Name ______________________ Section ____________ Date ____________

Laboratory 22

Speed of Sound—Resonance Tube

PRELABORATORY ASSIGNMENT

Read carefully the entire description of the laboratory and answer the following questions based on the material contained in the reading assignment. Turn in the completed prelaboratory assignment at the beginning of the laboratory period prior to the performance of the laboratory.

1. What is the equation that relates the speed V, the frequency f, and the wavelength λ of a wave?

2. How are standing waves produced?

3. What name is given to a point in space where the wave amplitude is zero at all times?

4. What name is given to a point in space where the wave amplitude is a maximum at all times?

5. What are the conditions that must be satisfied in order to produce a standing wave in a tube open at one end and closed at the other end?

6. For an ideal resonance tube, an antinode occurs at the open end of the tube. What property of real resonance tubes slightly alters the position of this antinode?

7. A student using a tuning fork of frequency 512 Hz observes that the speed of sound is 340 m/s. What is the wavelength of this sound wave?

8. A student using a resonance tube determines that three resonances occur at distances of $L_1 = 0.172$ m, $L_2 = 0.529$ m, and $L_3 = 0.884$ m below the open end of the tube. The frequency of the tuning fork used is 480 Hz. What is the average speed of sound from these data?

Laboratory 22
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OBJECTIVES

A traveling wave is characterized by a speed V, a frequency f, and a wavelength λ. The relationship between these three quantities is given by $V = f\lambda$. When two waves of the same speed and frequency travel in opposite directions in some region of space, they can produce standing waves. When standing waves are produced in a tube, the amplitude of vibration becomes very large, and the system is said to be in resonance. A tube partially filled with water acts as a resonance tube for producing standing waves. In this laboratory, a tuning fork will be used to produce sound waves in a resonance tube to accomplish the following objectives:

1. Determination of several effective lengths of the closed tube at which resonance occurs for each tuning fork
2. Determination of the wavelength of the wave for each tuning fork from the effective length of the resonance tube
3. Determination of the speed of sound from the measured wavelengths and known tuning fork frequencies
4. Comparison of the measured speed of sound with the accepted value

EQUIPMENT LIST

1. Resonance tubes (with length scale marked on the tube)
2. Tuning forks (range, 500 to 1040 Hz), and rubber hammer
3. Thermometer (one for the class)

THEORY

For traveling waves of speed V, frequency f, and wavelength λ, the relationship between these three quantities is given by

$$V = f\lambda \tag{1}$$

If the frequency and wavelength of a wave are known, the speed of a traveling wave can be determined using equation 1. In practice, it is difficult to measure the properties of a traveling wave directly. Instead, experimentally it is easier to arrange for the traveling waves to interfere in such a way that standing waves result. Standing waves are produced by the interference between two waves of exactly the same speed, frequency, and wavelength traveling in the same region in opposite directions.

This laboratory uses a resonance tube to produce standing waves from the sound waves emitted from a tuning fork. The can shown in Figure 22.1 contains water, and as the can is moved up and down its support rod, the level of the water in the tube can be varied. The water acts as the closed end of the tube, and changing the water level changes the effective length of the resonance tube.

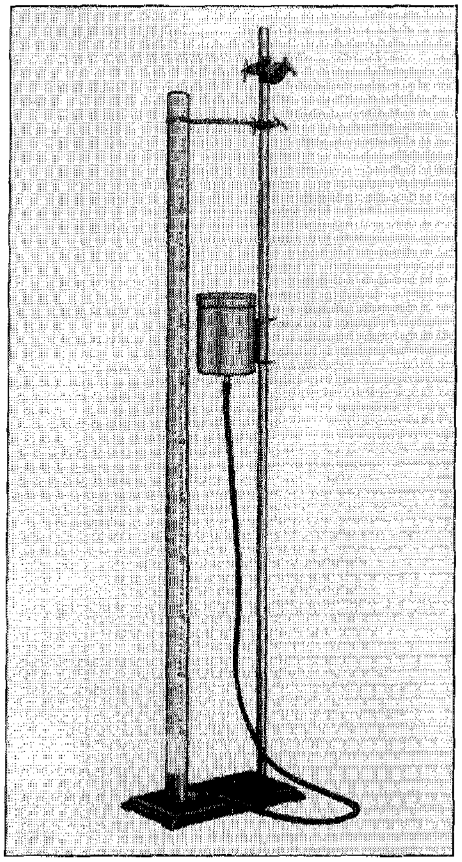

Figure 22-1 Resonance tube apparatus (Photo courtesy of Sargent Welch Scientific Co.).

