

PHYSICS 1030L Laboratory

Measuring the Speed of Sound in Air Using a Resonance Tube

Objective: The purpose of this experiment is to measure the speed of sound in air by exploiting standing wave and resonance effects in *longitudinal* waves.

Equipment: Tuning forks (256 Hz, 426Hz, 512 Hz, 1024 Hz), rubber striker block, resonance tube apparatus.

Theory: We have already examined the theory of standing waves and resonance in *transverse* waves (*Standing Waves on a String*). In transverse waves the displacement of the medium through which the wave propagates is perpendicular to the direction of wave travel. Electromagnetic waves and waves on strings are examples of transverse waves. In longitudinal waves, the displacement of the medium through which the wave propagates is parallel to the direction of wave travel. Sound waves are a prominent example of longitudinal waves.

Recall that the condition for transverse standing wave formation on a string was:

$$v = 2 \frac{Lf}{n} \quad (1)$$

or

$$f = \frac{nv}{2L} \quad (2)$$

($n = 1, 2, 3, \dots$). Where f is the frequency of vibration in (Hz), L is the length of the medium (string) in (m), n is the number of half wave lengths, $\lambda/2$, (loops), and v is the propagation velocity of the wave in (m/s). For sound waves this relationship still holds. In this experiment f is the frequency at which a column of air vibrates (driven by a tuning fork), L is the length of the column of air, n is the number of half wave lengths $\lambda/2$, and v is the speed of sound in air.

In this experiment we will create longitudinal standing waves in a tube containing air. The tube is open at the end. By adjusting the piston in the tube, one may lengthen or shorten

the length, L , of the column of air in the tube. If a tuning fork is held over the open end of the tube and struck, it excites the air molecules in the tube and causes a sound wave to propagate down the length of the tube to the piston-air boundary where it is reflected back up the length of the tube to the open end. The end of the tube containing piston constitutes a "closed" end. In tubes, pipes or columns open at one end and closed at the other, a stable standing wave pattern requires that a displacement antinode exists at the open end and a displacement node at the closed end of the tube.

This means that the fundamental (first harmonic) standing wave in such a tube occurs when the column of air is of length $\lambda/4$.

The series of nodes and antinodes in a tube open at one end and closed at the other form an *odd harmonic series* (in tubes open at both ends or closed at both ends all harmonics are possible). Thus the condition for a standing wave to form in a tube closed at one end is

$$f = \frac{nv}{4} L \quad (3)$$

or $\lambda = 4L/n$ ($n = 1, 3, 5, \dots$).

Superposition

Observations of waves in nature reveal that waves interact with each other in special ways. If you throw two stones into a pond for example, and watch the wave pattern created by each, you will observe that the patterns interact with each other in passing, but the individual patterns remain intact and continue to propagate after the interaction.

These observations are indicative of the principle of superposition. Multiple waves may interact with each other without losing their individual character. The interaction is generally referred to as interference. For our purposes the interaction of sound waves in this experiment will be considered to be linear.

Superposition of sound waves moving through air can be very complicated. The air molecules are already moving in a random motion. As a sound wave(s) travels it imposes an ordered vibrational motion on the already moving molecules. The motion of a molecule at any instant will be a combination of random motion and the oscillations caused by any number of sound waves present at that instant.

Resonance

The principle of superposition leads to a phenomenon known as resonance. In this experiment sound resonance occurs when the wavelength of the sound "fits" the cavity in which it is travelling. Consider a long tube closed at one end. A sound wave enters the open end and travels along the tube until it hits the closed end. Upon striking the closed end the sound

wave reverses direction (reflection) and travels back down the tube toward the open end.

When a wave is reflected in this manner there is an 180° phase change in the wave; this is a very important factor for resonance.

Audible sounds travelling through air will have wavelengths ranging from approximately 3 to 300 cm. Wavelengths of this size are easy to study. We will employ sound resonance in a tube to determine the wavelength of the sound waves (λ), and using the given frequency (f) of the tuning fork and consequently calculate the speed of the wave as the product of f and λ .



