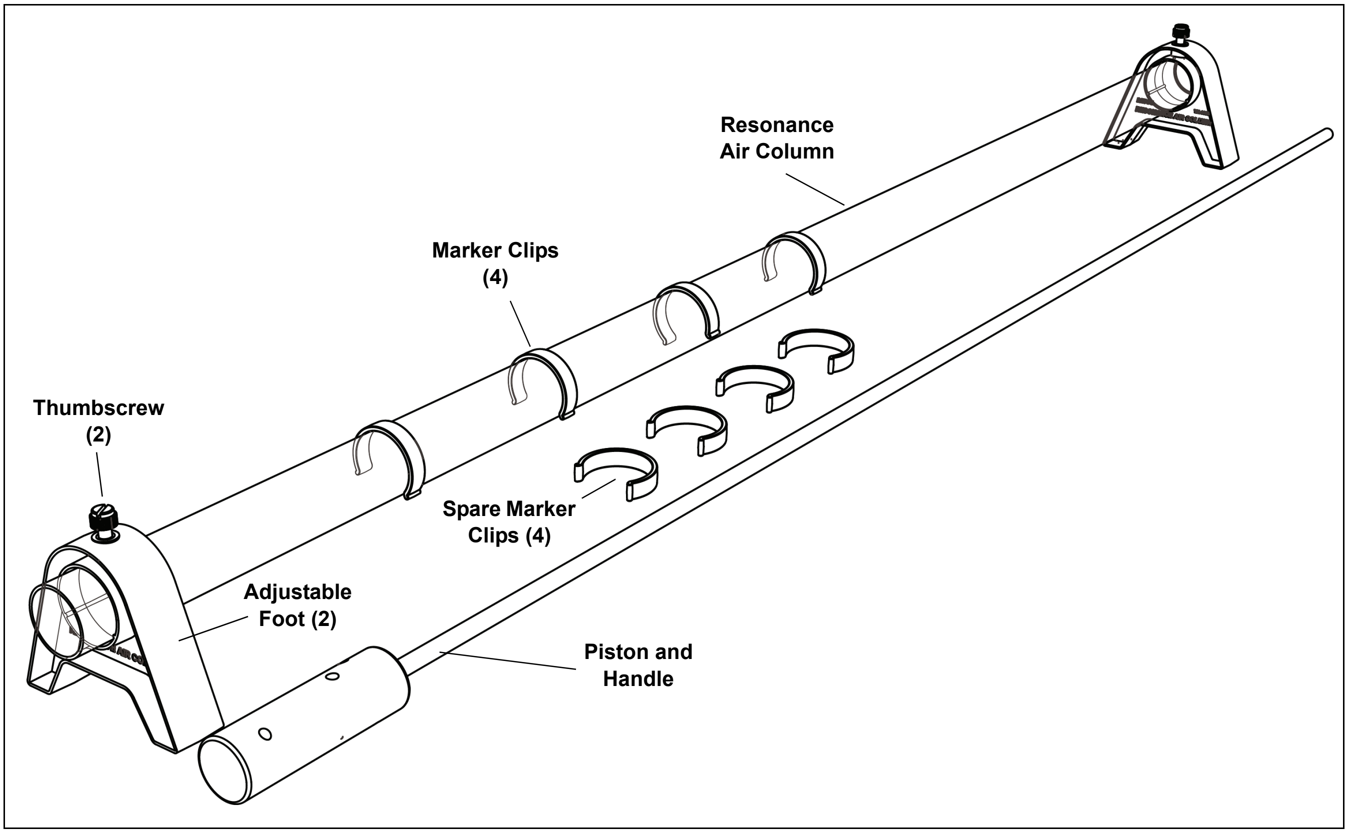
Resonance Air Column

WA-9606



Equipment

Included Items
Resonance Air Column, 120 cm
Adjustable Foot (2)
Piston and Handle
Marker Clip (8)

The WA-9606 Resonance Air Column is designed to work with the PASCO WA-9605 Mini Speaker. To produce sound and to work with the Resonance Air Column, the Mini Speaker needs a signal generator and a way to connect to the signal generator.

Required Equipment*
Mini Speaker (WA-9605)
Banana Plug Patch Cords (such as EM-9740)
Signal Generator (See below.)

The Mini Speaker needs a signal generator, such as a Function Generator or a PASCO Interface with signal generator capability (such as the UI-5000 850 Universal Interface or the CI-7650 750 Interface) and PASCO Data Acquisition Software (such as PASCO Capstone*).

