

Measuring the speed of sound with a pan flute and a smartphone: a half-melodic and totally-didactic experiment

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Abstract

Teaching wave-physics and related phenomena with musical instruments results in a very pleasant and didactic approach for undergraduate students. Music allows teaching concepts such as frequency, amplitude, harmonics, resonance, and so on. In addition, one may use some instruments to calculate other quantities such as the air density or the speed of sound in the air. In this work, we use a conventional bamboo-made panflute and a smartphone to obtain the speed of sound in the air. The method is simple. It consists of making the pipes sound and measuring the frequency of the fundamental harmonic. The frequency is approximately proportional to the inverse of the pipe length and this dependence allows us to obtain the speed of sound quite accurately from the slope of the curve. We compare it with the theoretical value and analyze three possible causes of discrepancy such as the end correction, the air composition, or the straightness of the tubes. The proposed experiment can be carried out completely by the students since it does not involve any danger. Besides, it could be appropriate for undergraduate students or even school students.

Keywords: Speed of sound, smartphone, music, standing waves, pan flute.

1. Introduction

Music, Mathematics, and Physics are the three vertices of one of the most beautiful triangles in the world, or at least that is my humble opinion. Physics of sound results in a branch of physics that offers a lot of possibilities to explain wave-related concepts in the classroom [1]-[6]: frequency, amplitude, wave-velocity, interference, resonance, standing waves, harmonics, and so on. Very different musical instruments can be used to do it. String instruments such as a guitar [7]-[9] or wind instruments such as flutes, [10], [11], are the most

commonly used. The main frequency emitted by a string depends on its length and tension. On the other hand, the main frequency emitted by wind tubes depends mainly on their length. Each instrument has different harmonics and those harmonics give the instrument its characteristic sound, its timbre, [11]. Thus, the same note in a flute and in a cello sounds different. Besides common instruments, other objects can be used to play music, [15], but we will focus on one more conventional in this manuscript, a pan flute. The way all musical instruments emit sound is due to the formation of standing waves, [8], [16], or overtones, [17], [18]. A standing wave differs from a traveling wave because it seems to only

oscillate without propagation. It appears when two traveling waves of the same frequency, and the same amplitude, but opposite propagation directions, interfere. The only possible frequencies of the standing waves depend on mechanical parameters such as the length of the string/tube, the sound speed in the medium, the density of the medium in which propagates, and so on, [19], [20]. In this work, we use the sound produced by the pipes of a pan flute and a smartphone to obtain the speed of sound in the air. Other similar works have been published such as [21]-[27]. In this manuscript, we analyze why the obtained speed of sound differs a little bit from the one obtained with thermodynamic calculations. Three possible causes of the discrepancy are investigated and discussed such as the well-known end-correction, the air composition, and the straightness of the tubes. This experiment can be performed without problems by school, high school, and undergraduate students since it does not involve any danger.

2. Experimental measurement of the speed of sound in the air

It is easier to produce a note from the pan flute (also known as panpipes or syrinx) than other wind instruments. This instrument exists from antiquity and it has been used by many civilizations along the history. Nowadays, it is more commonly related to south American folk music. It consists of several bamboo tubes with increasing length that produce a quite pure sound when one blows each one. Fig. 1 shows the pipes taken from a typical pan flute. The way they emit these sounds is blowing at one side and generating standing waves into them.



Figure 1.- Photograph of the panflute pipes used for the experiment.

The kind of standing waves is of the type produced by pipes that are open only at one end, Fig. 2. The harmonic frequencies generated in this kind of tubes have been shown in many books and manuscripts and, as can be deduced, the length of the tube determines the main frequency that is able to play (fundamental harmonic).

We assume that the sound is principally composed by the first harmonic or fundamental (Fig. 2a) although others are also produced with lesser amplitude. Then the length of the tube, L , and the frequency of the fundamental harmonic, f , are related as

$$f = \frac{v}{4L}, \quad (1)$$

where v is the speed of sound in the air. We may take advantage of this relationship to obtain experimentally the speed of sound in the air, [31]-[33]. We only need the pan flute, some device to measure the fundamental harmonic emitted frequency of each pipe, and the ability to make it sound. To measure the frequency, we use a common smartphone, [34], [35], in which we have installed a free application called *Spectroid*, developed by Carl Reinke. Fig. 3 shows an example of a screen capture of the mentioned application when the sound emitted by a bamboo pipe is recorded. The sound spectrum corresponds to the green line (the upper one).

