The speed of sound

(exp. id 20210625-1-v1)

An experiment proposed by
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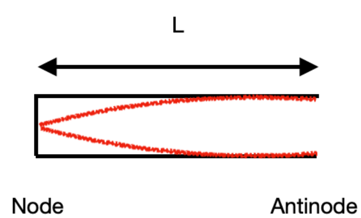
Overview

It is possible to measure the speed of sound producing standing waves in a pipe that is open at one end or at both ends. If you blow across the open end of the pipe, the column of air in the pipe vibrates primarily in its fundamental mode (first harmonic), with contributions from higher harmonics. The frequency of the harmonics depends on the length of the pipe and on the speed of sound, therefore, by measuring the frequency you can find the speed of sound.
Let's consider the case of a pipe of length L that is open at one end. The first harmonic for waves in a column of air that is open on one end are shown in the sketch.



This is the fundamental mode of vibration. Each of the following modes is produced by adding half a wavelength.
The length of the pipe is related to wavelength and wavelength is related to frequency and to the speed of sound. Therefore, by measuring the frequency of the vibration you can calculate the speed of sound.

Materials & Requirements

1. A smartphone with PHYPHOX installed
2. A small pipe or tube closed at one end and open at the other end (between 10 and 20 cm length)
3. A ruler to measure the length of the pipe
4. A thermometer to measure the temperature of the room where the experiment is performed.

Using the Audio Spectrum

You can find the Audio Spectrum among the tools in the ACOUSTIC section of PHYPHOX. It displays the frequency spectrum as well as the peak frequency of an audio signal recorded with the microphone.

Hold your pipe near the microphone of your smartphone, click on the small triangle on the top-right of the display (start button) and then blow on one end of your pipe. You can stop the experiment using the pause button and you can throw away the measurements clicking on the bin icon.

The app will produce a spectrogram of the frequencies of the first harmonics and it will also display the peak frequency, that is the first vibration mode (first harmonic).

Speed of sound from frequency

Repeat your experiment several times until you obtain a good spectrogram and you have a good reading of the frequency of your first harmonic.

Measure the length of the pipe with the ruler.

Find the relationship between length, frequency and speed of sound. Derive the speed of sound from your data.

Speed of sound and temperature

Measure your room temperature with a thermometer. The speed of sound depends on temperature. Do some research and find how to determine the expected value of the speed of sound as a function of temperature. Calculate the expected value at your room temperature and compare it with the value you obtained from your data.

Column of air open at both ends

You can repeat the experiment with a tube that is open at both ends, like a straw. What changes compared to the previous case?

General remarks

Always try to estimate the uncertainties of each measurement properly. Can you spot any source of systematic error? Can you estimate its size?

Before starting any series of measurements, make a few tests to train your ability to perform the required operations seamlessly. Write up the measurements neatly and in a complete way (indicating values, uncertainties and units). Use tables and graphs appropriately.

For the instructor

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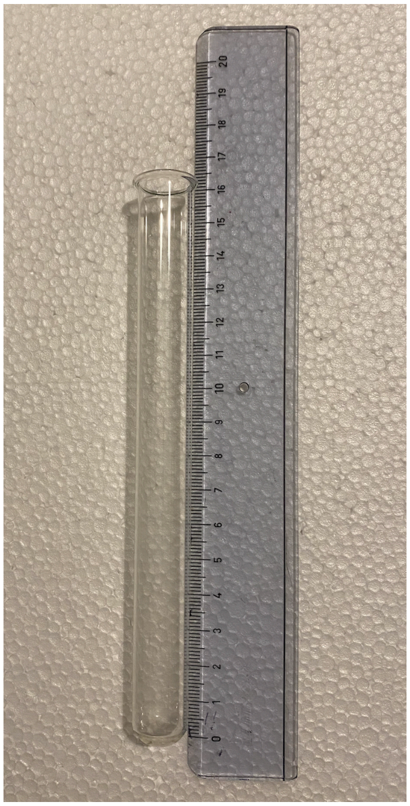
In the following example of the measure, a pipe closed at an end was used. A test tube from the chemistry lab was chosen, but you can try different objets, closed at one end or open at both ends, like a straw or any small tube.



The opening of the tube is an antinode for standing waves. If the pipe is closed at one end, the end of the pipe is a node. Therefore any standing wave in the pipe must have an antinode at the open end and a node at the closed end. The lowest frequency standing wave consistent with those requirements is the one which fits one-quarter of a wavelength in the pipe.

For a pipe of length L you have the following conditions for the first harmonic:

