Transforming Acoustic Control: The First Tunable Broadband Origami-Based Helmholtz Resonator

Amine Benouhiba†, Patrick Rougeot, Nicolas Andreff, Morvan Ouisse, Kanty Rabenorosoa
Université de Franche-Comté, SUPMICROTECH, CNRS, Institut FEMTO-ST, Besançon, 25000, France
E-mail: `amine.benouhiba@epfl.ch`, `kanty.rabenorosoa@femto-st.fr`

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Abstract. Helmholtz resonators have long been essential for acoustic control, enhancing or nullifying sound at specific frequencies. Traditionally, these resonators are effective for fixed-frequency applications, but lose efficacy if the excitation frequency changes. This paper presents the first tunable broadband origami-based Helmholtz resonator, featuring a compliant origami design with auxetic properties for optimal volume variation. Multiphysics simulations determined the adaptive cavity geometry, and experimental tests validated the models, showing high tunability (up to 25% around a central frequency of 461 Hz with a 95% absorption rate) and broad bandwidth (up to 13% around the central frequency with a 95% absorption rate) with minimal geometry variation (8 mm in diameter). This work marks a significant advancement over traditional Helmholtz resonators.

Keywords: Helmholtz resonator, origami design, noise control, smart structure, adaptive system.

1. Introduction

Helmholtz resonance is the phenomenon of resonance that occurs in a cavity connected to the surrounding atmosphere (air) by one or more narrowed necks. Hermann L. F. von Helmholtz [1] was the first to establish the phenomenon's physical and mathematical principles, hence the name. The most common examples of Helmholtz resonators are bottles and stringed instruments, especially bottles, as they fit the description very well (small opening in a large chamber) [2].

Helmholtz resonators are very useful for controlling steady harmonic sound fields with narrow bandwidth spectra. In addition, their interesting vibro-acoustic properties have made them prime candidates for many applications, including architectural resonators in churches [3], mufflers for pipes and duct silencers [4], etc. The primary qualities

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† Corresponding author

of a Helmholtz resonator are its simplicity and high efficiency in the low-frequency domain (0-500 Hz). However, its narrow bandwidth represents a major drawback, significantly limiting its use and field of application. Therefore, a Helmholtz resonator must be precisely tuned to achieve the desired outcome (noise reduction). Furthermore, any fluctuation in the incident frequency or environmental conditions requires a readjustment of the resonator. Otherwise, a poorly tuned resonator may lead to the opposite desired result (noise generation).

The resonance frequency of a Helmholtz resonator is defined by its geometrical properties [5, 6, 7]. Thus, controlling the geometrical properties (i.e., the cavity volume) of Helmholtz resonators allows for controlling the frequency at which the noise reduction occurs. In other words, a tunable Helmholtz resonator is a device that can adapt its resonance frequency in real time to match the incident sound wave by adjusting its geometrical properties. There are few examples of tunable Helmholtz resonators mentioned in the literature. De Bedout et al. [8, 9] proposed an adaptive-passive noise control with self-tuning Helmholtz resonators. Using two rigid walls and a DC motor attached to the back plate of the cylindrical resonator, they were able to vary its volume, thus controlling its frequency. Yu et al. [10] proposed a tunable acoustic metamaterial with an array of resonators (not Helmholtz resonators) actuated *via* dielectric elastomer actuators. Abbad et al. also used similar material to control an elastic resonance of a membraned Helmholtz resonator [11], as well as to control its volume [12].

Origami, from ori meaning folding and kami meaning paper, denotes the ancient oriental art of paper folding. In brief, it is the art of creating 3D models from a single sheet of paper, by successive folding. Folding, as a fabrication process, is one of the primary tools of nature. For instance, leaves of many plants and petals of various flowers are folded within the bud, insect wings often display folding inside carapaces and cocoons, and multiple proteins inherit their functions from the fashion their amino-acid chains fold. Origami presents itself as a remarkable design and fabrication tool for scientists and engineers across various scales, from the micro [13] to the macro [14] level. From a single flat sheet of material, 3D complex structures with various properties for different purposes can be achieved. Depending on the desired functionality, origami structures can adjust their shape to meet the requirements. Therefore, multifunctional devices with on-demand properties can be obtained.

