Estimation of the speed of sound waves using a modular 3D printed Helmholtz resonator

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Abstract. This work shows the redesign of an elemental experience based on the Helmholtz resonator using 3D printing. A Helmholtz resonator is based on a volume and at least one opening that can include a tube or not. The air column inside the tube can be considered the mass of the system, whereas the volume represents the system's stiffness. Due to these analogies between acoustics and mechanics, the Helmholtz resonator is an interesting example of a harmonic oscillator. The relevance of harmonic motions is well known, and this topic is present in the syllabus of many technical and scientific education degrees. In this work, a bottle has been designed and fabricated using 3D printer technology. The design aimed to create a Helmholtz resonator with a variable frequency of resonance. Different mouthpieces have also been designed. The bottle is composed of a set of cylindrical sections that can be attached, enlarging the length of the container. For ensuring that the different parts set a tight enclosure, an O-ring seal has also been designed and fabricated. As more rings and O-seal junctions are attached, the volume of the resonator grows. By blowing the mouth of the Helmholtz resonator with different sections, different resonance frequencies can be measured. From these measurements, several parameters can be estimated indirectly, such as the speed of sound waves, the room temperature, and air density. 3D printing permits to analyse several scenarios without using uncomfortable strategies to vary the bottle's volume, such as water, reducing the hazard in a laboratory with electronic instrumentation.

Keywords: 3D printing, Helmholtz resonator, laboratory, Acoustics, resonance.
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1. Introduction

The research of new approaches and examples in Engineering education is a target for teachers. Many examples in the literature demonstrate the innovation and new methodologies applied in education, thanks to new technologies. Surprisingly, the first 3D printers were produced in the early 1980s. However, it was not until the last decade when 3D printers became more accessible and, hence more popular [1]. During this time, researchers and educators agreed that considering 3D printers in their fields is very positive due to their versatility and benefits [2–6]. One example of this issue is the consideration of this technology by the education community for incorporating new technologies in science, technology, engineering and mathematics (STEM) syllabus [7–9]. In consequence 3D printing has emerged as a new instrument that provides a huge amount of possibilities in different fields, e.g, learning mathematics in middle school [10], Acoustics [11], Art Education [12], Medicine [13–15], Physics [16], fabrication of compound structures [17, 18] or MEMS [19–21], Optics [22, 23] and Electronics [24] amongst others.

Resonance phenomenon and harmonic motions are fundamental concepts covered in many degrees of physics and engineering disciplines. The acoustical equivalent of the mass-spring system is the well-known Helmholtz resonator. A simple example of a lumped acoustic system is a device that consists of a rigid-walled cavity with a volume filled with air that induces stiffness in the system. This system must have an opening based on a hole with a neck where the sound is radiated. This part of the system provides radiation, and since the air inside the neck moves as a unit, it provides the mass element needed to make the analogy between the traditional mass-spring harmonic oscillator. When one blows into the open end of the neck, the air inside is pushed down into the body, compressing the air. This compression in the body cavity induces a restoring force that expands the air, and the mass of air in the neck is pushed upwards. Since the mass has inertia, the mass goes through the equilibrium. However, the restoring force of the air again compresses the air inside the body. Here, the air mass in the neck is pushed upwards, repeating this process again and again. This process can be understood as a simple harmonic motion, and hence the production of resonance. The system here described based on a Helmholtz resonator fits with a traditional bottle and plays an essential role in the development of Acoustics and technical applications [25–28]. A whistling bottle is an element easy to obtain that can be present in many laboratories in modern Universities. However, determining physical parameters, i.e., the speed of sound waves, the air density or the air temperature, implies different bottles with different volumes or acoustical mass (different neck lengths) to obtain a set of data for a proper fitting. Water is the most popular option for reducing the volume of a bottle since water has a higher impedance than air [29]. Therefore, the user can reduce the volume of air by partially filling the bottle with water. This scenario can be substituted by the setup here proposed, based on a bottle fabricated with a 3D printer. The bottle design is part of the "Extendable Modular Tube Container" [30] which has been modified to increase water tightness. The bottle is composed of at least two pieces: one with the bottle's neck and the second one with the bottle's base. Different rings can be attached between these two pieces for increasing the total volume of the cavity. An O-ring seal has also been designed and fabricated through 3D printing technology, and it is included between pieces. This setup avoids not only using water in a laboratory environment [29], making this experience more accessible and safer since measuring the bottle mass is no longer needed; it also simplifies the measuring process limiting it to only to acquire the fundamental resonance frequency and the dimensions of the bottle.