A tuning fork is held by hand just above the open end of the tube and struck with a rubber hammer to make it vibrate. Sound waves travel down the tube, and they are reflected when they strike the water. Because of these reflected waves, there are traveling waves going in both directions inside the tube, which means that standing waves can be produced. The sound waves reflected from the closed end of the tube undergo a phase change of 180°, which places them completely out of phase with the incident sound waves. This means that the amplitude of the combination of incident and reflected waves must be zero at the closed end of the tube. Such a point in space where the wave amplitude must be zero at all times is called a "node," or N. From similar considerations of the relative phase between the incident and reflected waves, the open end of the tube is a point where the combined wave amplitude must be a maximum at all times. Such a point is called an "antinode," or A.

The standing waves that are produced in the tube are said to be in resonance with the tube, and this can occur only when there is a node at the closed end of the tube and an antinode at the open end of the tube. The speed of sound is fixed, and for a given tuning fork, the frequency is fixed. Therefore, the resonance conditions can be satisfied only for certain specific lengths of the tube that bear the proper relationship to the wavelength of the wave.

The necessary relationship between the length of the tube and the wavelength of the wave is illustrated in Figure 22.2 for the first four resonances of the tube. Sound waves are an example of a type of wave known as longitudinal. The amplitude of a sound wave is determined by pressure variations in the air along the direction of wave motion. The sound waves in the figure are pictured as if they were transverse waves merely for ease of representation.

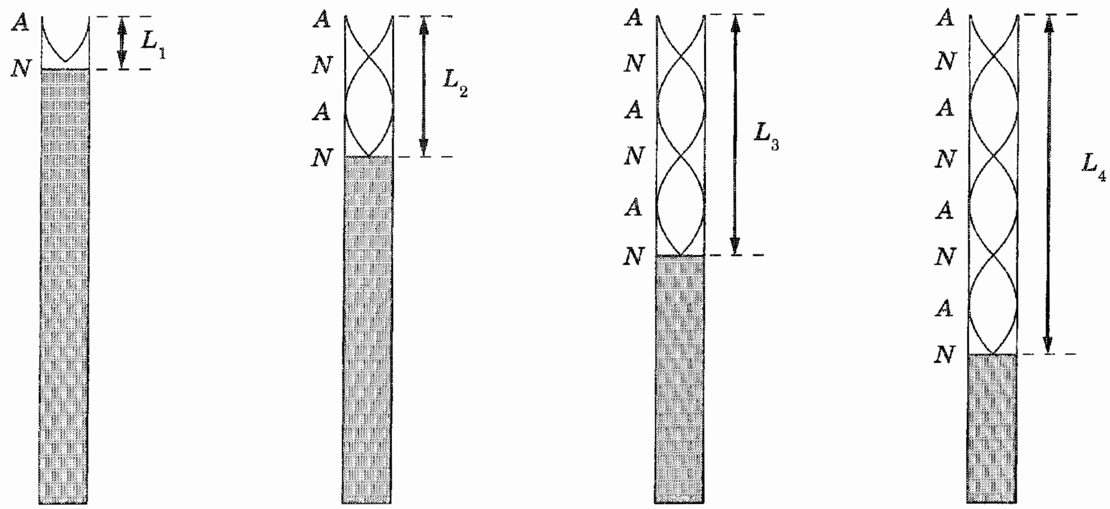

Figure 22.2 Nodes and antinodes for the first four resonances of a tube closed at one end.

