

Study of acoustic resonance in a cylindrical Helmholtz resonator excited by a tangential jet of air through a lateral slit

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Abstract

We report an experimental investigation of a cylindrical Helmholtz resonator with a lateral slit, excited by an oblique air jet generated by a rotational motion of the resonator. Despite the small size of the cavity, the system produces clearly audible tones. The acoustic response can be analysed using a smartphone-based audio spectrum analyser. The dominant resonance frequency is found to vary systematically with the slit length. The experimental results are described by the classical Helmholtz resonance model, which relates the observed frequencies to the geometrical parameters of the resonator through an effective mass–spring description. The apparatus is inexpensive, easy to construct, and suitable for both classroom activities and undergraduate laboratory experiments. The activity provides a clear and quantitative framework for exploring acoustic resonance, connecting concepts from mechanics, thermodynamics, and acoustics.

Keywords: Helmholtz resonator, acoustic resonance, slotted acoustic cavity, undergraduate laboratory experiments, smartphone-based experiments

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1. Introduction

A Helmholtz resonator is an acoustic cavity filled with gas, usually air, connected to the external environment through an opening or a narrow neck [1–3]. At the resonance frequency, the air in the opening oscillates as an effective mass, while the compressibility of the air inside the cavity provides the restoring force. A familiar example is an empty bottle that emits a tone when air is blown across its neck [4–8].

Helmholtz resonators represent a classical and instructive example of acoustic resonance and are widely used in physics education [6–11]. Although they are typically introduced within acoustics, their analysis naturally involves key concepts from both mechanics and thermodynamics. From a mechanical point of view, the system can be described as a simple harmonic oscillator: the air plug in the neck behaves as an effective mass, while the compressible air inside the cavity provides a restoring force analogous to that of a spring. This interpretation allows students to apply the formalism of harmonic motion in a concrete setting and to engage with concepts such as effective mass and effective spring constant. A complete description also requires thermodynamic reasoning. The pressure and volume variations occur rapidly and can therefore be approximated as adiabatic transformations. This provides an opportunity to relate macroscopic observables to thermodynamic properties of gases, including the role of the adiabatic exponent γ .

In its simplest form, Helmholtz resonance is studied using a bottle, by blowing across the opening at the top of its neck. The resonance frequency is typically analysed as a function of the cavity volume, which can be varied by changing the geometry of the resonator (see figure 1) or by partially filling it with water [4–11]. In this paper, we present a simple experimental setup designed to explore acoustic resonance in a cylindrical resonator excited by a tangential air jet through a lateral slit. Although Helmholtz resonators have been studied in a variety of geometrical configurations, the dependence of the resonance frequency on slit length appears to have received little attention. The proposed experiment allows this relationship to be investigated systematically, providing a simple and flexible way to explore

geometrical effects that are not easily accessible with standard bottle resonators. We show that the observed behaviour can be interpreted within the framework of the Helmholtz resonance model, making the apparatus a useful educational tool for illustrating the physical origin of acoustic resonance and the role of effective geometrical parameters.

2. Historical background

The use of hollow ceramic vessels as sound-producing instruments dates back to the third millennium BCE [12]. In many cultures, simple containers were made to resonate by blowing across an opening and were used in musical and ritual practices. The scientific study of acoustic resonance developed significantly during the nineteenth century. In 1863, Hermann Helmholtz (1821–1894) introduced the resonator that now bears his name as a tool for analysing complex sounds in terms of their frequency components [1, 11]. His original design consisted of a spherical cavity with a neck, tuned to resonate at a specific frequency. Figure 1 shows examples of both fixed and variable Helmholtz resonators produced by Rudolph Koenig (1832–1901) in Paris [3]. They are operated by holding the small orifice close to the ear, with the neck facing the sound source: the perceived sound intensity reaches a maximum at resonance.

Figure 2 shows a partial set of spherical metallic resonators constructed by Koenig and acquired in 1867 by Pietro Blaserna (1836–1918) during his tenure at the University of Palermo, Italy, as director of the former Istituto di Fisica. These instruments are now part of the Historical Collection of Physics Instruments of the University of Palermo [13, 14] and provide a valuable example of nineteenth-century experimental acoustics [2].