Recommended Equipment*
Function Generator (such as PI-8127)

OR

PASCO Computer Interface
PASCO Data Acquisition Software

*Visit the PASCO web site at www.pasco.com for more information.

Introduction

The PASCO Resonance Air Column is a clear plastic tube that works with the WA-9605 Mini Speaker to demonstrate the propagation of sound waves in a tube. It is possible to set up standing wave patterns and locate nodes and antinodes in the air column. The speed of sound in air can also be measured.

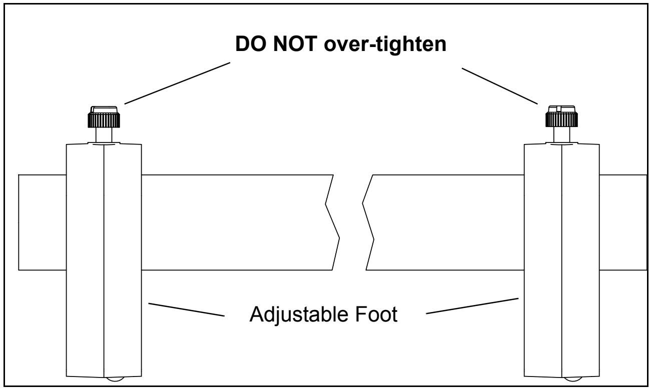
The movable piston allows the length of the resonating air column to be adjusted.

Setup

Assemble the Resonance Air Column

Put an adjustable foot on each end of the resonance air column, about 2 cm from the end of the tube. Use a thumbscrew to hold the foot in place.

- **CAUTION**: Do not over-tighten the thumbscrews because this may distort the tube.



Mini Speaker Setup

Place the Mini Speaker at one end of the resonance air column so that the Mini Speaker housing is in the end of the tube. Connect the end of two banana plug patch cords into the shrouded banana jacks on both sides of the base of the Mini Speaker. Plug the other ends of the patch cords into a signal generator, such as the PI-8127 Function Generator, or a PASCO Computer Interface with signal generator capability, such as the UI-5000 850 Universal Interface.

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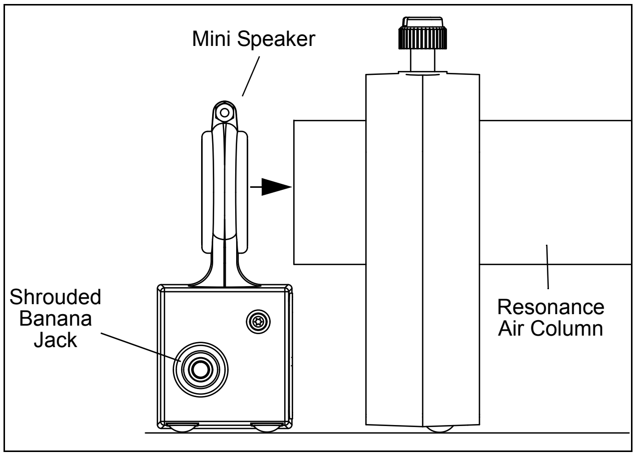


Set the frequency of the signal generator to about 100 hertz (Hz) and the amplitude to zero. Turn on the signal generator. Slowly adjust the amplitude of the signal until you hear a sound from the speaker.

WARNING: Do not exceed an amplitude of 4 volts.

Adjust the Air Column Length

The piston and handle can be used to adjust the length of the resonating air column in the tube. Insert the piston into the tube at the end opposite to the Mini Speaker. Use the handle to slide the piston to a new position in the tube.

Marker Clips

The Marker Clips snap on to the tube and can be used to mark the position of the piston that corresponds to a length for the air column that produces a resonance mode.

Investigating Resonance Modes

The resonance modes of the air column can be investigated by adjusting the frequency of the sound waves from the speaker or by adjusting the length of the air column in the tube. Listen to the volume of the sound waves in the tube and note what happens to the volume when the frequency of the sound waves and/or the length of the air column is changed.

- **NOTE**: By convention, an open tube is considered to be a tube that is open at both ends. A closed tube is considered to be a tube that is closed at one end and open at the other. Therefore, the Mini Speaker should be positioned a few centimeters away from the end of the tube so that the speaker end of the tube is “open”.

