

Equipment SWS, complete resonance tube (tube, piston assembly, speaker stand, piston stand, mike with adaptors, channel), voltage sensor, 1.5 m leads (2), (room) thermometer, flat rubber stopper

Reading Sections in your text books on waves, sound, resonance, and normal modes

1 Purpose

This lab will investigate standing sound waves in a tube subject to different boundary conditions. One end of the tube is closed off with a small speaker. The other end of the tube can be closed off with a movable piston which can be used to change the length of the tube. The piston can also be removed leaving one end of the tube open. Sinusoidal sound waves are excited in the tube with the speaker. A small microphone (mike) in the tube detects the sound waves. At the resonant frequencies of the tube the sound waves in the tube will be enhanced.

In another experiment, a pulse of sound will be sent down the tube and the reflected pulse examined. The nature of the reflected pulse will depend on whether the end of the tube is open or closed. It will also be possible to make a rather direct measurement of the speed of sound.

2 Theory

2.1 Air As A Spring

Gas is a springy material. Consider gas inside a cylinder that is closed off with a piston. Initially, assume that the pressure on both sides of the piston is the same. If the piston is pushed in, the entrained gas is compressed, the pressure rises, and there is a net force pushing the piston out. If the piston is pulled out, the entrained gas is rarefied, the pressure drops, and there is a net force pushing the piston back in. Because a gas acts like a spring and has mass it can support oscillations and waves. In this experiment we confine our attention to the mixture of gases we call air, which is roughly 80% N_2 and 20% O_2 .

2.2 Traveling Sound Waves in Air

When the cone of a loud speaker moves out, it compresses the air next to it and also imparts an outward velocity to the air molecules. This velocity is in addition to the random thermal velocities of the air molecules. Those air molecules nearest the speaker collide with the adjacent air molecules and impart to those molecules their motion. In this way the compression propagates away from the speaker, and sound is produced. Similar statements apply to the rarefactions produced when the speaker cone moves in. If the speaker cone is vibrated sinusoidally, a propagating sinusoidal sound wave or traveling wave moves out from the speaker. The wave relation, $\lambda f = v$, is satisfied by this wave. Here, λ is the wavelength, f is the frequency, and v is the wave speed. As the motion of the air molecules is along the direction in which the wave propagates, the waves are called longitudinal waves. This is in contrast to the waves on string which are called transverse waves as the elements of the string move transverse to the direction in which the wave travels.

In traveling sound waves the displacement of the air particles satisfies the wave equation. It is found that the velocity of the waves v is given by

$$v = \sqrt{\frac{\gamma p}{\rho}} \quad (1)$$

where p is the air pressure and ρ is the air mass density. The quantity γ is the ratio of the specific heats at constant pressure and constant volume, C_P/C_V . The quantity γ appears because the compressions and rarefactions that occur in sound waves are so fast that the process is adiabatic (there is no heat flow). For air, which is composed mostly of diatomic molecules, $\gamma = 1.4$.

With the aid of the ideal gas law, Eq.(1) can be written as

$$v = \sqrt{\frac{\gamma RT}{M}}, \quad (2)$$

where R is the molar gas constant, T is the absolute temperature, and M is the molar mass. For a given gas the speed is only proportional to the square root of the temperature. Some insight into this fact is given by noting that the root mean square thermal speed (v_{rms}) of the molecules in a gas is

$$v_{rms} = \sqrt{\frac{3RT}{M}}. \quad (3)$$

The speed of sound in a gas is quite close to the thermal speed of the molecules in the gas. The disturbance of the wave is propagated by the molecules colliding with each other, and the velocity of propagation is essentially the thermal speeds of the molecules.

A convenient expression for the speed of sound v in air at room temperatures is given by

$$v = 331.5 + .606T \text{ m/s}, \quad (4)$$

where T is the temperature in centigrade.

2.3 Traveling Sound Waves in a Tube

Sound waves can travel down a tube of constant cross section very much as they do in free space. It is assumed here that the walls of the tube are rigid so that they do not flex under the pressure variations of the wave, and that the walls of the tube are smooth so that there is not much attenuation of the wave. The speed of the waves in the tube is essentially the same as in free space.

