* *4050 N*

25.) A stretched string fixed at each end has a mass of 40.0 g and a length of 8.0 m. The tension in the string is 49 N. Determine the position of the nodes and antinodes for the third harmonic.
Nodes at 0 m, 2.67 m, 5.33 m and 8.00 m *Antinodes at 1.33 m, 4.00 m and 6.67 m*

Standing Waves in Air Columns: Closed-Pipe Resonators: $\lambda = 4(L + 0.4d)$ $f_n = nv/4L$ (n = 1, 3, 5…)

Standing longitudinal waves can be set up in a tube of air (such as an organ pipe) as the result of interference between longitudinal waves traveling in opposite directions. The closed end of an air column is a displacement node, just as the fixed end of a vibrating string is a displacement node. Since the pressure wave is

90° out of phase with the displacement wave, the closed end of an air column corresponds to a pressure antinode (that is, a point of maximum pressure variation). The open end of an air column is approximately a displacement antinode and a pressure node.

The length of the air column determines the resonant frequencies of the vibrating air. A resonating tube with one end closed is called a **closed-pipe resonator.** The shortest column of air that can have an antinode at the bottom and a node at the top is one-fourth wavelength long. As the air column is lengthened, additional resonances are found. Thus columns of $\lambda/4$, $3\lambda/4$ and $5\lambda/4$ and so on – will all be in resonance with a tuning fork. In practice, the first resonance length is slightly longer than one-fourth wavelength. This is because the pressure variations do not drop to exactly zero at the end of the pipe. Actually, the node is approximately 0.4 pipe diameters beyond the end. Where d is the diameter, L is length, and λ is the wavelength. Each additional resonance length, however, is spaced by exactly one-half wavelength. Since the closed tube is resonant at odd quarter-wavelength intervals, the resonant frequencies are harmonics, but only the odd harmonics of the fundamental mode are present.

26.) A closed organ pipe 0.82 m long produces a 317 Hz tone in its second mode of vibration. What is the speed of sound in the pipe? *347 m/s*

27.) If the frequency of the 2nd mode in a closed organ pipe is 514 Hz, what is the frequency of the first mode? *171 Hz*

28.) On a day when the speed of sound is 330 m/s, the third mode of a closed organ pipe sounds at 550 Hz. What is the length of the pipe? *0.75 m*

29.) An organ pipe closed at one end is 76.5 cm long and has a diameter of 5.0 cm. The air temperature is 12°C. a.) Determine its fundamental frequency. b.) What are the frequencies of the two lowest harmonics produced along with this fundamental tone? *110 Hz* *330 Hz* *550 Hz*

30.) The auditory canal leading to the eardrum is a closed pipe 3.0 cm long. Find the approximate value (ignoring end corrections) of the lowest resonant frequency at 30 °C. *about 2.9 kHz*

31.) An open vertical tube is filled with water and a tuning fork vibrates over its mouth. as the water level is lowered in the tube, resonance is heard when the water level has dropped 15 cm, and again after 47 cm of distance exists from the water to the top of the tube. What is the frequency of the tuning fork at 25 °C? *541 Hz*

32.) A clarinet sounds a 370 Hz note. It produces only odd multiples of the fundamental frequency. What are the frequencies of the next three harmonics produced by the clarinet? *1110 Hz* *1850 Hz* *2590 Hz*

33.) A closed organ pipe has a length of 2.40 m. a.) What is the frequency of the note played by the pipe? Use 343 m/s as the speed of sound. b.) When a second pipe is played at the same time, a 1.40 Hz beat note is heard. By how much is the second pipe too long? *35.7 Hz* *0.10 m*

Standing Waves in Air Columns: Open-Pipe Resonators: $\lambda = 2(L + 0.8d)$ $f_n = nv/2L$ (n = 1, 2, 3…)

A tube with both ends open will also resonate with a sound source and is called an **open-pipe resonator.** There are pressure nodes (displacement node) near each of the ends, and at least one antinode (displacement node) between. There is also some sound transmission at the open ends of the tube. We hear the transmitted sound. The remainder is reflected to form a standing wave within the tube. The minimum length of a resonating open pipe is one-half wavelength. Again, by applying a small empirical correction for the edge effects, an equation for the wavelength can be written. An open tube, which is a half-wavelength resonant column at its fundamental frequency is a full wavelength long at the second mode of vibration. It is $3\lambda/2$ at the third mode of vibration, and so on. The resonant frequencies of an open pipe are harmonics, and all harmonics of the fundamental mode are present.

