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Simulation and Experimental Investigation on End Plate Flexibility of Helmholtz Resonators

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Abstract

This study investigates the effect of varying mechanical properties of flexible materials on the resonance frequency of Helmholtz resonators. A simulation model was developed using COMSOL Multiphysics, which coupled the acoustic pressure field with the mechanical structural field to obtain the dynamic response of resonators with different end plate materials. The simulations were performed for two primary materials—PVC and aluminum foil—selected based on their contrasting mechanical properties. To validate the simulation results, a hexagonal resonator prototype was fabricated using 3D printing technology with PLA material. The setup includes a speaker driven by a signal generator as the sound source. Two microphones were used to measure acoustic pressure. For the PVC material, an amplification peak was observed around 440 Hz, while for the aluminum material, two peaks were observed around 260 Hz and 570 Hz in both the experimental and simulation methods. The results showed a good correlation between the experimental and simulation data. Using the developed model, a simulation was conducted by varying the Young's modulus. The results illustrated that as the stiffness of the material increases, the system's resonance frequency shifts upwards. This study highlights the potential of using flexible materials in Helmholtz resonator designs to fine-tune acoustic performance. The validated simulation model can serve as a tool for optimizing the acoustic behavior of resonators for various applications, such as noise attenuation and energy harvesting, by adjusting material properties to achieve desired resonance characteristics.

Keywords: Helmholtz resonator; flexible plate; resonance frequency; simulation

1. Introduction

Helmholtz resonators have attracted considerable attention in recent years due to their versatile applications in noise attenuation, acoustic metamaterials, and energy harvesting systems. Traditionally, these resonators have been utilized for their ability to target specific frequencies determined by their geometric properties [1]. However, recent advancements have significantly extended their functionality through structural modifications [2]. By integrating flexible plates, membranes, and mass-loaded elements, the classic single-frequency Helmholtz resonator has evolved into a complex multi-degree-of-freedom (MDOF) system, capable of achieving broader bandgaps, multi-resonance behavior, and enhanced energy conversion efficiency [3].
A prominent area of research involves the application of Helmholtz resonators in energy harvesting. By coupling resonators with piezoelectric elements or incorporating compliant structures, it has been demonstrated that vibration and acoustic energy can be effectively converted into electrical power. Yuan's [4]study exemplifies this approach by integrating a flexible circular plate at the end of a Helmholtz resonator to optimize energy capture. Similarly, Zhang et al.[2] introduced a novel metamaterial composed of an array of Helmholtz resonators coupled with mass-loaded membranes, which facilitated both broadband noise reduction and efficient energy harvesting through multiple resonances. This configuration has proven effective in converting ambient vibrational energy into electrical power, making it suitable for applications in structural health monitoring and smart material systems. Helmholtz resonators have also been explored extensively for their adaptability in noise control applications. Liu and Du [1] examined membrane-cavity resonators embedded in ducts under mean flow conditions, demonstrating that such configurations are highly adaptable for noise attenuation in environments with complex flow dynamics, such as exhaust systems. In the realm of adaptive acoustic performance, Abbad [5] proposed using electroactive polymer (EAP) membranes in Helmholtz resonators, enabling real-time tuning of resonance characteristics. This integration allows for precise control of acoustic properties, making it ideal for varying environmental conditions.

The study by Naida et al. [6] further explored the use of flexible membranes in Helmholtz resonators and showed that these modifications resulted in complex resonance patterns across a wide frequency range, closely aligning with simulation data. The agreement between experimental and computational results underscores the potential of using simulations to optimize resonator designs, thereby minimizing the need for resource-intensive experimental setups. This capability is particularly valuable for energy harvesting and noise amplification applications, where accurate resonance prediction is critical for device performance. Earlier studies have also highlighted the benefits of flexible plates in Helmholtz resonators. Nudehi et al. [7] presented a dynamic model of a Helmholtz resonator with a flexible end plate, revealing that the incorporation of a compliant element leads to multiple resonance frequencies, which significantly enhances acoustic control. This characteristic is crucial for applications requiring precise frequency management, such as acoustic filters and resonant-based sensing devices. Overall, these advancements illustrate the transformative potential of integrating flexible components into Helmholtz resonator designs, enabling multifunctional capabilities that extend beyond traditional applications.

In this study, a novel-designed resonator is used to develop a simulation model. Designing a Helmholtz with a noise collector helps to capture more sound energy and be more effective for both energy harvesting and noise attenuation.

