THE SPEED OF SOUND

I. Introduction

Energy can be transported from one point in space to another by two means: by particles (such as a baseball traveling from a bat to a neighbor's window) or by waves (such as electromagnetic waves which are our radio and television signals). Suppose you were concerned about the speed with which sound can transport energy. How could you measure this speed?

If we don't concern ourselves with the nature of sound, we might set up this simple procedure. Develop a device that will emit a short pulse of sound, a device that will receive the sound and a device that can measure the time between when the sound leaves the first device and when it is received by the second device. Place the device that emits the sound a known distance from the device that receives the sound. Measure the time it takes the sound to travel the known distance and then divide the distance by the time to get the speed.

This sounds very simple and straightforward, but it isn't as accurate or easy in practice as it might be. As it turns out, there's another method, a little less direct, which works considerably better. We'll use both the simple time-of-flight method and a more sophisticated method to measure the speed of sound.

For the first time in this lab, we're making considerable use of electronic equipment. You don't need to know (yet) how these things work – we're treating them as 'black boxes', and you shouldn't let them scare you. Concentrate on what they tell you, and what's going on in principle, rather than the everyday electronic miracles occurring in the equipment.

Even though we're assuming a 'black box' attitude toward the equipment, it's good to have a rough idea of what they do. The main tool you'll be using is an *oscilloscope*. This marvelous device takes an electrical signal and makes a visual display of it on a display tube, which is a distant cousin of a TV picture tube or a computer screen. The signal is represented by a bright green dot on the screen. There's tremendous flexibility as to how the signal is displayed, and one can graphically display phenomena which take place much more quickly than human perception can follow. This power and versatility make the oscilloscope an indispensable tool in any electronics shop. We'll use the oscilloscope in two ways.

First, we'll use the input signal to move the dot up and down, while the dot scans to the right at a constant speed. The resulting trace is a display of the electrical signal (a voltage, technically) as a function of time. We'll be using the 'triggering' feature of the scope, which means that we command the scope to start the dot sweeping across the screen the moment it receives a trigger signal, which we supply.

In our second mode of use, we'll cause the scope to display one signal on the horizontal axis and another on the vertical axis. In our setup, one signal will be a slightly time-delayed copy of the other. Our display strategy lets us very accurately measure the amount by which one signal is delayed with respect to the other.

Other equipment we'll use includes a microphone, which simply converts sound into an electrical signal, and a loudspeaker, which does the reverse. Both of these are familiar. Less familiar is the oscillator, which creates an electrical signal which repeats rapidly, and the frequency counter, which counts how many repetitions of the signal come in each second. These are both fairly straightforward.

To set up the experiments, you'll be connecting these pieces of equipment together with wires. These plug into receptacles on the front panels in a simple way. The drawings in this writeup mostly show these wires as perfectly straight, but the drawings are only schematics! In most cases, you'll have to connect two wires to carry a signal, in order to have a complete circuit. The reasons for this – and the whole physical basis for this kind of electrical measurement – will be much clearer after you've taken Physics 4! In the meantime, just follow the directions and concentrate on measuring the speed of sound.

We will measure the speed of sound in air in two ways. The first method is essentially that which was described in paragraph two. The second method makes use of the fact that sound is a wave phenomenon and as such we need only measure the wavelength and the frequency of the sound to calculate the speed.

II. Method 1

In this method we simply measure the time-of-flight of a sound pulse across a measured distance. The experimental apparatus is shown in figure 1.