Theory of Waves in Tubes

Sound Waves

When the diaphragm of a speaker vibrates, a sound wave is produced that propagates through the air. The sound wave consists of small motions of the air molecules toward and away from the speaker. If you were able to look at a small volume of air near the speaker, you would find that the volume of air does not move far, but rather it vibrates toward and away from the speaker at the frequency of the speaker vibrations. This motion is very much analogous to waves propagating on a string. An important difference is that, if you watch a small portion of the string, its vibrational motion is transverse to the direction of propagation of the wave on the string. The motion of a small volume of air in a sound wave is parallel to the direction of propagation of the wave. Because of this, the sound wave is called a longitudinal wave.

Another way of conceptualizing a sound wave is as a series of compressions and rarefactions. When the diaphragm of a speaker moves outward, the air near the diaphragm is compressed, creating a small volume of relatively high air pressure, a *compression*. This small high pressure volume of air compresses the air adjacent to it, which in turn compresses the air adjacent to it, so the high pressure propagates away from the speaker. When the diaphragm of the speaker moves inward, a low pressure volume of air, a rarefaction, is created near the diaphragm. This *rarefaction* also propagates away from the speaker.

In general, a sound wave propagates out in all directions from the source of the wave. However, the study of sound waves can be simplified by restricting the motion of propagation to one dimension, as is done with the Resonance Air Column.

Standing Waves in a Tube

Standing waves are created in a vibrating string when a wave is reflected from an end of the string so that the returning wave interferes with the original wave. Standing waves also occur when a sound wave is reflected from the end of a tube.

A standing wave on a string has nodes—points where the string does not move—and antinodes—points where the string vibrates up and down with a maximum amplitude. Analogously, a standing sound wave has displacement nodes—points where the air does not vibrate very much—and displacement antinodes—points where the amplitude of the air vibration is a maximum. Pressure nodes and antinodes also exist within the waveform. In fact, pressure nodes occur at displacement antinodes and pressure antinodes occur at displacement nodes. This can be understood by thinking of a pressure antinode as being located between two displacement antinodes that vibrate 180° out of phase with each other. When the air of the two displacement antinodes are moving toward each other, the pressure of the pressure antinode is a maximum. When they are moving apart, the pressure goes to a minimum.

Reflection of the sound wave occurs at both open and closed tube ends. If the end of the tube is closed, the air has nowhere to go, so a displacement node (a pressure antinode) must exist at a closed end. If the end of the tube is open, the pressure stays very nearly at room pressure, so a pressure node (a displacement antinode) exists at an open end of the tube.

Resonance

As described above, a standing wave occurs when a wave is reflected from the end of the tube and the return wave interferes with the original wave. However, the sound wave will actually be reflected many times back and forth between the ends of the tube, and all these multiple reflections will interfere together. In general, the multiply reflected waves will not all be in phase, and the amplitude of the wave pattern will be small. However, at certain frequencies, all the reflected waves are in phase, resulting in a very high amplitude standing wave. These frequencies (when the sound in the tube is loudest) are called resonant frequencies.

In investigating the relationship between the length of the tube and the frequencies at which resonance occurs, the conditions for resonance can be understood in terms of the wavelength of the wave pattern, rather than in terms of the frequency. The resonance modes also depend on whether the ends of the tube are open or closed. For an open tube (a tube open at both ends), resonance occurs when the wavelength of the wave (λ) satisfies the condition:

$L = n\lambda/2,\ n = 1, 2, 3, 4, 5, \ldots.$

where L is the tube length.

These wavelengths allow a standing wave pattern such that a pressure node (displacement antinode) of the wave pattern exists naturally at each end of the tube. Another way to characterize the resonance states is to say that an integral number of half wavelengths fits between the ends of the tube.

For a closed tube, resonance occurs when the wavelength of the wave (λ) satisfies the condition:

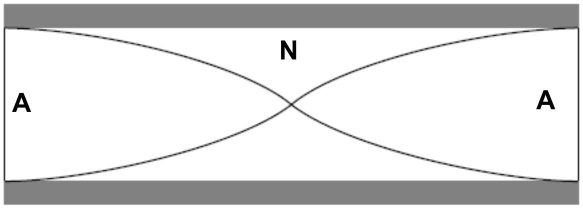
$L = n\lambda/4,\ n = 1, 3, 5, 7, 9, \ldots.$

where L is the length of the air column.