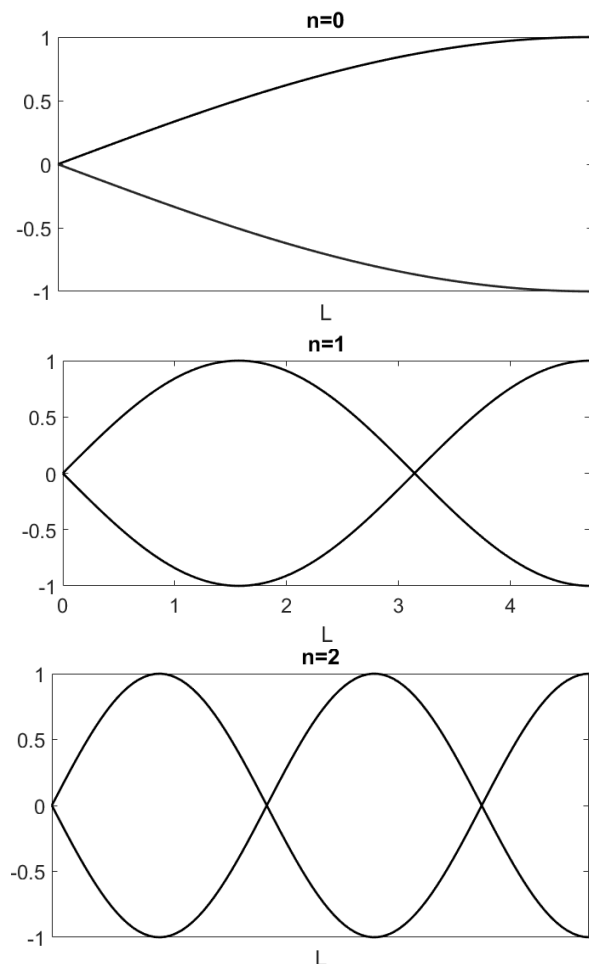


Figure 2.- First three standing waves or harmonics of an air tube open at one end only (right side of the plots).

Once everything is ready, we must blow into the pipes and take note of the frequencies given by the application, Table 1 (first row). Then, we measure the length of the tubes, considering that the closed extremes will be slightly inside the tube. We may localize them by using two different methods: looking at the bamboo joint from the outside or introducing a stick through the open side and measuring the length that enters inside the tube, Table 1 (second row). Finally, by plotting f_{exp} versus $1/4L$ and performing a linear regression, the sound speed in the air is obtained from the slope of the fitting,

Fig. 4 (blue points). From the experimental measurements, it results 300.2 m/s.

Table 1. First row: Experimental frequency measured with the phone app for all tubes of the pan flute. Second row: Internal lengths of the tubes measured by introducing a stick inside them.

f_{exp} (Hz)	387	463	574	662	797	926	1160	1418
L (cm)	21.3	17.8	14.4	12.1	10.2	8.7	6.8	5.4

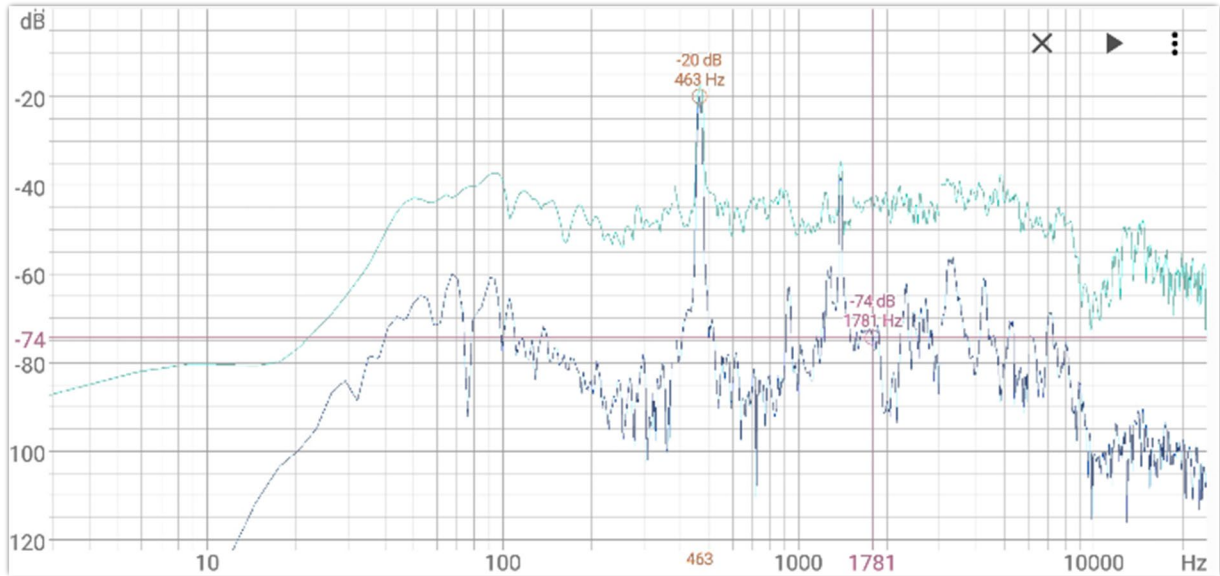


Figure 3.- Screen capture of the smartphone application (*Spectroid*). It corresponds to the measurement of the second longest pipe (upper green line). The peak frequency is 463 Hz.