34.) A bugle can be thought of as an open pipe. If a bugle were straightened out, it would be 2.65 m long. a.) If the speed of sound is 343 m/s, find the lowest frequency that is resonant in a bugle (ignoring end corrections). b.) find the next two higher resonant frequencies in the bugle. *64.7 Hz* *129 Hz* *194 Hz*

35.) A soprano saxophone is an open pipe. If all keys are closed, it is approximately 65 cm long. Using 343 m/s as the speed of sound, find the lowest frequency that can be played on this instrument (ignoring end corrections). *264 Hz*

36.) On a day when the speed of sound is 340 m/s, find the frequency of the 3rd mode of vibration in an open organ pipe 3.7 m long. *138 Hz*

37.) An organ pipe open at both ends is 1.23 m long and has a diameter of 10 cm. a.) What is its fundamental frequency when the air temperature is 15 °C? Do Not Ignore End Considerations! b.) What are the frequencies of the two lowest harmonics produced along with the fundamental tone? *130 Hz* *260 Hz* *390 Hz*

38.) The second harmonic in an open pipe is 1200 Hz. What would be the frequency of the second mode of vibration for the same pipe if one end were closed? *900 Hz*

39.) The speed of sound is 343 m/s. The lowest note on an organ pipe is 16.4 Hz. a.) What is the shortest organ pipe that will resonate at this frequency? b.) What would be the pitch if the same organ pipe were closed? *10.5 m* *8.2 Hz*

Beats: Interference in Time:

The interference we have been dealing with so far involves the superposition of two or more waves with the same frequency traveling in opposite directions. Since the resulting wave form in this case depends on the coordinates of the disturbed medium, we can refer to the phenomenon as spatial interference. Standing waves in strings and pipes are common examples of spatial interference. We now consider another type of interference effect, one that results from the superposition of two waves with slightly different frequencies traveling in the same direction. In this case, when the two waves are observed at a given point, they are periodically in and out of phase with each other. That is, there is an alternation in time between constructive and destructive interference. Thus, we refer to this phenomenon as interference in time or temporal interference. For example, if two tuning forks of slightly different frequencies are struck, one hears a sound of pulsating intensity – called a beat. A beat can therefore be defined as the periodic variation in intensity at a given point due to the superposition of two waves having slightly different frequencies. The number of beats one hears per second – or beat frequency – equals the difference in frequency between the two sources. The maximum beat frequency that the human ear can detect is about 20 beats/second. The frequency of the sound heard is the average of the two frequencies played.

40.) Two tuning forks of 320 Hz and 324 Hz are sounded simultaneously. What sound will be heard by the listener? *322 Hz with a beat frequency of 4 Hz*

41.) A 330 Hz and a 333 Hz tuning fork are struck simultaneously. What will the beat frequency be? *3 Hz*

42.) One tuning fork vibrates with a frequency of 445 Hz. When a second fork is struck, beat notes occur with a frequency of 3 Hz. What are the two possible frequencies of the second fork? *442 Hz* *448 Hz*

43.) The Doppler shift was first tested in 1845 by the French scientist B. Ballot. He had a trumpet player sound an A note (440 Hz) while riding on a flatcar pulled by a locomotive. At the same time, a stationary trumpeter played the same note, Ballot heard 3.0 beats per second. How fast was the train moving toward him? *2.3 m/s*

The Quality of Sound:

When two waves differ by more than 7 – 20 Hz (it depends on the individual), the ear detects a complex wave. If the resulting sound is unpleasant, the result is called a dissonance. If the sound is pleasant, the result is a consonance, or a chord. As discovered by Pythagoras, consonances occur when the wave frequencies have ratios that are small whole numbers, such as 2:1 (octave), 3:2 (fifth), 4:3 (fourth) and 5:4 (major third).

Interference of Longitudinal Waves, Again: Recall: Antinode: $n\lambda/d = x/L$ Node: $(n-\frac{1}{2})\lambda/d = x/L$ where "n" is the number of the node or antinode, "d" is the distance between sources, "x" is the perpendicular distance between the observer and the central maxima and "L" is the distance between the observer and the mid-point of the sources – See the diagram below and recall our work with ripple tank diffraction and interference patterns.

Use 340 m/s for the speed of sound in each problem.

44.) A pair of speakers separated by 3.0 m are driven by the same oscillator. The listener is originally a perpendicular distance of 8.0 m from the midpoint of the line connecting the speakers. The listener walks a perpendicular distance of 0.35 m before reaching the first minimum in sound intensity. What is the frequency of the oscillator? *1296 Hz*

45.) The distance between the two speakers is 2.0 m, and they are driven at a frequency of 1500 Hz. An observer is initially at a point 6.0 m along the perpendicular bisector of the line joining the two speakers. a.) What distance must the observer move along a line parallel to the line joining the two speakers before reaching the first minimum in intensity? b.) At what distance from the perpendicular bisector will the observer find the first relative maximum? *0.34 m* *0.68 m*

46.) Two identical sound sources are located along the y-axis. Source 1 is located at (0,0.1) m and Source 2 is located at (0,-0.1) m. The frequency of the two sources is 1715 Hz. A listener is located along the x-axis 5.0 m from the origin. The listener walks along x = 5 into the first quadrant where he notices an absence of sound. If he keeps walking, how far from the x-axis will he hear the first maximum in sound intensity? *35.1 m*

47.) Two speakers are located as described in problem 46. The frequency of each source is variable. An observer is located at the point (1, 0.5) m. a.) What is the lowest frequency that will produce a relative maximum at the location of the observer? b.) What is the lowest frequency that will produce a relative minimum at the observer's location? *3795 Hz* *1898 Hz*