$$L = \frac{1}{4}\lambda$$

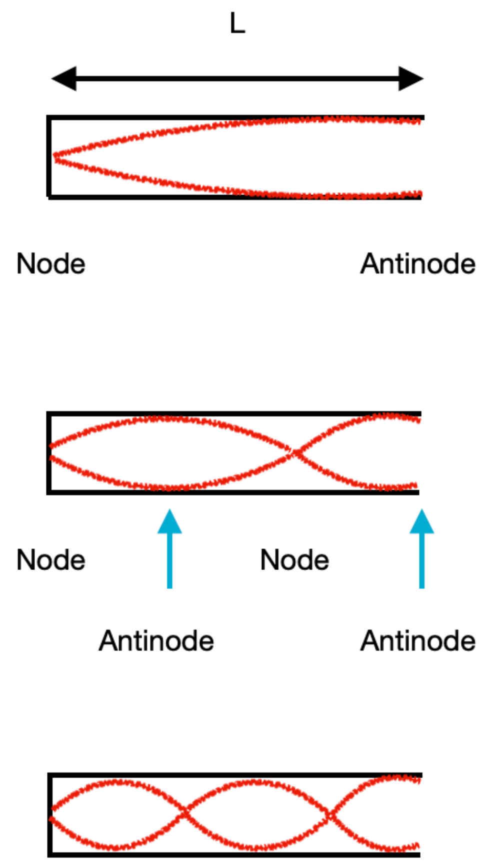
$$\lambda f_1 = v$$

therefore

$$f_1 = \frac{v}{\lambda} = \frac{v}{4L}$$

$$v = 4Lf_1$$

Each of the following harmonics is obtained by adding half a wavwelength.



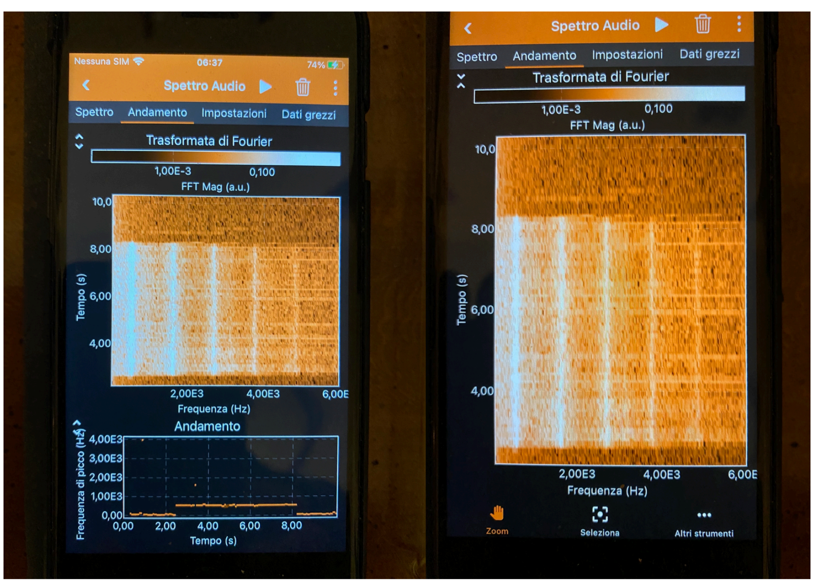
The progression is described by the following frequencies

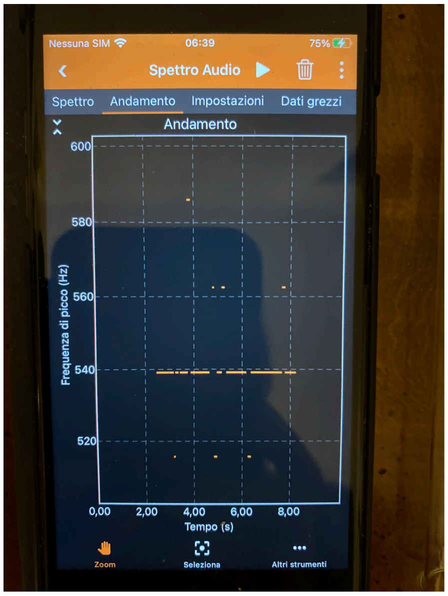
$$f_k = k f_1$$

where k is an odd number, $k = 1, 3, 5, ...$

You can use any of the frequencies to determine the speed of sound, but if you download data from PHYPHOX you will be provided with the values for the first harmonic, that is the strongest frequency. However the spectrogram also shows the next frequencies and you can see that they fit with expected values from the above formula.

Here is an example of the spectrogram and graph you can obtain





2,31333895	46,875
2,37737912	23,4375
2,43848533	23,4375
2,50512108	539,0625
2,56993525	539,0625
2,63283141	539,0625
2,69743412	539,0625
2,76164570	539,0625
2,82178916	539,0625
2,88845945	539,0625
2,94962758	539,0625
3,01893229	539,0625
3,08195095	539,0625
3,14617395	539,0625

In the downloaded data you can see that the frequency of the first harmonic is 539 Hz. The length of the pipe was $0,160$ m, therefore the speed of sound is

$$v = f_1 \cdot (4L) = 539 \cdot (4 \cdot 0,160) = 345 \ \frac{m}{s}$$

The value of the speed of sound depends on various factors, the main one being the temperature. Dependence on temperature can be described by the formula

$$v = 20,055\sqrt{T}$$

where T is the temperature in kelvin. The experiment was made at 23 °C, corresponding to 296 K, which gives an expected value of 345 m/s for the speed of sound. This is the same value found from data analysis.

Objectives, Level of deployment, and Duration

1. Primary objective: Enjoyment and practice in empirical experiments.
2. Primary objective: Development of scientific investigating skills.
3. Suitable for: high school
4. Duration: less than one hour of data acquisition, + one hour of data analysis, + writing short report.

Further Info Online

Please leave feedback, suggestions, comments, and report on your use of this resource, on the channel that corresponds to this experiment on the Slack workspace "smartphysicslab.slack.com". Instructors should register on the platform using the form on `smartphysicslab.org` to obtain login invitation to the Slack workspace, and/or to request being added to the mailing list of smartphysicslab.