2. Background theory

In this section, an introduction to the Helmholtz resonator is provided for a better understanding of the numerical modeling that follows.

2.1 Natural frequency

The Helmholtz resonator can be modeled as a simplified mass–spring–damper system. When subjected to external acoustic excitation, the air within the resonator's cavity acts like an air spring, while the air in the neck region oscillates similarly to a mass, forcing the air spring to expand and contract in a cyclical motion. The damping effect is primarily due to viscous losses from the friction of oscillating air within the neck and radiation losses at the neck's end. Formulation of the resonance frequency (f_0) of the cavity can be expressed as[8] :

$$f_0 = \frac{c}{2\pi}\sqrt{\frac{A}{VL}} \tag{1}$$

where c is the speed of sound in the medium, A is the cross-sectional area of the neck, V is the volume of the cavity, and L is the effective length of the neck.

2.2 Numerical model

The model is simulated using COMSOL Multiphysics 6.1 by coupling the acoustic pressure field with the mechanical structural field. The end plate of the resonator was defined as a shell with varying material properties, while all other walls were assumed to be rigid and set as hard wall boundaries. An incident sound wave was applied at the top of the resonator, and the resulting sound pressure was measured at the bottom surface. To optimize computational efficiency and reduce solving time, the symmetry condition of the resonator is utilized to model the resonator (Figure 1). Two different materials, PVC sheet with a thickness of 3.5 mm and aluminum foil with a thickness of 0.07mm, were selected in simulations. Their corresponding mechanical properties are presented in Table 1.

Table 1. Properties of used material for the end plate of resonator

Property	Aluminum	PVC
Young's modulus (Gpa)	69	2.8
Poisson ratio	0.33	0.4
Density(kg/m^3)	2700	1400