2.4 Standing Sound Waves in a Finite Tube

Traveling sound waves in a finite tube are reflected at the ends of the tube. If the tube length and boundary conditions at the two ends of the tube are appropriate, resonance can occur at certain frequencies which are called resonant frequencies. (These are also the normal modes of the air entrained in the tube.) Resonance occurs when the reflected waves at the two ends of the tube reinforce each other. A small excitation builds up a large standing wave resonance.

The "pressure" of the air in the wave is understood to be the change in the pressure from the average value. The "displacement" of the air in the wave is understood to be the

displacement of the air from its equilibrium position. At resonance, both the pressure and displacement vary sinusoidally in space and time. Points in the tube where the pressure variations are maximum are called pressure antinodes, and points in the tube where the pressure variations are zero are called pressure nodes. Points where the displacement variations are maximum are called displacement antinodes, and points where the displacement variations are zero are called displacement nodes. In standing sound waves pressure nodes occur at displacement antinodes and pressure antinodes occur at displacement nodes.

The open end of finite tube is a pressure node because of the reservoir of normal air pressure outside the tube. (Actually the pressure node occurs a bit outside the end of the tube.) The same point must be a displacement antinode. The end of a closed tube must be a displacement node and a pressure antinode. From these boundary conditions the resonance frequencies of a tube open at both ends, closed at both ends, and open at one end and closed at the other end, can be calculated. A tube with both ends open is called an open tube. A tube with one end open and one end closed is called a closed tube. Fig. 1 shows the air displacement for the first 4 resonances of an open tube and a closed tube. The resonance wavelengths are determined by fitting standing waves into the tube so that the boundary conditions at both ends are satisfied. The lowest resonant frequency is called the fundamental or 1st harmonic. The n^{th} harmonic is n times the fundamental. Not all harmonics need be present.

3 Apparatus

The resonance tube is shown assembled in Fig. 2, and the parts are shown in Fig. 3. The tube has a built in metric scale. The speaker-microphone stand is affixed at one end of the tube and secured by shock cord. This stand has a vertical plate that holds the speaker. A hole in the plate accommodates the small microphone (mike). Note that the mike is sensitive to pressure variations. A thumbscrew holds the microphone in place. PLEASE TIGHTEN THIS THUMBSCREW ONLY SLIGHTLY. Always make sure that the plate holding the speaker and mike presses firmly against the tube.

For the pulse experiments it is necessary to move the mike into the tube to the 10 cm mark. To do this, loosen the thumbscrew holding the mike. Move the speaker stand out a few cm from the resonance tube and then push the mike by its cord into the resonance tube. Then place the speaker stand back firmly against the resonance tube. This procedure is necessary because the mike just catches the inner diameter of the resonance tube.

The other end of the resonance tube is held by the piston stand, also secured by shock cord. The piston fits inside the tube and is attached to a rod that goes through a vertical plate in the stand. The position of the piston is determined by the scale on the resonance tube.

For one experiment, the piston and its stand are removed from the end of the resonance tube. There is a piece of channel which can be used to support the end of the resonance tube for this experiment. This piece of channel can also be used to support the end of the piston rod when the piston is in the tube.

The lead from the mike goes to a small battery powered preamplifier which has an off-on switch. At the start of the experiment, turn the switch on (red showing next to switch). To conserve the battery, turn the switch off when you are through. The output of the preamplifier goes to a phone plug. There are adaptors that receive the banana plugs of a voltage sensor.

The speaker is driven by the power amplifier sitting on top of the interface. Check that the output of the power amplifier is connected to the speaker by two leads. **DO NOT OVERDRIVE THE SPEAKER.** Limit voltages to the speaker to 2 V. You should hear sound, but it should not be very loud. Connect a voltage sensor to channel A of the interface and to the output of the preamplifier.

Program the interface as follows.