3. Experimental setup and results

To investigate acoustic resonance in a Helmholtz resonator, we constructed a simple device consisting of a cylindrical plastic cavity with height $H = (42 \pm 1)$ mm and diameter $D = (27.0 \pm 0.2)$ mm, having a volume $V_0 = (24.1 \pm 0.9)$ cm³. A

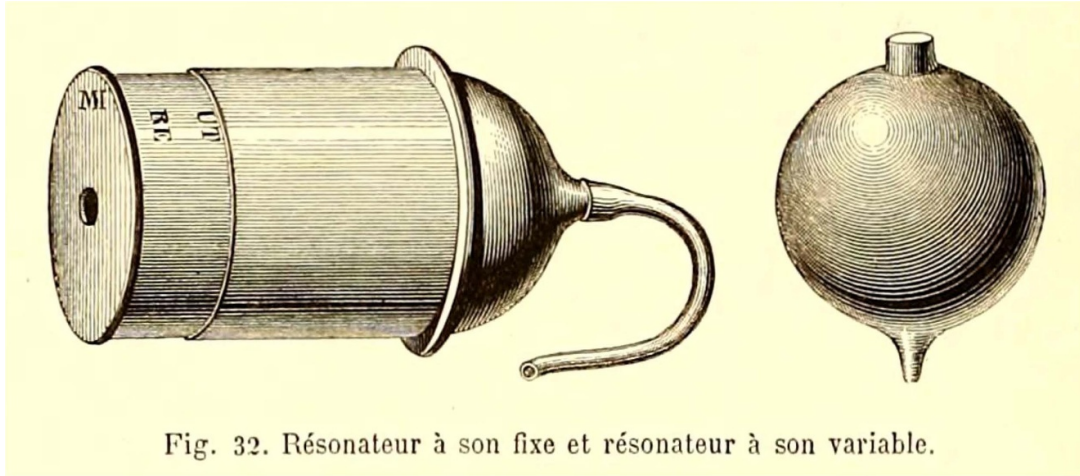


Figure 1. Helmholtz resonators [3]: (left) variable cylindrical resonator; (right) fixed spherical resonator.



Figure 2. Historical Helmholtz resonators of different diameter D , from the Historical Collection of Physics Instruments of Palermo University ($D_1 \approx 4$ cm, $D_2 \approx 10$ cm, $D_3 \approx 13$ cm, $D_4 \approx 17$ cm, $D_5 \approx 23$ cm).

rectangular slit is cut into the lateral surface of the cylinder, with cross-sectional area $S = w \times \ell$ (see figure 3). The slit has a fixed width $w = (2.3 \pm 0.1)$ mm, while its length ℓ can be varied along the axis of the cylinder by using removable tape to partially cover it. The depth of the slit, which corresponds to the thickness of the cylinder wall, is $t = (1.3 \pm 0.1)$ mm.

Unlike traditional Helmholtz resonators that are excited by blowing across a neck, the present setup uses rotation to generate a controlled

and reproducible airflow. The resonator is set into rotational motion, and the resulting airflow impinges on the lateral slit at an oblique angle, exciting pressure oscillations inside the cavity. The device is driven by a string approximately 60 cm long attached to the base of the cylinder. The cylinder is rotated manually at approximately 120 rpm (corresponding to ≈ 2 Hz). The resulting tangential velocity is $v_t \approx 8 \text{ m s}^{-1}$. It can be further optimised to produce a stable acoustic signal.

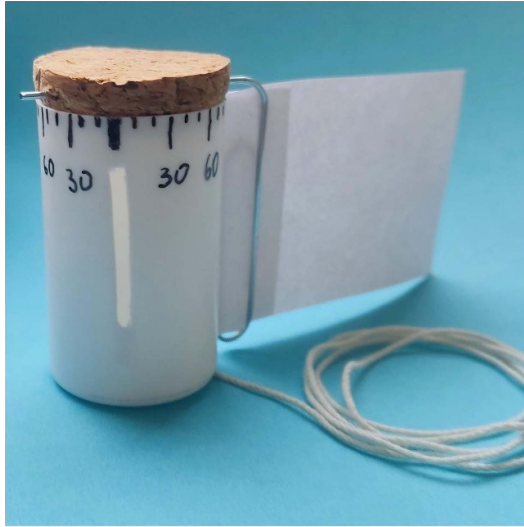


Figure 3. Cylindrical resonator with a lateral rectangular slit, of adjustable length, and a stabilising square sail.