In this study, we introduce a novel approach to passive-adaptive noise control through a broad bandwidth tunable Helmholtz resonator based on compliant origami design. There are numerous advantages to incorporating flexibility in Helmholtz resonators, including enhanced low-frequency absorption [16], compact design [11], lightweight construction, broader bandwidth [17], and tunability [18]. These benefits are also present in our flexible origami Helmholtz resonator . However, while traditional flexible structures broaden the bandwidth by introducing additional resonance frequencies at low frequencies, this typically results in only modest improvements. Our flexible origami Helmholtz resonator stands out by significantly extending the resonance frequency range, from just a few hertz to tens or even over a hundred hertz. This enhancement is

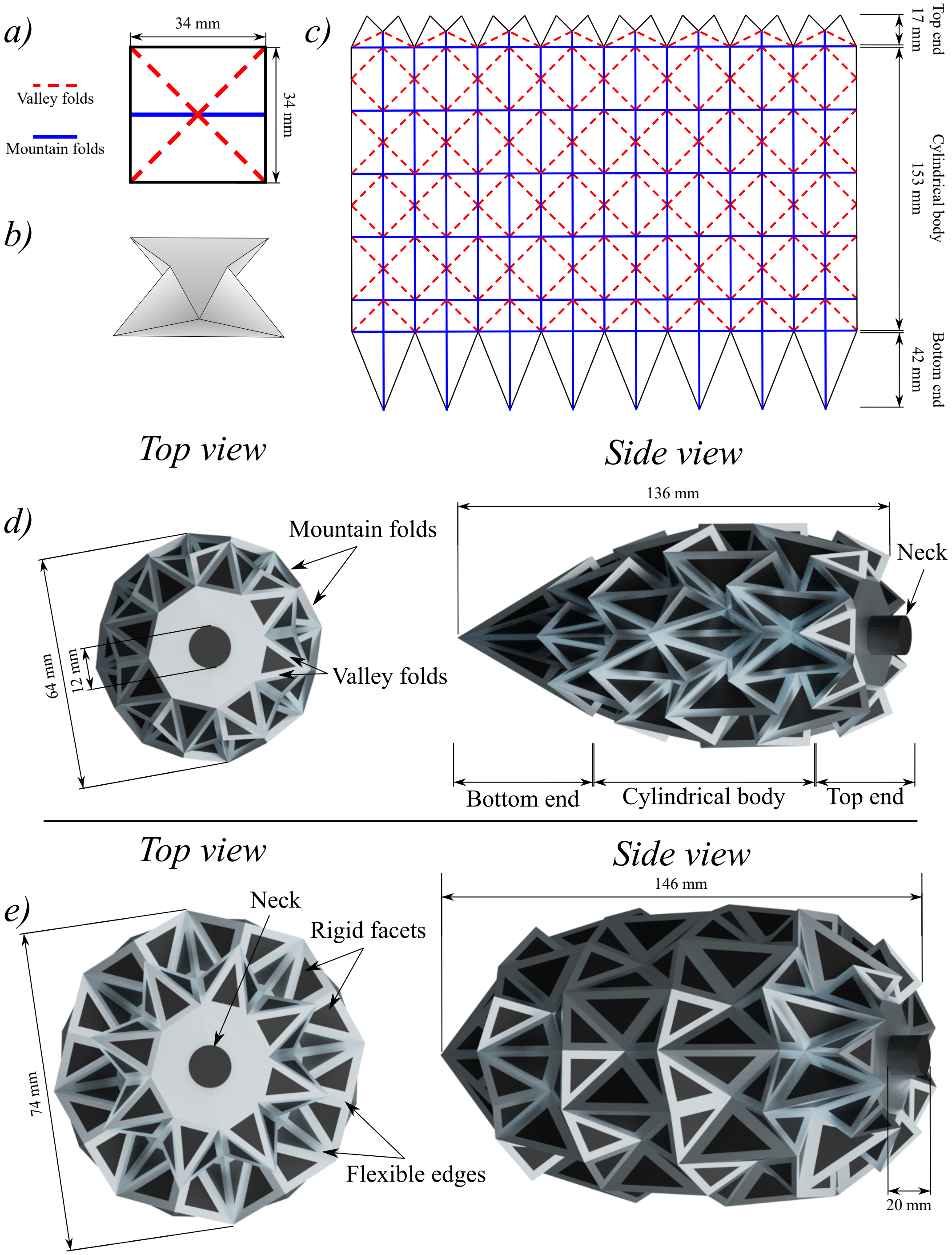

Figure 1. Origami-based design of the tunable broadband Helmholtz resonator. a) Waterbomb origami base, the blue lines for the mountain folds and the red ones for the valley folds: a) flat and b) folded configurations. c) 2D design of the origami-based Helmholtz resonator made using oripa software [15]. d) and e) are the 3d design of the origami resonator in the folded and unfolded states, respectively.