- Drag the analog plug icon to channel C and choose power amplifier. The voltage out button is automatically depressed.
- Drag the analog plug icon to channel A and choose voltage sensor.
- Double click the voltage sensor icon to open the voltage sensor setup window. Change the sensitivity from the default of "low" to medium. (SWS has an analog to digital converter (ADC) of $2^{12} = 4096$. At a sensitivity of low, voltages from -10 to $+10$ volts are digitized by dividing this voltage interval up into 4096 steps. Each step is about 5 mV. At medium sensitivity the voltage interval is -1 to $+1$, and each step is about 0.5 mV. At high sensitivity, the voltage interval is -0.1 to $+0.1$ and each step is 0.05 mV.)
- Drag the scope icon to the voltage output terminals. The signal generator voltage is now applied to the top channel (green) of the scope. This is also the channel that the scope triggers on. (It is preferable to trigger on the larger voltage driving the speaker than on the much smaller preamplifier voltage.)
- Click the input menu button for the middle channel (red) of the scope and choose channel A, or mike output.

4 Experiment: Measuring Wavelength

Set the signal generator for a 500 Hz sine wave with an amplitude of 1.0 V. Click AUTO and MON and adjust the scope so that both traces are observable. With the piston in the tube, determine the positions of the piston that result in maximum signal from the mike. These are the resonant frequencies of the tube. Start with the resonance for the shortest tube (piston nearest the speaker). Make a number of measurements so as to build up statistics and to determine how well you can make the measurement. Then move the piston out, determining which piston position results in the next resonance. For this frequency, you will be able to adjust for only two resonances. Successive piston positions for resonance are a half wavelength apart. Determine the wavelength λ from your data, averaging appropriately. Compare your measured wavelength to the theoretical value, given by $\lambda f = v$.

In units of wavelength, how close is the speaker to a displacement minimum or maximum? Can you make a comparison to the driven string experiment?

Repeat the above measurements for frequencies of 1000 Hz and 1500 Hz, and make the same analysis. These are shorter wavelengths and more resonances will be observable. Do the wavelengths change with frequency in the way you expect?

5 Pulsed Experiments

In these experiments, short pulses will be sent down the tube from the speaker. This is achieved by driving the speaker with a relatively low frequency square wave of 10 Hz. The

speaker cone move very quickly one way and then stops. This sends a short compression or rarefaction pulse down the tube. This pulse is reflected from the end of the tube and propagates back toward the speaker. It bounces off the speaker end of the tube, and continues to go up and down the tube until it is damped. The period of the square wave is chosen long enough so that the pulse is completely dissipated before the speaker cone moves the other way in response to the square wave and sends the next pulse down the tube. The pulses alternate between compressions and rarefaction.

5.1 Speed of Sound

In this section, think carefully about what you are seeing on the scope. If you completely understand what you see, you understand what an oscilloscope is doing. Set the signal generator for a 10 Hz symmetric square wave with an amplitude of 2 V. Loosen the thumbscrew holding the mike, back off the speaker stand, and slide the mike into the tube to the 10 cm mark on the tube scale. Push the speaker stand back against the tube. Move the piston out to 80 cm, supporting the end of the piston rod with the channel. Click MON and adjust the scope so that the pattern looks something like Fig. 4. Explain the scope trace. Now increase the scope sweep speed so that the trace looks like Fig. 5. You may need to switch the speaker leads to invert the trace. The first pulse after the change in the voltage of the square wave is the outgoing pulse passing over the mike. The second pulse is the reflected pulse passing over the mike. Is the reflected pulse inverted? By using the stated horizontal sweep speed of the scope, determine the speed of sound. You will need to choose a point in the pulse which can be identified with minimum error. In your report, state which point in the pulse you chose.

With the scope running, slowly move the piston toward the speaker. What do you see on the scope? Explain.