To maintain a stable orientation during rotation, a small square sail is fixed along the axis of the cylindrical cavity and positioned at an angle of approximately 30° relative to the slit (see figure 4). A goniometric scale marked on the lateral surface of the cylinder allows the sail orientation to be adjusted reproducibly. This stabilising element ensures that the slit maintains a constant orientation relative to the airflow, thereby improving the repeatability and reliability of the measurements. A schematic representation of the setup is shown in figure 4. Similar results have been obtained using a spherical plastic resonator of inner radius $R \approx 24$ mm with a lateral slit.

The emitted sound is analysed using the 'Audio Spectrum' tool of the Phyphox app [15–17]. This tool uses the smartphone's built-in microphone [18]. The signal is analysed using a fast Fourier transform to determine the dominant frequency and display the corresponding sound spectrum. In the phyphox configuration used here, 2048 samples are acquired over a time window of approximately $T \approx 42.7$ ms, yielding a frequency resolution $\Delta f = 1/T \approx 23$ Hz. This discretisation limits the precision with which the peak frequency can be determined and therefore constitutes the dominant source of uncertainty. Increasing the acquisition time would improve

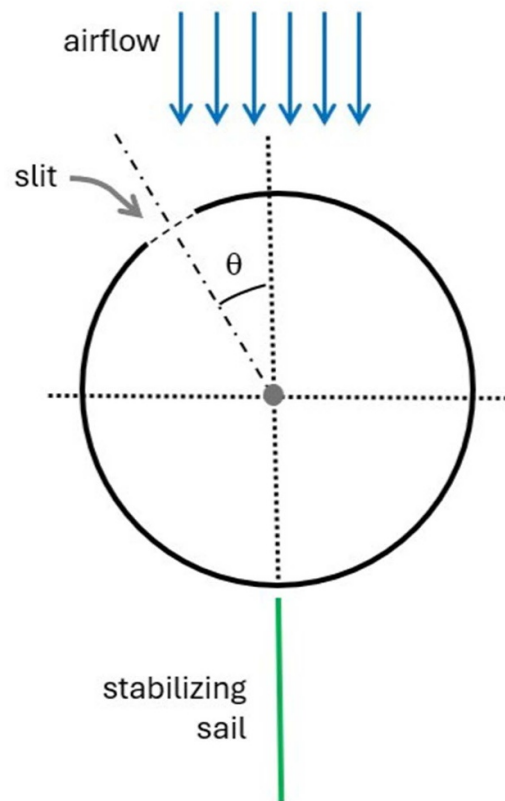


Figure 4. Schematic representation of the rotating Helmholtz resonator. The airflow generated by rotation excites the resonance through the lateral slit, while a small square sail ensures directional stability during the rotation.

the frequency resolution at the expense of temporal resolution. Figure 5 shows a representative audio spectrum, in which the sound amplitude is plotted as a function of frequency on logarithmic scales. Similar spectra are obtained for different values of the slit length.

For each value of the slit length ℓ , a clearly identifiable tone is observed and its frequency is measured. The uncertainty is determined by combining the statistical uncertainty of the average frequency with the instrumental resolution, $\delta_f \approx 23$ Hz, which reflects the frequency resolution of the Fourier analysis. All measurements were performed at the ambient temperature of approximately 25°C . The measured frequencies are reported in figure 6, which shows the dependence of the resonance frequency on the slit length. A