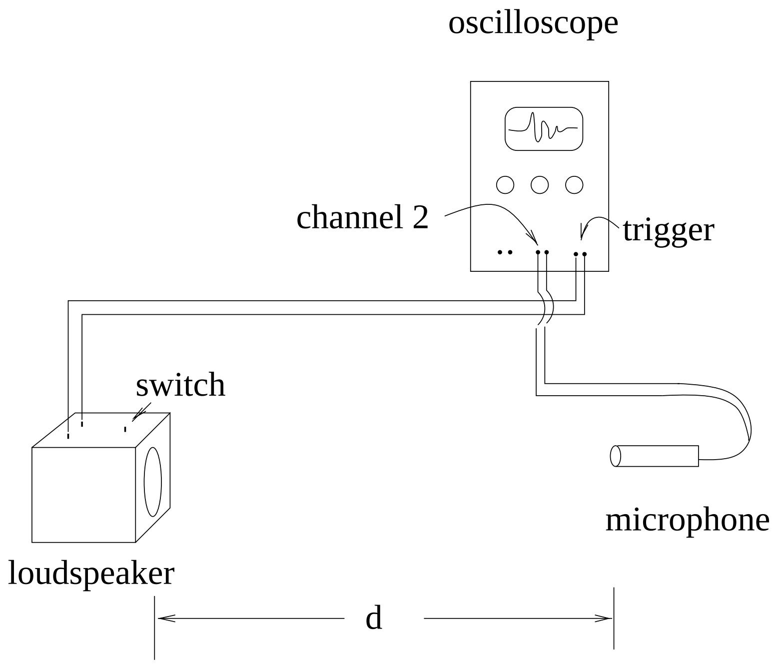

Figure 1.

On the top of the speaker box there is a red button switch which is connected to the speaker inside the box and to the external trigger on the oscilloscope. When it is pushed, a capacitor is discharged through the speaker creating a sharp pulse of sound and simultaneously the horizontal trace on the scope is started (triggered). The sound that radiates outward from the speaker is picked up at a later time by a microphone which has been placed a known distance d away from the speaker. The microphone changes the sound into electrical impulses which are fed into the vertical input (channel 2) of the oscilloscope and displayed on its screen (see figure 2). Since we know the horizontal trace started when the pulse left the speaker, the time it took the pulse to reach the microphone is represented by the flat portion of the display. Using the calibrated time base of the oscilloscope, the time can be determined, and from that and the known distance, the speed of sound in open air can be calculated.

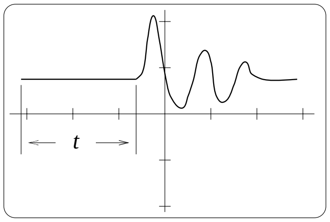

Figure 2.

III. Method 2

In this method the wave nature of sound is used to measure its speed in air in a tube; we measure both the frequency of the sound, f, and its wavelength, λ. The product of these two parameters gives us the speed of the wave, because $v = \lambda f$. The experimental apparatus is shown in figure 3.

