Year 1 Laboratory Manual
Introductory Experiments:
Speed of Sound

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1. Measuring the Speed of Sound in Air

1.1 Introduction

The main aim of this experiment is to help you learn how to use a key device in the laboratory: the oscilloscope. This experiment will also help you develop your knowledge about phase difference, a fundamental principle of wave propagation as you will use the principal of phase difference to measure the speed of sound.

You will be using an oscilloscope, a very important and common piece of lab equipment. Oscilloscopes are tools which can display signal voltages which vary in time, and can be used to measure properties of these such as amplitude, frequency, rise time, time interval, and others.

This lab will help teach you the basics of using an oscilloscope—if you have time you should feel free to play with the different scope functions learning what it can do, as this will pay dividends in future laboratories.

1.2 Physical Principles

Phase Difference

To measure the speed of sound in air we will use the fact that there will be a phase difference between the sound wave emitted by a source and the sound detected some difference away. This is because it takes a finite time for the peaks and troughs of the wave to propagate to the detector. We will use a time varying voltage signal to drive a speaker, and a microphone to measure the sound. The phase of the signal supplied to the speaker will differ from the phase recorded by the microphone due to the finite time it takes for the wave to propagate between them.. This is illustrated using figure 1.1.

In this graph, we observe that, at any given moment in time for a given detector distance (vertical line) the atmospheric pressure change, ΔP, at the location of the source and at the detector are different because the sound waves takes a finite time to propagate from the source to the detector. Whilst the pressure at the two locations changes with time as the wave propagates, the difference in phase remains constant.

To calculate the speed of sound using this method, we can, for a known signal frequency, ν, measure the phase difference at different source-detector separations. A phase shift of 2π corresponds to a distance difference of one wavelength, the relationship can therefore be described by

$$\Delta\phi = \frac{2\pi}{\lambda}x, \tag{1.1}$$

where $\Delta\phi$ is the phase difference, x is the source-detector separation, and λ is the wavelength of the sound.

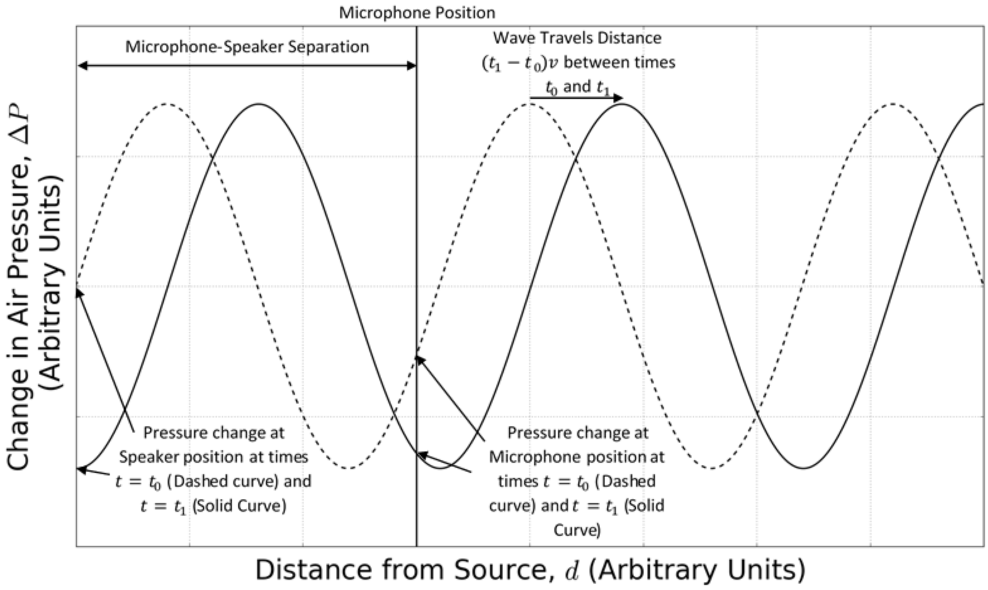

Figure 1.1: Illustration of the phase shift between a source (speaker) and detector (microphone). Here the air pressure at a distance of 0 represents the signal being emitted by the speaker at times $t = t_0$ (dashed line) and a later time $t = t_1$ (solid line). The vertical line represents the distance between the detector and the source. The points at which this vertical line intersects the graphs indicates the signal measured by the detector at $t = t_0$ and $t = t_1$.