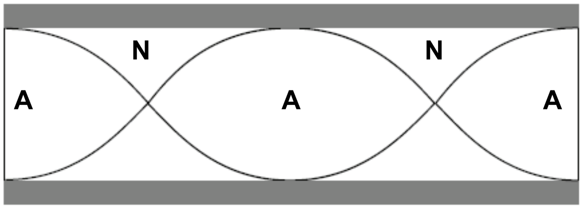
These wavelengths allow a standing wave pattern such that a pressure node (displacement antinode) occurs naturally at the open end of the tube and a pressure antinode (displacement node) occurs naturally at the closed end of the tube. As for the open tube, each successive value of n describes a state in which one more half wavelength fits between the ends of the tube.

Resonance Modes

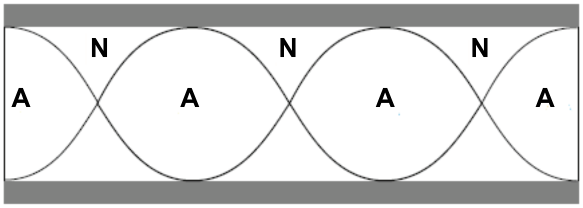
The first four resonance modes for open and closed tubes are shown below. The first resonance mode ($n = 1$) is called the fundamental. Successive resonance modes are called overtones. The representation in each case shows relative displacement. A displacement node is marked **N** and a displacement antinode is marked **A**.



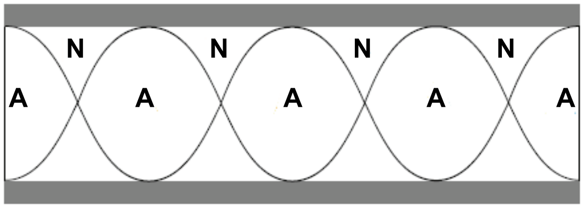
Open Tube Fundamental



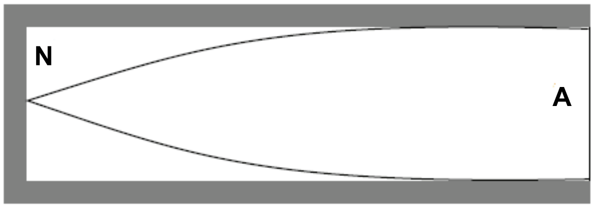
First Overtone



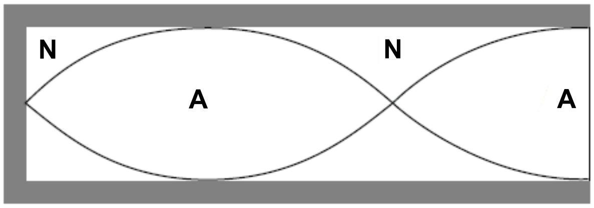
Second Overtone



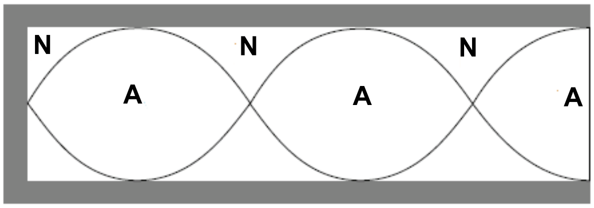
Third Overtone



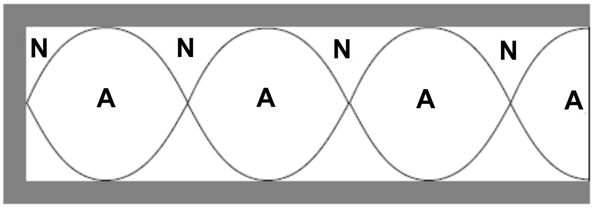
Closed Tube Fundamental



First Overtone



Second Overtone



Third Overtone

The formulas and diagrams for resonance in a tube are only approximate, mainly because the behavior of the sound waves at the ends of the tube–especially at the open end–depends partially on factors such as the frequency of the waves and the diameter of the tube. The ends of the tube are not exact nodes or antinodes.

End-Effect Correction

It is a useful experiment to investigate the wave behavior at the ends of the tube. Due to the behavior, the effective length of the tube is slightly longer than the measured length. The following empirical formulas give an approximate description of the resonance requirements for standing waves in a tube.

For an open tube, $L + 0.6(d) = n\lambda/2$, $n = 1, 2, 3, 4,...$

where L is the length of the tube and d is the diameter of the tube.

For a closed tube, $L + 0.3(d) = n\lambda/4$, $n = 1, 3, 5, 7,...$

where L is the length of the tube and d is the diameter of the tube.

Experiments

Constant Frequency, Variable Length

Put the piston into the Resonance Air Column and move the piston so that the length of the air column is 10 centimeters (0.1 m). Set the signal generator to produce a frequency of 100 Hz. Turn on the signal generator and adjust the amplitude so that sound from the speaker can be heard.