The resonances are pictured from left to right as they are encountered when the level of the water in the tube is lowered, thus increasing the effective length of the tube closed at one end. The distances L_1, L_2, L_3, and L_4 refer to the distance from the top of the tube to the water level for the first four resonances that occur in the tube. The locations of all of the nodes N and antinodes A that occur for each of these resonances are also shown. In the first resonance there is a single node and antinode. The second resonance then introduces an additional node and antinode. Each successive resonance adds an additional node and antinode. In every case the distance between a node and the next antinode is one fourth of a wavelength (1/4 λ). The distance between nodes is half of a wavelength (1/2 λ).

In this laboratory, the location of several of the resonances that occur for each tuning fork will be experimentally determined. If the situation were ideal, the following relationships would be implied by Figure 22.2 for the first four resonances shown:

$$L_1 = {}^1\!/_4\,\lambda \qquad L_2 = {}^3\!/_4\,\lambda \qquad L_3 = {}^5\!/_4\,\lambda \qquad L_4 = {}^7\!/_4\,\lambda \tag{2}$$

Examine Figure 22.2 carefully to be sure that you understand how the relationships given in equations 2 are implied by the figure.

In fact, the relationships given in equations 2 are not valid for a real resonance tube because there is a small effect due to the diameter of the tube that is not taken into account in those equations. For a real tube, the point at which the upper antinode actually occurs is just outside the end of the tube. The exact location depends on the diameter of the tube. Thus, equations 2 are not directly useful to determine the wavelength λ of the wave.

The end effect is the same for each of the resonances. Therefore, it will have no effect if differences between the locations of the individual resonances are considered. Considering the differences between adjacent resonances gives the following:

$$L_2 - L_1 = L_3 - L_2 = L_4 - L_3 = \lambda/2 \qquad \textbf{(3)}$$

Equations 3 imply that if several resonances for a given tuning fork are located, each of the differences between the resonances provides an accurate determination of the wavelength of the wave. The frequency of the tuning fork is known. Therefore, when the wavelength is known, equation 1 allows a determination of the speed of sound.

In fact, if equations 3 are used directly and the results are then averaged, there is a loss in some information contained in the data. Equations 3 would produce three values of the wavelength from the first four resonances. If these three values for the wavelength were then averaged, that would amount to taking the sum of twice the three differences and then dividing by three. In that process, all but the first and last resonance positions cancel from the calculation. In effect, one might as well not have measured them. Note that there is nothing incorrect about such a procedure, but it does lose some of the information contained in the data. This is a classic example of the fact that there is often more than one way to analyze data, but usually some techniques give more information than others.

The problem described above is solved if each wavelength is computed not from the adjacent differences but from the differences between each resonance and the first resonance. The resulting equations for the wavelength are given below. A subscript has been placed on the wavelength, but it is still understood that each of the wavelengths λ_1, λ_2, and λ_3 refer to the same wavelength calculated from three different sets of resonances. The equations are

$$\lambda_1 = 2(L_2 - L_1) \qquad \lambda_2 = (L_3 - L_1) \qquad \lambda_3 = 2/3(L_4 - L_1) \qquad \textbf{(4)}$$

The speed of sound in air depends slightly on the temperature of the air. For a limited range of temperatures, the dependence is approximately linear. If V_T stands for the speed of sound at a temperature of T°C, to an excellent approximation it is given by

$$V_T = (331.5 + 0.607\,T)\ \text{m/s} \qquad \textbf{(5)}$$

This equation will be used to determine the accepted value for the speed of sound in air.

EXPERIMENTAL PROCEDURE

Note carefully that tuning forks should be struck only with the rubber hammer. Care must be taken to ensure that neither the hammer nor a vibrating tuning fork comes in contact with the tube.

1. Measure the room temperature of the air and record it in Data Table 1.
2. Adjust the water level until the can is essentially empty when the the tube is almost full. The water level in the tube should come at least to within 0.05 m of the open end of the tube. It may be necessary to remove some water from the can when the water level is lowered near the bottom of the tube.

