A home-lab experiment: resonance and sound speed using telescopic vacuum cleaner pipes

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Abstract
We propose a home laboratory in which a telescopic vacuum cleaner pipe and a smartphone are used to investigate sound speed and acoustic resonance. When the pipe is hit or the hands clapped near one end, the sound produced is registered by a smartphone. The resonant frequency is obtained using a smartphone and an appropriate application. Varying the pipe’s length and registering the corresponding resonant frequency allows to obtain the sound speed. This home-lab, first proposed during Covid-19 pandemic, has been incorporated as a home challenge to experiment with acoustic resonance in new normal times.

Keywords: resonance, sound speed, home-lab, smartphones

1. Resonances in telescopic pipes
When we listen to music coming from a wind instrument, such as a flute or clarinet, we are witnessing a phenomenon known as acoustic resonance. The instrumentalist injects air into the edge of a hole, or through a mouthpiece, or a reed, depending on the type of instrument, and the resulting vibrations generate waves of various frequencies in the air inside the instrument. According to the shape of the tube, some specific frequencies, known as resonance frequencies, acquire predominant energies, which determine the characteristic musical sound. The lowest frequency, also called the fundamental one, corresponds to the musical note, while the higher frequencies, called harmonics (which are integer multiples of the fundamental), are responsible for the timbre or characteristic sound of the instrument [1].

Let us consider a cylindrical pipe of length $L$ open at both ends. In this case, the pressure at these points remain constant, so, they behave as pressure nodes. Taking into account this boundary condition, the only stationary waves that can resonate in the tube are those with pressure nodes at both ends. Since the distance between nodes is equal to half a wavelength, $\lambda$, then for resonant
waves it must be true that the length of the tube must be an integer number of half-wavelengths: \( L = n \lambda / 2 \) where \( n \) is a natural number called a harmonic number. When abruptly perturbing the pipe, for example hitting it with a blunt object, the fundamental frequency which corresponds to \( n = 1 \), prevails over the harmonics. When varying the length of the pipe, the resonant frequency, \( f = c / \lambda \), where \( c \) is the sound speed, is related to the length \( L \) by the following relationship

\[ f = \frac{c}{2L} \]

2. The home experiment
In recent years, due to restrictions related to Covid-19 pandemic, several laboratory activities were modified to be proposed as home-labs [2]. A simple experiment can be performed producing resonance inside a telescopic vacuum cleaner pipe for different lengths. There are many ways to generate sound with a tube. Here we propose to do it with a small stroke of the hand. One end of the tube is placed near the smartphone and the opposite is tapped giving a sharp blow with the palm of the hand. At that moment you can see the frequency of the fundamental harmonic on the smartphone screen as a peak graph with the frequency value next to it (see right panel in figure 2). As this harmonic fades quickly, the pause function of the app must be used, to record the resonance frequency.

The resonance frequency can be measured very simply and economically using smartphones sensors [3–5] and one of the many free applications that analyse sound, such as Physics Toolbox, Phyphox, Spectroid or Advanced Spectrum [6]. These apps (and others) use the great computing power of these pocket computers to perform a fast Fourier transform in real time and thus determine the frequencies present in the sound that reaches the microphone of the phone. In general, to perform a specific measure, it is necessary to freeze the values displayed on the screen. In figure 1, we show the experimental setup and the few elements needed to perform this proposal.

3. Results and discussion
The screenshot of the Advanced Spectrum app allows to obtain the spectrum of the sound as shown in figure 2. Repeating this measurement for different values of the length of the telescopic tube it is possible to register the resonant frequency for each length. In figure 3, we plot the frequency as a function of the inverse of the length of the tube and perform a linear fit whose slope corresponds to half the speed of sound. In this case, \( c = (343 \pm 3) \text{ m s}^{-1} \). This value of the sound speed agrees very well with the expected for the temperature at which the experiment was performed, that is 22 °C. Theoretically the speed of sound in a gas is, \( c = \sqrt{\frac{\gamma RT}{M}} \), where \( \gamma \) for air is 1.4, \( R \) is the universal gas constant (8.31 J K·mol\(^{-1}\)) and \( M \) is the molar mass, which for air is, \( M = 0.029 \text{ kg mol}^{-1} \) [1]. With these values the expected speed of sound at 22 °C is \( c = 344 \text{ m s}^{-1} \) in very good agreement with the experimental value.

4. Final remarks
Recent Covid-19 pandemic obliged to rethink the way we teach and learn physics. Home activities have acquired considerable importance larger than before. This proposal provides an interesting opportunity to experiment acoustic resonance and sound speed with everyday elements. Several extensions could be presented in particular activities about Helmholtz resonators [7], stationary waves in standard drain pipes [8], Kundt’s tubes [9] or the measurements of pressure profiles [10] among many others.
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Figure 2. The left panel shows the way to produce the sound in the tube while the right panel exhibits a screenshot of the Advanced Spectrum app with the spectrum of one of the measurements. The horizontal axis is frequency (Hz) and the vertical axis is energy (decibel). The main peak is the fundamental frequency measured for the tube with length 79.8 cm.

Speed of sound: \( c = 2 \times \text{slope} = (343 \pm 3) \text{ m/s} \)

Figure 3. Resonance frequency as a function of the inverse of the length. The linear fit indicated in the legend allows to obtain the sound speed.
Data availability statement
The data that support the findings of this study are available upon reasonable request from the authors.

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