WARNING: Do not exceed an amplitude of 4 volts!

Slowly increase the length of the air column by moving the piston away from the speaker. Note the positions of the piston at which resonance (loudest sound) occurs. Place a Marker Clip on the resonance air column at each position. Measure the distance between each Marker Clip.

Constant Length, Variable Frequency

Put the piston inside the Resonance Air Column at a position so that the length of the air column is 50 cm (0.5 m). Set the signal generator to produce a frequency of 50 Hz. Turn on the signal generator and adjust the amplitude so that the sound from the speaker can be heard

WARNING: Do not exceed an amplitude of 4 volts.

Change the frequency of the signal. Note the frequencies at which resonance occurs.

Speed of Sound in Air

Create a standing wave and then determine the wavelength of the sound from the standing wave pattern. Multiply the wavelength by the frequency to determine the speed of sound using $\mathbf{v} = \lambda \mathbf{f}$ where $\mathbf{v}$ is the speed, λ is the wavelength, and $\mathbf{f}$ is the frequency.

Suggested Demonstration

Sprinkle a small amount of cork dust evenly along the bottom of the inside of the resonance air column. Rotate the tube slightly so that the cork dust is positioned slightly up on the side of the tube.

Set the Mini Speaker at one end of the tube. Adjust the frequency and amplitude to obtain a standing wave pattern in the tube.

- Rapid movement of the cork dust will show displacement antinodes and minimal movement of the cork dust will show nodes.

Adjust the frequency to create other standing wave patterns.

Put the piston into the tube and observe the difference in a closed tube standing wave compared to the open tube standing wave.

Technical Support

For assistance with any PASCO product, contact PASCO at:

Address: PASCO scientific
10101 Foothills Blvd.
Roseville, CA 95747-7100

Phone: +1 916 786 3800 (worldwide)
800-772-8700 (U.S.)

E-mail: support@pasco.com

Web www.pasco.com

For the latest information about the Resonance Air Column or the Mini Speaker, go to the PASCO web site at www.pasco.com and enter the model number or the product name in the search window.

Experiment 1:

Resonance in a Closed Tube of Variable Length

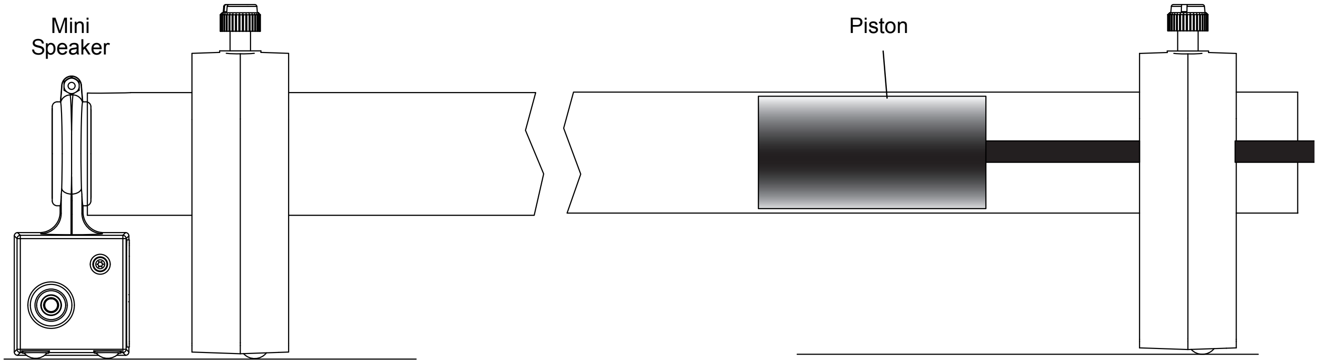
Equipment	Part Number
Resonance Air Column (WA-9606)	Mini Speaker (WA-9605)
Signal Generator (such as WA-9867)	Banana Plug Patch Cords (such as EM-9740)
Meter Stick (such as SE-8695) or Measuring Tape	

Introduction

This experiment explores the relationship between the wavelength, wave speed, and frequency of sound waves in a closed tube.