5.2 Boundary Conditions

Very generally, when a wave or a pulse hits the boundary of the medium in which it has been traveling, it is partially reflected and partially transmitted. An example would be light impinging on glass. For some boundary conditions there is no transmitted wave. An example would be light that undergoes total internal reflection. For the resonance tube, this will be the case for the boundary conditions which will be examined. The nature of the reflected pulse depends on the boundary conditions. The pulse that is reflected must have a form so that the boundary conditions are satisfied. If the end of the tube where the pulse is reflected is open, the pressure in the reflected pulse must be inverted so as to cancel the pressure of the incoming pulse. The end of the tube is a pressure node. If the end of the tube where the pulse is reflected is closed, the pressure in the reflected pulse is not inverted. The end of the tube is a displacement node and a pressure antinode.

Remove the piston and piston stand from the tube and support the end of the tube with the channel. Observe the nature of the reflected pulse. Now close the end of the tube with the rubber stopper provided and note the change in the nature of the reflected pulse. Discuss what you see.

With the stopper in place on the end of the tube, try "cracking" open the end of the tube a bit by bending the stopper. How much of a crack is necessary to change the reflected pulse?

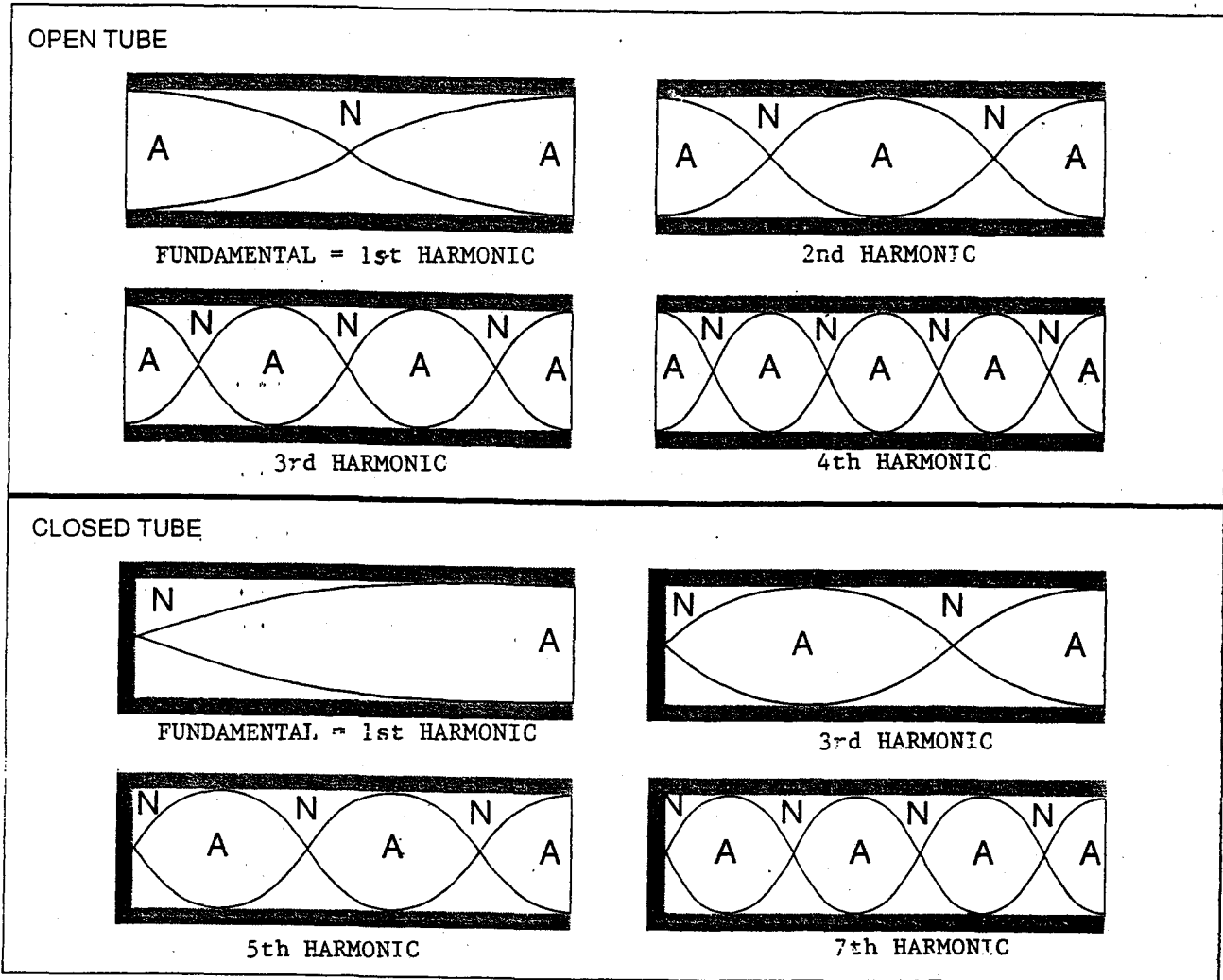
6 Questions

1. Let the length of the tubes in Fig. 1 be L . What are the wavelengths at the fundamental frequencies of the two types of tubes?
2. What is the wavelength at the fundamental frequency of a tube of length L closed at both ends?
3. Show that Eq.(2) follows from Eq.(1).

7 Finishing Up

Please leave the bench as you found it. TURN OFF THE MIKE PRE-AMPLIFIER SO AS TO CONSERVE THE BATTERY. Thank you.