There are many works related to the application of 3D printing in Acoustics, i.e., the design and fabrication of 3D small-scale Helmholtz resonators [31], waveform interaction [32] or ultrasonic levitation [33]. To the best of our knowledge, this is the first application of 3D printers to the design of a bottle behaving as a Helmholtz resonator with variable resonance frequency. This work aims to show the benefits of this design in the Telecommunication degree syllabus or technical degrees. Since it combines new technologies applied to a laboratory simplifying the experience, the resonator here designed can be used in an experimental practice in which the sound speed, the temperature of the room and the air density can be determined indirectly. The methodology is based on measuring the different resonance frequencies considering different sections or rings for the bottle. As the number of rings rises, the bottle's volume also grows, and the fundamental resonance frequency decreases. The sound speed c can be estimated with its error from a proper fitting of the measurements. The rest of the parameters can be easily derived from c. Finally, some conclusions about the accuracy of the results obtained and the benefits of the experience here proposed are given.

2. Experiment design

In this section, the experimental setup is detailed. Firstly, the motivation of this work is summarised. Secondly, some basics related to the theoretical background are provided in section 2.2. Thirdly, the details concerning the 3D design are included in section 2.3. Finally, section 2.4 summarises the setup for performing the experience, including some alternatives for lower budget environments.

2.1. Motivation

The motivation behind developing a resonator based on a 3D printer with a variable resonance frequency was to suppress unnecessary hazards due to the traditional way of performing this experience. Before this scheme, traditional glass bottles and water were used to change the resonator's inner volume. This laboratory experience aspect dealt with some risks due to water and electrical equipment's potential interaction. Moreover, COVID-19 has reduced the possibility of performing this type of laboratory activities based on students blowing a bottle in a closed environment such as a laboratory. However, many bottles can be designed and provided to students to complete the laboratory activity at home with a set of reduced equipment, i.e., computer and measuring tape, thus simplifying the experience.

2.2. Helmholtz resonator

The theory of the Helmholtz resonator [34] describes the first acoustic theory of cavity resonators. A Helmholtz resonator is a simple acoustic system made up of a rigid cavity conforming a volume V with a transversal neck-shaped opening with area S, radius R and length L. That is the reason why it can take the form of a simple glass bottle. The fundamental resonance frequency depends on the volume. However, this volume's shape does not affect this resonance frequency, i. e., cavities with the same volume, but different forms produce the same frequency. Other parameters that affect the fundamental resonance frequency are the radius of the hole, the tube's length, and the sound propagation speed.

The opening of the neck radiates sound, and the air inside the neck can be modelled as a body mass:

$$m = \rho S L' \tag{1}$$

being S the area of the neck , and L' is the effective length of the resonator neck. If the outer end of the resonator is unflanged, the effective length is defined as

$$L' = L + \frac{16R}{3\pi} \tag{2}$$

R being the radius of the transversal area S of the neck resonator. This correction over the real length L has its origin on the radiation mechanical impedance which is the parameter that quantifies the opposition of the media against the vibration of the radiant system R [25, 29, 34]. The term ρ in Eq. (1) is the air density defined as

$$\rho = \frac{\gamma P_{\text{atm}}}{c^2} \tag{3}$$

where $\gamma = 1.402$ is the adiabatic constant of the gasses and $P_{\text{atm}} = 101300$ Pa is the atmospheric pressure. The derivation of Eq. (3) can be found on chapter 5 in [27].