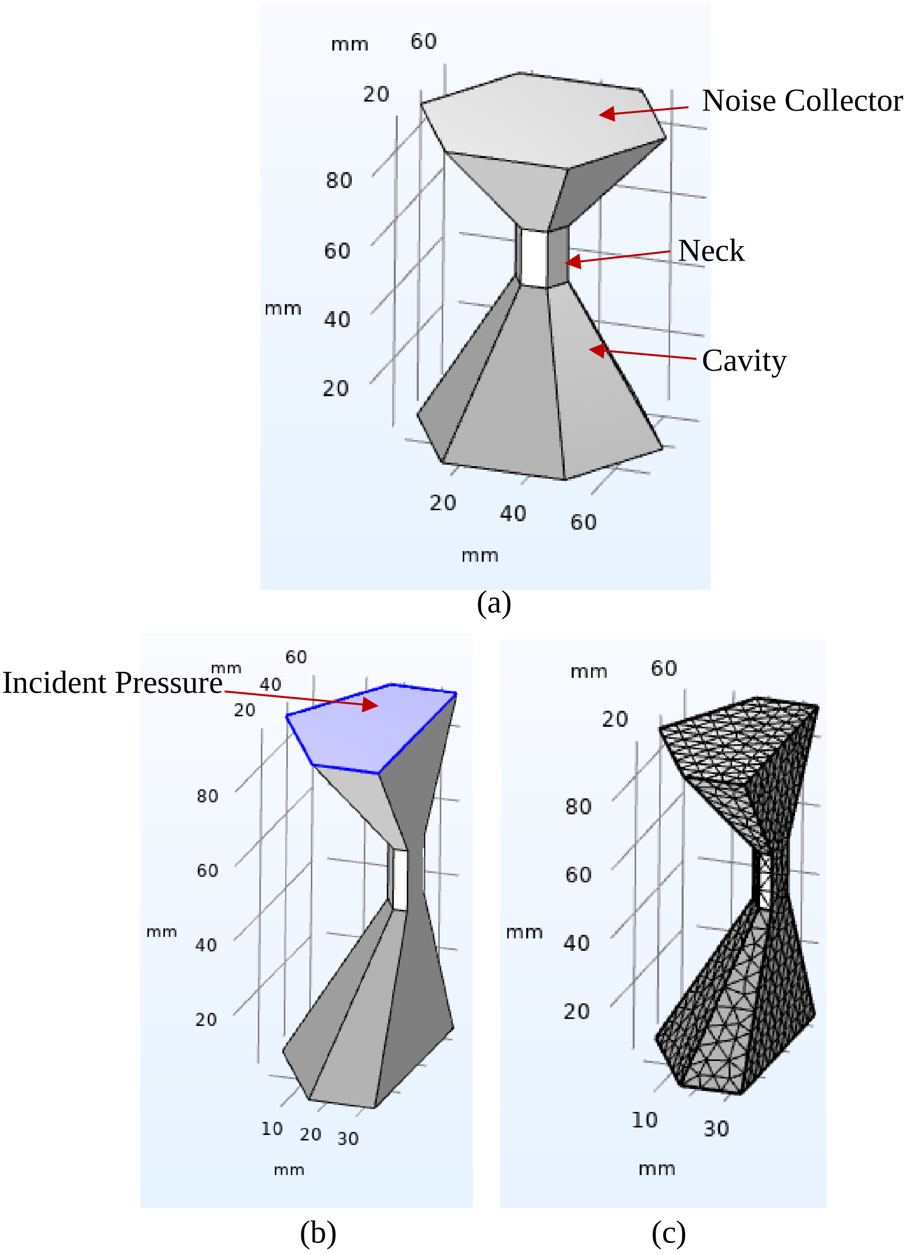

Figure 1: Model of resonator a) introducing different part of resonator b) Symmatry model with incident pressure c) Tetrahedral meshing

3. Experimental validation

This section details the construction of a hexagonal Helmholtz resonator prototype and the experimental setup used to validate the simulation results.

3.1 Helmholtz construction

To validate the simulation results, a new design hexagonal resonator prototype was fabricated using 3D printing technology with PLA (Polylactic acid) material. To enhance the acoustic isolation properties of the resonator, a thin layer of polyester resin was applied to its surface. Two different materials, PVC sheet and aluminum foil, were selected for testing with mechanical properties summarized in Table 1.

3.2 Experimental setup

The experimental setup as shown in Figure 2, consists of two microphones, one at inlet to measure the incident sound pressure and another fixed near the end of the resonator to record the output sound pressure. The data acquisition was conducted using a Dewesoft system. The amplification factor of the resonator was determined by calculating the ratio of the output to the input sound pressure levels. A VISATON KT100V speaker was used as the sound source, driven by an HMF2525 (HAMEG) signal generator, which provided a sine sweep ranging from 50 Hz to 1000 Hz.

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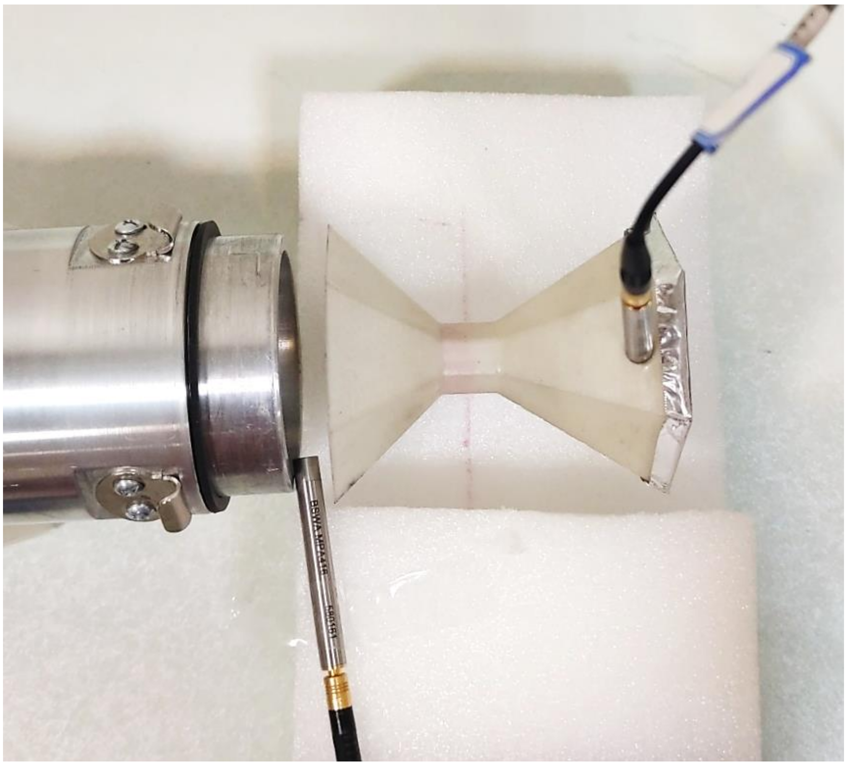

Figure 2: Experimental Setup

4. Results and discussion

A comparison between experimental and simulation results is conducted in this section. Furthermore, in the following, a model with varying Young’s modulus is simulated.