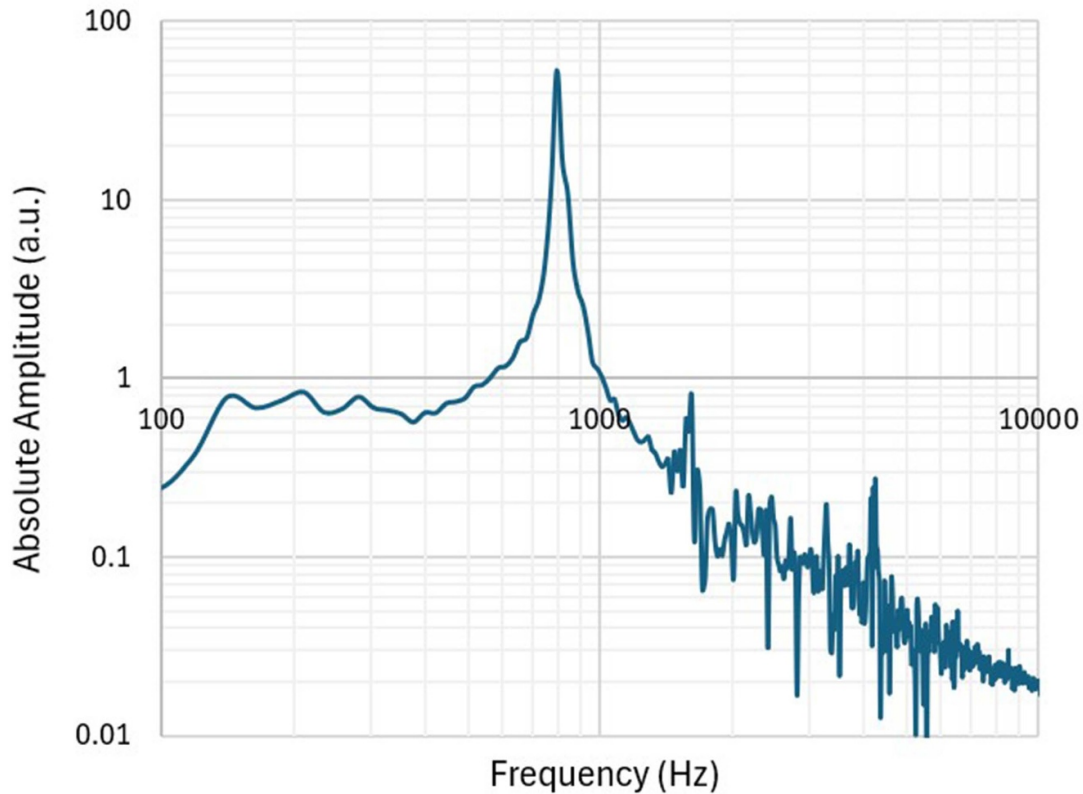


Figure 5. Representative audio spectrum obtained using the phyphox app. The dominant peak at $f = 797$ Hz corresponds to the resonance frequency of the cavity with $\ell = 11.2$ mm.

clear decrease in the frequency is observed as the slit length ℓ is reduced.

4. Theoretical background

The observed resonant frequencies suggest that the system behaves as a Helmholtz-type resonator, since they are substantially lower than those expected for longitudinal standing-wave modes of the cavity. Moreover, the cavity dimensions are much smaller than the acoustic wavelength corresponding to the observed frequencies, while the lowest longitudinal standing-wave mode of the cavity would occur at approximately $f \approx v/(2H) \approx 4.1$ kHz, several times higher than the observed frequencies. Within the framework of the lumped-element Helmholtz resonance model, the air inside the cavity is assumed to undergo rapid, approximately adiabatic compressions and rarefactions, providing a restoring force analogous to that of a spring with effective elastic

constant k . At the same time, the air in the opening is assumed to oscillate as an effective mass m , moving in and out of the cavity. The system therefore behaves as a mass–spring oscillator, and its resonance frequency can be expressed in terms of the geometrical parameters of the resonator and the physical properties of the gas [10, 19] Accordingly, it can be modelled as an equivalent harmonic oscillator, with resonance frequency given by

$$f = \frac{1}{2\pi} \sqrt{\frac{k}{m}} = \frac{v}{2\pi} \sqrt{\frac{S}{V_0 L_{\text{eff}}}}, \quad (1)$$

where v is the local speed of sound, S is the cross-sectional area of the slit, V_0 is the unperturbed cavity volume and L_{eff} is the effective length of the oscillating air plug in the slit of the cavity. The speed of sound depends on the temperature and, at $T = 20^\circ\text{C}$, it is $v \approx 343 \text{ ms}^{-1}$ in air [20]. It is worth noting that the resonance

