Measuring the Speed of Sound in Air

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.

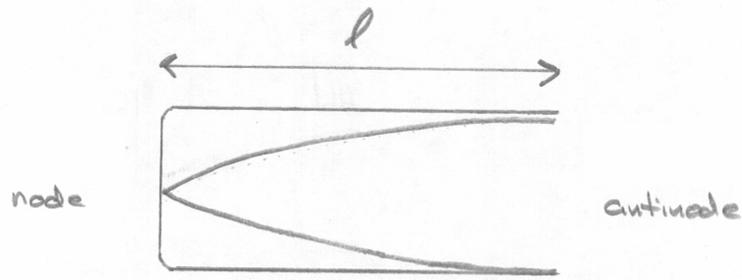
Equipment: Tuning forks (256 Hz, 512 Hz, 1024 Hz), rubber mallet, resonance apparatus, water.

Physics 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.

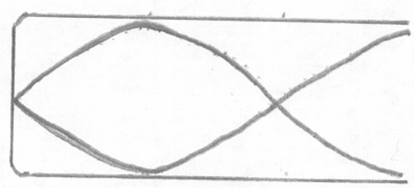
Recall that the condition for transverse standing wave formation on a string was $v = \frac{2\ell f}{n}$ or $f = n\frac{v}{2\ell}$ (n = 1, 2, 3, …) where f is the frequency of vibration, ℓ is the length of the medium (string), n is the number of half wave lengths, $\frac{\lambda}{2}$, (loops), and v is the propagation velocity of the wave. 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, $\frac{\lambda}{2}$, 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 top. By adjusting the amount of water 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 air-water boundary where it is reflected back up the length of the tube to the open end. The end of the tube containing water 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 exist at the open end and a displacement node at the closed end of the tube. This means that the fundamental (first harmonic) standing wave such a tube occurs when the column of air is of length $\frac{\lambda}{4}$. 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 $f = n\frac{v}{4\ell}$ or $\lambda = \frac{4\ell}{n}$ (n = 1, 3, 5, …).

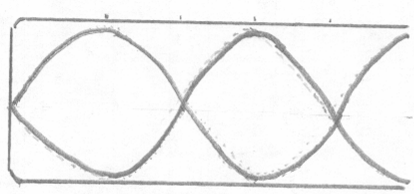
Harmonic Series for a Tube Open at One End



$\ell = \frac{\lambda}{4}$ Fundamental, 1st Harmonic (f)



$\ell = \frac{3\lambda}{4}$ 1st Overtone, 3rd Harmonic ($3f$)



$\ell = \frac{5\lambda}{4}$ 2nd Overtone, 5th Harmonic ($5f$)

$\lambda = \frac{4\ell}{n}$ $n = 1, 3, 5 \ldots$

$f = \frac{nv}{4\ell}$ $n = 1, 3, 5 \ldots$

Experimental: 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 level of water at 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 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:

$$v = \lambda f$$

Fill the reservoir of the resonance apparatus with water (position it near the bottom of the tube before doing this to prevent overflow). Note how moving the reservoir up and down the attachment rod raises and lowers the level of water in the resonance tube. Begin with the 256 Hz tuning fork. Strike the fork on its tines (a great deal of force is not necessary) with the rubber mallet. 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 level of water in the tube by moving the reservoir up. You will notice that the tube will emit loud tones of the same frequency as the tuning fork for certain water levels. This indicates resonance and the presence of an antinode at the mouth of the tube. The first resonance will occur when the water level is $\frac{\lambda}{4}$ beneath the mouth of the tube, the second when the water level is $\frac{3\lambda}{4}$ beneath the mouth of the tube, the third at $\frac{5\lambda}{4}$, etc. Note that the distance between successive antinodes is $\frac{\lambda}{2}$. 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 notebook 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 few times and compute the mean $\bar{x}$ 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 $\frac{\lambda}{2}$. We seek λ since $v = \lambda f$. 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, determine the mean distance between each resonance for a given frequency, e.g., $|\bar{x}_1 - \bar{x}_2| = \frac{\lambda}{2}_{\text{ave}}$. Compute the standard deviation of this data.

2. To compute the mean and standard deviation of λ from $\frac{\lambda}{2}_{\text{ave}}$, we use $\sigma\lambda_{ave} = 2\sigma\frac{\lambda}{2}_{\text{ave}}$, where $\sigma\lambda_{\text{ave}}$ is the standard deviation of the average value of λ and $\sigma\frac{\lambda}{2}_{\text{ave}}$ is the standard deviation of the average value of $\frac{\lambda}{2}$ from step 1. Using this formula compute the standard deviation of the average value of λ and record it. Do this for each frequency.

3. Calculate the velocity of sound and it's standard deviation for each frequency using $v = \lambda f$ and $\sigma v_{ave} = f\sigma v_{ave}$

4. Create a plot of *v* vs. *f*. Use error bars to represent the standard deviation of *v*.

5. The speed of sound in air in eastern Idaho at STP is about 331 m/s. Statistically speaking, how do your results compare with this?

Questions:

1. Is the speed of sound independent of frequency?

2. Does the speed of sound depend on anything that could be easily varied in this experiment?

3. Compare and contrast transverse and longitudinal waves.

4. What limited the number of resonances you found in the tube in this experiment for a given frequency?