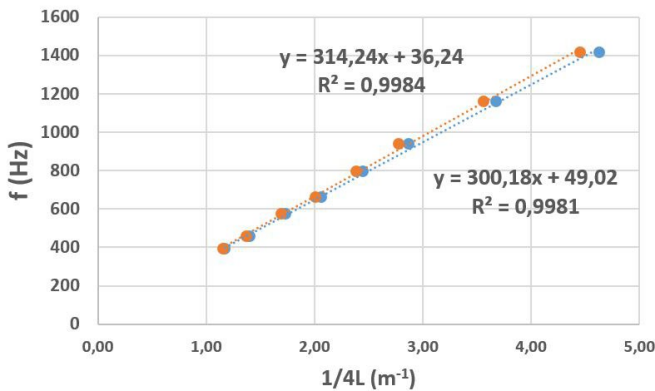


Figure 4.- Linear regression of the experimental data without considering the end-correction (blue plot) and considering the end-correction (orange plot).

On the other hand, the speed of sound depends on the air composition (molar mass), the room temperature, etc, as

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

where γ is the adiabatic coefficient of the air, R is the ideal gas constant, T is the room temperature in kelvin, and M is the molar mass. For the air, $\gamma=1.4$, $M=29$ g/mol, and the room temperature was $T=296K$ at the moment of the experiment. Thus, the v_{theo} obtained with Eq. (2) results 344.7 m/s. As can be observed, both sound speeds result slightly different. Along the next section, we discuss three possible causes of this discrepancy between the experimental and the theoretical speed of sound in the air.

3. Discussion

The discrepancy between theoretical and experimental speed of sound may have at least three causes:

- The first one is the so-called end-correction that we have not considered in the previous calculations. The end-correction must be applied to standing waves in tubes since the outer anti-node of the open end is actually placed outside the tube at a certain distance that depends

on the radius of the tube. This correction is applied by considering the length of the tube slightly longer, as we will show after.

- Irregularity of the pipes. Non-constant diameter and curvature of the pipe could produce different vibration modes.
- Air composition. The experiment was performed in an enclosed space with probably a higher concentration of carbon dioxide, and therefore the molar mass could be different.

As we have mentioned, the first cause of discrepancy could be the so-called end correction. It has been proved that the anti-node formed at the open ends of a tube is placed outside the tube at a certain distance. Therefore, to calculate the harmonic frequencies, we must increase the length of the tube by a constant length related with the radius of the tube, r . This relationship has been obtained empirically and it seems to be around $L_e = 0.6r$. Adding this length to the nominal length of the tubes ($L' = L + L_e$) will result in a different experimental fitting. The radii of the tubes and the new lengths are shown in Table 2 (first and second rows, respectively). In addition, the new fitting is shown in Fig. 4 (orange dots). In this case, the speed of sound results 314,2 m/s. This value is still a little far from the theoretical one but the order of magnitude is the same, with a discrepancy of the 8,8%, which we may assume as acceptable.

Table 2. Radii of the tubes (first row) and length of the tubes by considering the end-correction.

r (mm)	5.5	5.0	4.75	5.5	4.5	4.5	3.75	3.5
L' (cm)	21.63	18.1	14.7	12.4	10.5	9.0	7	5.6

Anyway, we may test also the influence of the form of the tube. To do it, we have manufactured several perfectly straight tubes with a 3D printer, Fig. 5. These tubes have the same lengths but different diameters. One of them has been designed with the same diameter as the second tube of the pan flute ($f_{\text{exp}} = 463 \text{ Hz}$). After measuring the resonant frequencies, we conclude that the main frequency (fundamental harmonic) is the same as the one produced by the bamboo tube, Fig. 6. Then, the straightness of the tube does not influence the main frequency. What is observed in Figs. 3 and 6 is the difference in the spectra. Despite the main frequencies coincides, the rest of the spectrum is different.