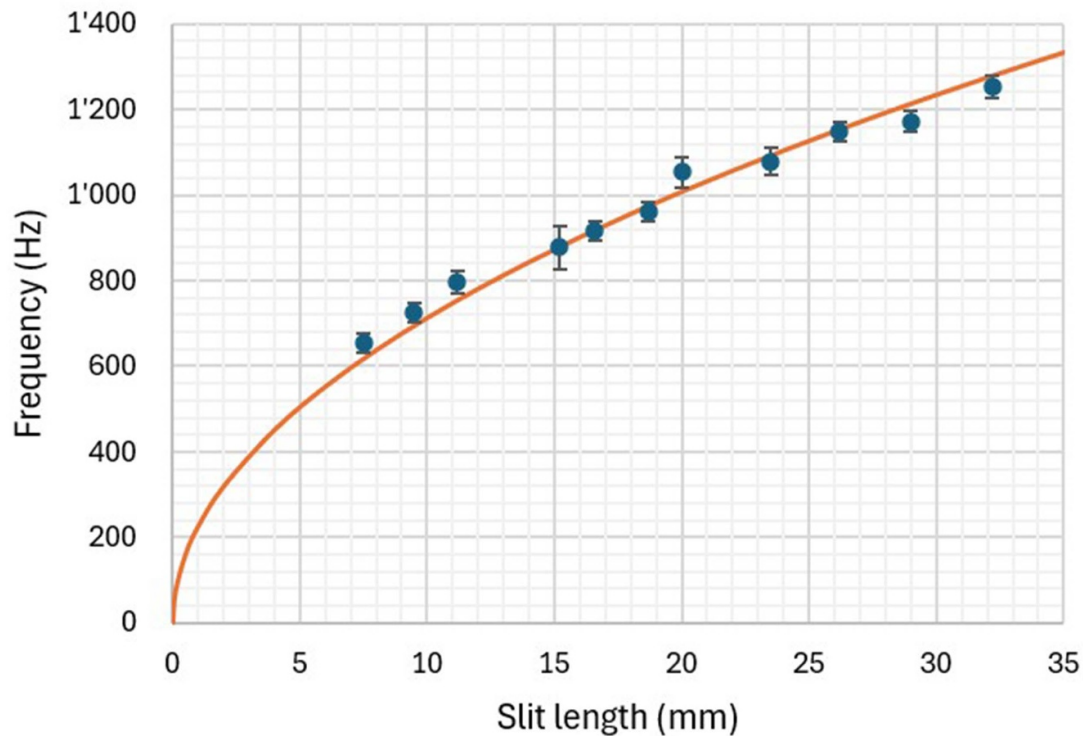


Figure 6. Resonant frequency as a function of the slit length ℓ . Symbols represent the experimental data, while the solid line shows the theoretical prediction described in the text.

frequency increases with S and decreases with V_0 . A concise derivation of equation (1) is provided in the [appendix](#). In classroom practice, the model may often be introduced directly in its final form, allowing the emphasis to be placed on its physical interpretation and experimental validation.

For the present geometry, the cavity volume V_0 and the slit width w are fixed, while the slit length ℓ is varied. Assuming that the effective length L_{eff} depends only weakly on the slit length ℓ , the resonant frequencies can be described by equation (1) as a function of ℓ , using L_{eff} as a fitting parameter. The results are shown in figure 6, where the speed of sound $v = 346 \text{ m s}^{-1}$ at 25°C is used. From the best fit we obtain $L_{\text{eff}} = (5.7 \pm 0.4) \text{ mm}$, which significantly exceeds the wall thickness $t = 1.3 \text{ mm}$, confirming the importance of end corrections. The uncertainty was estimated graphically by varying L_{eff} around the best-fit value and identifying the range for which

the theoretical curve remained consistent with the experimental data within their uncertainties.

The model reproduces the measured frequencies well, confirming its validity. However, one can note that at shorter slit lengths the curve lies below the experimental data and at larger slit lengths it lies above the experimental data. These systematic deviations indicate that the effective length L_{eff} is not strictly constant. For a rectangular slit, the end correction is expected to depend weakly on the aspect ratio ℓ/w , leading to geometry-dependent values of L_{eff} [21]. Additional deviations may originate from aeroacoustic coupling between the slit and the exciting airflow. These effects may explain the deviations from the ideal scaling law $f \propto \sqrt{\ell}$. Considering the simplicity of the model and the uncertainties associated with the effective slit length, viscous losses, and aeroacoustic coupling, the agreement between theory and experiment can be regarded as satisfactory.