For determining the stiffness of the system, the neck fitted with an airtight piston can be considered. If the piston is pushed a distance ξ, a change in the volume of the cavity is induced by $\Delta V = -S\xi$, producing a condensation $\Delta\rho/\rho = -\Delta V/V = S\xi/V$. Relating the condensation with the sound pressure the following relationship can be defined [27]:

$$p = \rho c^2 \Delta\rho/\rho = \rho c^2 S\xi/V, \tag{4}$$

where c is the speed of sound waves. From Eq. (4) and taking into account that the relationship between force and pressure $f = Sp$, and the Hook's law ($f = s\xi$), the effective stiffness s can be defined as:

$$s = \rho c^2 S^2/V, \tag{5}$$

This identity reveals that air filling the bottle behaves like a spring, and with Eq. (1) an analogous body-spring system is set up.

$$m\frac{d^2\xi}{dt^2} + R\frac{d\xi}{dt} + s\xi = f(t), \tag{6}$$

Eq. (6) is analogous to the differential equation that rules the motion of a simple oscillator. Hence, the natural frequency of the oscillation, or resonance frequency, of a Helmholtz resonator is determined by the following relationship considering Eq.(1) and Eq.(5):

$$\omega_0 = \sqrt{\frac{s}{m}} = c\sqrt{\frac{S}{L'V}}, \tag{7}$$

It is worth mentioning that the simple harmonic model, and hence Eq. (7), are valid only for low frequencies since the model is based on assuming lumped or discrete elements for the mass, stiffness and resistance. However, as the frequency rises, this model is not accurate, and higher-order, nonlinear phenomena or the influence of the shape of the entire element cannot be included under the simple harmonic motion formalism. More complex formalisms should be considered to accurately analyse this problem, such as n-degree of freedom approach, or numerical analysis such as finite-difference of finite element modelling. However, for the frequency range involved here ($f \approx 600$ Hz, $\lambda \approx 58$ cm) the model of the simple harmonic motion is good enough since all the elements here considered are smaller compared to the wavelength ($\lambda \gg L$, $\lambda \gg \sqrt{S}$ and $\lambda \gg \sqrt[3]{V}$). Besides, the simplicity of the model and its analogy with the traditional mechanical simple harmonic motion is why this experience is helpful from the educational point of view.

Eq.(7) establishes the linear relationship between the fundamental resonance frequency of the system and the sound speed of air through a factor that only depends on the resonator size. Eq.(7) can be expressed in a more convenient way

$$\omega_0^2 = \frac{c^2\, S}{L'}\frac{1}{V} \tag{8}$$

If the angular frequency of resonance is measured for different values of the volume V, a graphical representation of ω_0^2 as a function of $1/V$ should satisfy a straight line with the form $y = ax + b$, being $y \equiv \omega_0^2$ and $x \equiv \frac{1}{V}$. Through the least-squares fitting, it is easy to obtain the value of the speed of sound in the air. The slope of the data analysed is defined as:

$$a = c^2\frac{S}{L'}. \tag{9}$$

From Eq. (9) the section area, S and the effective length L' are already known.

It is worth mentioning that the measures are closely related to the angular frequency ω of the damped oscillation, but since the thermoviscous losses are negligible, the small radiation resistance is the one that induces high-quality factors. Hence, the following assumption can be considered $\omega \simeq \omega_0$, since the system can be assumed underdamped (interested reader can find more specific information about this aspect in page 285 in [27]).

Once the speed of sound c is estimated, it is possible to determine the density of air ρ. Regarding temperature, the following approximate relationship between sound speed and temperature in air can be considered [27]:

$$c = 331.6 + 0.6T \tag{10}$$

2.3. 3D design

The 3D design of the bottle is based on the "Extendable Modular Tube Container" design by Murray Clark [30]. Specifically, the following parts were used: female cap tall and 50 cm hollow sections (see Figure 1). The male cover was obtained by modifying the design of the hollow section. The upper part was closed, creating a horizontal surface leaving a central hole of 1.8 cm to be blown through. The tube lost air through the joints of the different segments due to the corrugated and thin internal walls. The design of the elements had to be modified for ensuring water tightness and proper seal. The joints contacts between parts were increased and readjusted. The interior walls were also increased until the inner-volume had the shape of a cylinder. The material used to 3D print the bottle parts was acide poly lactic (PLA), the most commonly used 3D printer material, as it is generally easy to print with.