Figure 2 Resonance Tube Set Up

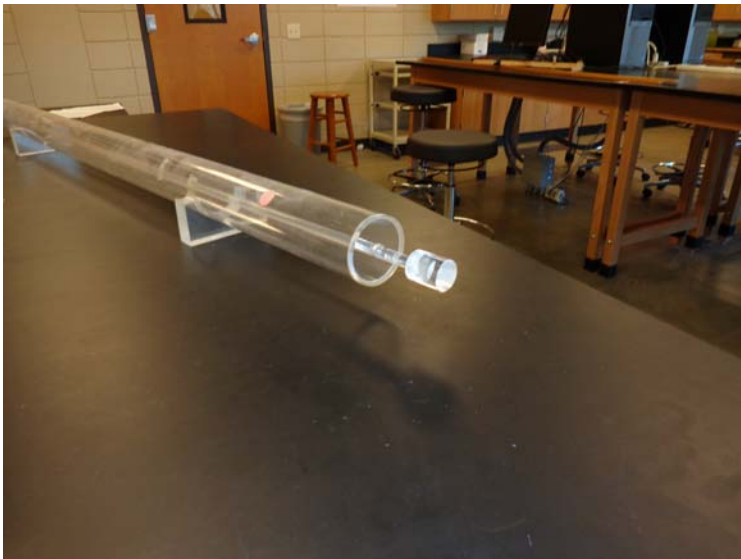


Figure 3 Resonance Tube set up other end. Use this end to adjust the location of the Piston.