4.1 Experimental and simulation comparison

As illustrated in Figure 3, an amplification peak is observed around 440 Hz, indicating a strong correlation between the experimental and simulation results for the PVC sheet. This alignment suggests that the model accurately captures the resonance behavior for this material. Figure 4 shows two distinct resonance peaks for the aluminum foil, occurring at approximately 260 Hz and 570 Hz for both experimental and simulation results, and also two anti-resonance at 420 Hz and 800 Hz. These additional resonance modes can be attributed to the aluminum foil's thinner thickness (related to its flexibility) compared to the PVC sheet. Consequently, there is a good agreement between simulation and experimental data for both resonance and anti-resonance frequencies.

It is worth mentioning that while the resonance frequencies are consistent between the simulations and experiments, the amplitude of the peaks in the simulation results is not entirely reliable. This discrepancy is likely due to the absence of damping in the simulation model, which would normally attenuate the resonance amplitudes in a real-world setup. Thus, although the frequency predictions are accurate, the amplitude values should be interpreted with caution.

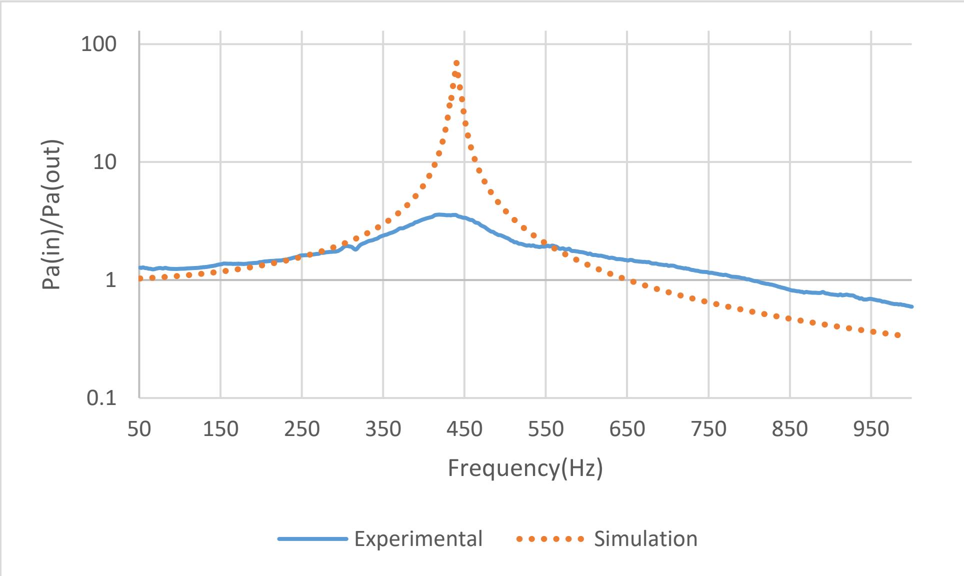

Figure 3: Experimental and numerical frequency responses of the Helmholtz resonator with PVC sheet end plate