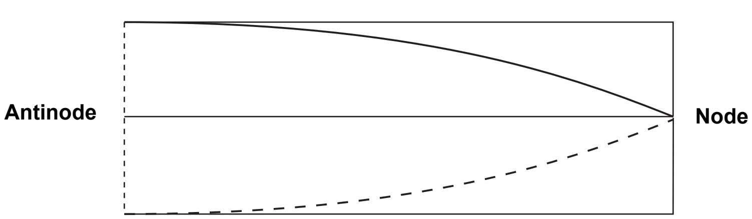
Set-up

1. Turn on the Signal Generator and turn the amplitude knob all the way down (counter-clockwise).
2. Connect the generator to the Mini Speaker using two banana patch cords. Polarity does not matter.
3. Place the Mini Speaker at an open end of the Resonance Air Column, as shown, with the housing of the Mini Speaker just inside the end of the tube. Put the piston in the other end of the Resonance Air Column.



Theory

A resonating air column in a tube with one end open and the other end closed will have a node at the closed end and an anti-node at the open end. A node represents an area where the displacement of the air is a minimum (zero), and an anti-node represents an area where the displacement of the air is a maximum. If the air column is resonating in the fundamental mode (lowest possible frequency) it will have no other nodes or anti-nodes. This is shown in the diagram below, where the curved lines represent the displacement profile of the air in the tube.



On a sine wave, the distance from one of the maxima to the next point where it crosses zero is a quarter wavelength. Thus, for an air column in a tube with one open end and one closed end, the length of the resonating air column, L, and the wavelength, λ, are related by:

(eq. 1)

$$\lambda = 4L$$

For all types of waves, the relationship between the frequency (***f***) and the velocity (**v**) of the wave is:

(eq. 2)

$$v = \lambda f$$

For a resonating air column in a tube, **v** is the speed at which sound travels through the air, and ***f*** is the frequency of the sound. In this experiment, the sound frequency is the frequency of the Sine Wave Generator.

Combining equations *1* and *2* yields:

(eq. 3)

$$L = \tfrac{1}{4} v \frac{1}{f}$$

The length of the air column is inversely proportional to the fundamental frequency.

Procedure

1. Place the piston so that its end is 110 cm from the end of the tube.

2. Set the Signal Generator frequency to 50 Hz, and turn up the amplitude to a reasonable level so that you can hear the sound from the Mini Speaker.

- **NOTE: Do not exceed 4 volts.**

3. Slowly increase the frequency of the signal generator, and listen for resonance. The loudness of the sound will increase noticeably when the frequency is within a few hertz of the fundamental frequency, (This resonance frequency should occur before the frequency reaches 100 Hz.) Slowly adjust the frequency up and down across the resonance. Listen carefully to determine at what frequency the sound is loudest. Try to determine the resonance frequency to the nearest 1 Hz. Record the air column length and frequency in a table.

4. Move the piston to decrease the length of the air column to 100 cm and repeat the previous step. Take data at 10 cm intervals down to a length of 40 cm. (The resonance frequency will eventually exceed 100 Hz.)

5. Make a graph of Air Column Length versus Inverse Frequency (L vs.1/f). Note that the horizontal axis is the inverse of frequency.

6. Find both the slope and the y-intercept of the best-fit line through this data.

7. From Equation 3, the slope of the graph is:

$$Slope = \tfrac{1}{4} v$$

   Use the slope from your graph to calculate the speed of sound in air. Estimate the uncertainty.

8. The actual speed of sound depends on the temperature of the air:

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

   where T is the temperature of the air in degrees Celsius. Measure the air temperature and calculate the actual speed of sound.

9. Compare your measured speed of sound from step 7 to the actual speed of sound. Calculate the percent difference.

$$\%\ \text{Difference} = \frac{\text{Measured} - \text{Actual}}{\text{Actual}} \times 100\%$$

Questions

1. On your graph of L vs. 1/f, why isn't the y-intercept zero?

2. Is the intercept negative?

End Effect

A negative intercept indicates that the effective length of the tube is longer than the actual length. The anti-node at the open end of the tube is actually formed past the end, slightly outside the tube. This phenomenon is called the “end effect”. The extra end-effect length is proportional to the diameter of the tube, and can be empirically represented as

$$\text{End Effect} = 0.3 \times \text{Diameter of Tube}$$

- Measure the diameter of the resonance air column and use this equation to calculate the end effect.

Question

3. How does this value for the extra end-effect length compare with the y-intercept of your graph?

Further Investigations

1. Set the frequency to 230 Hz, and place the piston so the length of the air column in the tube is 110 cm. Without changing the frequency, use the piston to slowly shorten the air column in the tube until you hear resonance. Adjust the length back and forth across the resonance to locate the position of the node. Record the position of the node (which is the length of the air column in the tube).