Also, an O-ring joint was designed and printed using thermoplastic polyurethane (TPU) filament. TPU is a flexible, abrasion-resistant thermoplastic filament.

All parts were printed using an Anet A8 3D printer. The printing settings used in the Slic3r were: layer height 0.20 mm, fill density 50%, nozzle temperature of 195 ºC and three shells.

2.4. Experiment setup

The setup used for measuring the results shown in section 3 is based on a carbon microphone and a preamplifier that adapts the audio signal level to the oscilloscope. In this work, the Tektronix TDS3000 can be used for plotting the waveform of the sound signal in resonance. To excite the resonator, a student can blow a stream of air into the bottleneck with a gentle and consistent breath. The fundamental frequency can be obtained through the oscilloscope cursors or the direct frequency measurement of the instrument. However, a more home-friendly setup based on a standard computer with a built-in microphone and a basic audio interface is good enough for this experience. User can record the sound produced by the cavity in resonance with the OS utilities or free software such as Audacity. Afterwards, a spectral analysis of the waveform recorded can be done in order to find the maximum that is directly related to the fundamental resonance frequency of the Helmholtz resonator. Figure 2 shows, as an example, both the waveform and the spectrum of one of the measurements related to Bottle 3 and five sections (see Table 2). The maximum in the spectrum is highlighted in Figure 2b, and the estimated frequency is also detailed. As it has been previously mentioned in section 2.2 the applicability of the simple harmonic model is limited and it does

Figure 1. 3D bottle from different perspectives. (a) Full bottle with 5 rings and the mouth and back pieces. (b) Upper perspective with the definition of d_{mouth}. (c) Ring with the detail of the O-ring seal designed of thickness l_{O}. (d) Mouth piece interior sight with the definition of the diameter d, d_{mouth} and length l_{B_i}, that is the length which contributes to the volume increase. (e) Diagram of the ring, here the ring where the O-ring seal is placed can be identified. (f) O-ring diagram. (g) Mouth-piece diagram with a different perspective.

not include the whole spectrum components seen the figure. However, as it has been explained, only the fundamental frequency is the information that the student needed in order to proceed with the experience.