3. One partner should hold a tuning fork over the top of the tube while the fork is struck repeatedly with the rubber hammer. It is important to keep the fork vibrating continuously with a large amplitude. With the tuning fork vibrating, another partner should slowly lower the water level from the top while listening for a resonance. The sound should become very loud when a resonance is reached. Attempt to measure the position of each resonance to the nearest millimeter. Raise and lower the water level several times to produce three trials for the measured position of the first resonance. Record the values of the three trials in Data Table 2. Record the frequency of the tuning fork in Data Table 2.
4. Repeat the procedure in step 3 to locate as many other resonances as possible. Depending on the frequency of the tuning fork used, either three or four resonances should be attainable. Record in Data Table 2 the location of the number of resonances that are attainable.
5. Using a second tuning fork of different frequency, repeat steps 1 through 3. Record in Data Table 3 the frequency of the tuning fork and the position of as many resonances as are attainable.

CALCULATIONS

1. Using equation 5, calculate the accepted value of the speed of sound from the measured room temperature. Record it in Data Table 1.
2. Calculate the mean and standard error of the three trials for the location of each of the resonances. Record each of the means and standard errors in the appropriate place in Calculations Tables 2 and 3.
3. Using equations 4, calculate the wavelengths that are appropriate. If four resonances were found, then all three values of λ can be determined. If only the first three resonances were measured, then only two values of λ can be determined. If this is the case, just leave the Calculations Table blank at the appropriate position. Be sure to use the mean values of the lengths to calculate the wavelengths.
4. Calculate the mean and standard error for the number of independent wavelengths measured for each tuning fork. Record those values in the Calculations Tables as $\bar{\lambda}$ and α_λ.
5. From the values of $\bar{\lambda}$ and the known values of the tuning fork frequencies, calculate the experimental value for V, the speed of sound.
6. Calculate the percentage error of the experimental values of V compared to the accepted value of the speed of sound in Data Table 1.

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LABORATORY REPORT

Data Table 1

Room temperature =	°C
Accepted speed of sound =	m/s

Data Table 2

Tuning fork frequency =			Hz	
Trial	L_1 (m)	L_2 (m)	L_3 (m)	L_4 (m)
1				
2				
3				

Calculations Table 2

$\overline{L_1}$ = m	$\overline{L_2}$ = m	$\overline{L_3}$ = m	$\overline{L_4}$ = m
α_{L1} = m	α_{L2} = m	α_{L3} = m	α_{L4} = m
$\lambda_1 = 2(L_2 - L_1)$ m	$\lambda_2 = (L_3 - L_1) =$ m	$\lambda_3 = 2/3(L_4 - L_1) =$ m	
$\bar{\lambda}$ = m	α_{λ} = m	$V = f\bar{\lambda}$ = m	% error =

SAMPLE CALCULATIONS

Data Table 3

Tuning fork frequency =		Hz		
Trial	L_1 (m)	L_2 (m)	L_3 (m)	L_4 (m)
1				
2				
3				

Calculations Table 3

$\overline{L_1}$ = m	$\overline{L_2}$ = m	$\overline{L_3}$ = m	$\overline{L_4}$ = m
α_{L1} = m	α_{L2} = m	α_{L3} = m	α_{L4} = m
$\lambda_1 = 2(L_2 - L_1)$ m	$\lambda_2 = (L_3 - L_1) =$ m	$\lambda_3 = 2/3(L_4 - L_1) =$ m	
$\bar{\lambda}$ = m	α_λ = m	$V = f\bar{\lambda}$ = m	% error =

SAMPLE CALCULATIONS

QUESTIONS

1. What is the accuracy of each of your measurements of the speed of sound? State clearly the evidence for your answer.

2. What is the precision of each of your measurements of the speed of sound? State clearly the evidence for your answer.

3. Equations 2 provide a means to determine the end correction for the tube. Using the value of $\bar{\lambda}$ for the first tuning fork, calculate values for L_1 and L_2 from those equations. They should be larger than the measured values of L_1 and L_2 by an amount equal to the end correction. Repeat the calculation for the second tuning fork. Compare these values for the end correction and comment on the consistency of the results.

4. Suppose that the temperature had been 10 C° higher than the value measured for the room temperature. How much would that have changed the measured value of $L_2 - L_1$ for each tuning fork? Would $L_2 - L_1$ be larger or smaller at this higher temperature?

5. Draw a figure showing the fifth resonance in a tube closed at one end. Show also how the length of the tube L_5 is related to the wavelength λ.