2. Without changing the driving frequency, continue to shorten the air column in the tube until you hear resonance again. Record the position of this node.

3. The distance between the two resonance positions (the distance between adjacent nodes) is 1/2 λ. Why?

4. Calculate the wavelength from the distance between the nodes. From this wavelength and the frequency of the Signal Generator, calculate the speed of sound. How does it compare with your earlier value?

5. Draw a companion sketch of the waveform diagram on the first page of this experiment, showing two nodes and the same frequency. Remember that there must be a node at the closed end and an anti-node at the open end. Hint: the tubes in the two drawings should not be the same length, but the wavelengths are the same.

Experiment 2:

Resonance in an Open Tube

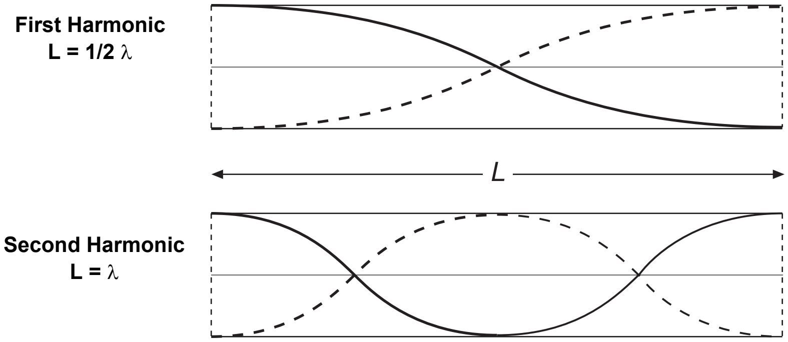
Equipment	Part Number
Resonance Air Column (WA-9606)	Mini Speaker (WA-9605)
Signal Generator (such as WA-9867)	Banana Plug Patch Cords (such as EM-9740)
Meter Stick (such as SE-8695) or Measuring Tape	

Introduction

This experiment explores the relationship between the wavelength, wave speed, and frequency of sound waves in an open tube.

Theory

A resonating tube with both ends open will always have an anti-node at either end, and at least one node in between. The number of nodes is related the wavelength and the harmonic. The first harmonic (or fundamental) has one node, the second harmonic has two, etc., as shown here:



At higher harmonics, the frequency is higher and the wavelength is shorter (length of tube does not change).

Procedure

1. Leave the piston out of the Resonance Air Column (that it, use only the with both ends open.)
2. Set up the Resonance Air Column, Mini Speaker, and Signal Generator as in the Closed Tube Experiment. Start with the frequency at 50 Hz and slowly increase it. Find the frequency of the fundamental (to the nearest 1 Hz) by listening for resonance. Record the fundamental frequency.
3. Calculate the wavelength from the frequency and the speed of sound. Use Equation 2, and the speed of sound that you found in Experiment 1.
4. Look at the diagram of the fundamental (first harmonic), and use that information to calculate the effective length of the tube.
5. Increase the frequency of the Signal Generator to the second harmonic. Confirm that the air column is again at resonance. Repeat for the third harmonic. Draw a companion sketch of the waveform diagrams on the first page of this experiment showing the third harmonic (remember that L is constant).
6. Return the frequency to the fundamental, and then place the piston in the end of the tube so it becomes a closed tube. Decrease the frequency of the signal generator until you find the fundamental resonance of the closed tube.
7. Calculate the ratio of the open-tube frequency to the closed-tube frequency.

Questions:

1. Why is the frequency of the fundamental higher for the open tube than it was for the closed tube?

2. How does the actual tube length compare to the effective length? (Hint: The effect is about twice as big compared to the previous tube because there are two open ends.)

3. When the frequency was returned to the fundamental, and the end of the tube was closed, was it still in resonance?

4. What should the ratio of the open-tube frequency to the closed-tube frequency be? Why?

Further Investigations

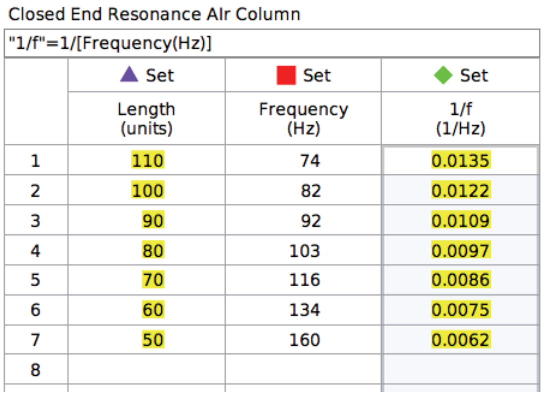
1. Why does a tube open at both ends play all the harmonics, but a tube with one end closed only plays the odd harmonics (1, 3, 5, etc.). What is the relationship between the tube length and the wavelength for the third harmonic of a closed tube?