Applying measured values of λ and ν to the equation

$$c_s = \nu\lambda \tag{1.2}$$

we can therefore calculate the speed of sound in air, c_s.

1.3 Experimental Procedure

In this experiment you will use a signal generator to generate a sinusoidal AC voltage signal which is converted into a sound wave using a speaker. A microphone will be used to detect the signal at some distance away from the speaker, and both the generated and the detected signal will be displayed by the oscilloscope, allowing you to measure the phase difference.

Setup

Position the speaker on one side of the bench and the microphone somewhere in the middle of the bench. Figure 1.2 shows the set up of the experiment and how you should connect individual parts together; each part is described individually in detail in the following sections.

Signal Generator (Built in the Oscilloscope)

The primary function of an oscilloscope is to display and measure the input signals, in this case coming from the microphone and the speaker (how to do this will be described shortly). However, the oscilloscope we have in 1st year lab has an extra feature–it can also generate a time-varying voltage signal, which we will use to drive the speaker.

To use this, turn the oscilloscope on (turn the power on using the switch at the back, and turn the scope on using the button at the front of the device). It's good practice to *reset* the oscilloscope before you start working with it. There are lots of different settings on a scope and resetting is a

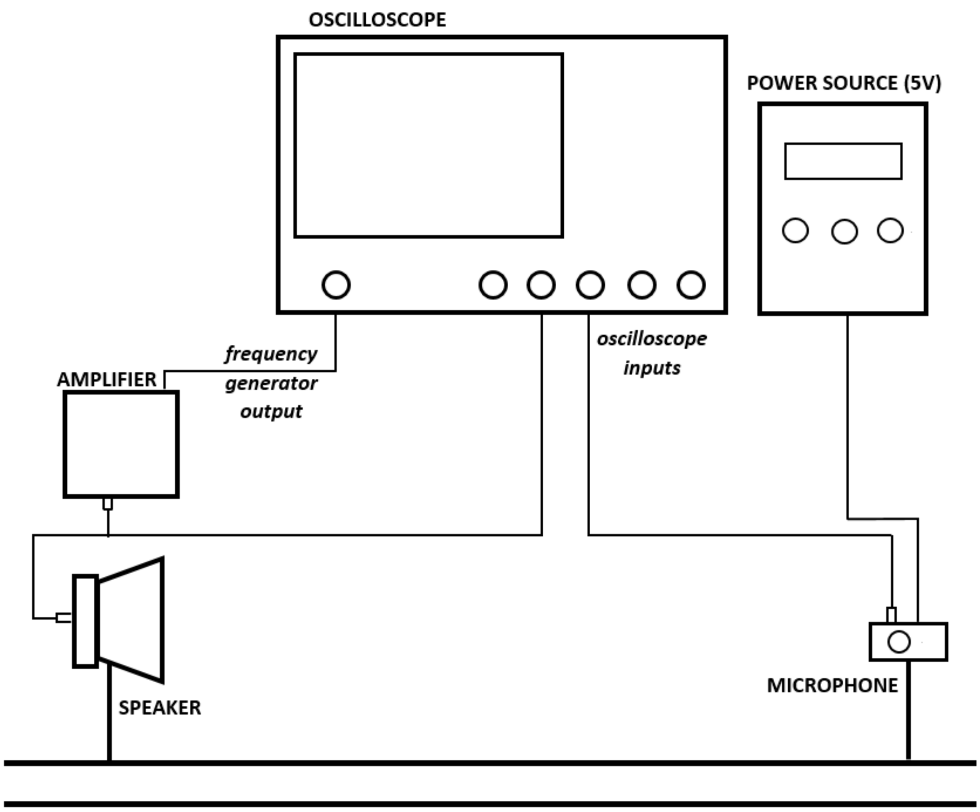

Figure 1.2: Schematic set up of the experiment

good way of making sure nothing strange has been applied. You can do this as follows: under the group of *action* buttons on the right hand side of the scope press the grey *SAVE/LOAD* button which will bring up a menu on the touch screen. Press *Setup* followed by *Factory default*.