5. Discussion

The Helmholtz resonance model provides a simplified lumped-element description of the acoustic resonator. Its validity requires cavity dimensions much smaller than the acoustic wavelength and assumes small-amplitude oscillations, negligible spatial pressure gradients inside the cavity, and a well-defined slit. Within these assumptions, the experimental results are in good agreement with the model predictions, confirming the validity of the model within the experimental uncertainty. The remaining discrepancies suggest that the effective length L_{eff} is not strictly constant and they may arise from geometry-dependent end corrections, viscous and radiative losses, and aeroacoustic coupling between the air jet and the slit. The activity therefore provides students with a concrete example of how a simplified physical model can successfully describe experimental data while also revealing its limitations.

The sound generation mechanism is related to a shear-layer instability at the slit, which provides feedback between the airflow and the acoustic oscillations inside the cavity [21]. Although this aeroacoustic mechanism initiates and sustains the oscillation, repeated measurements for a given slit length yield frequencies that are reproducible within the experimental uncertainty. Moreover, the limited scatter of the data in figure 6, despite the manual rotation of the resonator, indicates that small variations in rotation speed have little influence on the measured frequency. This result supports the interpretation that the observed tone is governed primarily by the Helmholtz resonance of the cavity rather than by the airflow velocity itself. From a pedagogical perspective, this distinction helps students recognise that the mechanism responsible for exciting and sustaining an oscillation is not necessarily the one that determines its frequency, providing a clear example of the difference between an excitation mechanism and a resonant response.

This experiment offers several advantages for physics education. It demonstrates that clearly audible sound can be generated by a small cavity through Helmholtz resonance and provides a concrete framework for discussing model assumptions, boundary conditions, and the validity of

simplified physical descriptions. Because of its simplicity and reproducible results, the activity is suitable for undergraduate laboratories, introductory acoustics courses, and teacher-training programmes. The experiment can be implemented at low cost using readily available materials together with a smartphone-based spectrum analyser.

The activity naturally supports an inquiry-based approach to learning. Students can be asked to predict how the resonance frequency depends on the slit length, perform measurements, compare the experimental results with the Helmholtz model, and discuss possible sources of discrepancy between theory and experiment. The experimental data make the square-root dependence of the resonance frequency on slit length readily apparent, allowing students to relate the observed trend directly to the Helmholtz model [7, 10]. In this way, they are encouraged to formulate hypotheses, analyse experimental evidence, and evaluate the assumptions underlying the physical model.

A particularly useful question concerns the physical origin of the observed sound. Students often associate acoustic resonance with standing waves inside a cavity, whereas Helmholtz resonance is more appropriately described as a lumped mass–spring oscillation. By comparing the experimentally observed frequencies (approximately 0.7–1.3 kHz) with the lowest longitudinal standing-wave mode expected near 4.1 kHz and with the predictions of the Helmholtz model, students can critically examine these alternative interpretations and develop a deeper understanding of acoustic resonance.

More broadly, the experiment provides a coherent framework in which mechanics, thermodynamics, and acoustics converge within a single experimental context, while also linking historical concepts in acoustics with modern experimental practice [22]. The use of smartphone-based measurements enables real-time data acquisition and immediate comparison between theoretical predictions and experimental observations, promoting active student engagement in the laboratory [23–26].

6. Conclusions

We have investigated the acoustic response of a cylindrical cavity with a lateral slit excited by an oblique air jet generated during rotation. The observed dependence of the resonance frequency on the slit length is consistent with the behaviour expected for a Helmholtz resonator and is well described by a simple mass–spring model. The agreement between the measured frequencies and the predictions of the model provides clear evidence that the observed sound originates from Helmholtz resonance rather than from standing-wave modes within the cavity and provides a quantitative test of the relationship between resonance frequency and resonator geometry. The experiment also illustrates the limitations of simplified models. Although the Helmholtz description successfully accounts for the main experimental trends, the observed deviations suggest the influence of geometry-dependent end corrections, viscous losses, and aeroacoustic coupling between the slit and the exciting airflow. From an educational perspective, the activity supports inquiry-based learning by encouraging students to formulate hypotheses, collect and analyse data, and compare experimental observations with theoretical predictions. In particular, it provides a direct way to distinguish between standing-wave interpretations and the lumped mass–spring description that underlies Helmholtz resonance. The setup is simple to construct from readily available materials and, combined with smartphone-based measurements, is well suited to introductory undergraduate laboratories. Future classroom implementations could be used to investigate its effectiveness in promoting conceptual understanding of acoustic resonance and addressing common misconceptions regarding the physical mechanisms responsible for sound generation.