Finally, the last possible cause is more difficult to test. If the air had a greater concentration of carbon dioxide than usual, the molar mass of air would be higher, since the molar mass of carbon dioxide (44 g/mol) is bigger than that of oxygen (32 g/mol). An enclosed space with bad ventilation could have a carbon dioxide concentration of 700 ppm, which

means the 0,07% of air. Normally, its concentration is around 0,04%. The difference is taken from the oxygen concentration so we may calculate approximately the molar mass of air in this case resulting 29,4 g/mol, slightly higher than the standard value. With this number, the speed of sound calculated with Eq. (2) results 342,7 m/s. Therefore, it seems that the increasing of the carbon dioxide concentration has not enough influence on the speed of sound in the air.

Before concluding, it is important to notice that the way the player blows the tube could influence the harmonic frequencies but the natural frequencies are those shown in Table 1.



Figure 5.- 3D printed pipes and corresponding bamboo pipe.

4. Performance in the classroom

After teaching stationary waves in the classroom, I performed once the experiment proposed in this manuscript. Due to hygienic causes, I was the only one who played the pipes and some of the students recorded the sounds and took note of the frequencies. The variations in the frequency given by each smartphone were negligible although we made an average of them to be sure. The obtained results were similar to those shown in this manuscript, which I obtained in my office. The interest of the students to do the experiment was huge and it also made the classroom environment to improve. Every time I take some experiment to the classroom I may see how the interest of the students in Physics increases. They enjoy Physics while they learn and that is very important.

5. Conclusions

Summarizing, we present in this work a very simple experiment to obtain experimentally the speed of sound in the air through the measurement of the frequencies emitted by the pipes of a pan flute. To do it, we have used a free mobile phone application called Spectroid. In addition, we compare the obtained results with that obtained theoretically from thermodynamic calculations and evaluate three possible causes of discrepancy such as the well-known end-correction, the straightness of the tubes and the air composition. Anyway, both speeds result with around 8% of error, which could be

acceptable for the level of the experiment. This experiment is perfect to explain wave-related concepts such as frequency, standing waves, and so on. It can be proposed as a find-out experiment and let the students to find the speed of sound in

the air, or being performed by the teacher. The experiment is appropriate for introductory physics courses and even school students, since there is not danger involved.

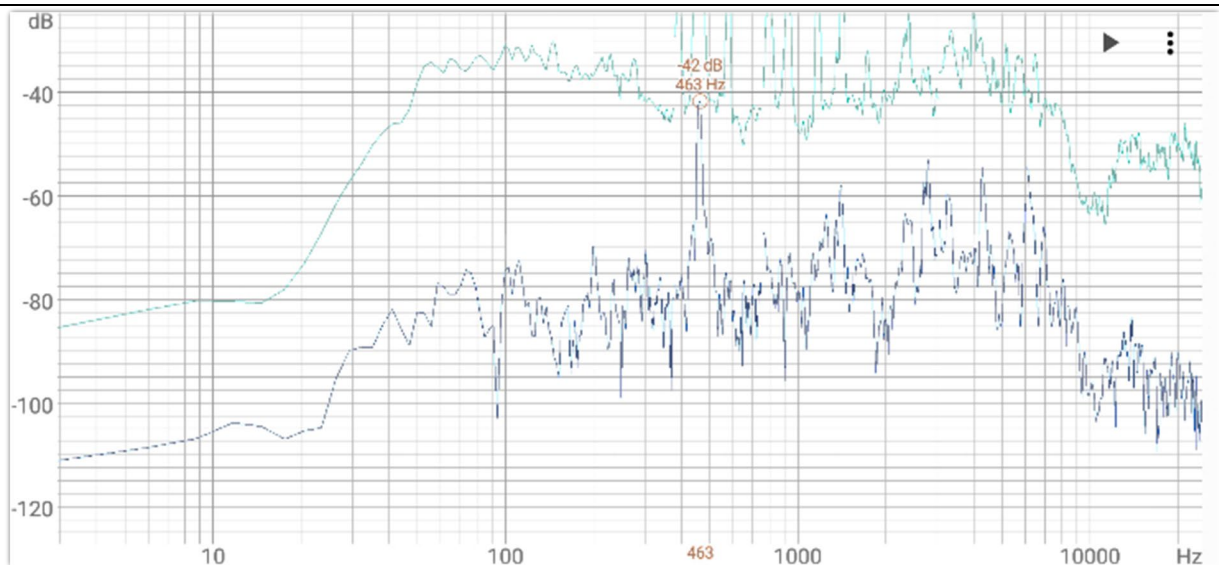


Figure 6.- Screen capture of the smartphone application (Spectroid). It corresponds to the measurement of the 3D printed tube of the same length and diameter than the second longest one of the pan flute (lower blue line). The peak frequency is 463 Hz.

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Ethical statement

No conflict of interest.

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