To access the signal generator settings, press the *Gen* button on the bottom right, or select the *Gen* option in the *Menu*. The signal will be generated at the *Aux Out* output—a coaxial cable connects this to the to the amplifier (see next section).
Once you have chosen your setting, to turn the signal generator on, change the *Output* option from 0 to 1.

The device allows you to set the *Function* type (sinusoidal, triangular, square...), the *Frequency* (ranging from 100 mHz to 25 MHz), and the peak-to-peak* *Amplitude* of the signal.

Amplifier

The signal generated by the signal generator is not capable of driving the speaker directly, so we need to use an amplifier. This is because there is a large resistance at the signal generator output (typically 600 Ω), so if you did not amplify the signal, the generator would not be powerful enough to drive the speaker.

A coaxial cable connects the output of the signal generator to the amplifier, the outputs of the amplifier are connected to the speaker. The output of the amplifier should be connected back to the oscilloscope. Before turning the amplifier on, make sure the amplification is set to minimum, and only then gradually increase it to the desired level.

*The peak-to-peak (pp) value corresponds to twice the amplitude, i.e. from the trough to the crest

For this experiment you will be driving the speaker with a sinusoidal wave at a frequency beyond the range of hearing (too many speakers on at once in the lab is very noisy!), but you can briefly try and hear what each of the signals sounds like just to get an idea and convince your self that the speaker is working properly.

Microphone

The microphone you will be using has a built-in amplifier, so is there is no need for further amplification of the signal. The microphone needs to be connected to its power source. The *VCC* output should be connected to the power supply, and the voltage should be set to $5V$. The *GND* output to should be connected to ground. The ground and the *OUT* output should be connected to the oscilloscope using a coaxial cable.

Oscilloscope

A more detailed description of all the different functions of the oscilloscope in the equipment guide document which you should refer to; however, a brief description of how to operate it for the purpose of this experiment is also provided here. There are a lot of settings on the oscilloscope that you can change, but you will only need to set a few for the purpose of this experiment.

You will need to display both the output signal of the microphone and the signal generator on the oscilloscope simultaneously. Connect the signals from the speaker to the scope *Ch1* input and the microphone to the scope *Ch2* input using coaxial cables.

Start with the microphone as close to the speaker as possible. Make sure you have set the signal generator to produce a 5V peak-to-peak, *Sine* wave with a frequency of about 2 kHz (for now, just to set up the oscilloscope), and turn the function generator on. You should to adjust the horizontal (time) and vertical (voltage) scales of the oscilloscope so that you can clearly see the sinusoidal shape of the signal.

Slowly increase the amplitude at the amplifier until you can hear the sound and detect the signal on the scope (one or two divisions on the amplifier dial should be enough; respect your peers and don't make the sound too loud). Once you have an audible signal properly displayed on the scope, increase the frequency on the signal generator until the sound cannot be heard (usually around 20 kHz), you will need to re-adjust the horizontal scale so that you can still clearly see the sinusoidal shape of the signal.

- Press the *Ch 1* button to display signals from the speaker.
- Press the *Ch 2* button to display signals from the microphone.
- Access the menu for each channel by pressing the corresponding button. For each channel, set the *Coupling* to *AC*; this removes any constant offset voltage from the signal and lets you see only the varying frequency part on top of this offset.
- You will need to set the trigger. The trigger function on a scope ensures that a repetitive signal is displayed properly, i.e. the wave function displayed doesn't keep "running" across the display but remains stationary. Press *Trigger* to access the settings. Set *Coupling* to *AC* and *Source* to the channel through which you're connecting the speaker. Turn *HF Reject* ON to reject high frequencies (to stop the oscilloscope from triggering from background noise). If the trigger level is set too high (i.e. above the amplitude of the voltage signal you are triggering from) the scope will not trigger properly. If the trigger level is set too low you may trigger off noise rather than the repetitive signal you want to trigger from.
- To get a clearer line for the signal, you might want to display the average value of the signal rather than a single sample. Go to the *Acquire* section in the menu (or press *Acquisition*)

and select *Average* as the *Acquire Mode*. Set the number of averages to a sensible value. The higher the number, the clearer will the signal be, but it will also take longer to adjust as you move the microphone.