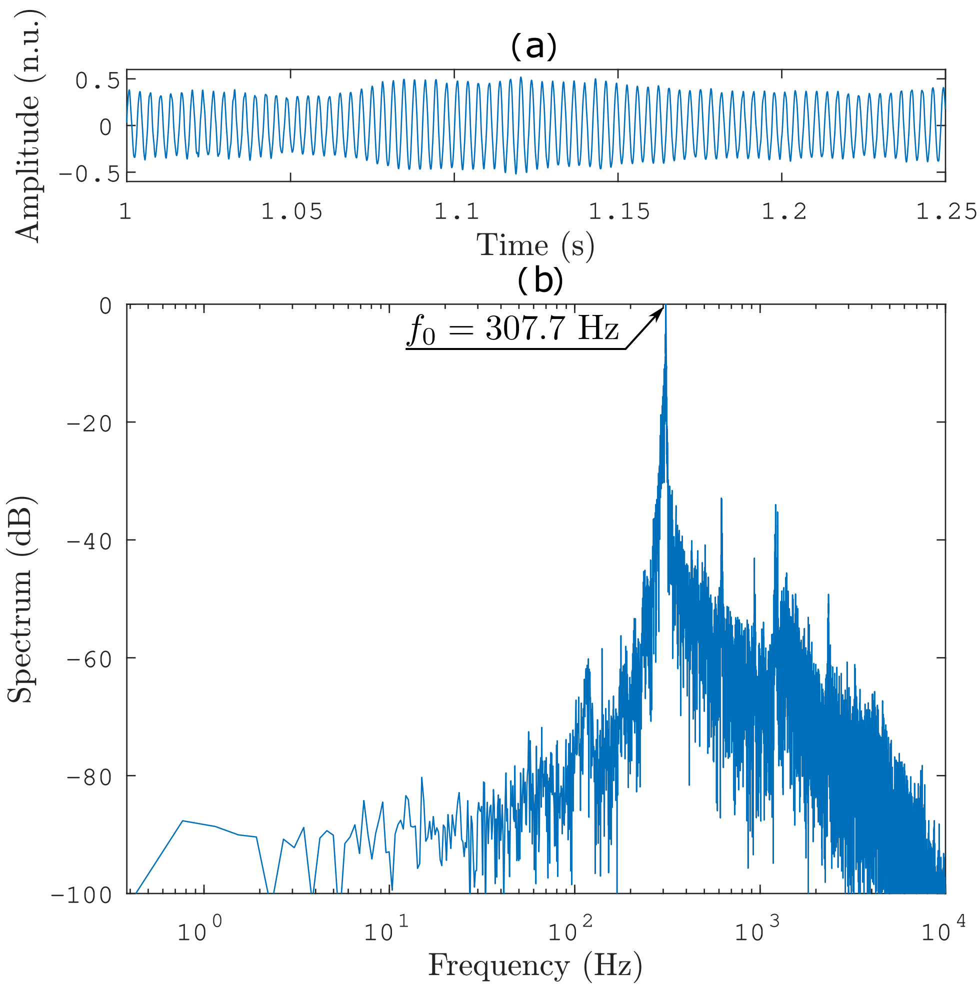

Figure 2. (a) Waveform detail and (b) spectrum of one of the full recording for Bottle 3 for the case Base+O^6+R^5+Mouth in Table 2

3. Results

This section shows the results derived from the analysis of the different fundamental resonance frequencies. The procedure here detailed follows the one performed by students in a laboratory. There are two phases in the study. Firstly, the measurement of the first resonance frequency must be performed. The harmonic sound produced can be recorded and post-processed, or the waveform can be represented in an oscilloscope. This part aims to measure the fundamental resonance frequency, and different strategies can be used for achieving this goal. The student can attach different rings to the bottle in order to increase its volume. It is highly recommended to take at least three different measurements when a new ring is attached to precisely measure each frequency. These measurements with the instrument sensibility permit to correctly estimate the magnitude and its error. Secondly, the measurements are processed through the least-squares fitting procedure for obtaining in the first place the slope of the trend and after that the rest of the parameters. The slope fitted by the least-squares procedure

Table 1. Dimensions for the different samples considered B1, B2, B3 and B4. The error for all measurement in this table is 0.02 mm

	B1	B2	B3	B4
l_{Bi} (mm)	31.54	31.10	31.52	31.34
d_{mouth} (mm)	18.84	17.70	17.50	17.36
L (mm)	7.26	32.74	53.00	82.26

Table 2. Measurements of the fundamental resonance frequencies for the four bottles considered.

Measurement	f_0^{B1}	f_0^{B2} (Hz)	f_0^{B3} (Hz)	f_0^{B4} (Hz)
Base+O+Mouth	585.87 ± 1.6	384.9 ± 2.4	317.8 ± 0.4	267.4 ± 0.8
Base+O^2+R+Mouth	478 ± 3	305.4 ± 1.5	260.3 ± 0.3	219.2 ± 0.7
Base+O^3+R^2+Mouth	415.9 ± 2.2	267.51 ± 0.16	224.1 ± 0.5	190.3 ± 0.3
Base+O^4+R^3+Mouth	362.6 ± 0.5	238.4 ± 0.3	196.7 ± 0.7	169.6 ± 0.8
Base+O^5+R^4+Mouth	335.0 ± 1.0	216.2 ± 0.7	179.4 ± 0.3	153.3 ± .5
Base+O^6+R^5+Mouth	303.9 ± 0.4	200.3 ± 0.7	166.9 ± 0.5	143.1 ± 0.8

can easily provide the estimation of c from Eq. (9). Once c is obtained with its error temperature T from Eq. (10), and density ρ from Eq. (3) can also be estimated with their error.