2. Draw a companion sketch of the waveform diagram in the first page of Experiment 1 (closed tube) showing the third harmonic in a tube of the same length. Remember that you must still have a node at the closed end and an anti-node at the open end. Why is this set of pictures different from what you drew in Experiment 1? In each case, what is forced to stay constant, and what is allowed to change?

Teacher's Notes

Experiment 1: Closed Tube

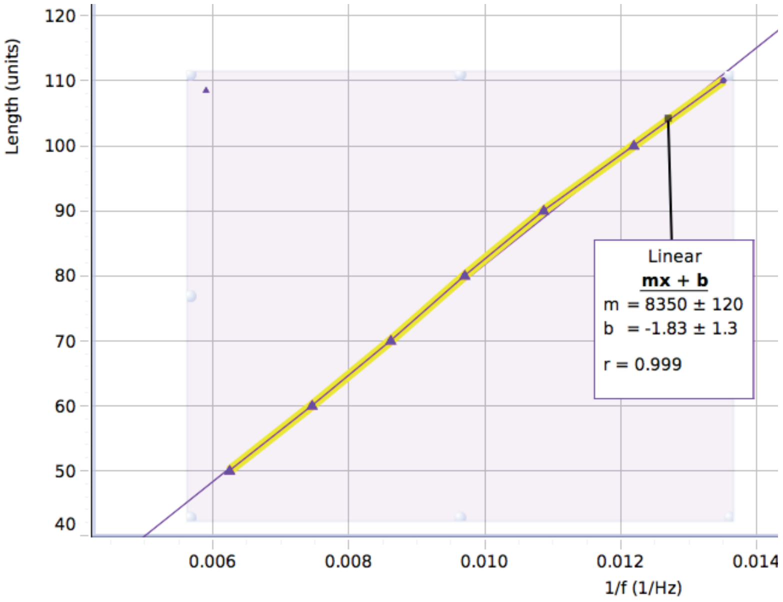
Sample Data



Closed End Resonance Air Column

"1/f"=1/[Frequency(Hz)]

	▲ Set	🟥 Set	◆ Set
	Length (units)	Frequency (Hz)	1/f (1/Hz)
1	110	74	0.0135
2	100	82	0.0122
3	90	92	0.0109
4	80	103	0.0097
5	70	116	0.0086
6	60	134	0.0075
7	50	160	0.0062
8			



Slope = 8350 cm/s = 83.5 m/s

Speed of sound in air = 4 (Slope) = 4 (83.5 m/s) = 334 m/s

Accepted value = 331 m/s + (0.6) (25 °C) = 346 m/s

Tube diameter = 3.5 cm

End-effect correction length = 0.3 (diameter) = 0.3 (3.5 cm) = 1.05 cm

The end-effect correction length is 1.05 cm compared to the y-intercept value of 1.83 ± 1.3. Compare the calculated result to the uncertainly of the y-intercept (± 1.3 cm)

Further Investigations

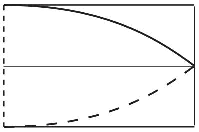
Frequency = 230 Hz

Position of first node = 104 cm

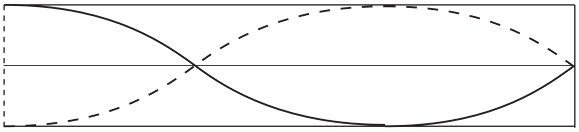
Position of second node = 28 cm

Wavelength = 2 (104 cm - 28 cm) = 152 cm

Wave speed is wavelength x frequency. **v** = λ**f** = 350 m/s



First Harmonic



Third Harmonic

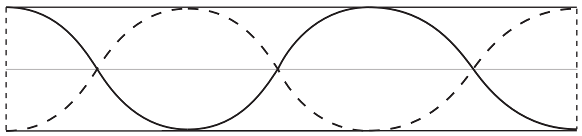
Experiment 2: Open Tube

Fundamental frequency = 117 Hz

Wavelength is wave speed divided by frequency. l = (346 m/s)/(117 Hz) = 2.95 m

Calculated tube length is 1/2 λ = 1.47 m.

Actual tube length = 1.20 m



Third Harmonic