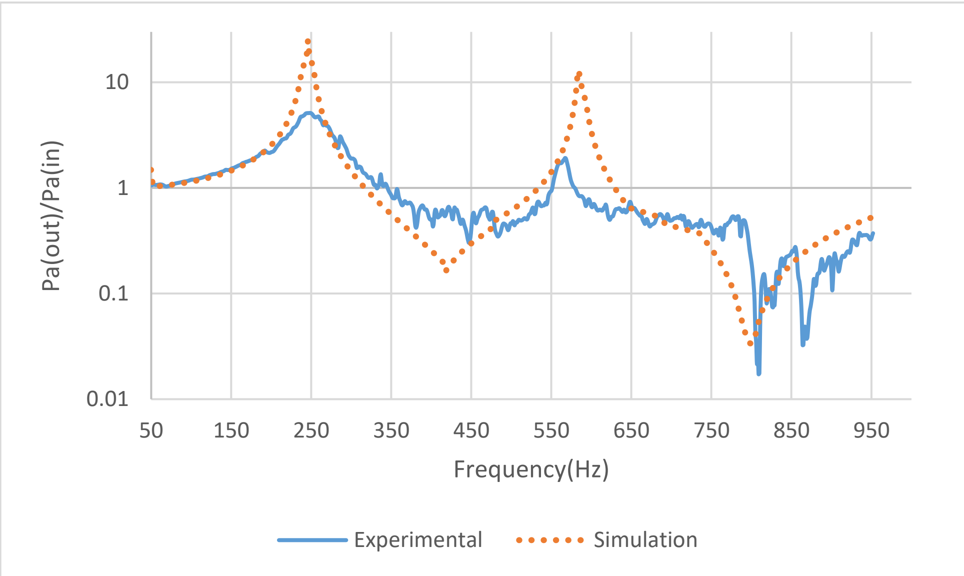

Figure 4: Experimental and numerical frequency responses of the Helmholtz resonator with Aluminum foil end plate

4.2 Simulation resonator with different Young' modulus of the end plate

This study investigates the effect of varying Young's modulus on the resonance behavior of Helmholtz resonators. Simulations were conducted using a constant plate thickness of 0.07 mm, with Young's modulus values set to 30 GPa, 55 GPa, and 80 GPa in a parametric study of Comsol. As illustrated in Figure 5, the results clearly demonstrate that as the stiffness of the material increases, the system's resonance frequency shifts upwards, leading to a lower density of resonance peaks within the same frequency range. Specifically, the material with Young's modulus of 30 GPa showed the highest number of resonant frequencies, while the material with a modulus of 80 GPa displayed fewer resonance peaks.

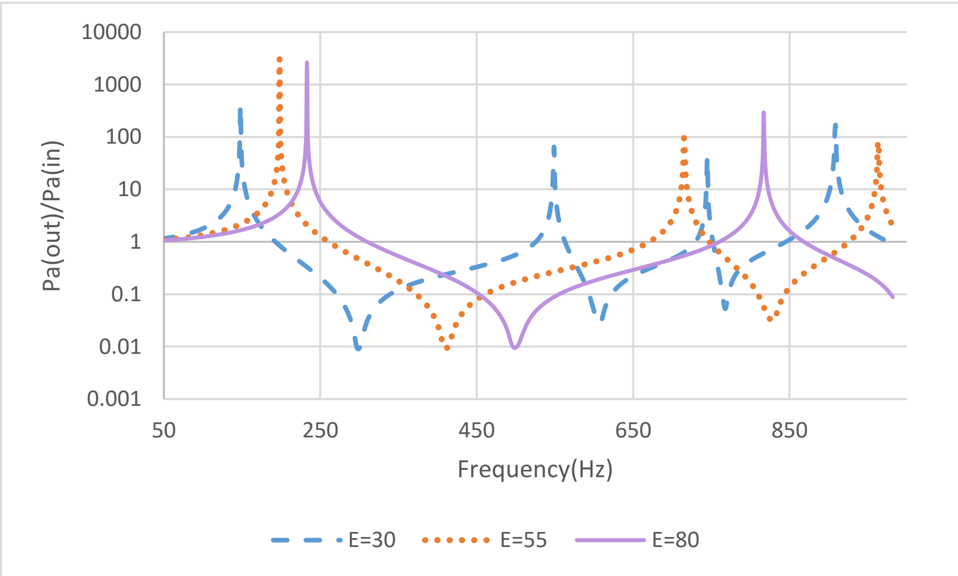

Figure 5: simulation result for different Young's modulus of the end plate of the resonator

5. Conclusion

This study investigated the effect of varying mechanical properties of flexible materials on the resonance frequency of a Helmholtz resonator, using both simulation and experimental methods. The model was validated by experimental data. For the PVC material with a thickness of 3.5 mm, a resonance peak was observed around 440 Hz, while for the aluminum material with a thickness of 0.07 mm, two peaks were observed around 260 Hz and 570 Hz, along with two anti-resonances at 420 Hz and 800 Hz. Using this model, a Helmholtz resonator with varying Young's modulus at the end plate was simulated. The results showed that increasing Young's modulus (from 30 GPa to 80 GPa) led to higher resonance frequencies. Materials with a higher Young's modulus exhibited fewer resonant modes within a given frequency range. Therefore, flexible materials hold potential in Helmholtz resonator designs to fine-tune acoustic performance. The validated simulation model can serve as a tool for optimizing the acoustic behavior of resonators for various applications, such as noise attenuation and energy harvesting, by adjusting material properties to achieve desired resonance characteristics.

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