DISPLACEMENT AT RESONANCE



Resonance States: Open and Closed Tubes

Fig. 1

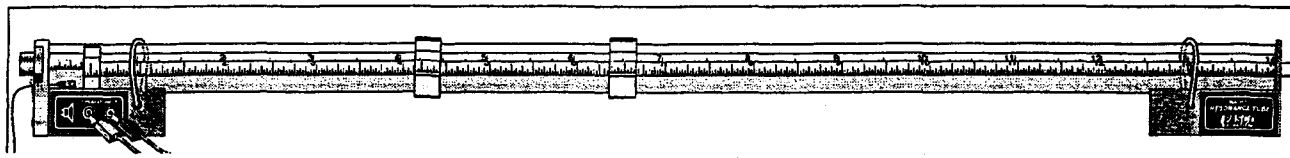


Fig. 2

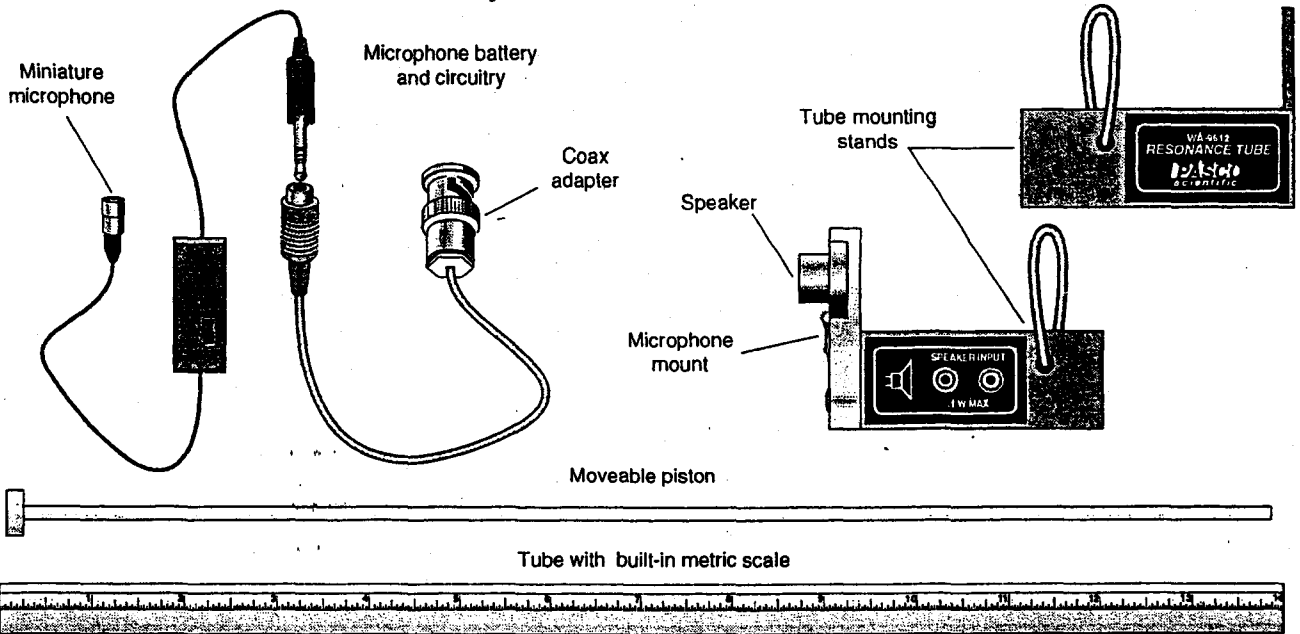