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Data availability statement

All data that support the findings of this study are included within the article (and any supplementary files).

Appendix. Helmholtz resonance frequency

The derivation of the Helmholtz resonance frequency is based on the standard lumped-element approximation for a Helmholtz resonator. The cavity dimensions are assumed to be much smaller than the acoustic wavelength, so that the pressure can be considered spatially uniform inside the cavity. The oscillations are assumed to be of small amplitude and the thermodynamic transformations of the enclosed air are treated as adiabatic. In this description, the oscillating mass m is associated with the air in the opening, while the compressibility of the air inside the cavity provides the restoring force [10, 19]. The system can therefore be modelled as an equivalent harmonic oscillator, with resonance frequency given by

$$f = \frac{1}{2\pi} \sqrt{\frac{k}{m}}, \quad (\text{A.1})$$

where k is the effective elastic constant associated with the compressibility of the gas in the cavity. For an adiabatic process:

$$pV^\gamma = \text{constant}, \quad (\text{A.2})$$

where p is the pressure, V is the volume, and $\gamma = C_p/C_v$ (for air, $\gamma \approx 1.4$). Differentiating equation (A.2):

$$d(pV^\gamma) = 0 \Rightarrow V^\gamma dp + \gamma p V^{\gamma-1} dV = 0. \quad (\text{A.3})$$

Dividing by V^γ :

$$dp + \gamma \frac{p}{V} dV = 0, \Rightarrow dp = -\gamma \frac{p}{V} dV. \quad (\text{A.4})$$

If the air plug in the slit is displaced by a small amount dx , the volume variation is:

$$dV = -Sdx, \quad (\text{A.5})$$

where x is defined positive when the air plug moves inward and $S = w \times \ell$ is the cross-sectional area of the slit. For small oscillations, the pressure and volume in equation (A.4) can be replaced by their equilibrium values p_0 and V_0 . Substituting equations (A.5) into (A.4) gives:

$$dp = \frac{\gamma p_0 S}{V_0} dx. \quad (\text{A.6})$$

The force exerted on the air plug is:

$$dF = -Sdp = -\frac{\gamma p_0 S^2}{V_0} dx. \quad (\text{A.7})$$

Equation (A.7) has the form of Hooke's law for small displacements, showing that the air enclosed in the cavity behaves as an elastic element with effective spring constant k . Comparing equation (A.7) with Hooke's law $dF = -k dx$, we obtain:

$$k = \frac{\gamma p_0 S^2}{V_0}. \quad (\text{A.8})$$

The oscillating mass is:

$$m = \rho S L_{\text{eff}}, \quad (\text{A.9})$$

where L_{eff} is the effective length of the oscillating air plug associated with the slit and ρ is the air density. The quantity L_{eff} exceeds the physical thickness of the opening because part of the surrounding air outside the slit is entrained in the oscillatory motion, giving rise to the well-known end correction [21]. Thus, from equation (A.1) the resonance frequency is:

$$f = \frac{1}{2\pi} \sqrt{\frac{k}{m}} = \frac{1}{2\pi} \sqrt{\frac{\gamma p_0 S^2 / V_0}{\rho S L_{\text{eff}}}} = \frac{v}{2\pi} \sqrt{\frac{S}{V_0 L_{\text{eff}}}}, \quad (\text{A.10})$$

where $v = \sqrt{\gamma p_0 / \rho}$ is the local speed of sound, $v \approx 343 \text{ ms}^{-1}$ in air at $T = 20^\circ\text{C}$ [20]. It is worth noting that the resonance frequency increases with the cross-sectional area S and decreases with the cavity volume V_0 . Equation (A.10) highlights the physical origin of Helmholtz resonance: V_0 acts as an elastic spring, while the air contained in and near the slit acts as an oscillating mass. Increasing the opening area of the slit increases the stiffness of the air spring proportionally to S^2 (equation (A.8)) and, at the same time, increases the oscillating mass proportionally to S (equation (A.9)). As a consequence, the resonance frequency scales as $\sqrt{S}$ (equation (A.10)). The increase in resonance frequency therefore results from the stronger dependence of the stiffness on S compared with that of the oscillating mass. In a teaching context, the emphasis can be placed on interpreting this result rather than on the full derivation.

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