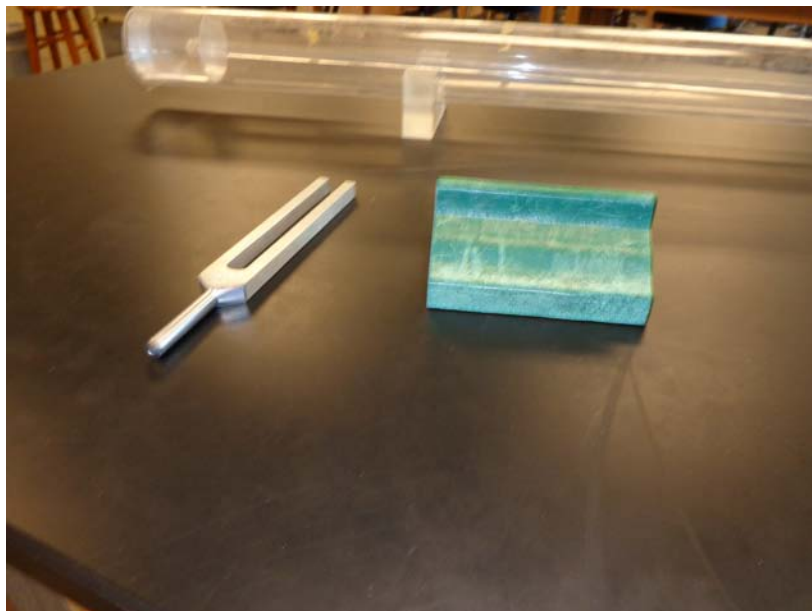


Figure 4. Tuning Fork and Striker Block

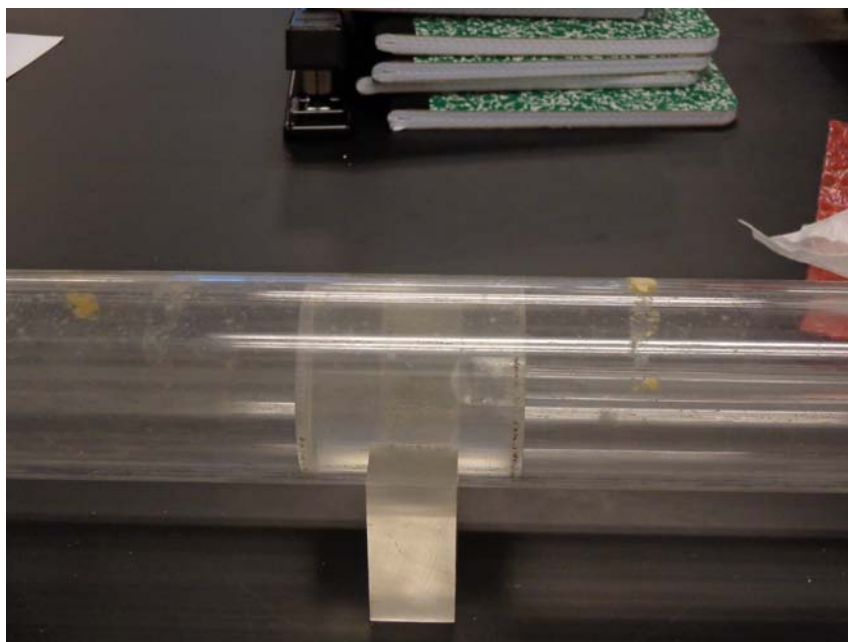


Figure 5: Piston

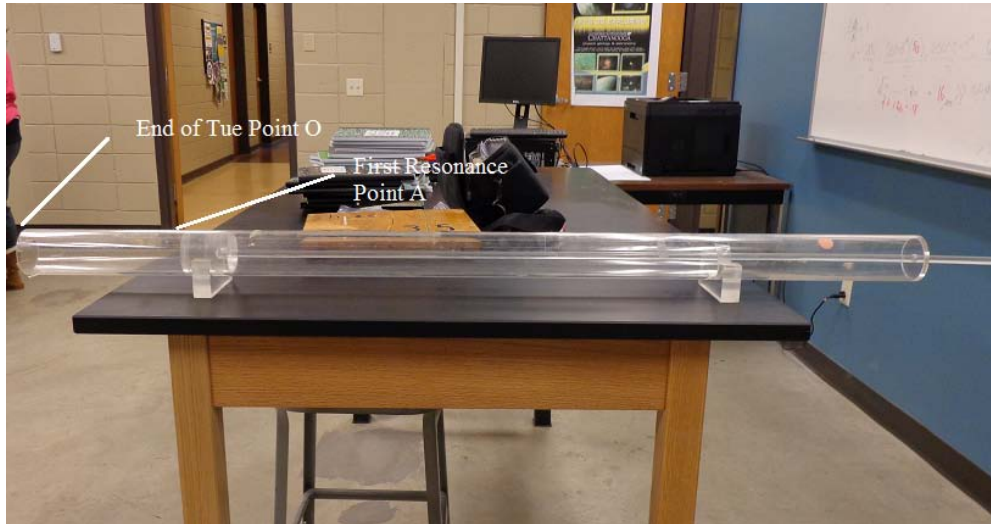


Figure 6: Point O at end of Tube and Point A the First Resonance Point

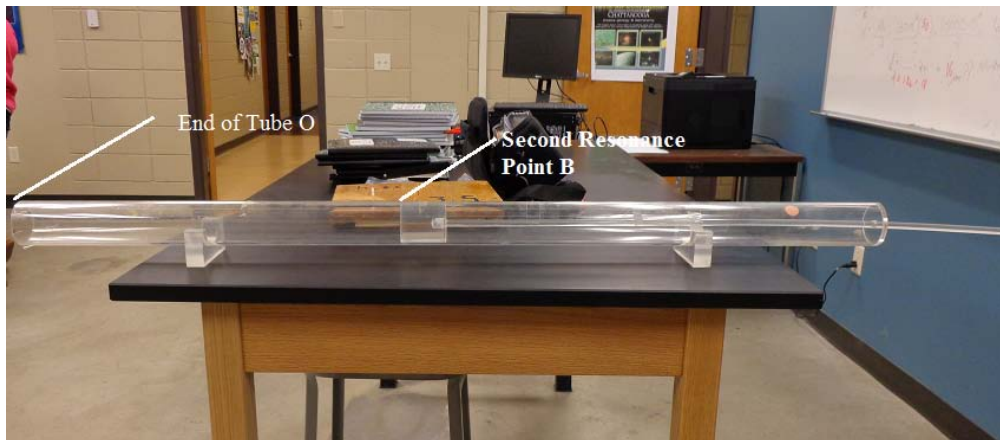


Figure 7: Point O at end of Tube and Point B the Second Resonance Point

Procedure: In this experiment the resonant frequencies are determined by the tuning forks that you will use to produce standing waves in a column of air in a tube open at one end. These are of known value. By adjusting the position of the piston the other end of the tube you will be able to adjust L , the length of the tube. In doing so you will be able to adjust the length of the column of air so as to form standing waves in the tube. Once a standing wave of a given frequency has been established by adjusting length the tube to the appropriate value of L for the fundamental of that particular frequency it will be possible to locate the position of each successive antinode along the wave by lengthening the tube. By measuring

the difference between successive nodes you will be able to compute the wavelength of the standing wave and from that the speed of sound in the column of air by:

$$v = \lambda f \quad (4)$$

The distance between the two resonances OA and OB

$$OB - OA = \lambda/2 \quad (5)$$

Begin with the 256 Hz tuning fork. Strike the fork on its tines (a great deal of force is not necessary) using the rubber striker block. It will produce a 256 Hz (middle C) tone audible to the ear. Hold the tuning fork over the mouth of the tube with the end of the tines vibrating perpendicularly to the mouth of the tube (Why is this necessary?) and adjust the length of the air column in the tube by moving the piston. You will notice that the tube will emit loud tones of the same frequency as the tuning fork for certain piston positions. This indicates resonance and the presence of an antinode at the mouth of the tube.