driven by the origami structure's high number of degrees of freedom, allowing its cavities to vibrate dynamically under acoustic excitation. Moreover, the wide bandwidth of the origami Helmholtz resonator is highly tunable, enabling greater acoustic control and the ability to cover a larger frequency range with precision. Moreover, while previous works have reported tunable broadband control of Helmholtz resonators through flexible boundaries, to our knowledge, this represents the first reported instance of utilizing an origami-based flexible acoustic design. This design not only achieves broadband control but also enables the primary resonance frequency to cover a significantly extended range. This work builds upon our previous study [19], which explored the initial application of origami design to Helmholtz resonators. While the previous study focused on the performance of the auxetic origami design, this paper introduces several significant advancements. Firstly, we present a comprehensive analysis of broadband acoustic control using a flexible origami-based Helmholtz resonator design, demonstrating enhanced performance across a wider frequency range. Secondly, this study incorporates a detailed experimental validation of the theoretical models, which is not included in the previous work. Additionally, we explore new aspects of the flexible design, such as high tunability. These improvements represent a substantial progression in the development and application of flexible Helmholtz resonators, providing more robust solutions for broadband acoustic control. In essence, the integration of a compliant multi-stiffness structure, featuring flexible folding lines and rigid facets, with the origami cavity shape, has yielded a broad bandwidth effect. Primarily, the origami design, coupled with its inherent compliance, overcomes the traditional limitation of narrow bandwidth in Helmholtz resonators. Furthermore, The resonator's cavity utilizes the waterbomb origami base, renowned for its auxetic properties characterized by a negative Poisson's ratio. This unique property enables simultaneous diameter and length adjustments, resulting in significant volume changes and subsequent frequency shifts for minimal geometric alterations. Given these attributes, these passive-adaptive devices hold the potential to be disruptive in applications requiring sound attenuation in the low-frequency spectrum.

2. Design, Modeling, and Experimental Setup

2.1. Design

The design of the origami Helmholtz resonator draws inspiration from the well-known waterbomb origami base (Fig. 1a-b). This choice is primarily motivated by the waterbomb base's inherent auxetic properties, which confer a negative Poisson coefficient to structures (such as cylinders) based on this origami pattern. Consequently, such structures exhibit optimal volume variation, increasing both length and radius simultaneously. This optimal volume variation translates into significant frequency shifts in Helmholtz resonators with minimal geometrical alterations.

Specifically, the design of the origami cavity comprises three key components, as depicted in Fig. 1c. The primary component is the cylindrical auxetic body, fashioned from the waterbomb origami base. The second component is the top-end piece, facilitating the later attachment of the neck. This design principle mirrors that used by Lee et al. [20] in their work on deformable wheels, where they devised end designs to accommodate shaft addition without compromising foldability. Lastly, for the bottom-end component, we devised a design inspired by the umbrella mechanism, essential for ensuring an airtight cavity in the Helmholtz resonator.

2.2. Materials

The 2D design is crafted from laser-cut PolyEthylene Terephthalate glycol (PETg) sheets, commercially known as Axpet (Exolon Group GmbH, Munich, Germany). Once laser cutting is complete, the 2D design is assembled using Scotch Magic tape adhesive (3M, Minnesota, USA) applied on both sides. Upon folding, the 3D structure is secured together using a flexible glue from Henkel AG & Company, Düsseldorf, Germany. The resonator's neck is 3D printed using Polylactic Acid (PLA) and is also affixed with Henkel's flexible glue. Finally, a flexible coating for airtightness is applied to the origami 3D structure using Plasti Dip from Plasti Dip International, Minnesota, USA.

2.3. Model

The advanced finite element (FE) model described here is designed to capture the 1D acoustic behavior of both conventional and origami-based Helmholtz resonators. It reproduces acoustic tests with consistent boundary conditions, but unlike simpler models, it represents the resonator walls as thin shell structures. Flexible shells model the folding lines, while more rigid shells represent the structural facets. The Johnson-Champoux-Allard equivalent fluid model is utilized to account for both viscous and thermal dissipations in the resonator's neck and the constrictions in the origami valleys. A genetic algorithm is employed to optimize the varying dissipation parameters. Given the complexity of the vibro-acoustic phenomena, numerical simulations are validated solely against experimental results. The model leverages symmetry, allowing only an eighth of the device to be modeled, which significantly reduces computation time during parameter identification. For further details, refer to Section II of the supplementary materials.