- You might also want to adjust the vertical (voltage) and horizontal (time) scales. To adjust the vertical scale, select the relevant channel by pressing either *Ch 1* or *Ch 2*; use the bigger of the two dials in the *Vertical* section to change the voltage per division settings, and the smaller dial to change the offset (the vertical position of the signal). The offset simply moves the signal up and down on the screen and can be useful when you are examining multiple channels at once.
- To change the horizontal scale (time-base), use the dials in the *Horizontal* section. You should fit at least one and a half periods on the display.

Measuring the Phase Difference as a Function of Distance

You now need to measure the phase difference between the sound wave at the position of the source and the sound wave at position of the microphone, as a function of the distance between them. There are (at least)two methods for doing this.

The first method involves moving the microphone until there is an easily recognised phase difference between the two signals, e.g. the signals are in phase or 180° out of phase, and record the position, repeating this for successive positions. The second method involves measuring the phase difference at a series of arbitrary positions.

You can use the measure functions of the scope to measure the phase difference between the two signals directly for both methods. In *Menu* go to the *Measure* section, and set the *Type* to *Phase* (in the horizontal measurements section. Select *C1* and *C2* as the *Measure source* and the *Measure source 2* and turn *Statistics* on. The oscilloscope will start taking measurements of the phase difference and show the mean value, as well as the standard deviation. You can also use the measure functions to measure other properties of the sounds wave at the microphone, for example the amplitude. Before taking a new measurement it is good practice to press *Reset statistics* to make sure the previously recorded values are not being included in the average and standard deviation values the scope reports. This is especially important if you are averaging your signal over many samples.

At this point you need to start to think about the best strategy to get good quality data. Some questions you might want to consider include:

- How many different positions should you measure the phase difference at?
- Over what range of separations should you measure?
- What is the best way to measure the distances with sufficient accuracy? Will you get better accuracy by measuring the phase difference over a short distance (e.g. over a single wavelength) but measuring the distances very precisely (e.g. with vernier calipers), or will you get better accuracy by measuring the phase difference over many wavelengths?
- If you are moving the microphone to positions of defined phase difference, how will you determine the uncertainty in this position?
- If you are moving the microphone to arbitrary positions and measuring the phase difference and you move the microphone too quickly you might misinterpret the phase shift (e.g. record it as 20° when it was in fact 380°). How can you avoid this?

You should take some preliminary measurements to decide on your method before taking a definitive set of data. Make sure to note down your method and the reasons you chose this method in your notebook.

At the end of the session you should aim to have a series of measurements of the phase difference between the source and detector at a range of positions. As in any experiment, it is often very useful to make preliminary plots of the data as you go, so that you can spot, investigate and fix any potential problems before you leave the lab.

1.4 Data Analysis

To calculate the speed of sound from your data you should ensure the phase you measured is in radians (2π radians $= 360°$).

Phase Unwrapping

The relationship between the phase shift you measured as a function of distance should be linear. However, by definition, a phase shift of zero is the same as the phase shift of 2π radians (360°). If you have measured the phase over more than one wavelength and the phase difference is never more than 2π you will need to 'unwrap' the phase (i.e. add or subtract integer multiples of 2π to some of the data points.

Calculating the Speed of Sound

By plotting the change in phase, $\Delta\phi$ as a function of distance, x you should be able to fit the trend given by

$$\Delta\phi = kx + A\,, \tag{1.3}$$

where $\Delta\phi$ is the phase shift, x is the distance change, A is a constant depending on initial conditions, and k is the gradient of the graph, the value of which is given by

$$k = \frac{2\pi}{\lambda}\,, \tag{1.4}$$

where λ is the wavelength of the sound wave (k is actually a useful physical quantity we call the wavenumber).

This week most of you should be in a position to be able to do data plotting using Python. If you have completed the second computing worksheet you will also be able calculate the linear fit and the associated uncertainty using Python.

If you are not yet confident with python you can also use the LINEST function in Excel or you can plot your data by hand and use the min/max gradient method (i.e. the steepest and shallowest lines that go through your error bars and the mean (x,y) coordinate of your data.

By determining the slope of the graph (and the associated uncertainty) and rearranging equation 1.4, you can determine the wavelength of the sound used. Since the frequency is known (the signal generator has a high degree of accuracy), you can calculate the speed of sound in air and the associated error using equation 1.2.

Original Author: The authors of this lab script are Matthew Ward and Michaela Flegrova with updates by Stuart Mangles.