Four different bottles have been considered. These four bottles are based on the same set of rings and an O-ring seal for each pair of pieces. The inner diameter of all rings is d= 56.48 ± 0.2 mm. The length of each ring l_i=20.60 ± 0.2 mm. The length of the O-ring seal is l_{O} = 1.24 ± 0.2 mm. These dimensions are considered for all the different rings since all rings belong to the same batch, and the five rings fabricated do not show significative differences between them. The differences for the bottles analysed (B1, B2, B3 and B4) are related to the opening piece considered. Table 1 shows the measurements related to these samples. The term l_{B_i} is the length of each mouthpiece that contributes to increase the volume of the cavity, d_{mouth} is the inner diameter of the radiating aperture of the mouthpiece, and L is the length of the neck of each mouthpiece, L affects to the acoustical mass term, whereas l_{B_i} is related to the stiffness (see 1).

Table 2 summarises the measurements of the fundamental resonance frequencies of the four samples. In the measurement column in Table 2 the nomenclature for the terms base, O, R and mouth means the number of base pieces, the O-ring seal elements, ring pieces and mouthpieces, respectively. For instance, the sequence Base+O^2+R+Mouth means that one base piece, one mouthpiece, and a single ring with two O-ring seals (one between the base and the ring and the second one between the ring and the mouthpiece) elements sets up the bottle. The resonance frequency f_0^{Bi} (being i=1,2,3 and 4) is the mean value of the three measurements performed for each bottle and a specific number of rings. The relative deviation of each set of three measurements has been computed,

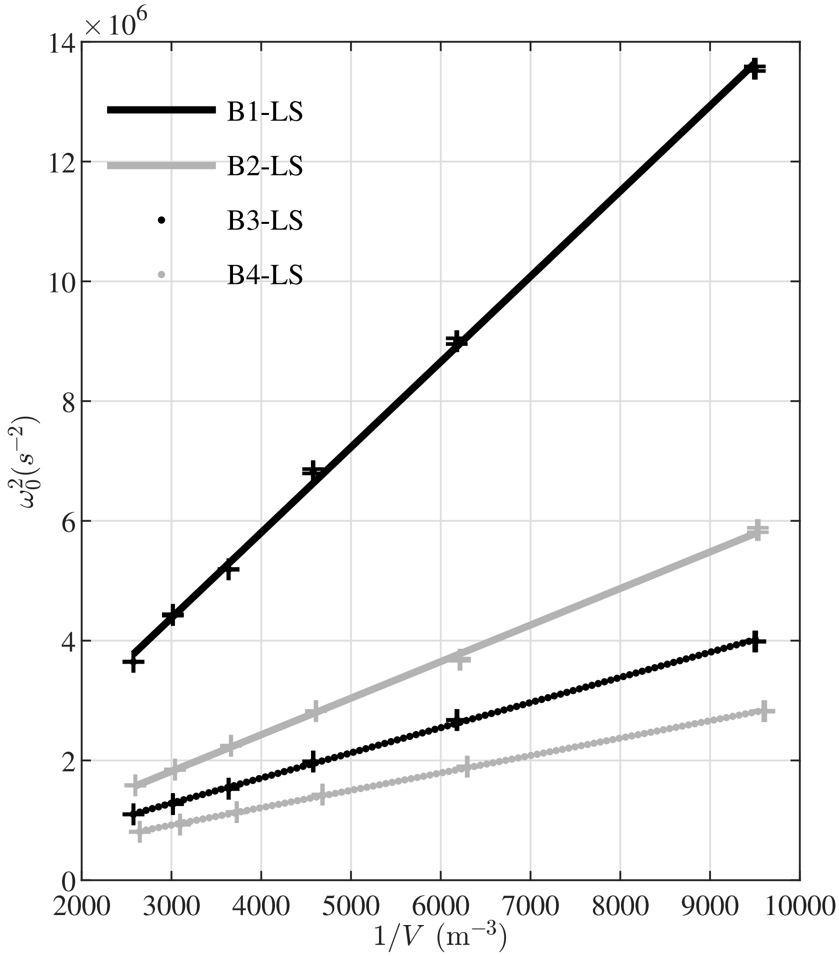

Figure 3. Resonance frequencies for the three bottles considered with the Least Mean squares fitting.