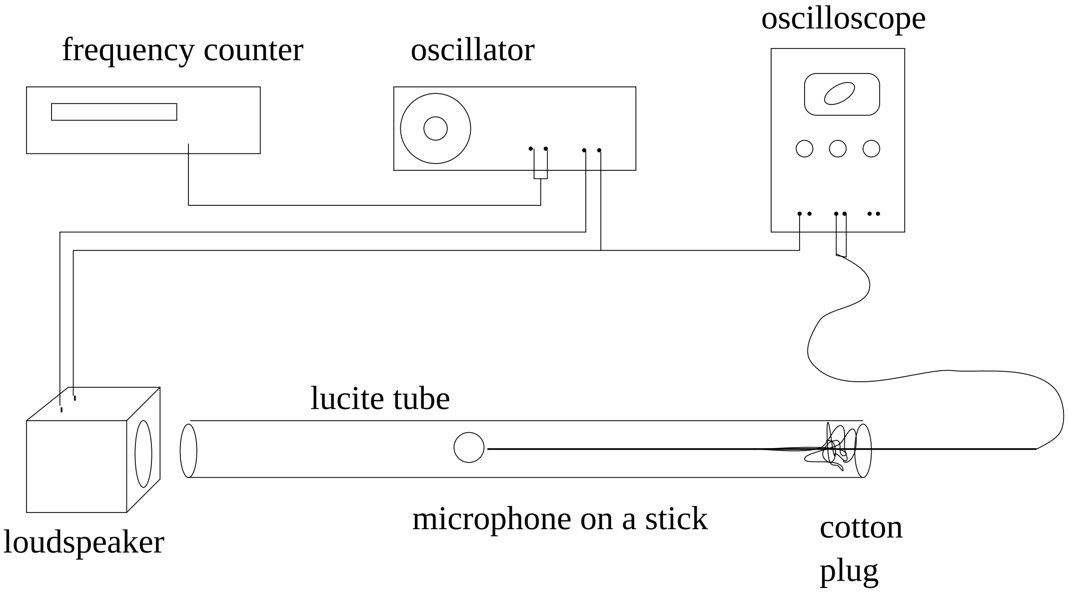

Figure 3.

A small speaker is mounted at one end of a Lucite tube which is about $2\frac{1}{2}$ inches in diameter and about 4 feet long. A sinusodial electronic signal is fed from an oscillator to the speaker producing sound waves which travel along the tube and are almost completely absorbed by a layer of surgical cotton at the far end. A microphone fastened to one end of a smaller aluminum tube can be moved along the axis of the larger tube. The alternating voltage that drives the speaker is also connected across the horizontal input of the oscilloscope, so that the *horizontal* motion of the oscilloscope beam corresponds to the oscillations of the sound waves at the position of the speaker. The output of the microphone is connected across the vertical input of the scope so that the *vertical* motion of the oscilloscope beam corresponds to the oscillations of the sound waves at the position of the microphone. The oscilloscope beam traces out a graph of y-input vs x-input known as a *Lissajous figure*. The shape of the Lissajous figure depends on the relative amplitudes, frequencies and phase of the two signals. In this case the oscillations necessarily have the same frequency, since they both derive from the same source, and the oscilloscope controls can be adjusted so the oscillations have the same amplitude on the display. The shape of the resulting Lissajous figures then depends solely on the relative phase of the horizontal and vertical oscillations. In general, it is an ellipse.

For the special case in which the oscillations are in phase (or in which they differ by 2π, 4π, etc.), the ellipse degenerates into a straight line which slopes upward to the right at a 45° angle with the horizontal and vertical axes. Note that the angle will be 45° only if the amplitudes are equal. If the amplitudes are not equal, it will still be a straight line, but at an angle other than 45° . If the oscillations are out of phase by 180°, the figures will again be a straight line, but this time it will slope upward to the left at a 45° angle with the horizontal and vertical axes. In between these two extremes, ellipses of various shapes will be seen. In a traveling wave, the phase of the oscillations increases continuously along the direction of propagation. Hence, if the microphone is moved along the tube, the Lissajous figure goes repeatedly through a sequence of shapes as shown in figure 4.

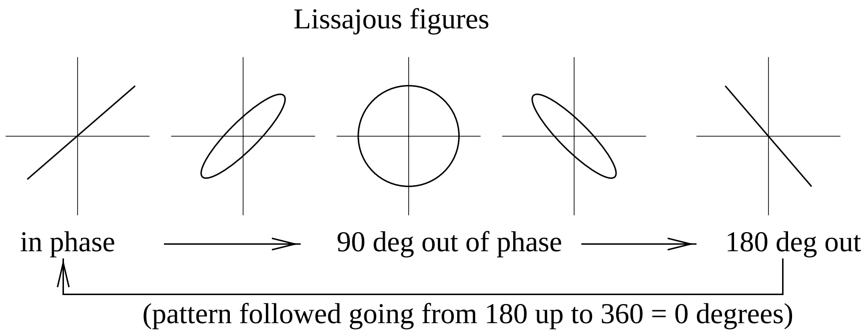

Figure 4.

The *wavelength* of a traveling sinusodial wave is defined as the distance between two points of the medium for which there is a phase difference of 2π. Suppose the microphone is first placed at a point in the tube where the Lissajous figure is a straight line. As the microphone is moved along the tube, a second point will be found where the pattern is again a straight line having the same slope as it did originally. The phase of the wave has, therefore, increased by 2π between the first and second points and the distance is one wavelength. We now need to determine the frequency of the wave. Since the frequency of the sound wave is the same as the frequency of the signal driving the speaker, we need only look at the oscillator dial to determine the frequency.