Fig. 3

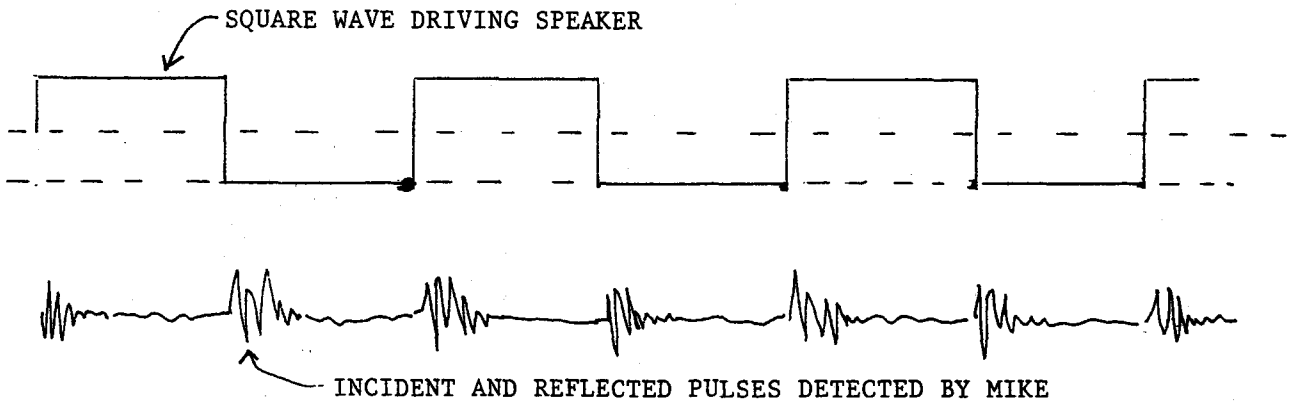


Fig. 4

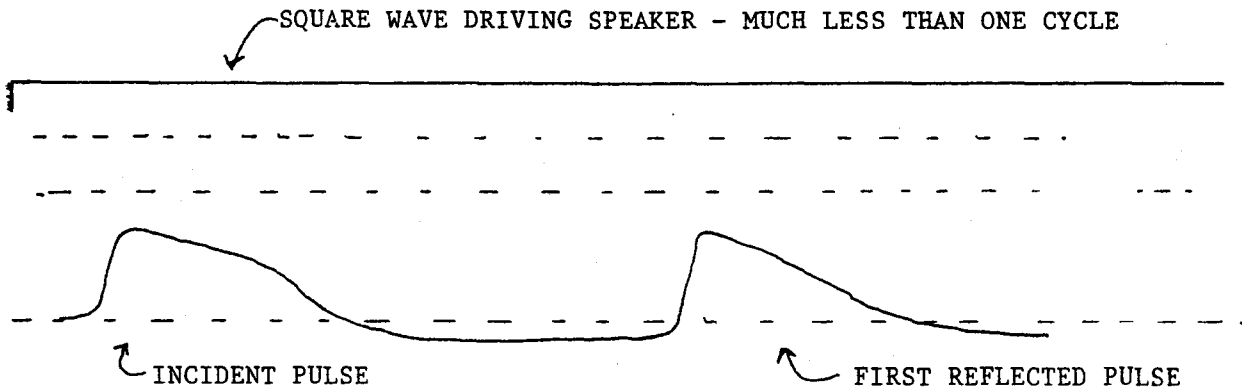


Fig. 5 (Fig. 4 with greatly expanded time scale)