Table 3. Results summary for the slope a, sound speed c, room temperature T and air density ρ with their absolute errors. The correlation coefficient r is also included showing a very high correlation in all cases.

	B1	B2	B3	B4
a ($m^3 \cdot s^{-2}$)	1425±25	610±10	420±7	290±3
r	0.9994	0.995	0.9995	0.9997
c (m/s)	348± 5	342± 5	344 ± 5	344 ± 5
T (°)	22±9	21± 9	21± 9	22± 8
ρ (kg/m^3)	1.18± 0.04	1.19 ± 0.04	1.19±0.04	1.19±0.03

obtaining a value lower than the 2% in all cases, thus validating the accuracy of each set of three measurements.

The representation of Eq.(8) is shown in Figure 3. The solid line and dots represent the least-squares fitting line computed from the measurements included in Table 2. The measurements are also represented in Figure 3 including error bars in both x- and y-axis. In all cases, it can be seen graphically that measurements follow a linear behaviour and that the error in all cases is significantly small. The slope for each sample is reduced as the length of the mouthpiece grows.

Table 3 includes the results of the least-squares fitting procedure: slope, correlation coefficient, sound speed estimation c, temperature T and air density ρ. From the slope fitted by the least-squares procedure, the estimation of c from Eq. (9) can be directly obtained. Next, error temperature T from Eq. (10) and density ρ from Eq. (3) can also be estimated with their error.

The estimation of c is obtained from Eq. (9), T from Eq. (10) and and ρ from Eq. (3). It is worth noting that all measurements were made in a standard air temperature between 18-22° C, thus considering a temperature gap between 18-22° the theoretical sound speed estimated should be in the interval 342.4-344.8 m/s using Eq. (10). Therefore, it can be stated that the results included in Table 3 show a good agreement since the values obtained for c with its error are close to those that are theoretically obtained from Eq. (10). Even the temperature error is considerably high; its estimation is consistent along with the different samples here considered. Using a more accurate set of instruments that reduce the error estimation of c would reduce the error estimation of air temperature. However, this approach's potential is its simplicity and the possibility of obtaining these parameters without the necessity of using high-end instrumentation. The air density results also fits with the expected value, which is expected to be approximately 1.2041 $\text{kg}\cdot\text{m}^{-3}$ at 20°.

4. Conclusions

This work shows the design and the results obtained from applying 3D-printing technology to the implementation of a tuneable Helmholtz resonator. The fundamental resonance frequency of the resonator can be varied by removing or adding a set of rings that modifies the resonator's volume. Three different pieces for the mouth of the bottle have been designed and tested. The experimental setup here is the same as that students can use in the laboratory experience. However, a basic PC-based setup with a microphone and free software for audio processing is enough for achieving successful results. Here, five rings have been considered for the three resonators studied, and all measurements have carried out in triplicate, considering in all process the proper error propagation. The results for sound speed and air density are close to the expected values. The room temperature in all cases was in the range between 18°-22° C, implying that theoretically, the speed of sound waves should be found in the interval 342.4-344.8 $\text{m}\cdot\text{s}^{-1}$. The results obtained for both sound speed and air density are precise and close to the expected values. However, the error propagation reveals a reduced accuracy for measuring the room temperature because the error is considerably high compared to the estimation. Even that, the authors consider that experience is positive in all senses due to several reasons. Firstly, the experience makes possible to estimate the speed of sound waves without expensive or high-end instrumentation. More precisely, this proposal includes new technology such as 3D printing in a classical experience in Acoustics, which can be useful in many educational scenarios related to physics and engineering. The opportunity to vary the fundamental resonance frequency without using liquids reduces the amount of instrumentation since a scale is no longer needed. The possibility of designing an unlimited number of mouths with different lengths, endings, and shapes, opens a wide range of experiences that students can do to analyse different elements of a Helmholtz resonator. The authors consider future works related to producing new mouth terminations to analyse its impact on the system's acoustical mass and new strategies to reduce the error propagation in the temperature estimation.

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