However, the frequency cannot be determined with great accuracy from the dial. Therefore, we will connect the output of the oscillator to a frequency counter, which is a device that counts the number of electronic impulses fed into its input per unit time and displays that number on a digital display. The measured frequency is then multiplied by the measured wavelength to calculate the speed of the sound wave.

Procedure

1. Familiarize yourself with the two modes of operation of the oscilloscope: (1) y-input vs t and (2) y-input vs x-input. To do this,

(a) Apply a sinusoidal voltage signal from a small transformer to channel 1. With the oscilloscope set to channel l, obtain a clear display on the scope. Observe what happens to the display when you change amplification and time scales. Using the calibrated time-base scale (the divisions in the horizontal direction), measure the frequency of the displayed wave. It should be 60 Hz (cycles per second).

(b) Turn the oscilloscope to the x-y display mode. With the transformer still attached to the channel 1 input, attach a sine wave from the oscillator into channel 2. Turn the oscillator to about 60 Hz and try to obtain a stable pattern. (What must be true to obtain a stable pattern?) With the display as stable as you can get it, vary the amplitude of the signal from the oscillator. Observe what happens to the display. Vary the frequency of the signal from the oscillator from 0-200 Hz. Observe what happens to the display.

2. Observe the wave form of some actual sounds. Connect a microphone to channel 1 and display several voice vowels at various gain settings and time base settings. Note the similarity of waveform for the same vowel with different speakers. Determine which vowels can be held as a sustained sound without a change in waveform.

3. Measure the speed of sound in open air by method 1. Use several distances and plot the arrival time of the pulse as a function of distance. From the graph, the velocity of sound in air can be calculated. Compute the percent deviation from the more accurately measured value of the speed of sound. This value depends on the temperature, is given by

$$v = 332\ \text{m/sec} + (0.61\ \text{m/(sec}\ ^\circ\text{C)})T$$

where T is the temperature in degrees Celsius.

4. Measure the speed of sound in the Lucite tube by method 2 for three frequencies between 2 and 5 KHz. When measuring a position where the x and y inputs are in phase, you will find that measurement of that same position another time will not yield the same result. In other words, if by looking at the scope you determine a position where the x and y inputs are in phase, moving the microphone slightly and remeasurement of that same position will not yield the same result. There is a certain amount of uncertainty introduced by the equipment used. Make four readings of one position and use the average of those

four readings in the calculation of the wavelength. The four readings can also be used to estimate the uncertainty introduced by the equipment and experimental technique.

Accuracy is improved if instead of measuring the distance between successive “in phase” positions you measure the distance between the first ”in phase” position and the last “in phase” position. To do this, push the microphone as close to the speaker as possible and then pull it away until you reach the first “in phase” position. Measure that position. Now pull the microphone away from the speaker counting the number of “in phase” positions you pass along the way. When you get to the last measurable “in phase” position measure that position. To calculate the wavelength, subtract the scale reading of the last “in phase” position from the scale reading of the first “in phase” position and then divide by the number of “in phase” positions passed through in going from the first position to the last. Compare the measured values with the theoretical value.

Lab Report Your analysis should contain the following:

(1) data table for method 1 - distance from speaker to microphone vs time of arrival.

(2) graph of the data for method 1 and calculation from that graph of the speed of sound in open air.

(3) data table for method 2 containing four measurements of each in phase position and the average of those four readings. Indicate the pairs of data used to calculate the wavelengths. Indicate how the wavelengths were calculated.

(4) data table for method 2 - wavelength vs frequency. Include in your table the calculation of the speed of sound for each pair.

(5) comparison of the results of method 1 and method 2. Discuss any discrepancies you find.

(6) comparison of experimental and theoretical values for the speed of sound. Discuss any discrepancies you find.