The first resonance OA will occur when the piston position is $\lambda/4$ from the mouth of the tube, the second OB when the piston position is $3\lambda/4$ from the mouth of the tube the third at $5\lambda/4$, etc., if the tube is long enough. Note that the distance between successive antinodes is $\lambda/2$.

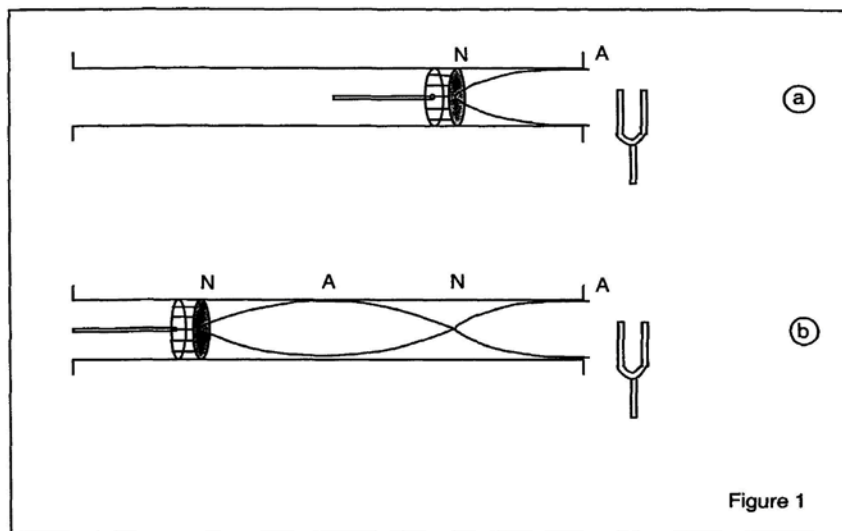


Figure 1

Figure 1: Because of the end correction, the tube length in figure 1a will be slightly less than $1/4 \lambda$. However, the distance between two nodes as shown in figure 1b will give the exact value of $1/2 \lambda$. Since the distance between two nodes is $1/2 \lambda$, we can obtain the wavelength, λ , and if the frequency of the tuning fork is known, the velocity of sound at room temperature can be obtained by equation 4.

Note, as well, that the number of resonances will increase with increasing frequency. Can you explain why?

Once you have located the approximate position of each resonance for a given tuning fork repeat the procedure again but this time measuring the position of each resonance as carefully as you can.

Record each measurement in your lab data sheet along with a sketch of the standing wave in the tube at the position that you are measuring. Once you have measured the position of each resonance, repeat the experiment a 3 more times and compute the mean x and standard deviation σ for the position of each resonance. When you are finished with this procedure for a particular frequency, repeat the procedure with tuning fork with the next highest frequency.

Data Analysis:

The distance between adjacent resonances (antinodes) is $\lambda/2$.

We seek λ since $v = f\lambda$. The calculations involving mean values are elementary. But in order to insure good statistics we must take care to carry the correct standard deviations from our measurements through our calculations. To do so use the following procedure:

1. Using mean values for each resonance points, \overline{OA} and \overline{OB} , determine the mean distance between each resonance for a given frequency, e.g., $\lambda/2_{\text{average}} = \left| (\overline{OB} - \overline{OA}) \right|$

Compute the standard deviation of this data.

2. To compute the mean and standard deviation of λ from $\lambda/2_{\text{average}}$, we use $\sigma_{\lambda_{\text{avg}}} = 2\sigma(\lambda/2_{\text{avg}})$ where $\sigma_{\lambda_{\text{avg}}}$ is the standard deviation of λ and $\sigma(\lambda/2_{\text{avg}})$ is the standard deviation of $\lambda/2$ from step one.

3. Calculate the velocity of sound and its standard deviation for each frequency using $v = f\lambda$ and $\sigma_{v_{\text{avg}}} = f\sigma_{\lambda_{\text{avg}}}$

4. Find the average velocity of sound and its error from the four tuning forks that you used.

5. Plot a graph of the wavelength λ vs. the period T ($1/f$) on linear graph paper or using a linear graph on Excel.

6. Find the slope of the best fit line. This is the velocity of sound in air.

7 Calculate the speed of sound for air using equation 6.

8. Calculate a per cent difference between the value obtained experimentally and the value obtained using equation 6.

Questions

1. Sound waves are longitudinal waves, meaning that the direction of the 'oscillation' is parallel to the direction of propagation of the wave. The speed at which the wave travels (propagation velocity) is dependent on the medium through which the wave is travelling. In a simple sense the stiffer the medium the faster the speed of sound. One indicator of 'stiffness' in materials or media is the bulk modulus (B). When combined with the density of the medium (ρ), the speed of sound (v) may be calculated as:

$$V = \sqrt{\frac{B}{\rho}} \quad (6)$$

	Bulk Modulus (Pa)	Density (kg/m ³)
Water	0.21×10^{10}	1.0×10^3
Steel	20×10^{10}	7.8×10^3
Aluminum	7×10^{10}	2.7×10^3

Table 1: Physical properties of water, steel, and aluminum.

Propagation of sound in a gas is a slightly more involved subject. Ignoring the details, the equation for calculating the speed of sound in a gas is:

$$V = \sqrt{\gamma \frac{RT}{M}} \quad (7)$$

Where:

γ = a constant particular to individual gases

R = the gas constant (8.314 Joules/ mol •K)

T = is the absolute temperature K

M= molecular mass of the gas Kg/mol

Typical values of γ and M:

Gas	γ	M (kg/mol)
Air	1.40	0.0288
Helium	1.67	0.0040
CO2	1.30	0.0280

Table 2: Various properties of gases.

If one considers the speed of sound in air then factors such as altitude, humidity, and pressure also enter into the calculation for the speed of sound.

A sound wave consists of alternating pressure changes called compressions and rarefactions. As the wave moves it compresses the air to a pressure greater than atmospheric pressure. Between successive compressions there is a region of low pressure called a rarefaction. The compressions and rarefactions occur along the path the wave is travelling.

Calculate the speed of sound for the 6 materials listed above. **Draw a graph that displays the speed of sound for the six materials.** Assume the temperature for the gases is 20⁰ C.

The ambient temperature in the lab is a little greater than 20⁰ C. Measure the room temperature using the thermometer provided to the class! Calculate the speed of sound in air using this temperature and compare it to your experimental results. Do they agree? Which of your frequencies actually results in the best data? Is there any pattern in your results, such as higher frequencies giving better results?

2. In practice the diameter of the tube used in the experiment also has an effect on the calculated speed of sound. The actual wavelength of the sound is calculated as $L + 0.4d = n\lambda/4$, where L is again the measured length of the tube and d is the diameter of the tube. If this equation was used instead of the one provided in the handout ($L = n\lambda/4$), what effect would this have on your results? Specifically, would the results for the speed of sound increase, decrease, or remain the same? Justify your answer.

3. Explain why we use two resonances instead of just one. What type of *systematic* error would we have in the experiment if we used only the first resonance to determine the speed of sound? Would this error give a higher or lower value for the speed of sound than expected?

Lab Report Format:

Your lab report for this experiment should contain:

- 1. Pre-lab (objective, theory, sketch of the experimental setup, and procedure).**
- 2. Original copy of both of your experimental data pages. (The instructor will keep the carbon copy of both pages handed in during lab.)**
- 3. Sample calculations: For this lab, an example needs to be shown for calculation for \overline{OA} , \overline{OB} , σ_{OA} , σ_{OB} , $\lambda/2$, λ , $\lambda\sigma(\lambda/2_{avg})$, experimental velocity of sound, velocity of sound using equation 6, the velocity determined by the graph of λ vs. $1/f$, and the percent difference between experimental velocity of sound and the velocity of sound using equation 6.**
- 4. Results: State your results (in complete sentences) for the experimental velocity of sound and its associated uncertainty. The percent difference between the experimentally determined velocity that obtained using equation 6. Make sure all values are properly rounded and have the correct number of significant digits. Assess what kinds of experimental variables could have caused this percent difference (that is, what physical things could have caused random variation in the data and/or a systematic error).**
- 5. Conclusions: Address how propagation of error of the measurements of the OA and OB affect your calculations of the predicted range of λ and thus the velocity of sound. Also use your answers to discussion questions 2 and 3 and explain and how they would affect the values you get for v .**