2.4. Fabrication and Experimental Setup

This study delves into the acoustic characteristics of an origami-based Helmholtz resonator employing compliant edges. Illustrated in Fig. 1 and Movie S1, the proposed origami design serves dual purposes: structurally, flexible edges facilitate tunability through folding and unfolding; acoustically, they enhance properties beyond mere tunability, aiming to broaden the resonance bandwidth in the low-frequency spectrum a central objective of this investigation. Fabricated from PolyEthylene Terephthalate glycol (PETg) sheets via laser cutting, the origami resonator incorporates compliant multi-material facets and edges-composed of two distinct materials-to achieve its desired properties. Following manual folding, an elastic coating is applied to ensure an airtight cavity, referred to as “flexible Helmholtz resonator” (as depicted in Fig. 2). Additional insights into the design, laser cutting process, and overall fabrication procedure can be found in the supplementary material, Section I. Following the fabrication of the flexible origami resonator (refer to Fig. 2), a series of acoustic tests is conducted to evaluate its acoustic absorption performance. The tests employed an impedance tube and a one load two-microphone technique, as described in ASTM standard [21]. Subsequently, the resonator is positioned backward, as depicted in Fig. 3, with a 10 mm gap between the resonator and the tube’s end wall. Different diameters are utilized to fold the resonator into varying states, adjusting the middle section of the origami cavity accordingly, with ring diameters ranging from 74 to 64 mm.

3. Results

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The experimental outcomes deviated significantly from conventional Helmholtz resonator expectations, represented by the rigid and quasi-rigid origami resonators. While these results are not discussed here due to their divergence from the study’s focus, they serve as a baseline for comparison with the flexible Helmholtz resonator. Further details regarding the rigid and quasi-rigid origami resonators and their outcomes can be found in our previous work [19].

In contrast, the flexible resonator exhibited pronounced peaks of acoustic absorption in the low-frequency range with a broad bandwidth, as illustrated in Fig. 4. Moreover,

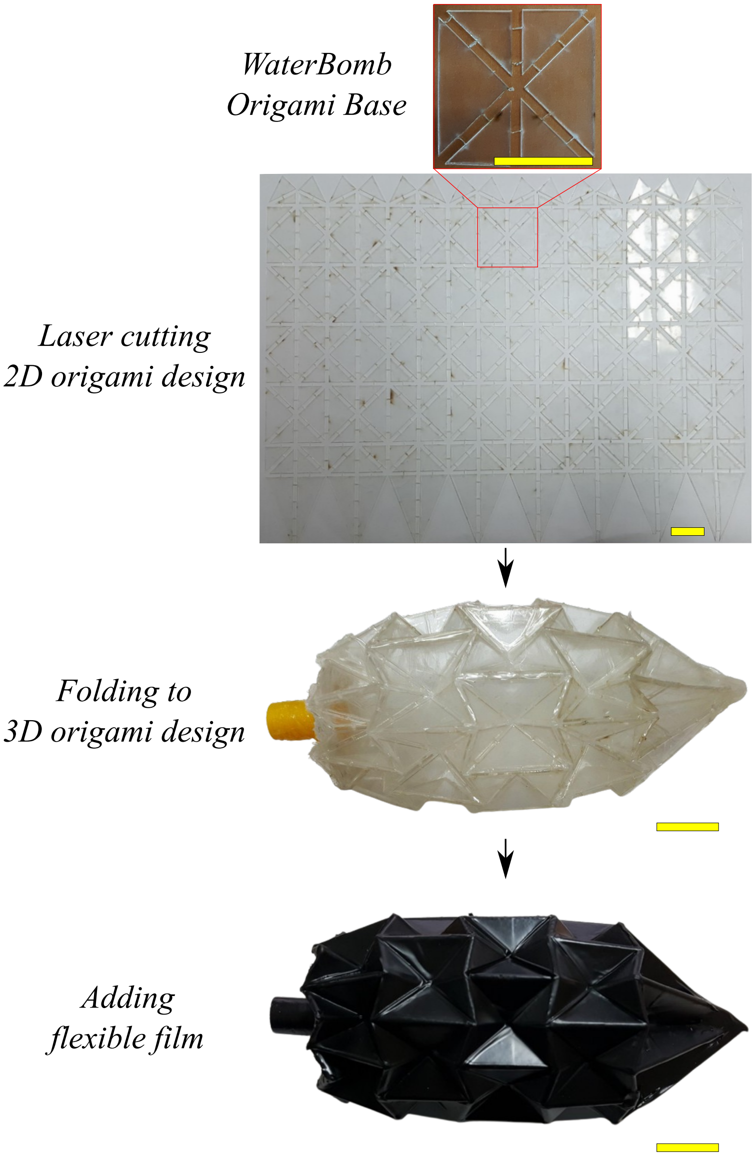

Figure 2. Fabrication process of the tunable broadband origami-based HR. The basic unit of the 2D design is made of the waterbomb base, which gives it its auxetic properties (minimal geometrical variation for maximum, volumetric variation). A CO_2 laser cutter is used to cut the 2D design from 0.5 mm thick PETg sheet. Thin layers of adhesive film are used to hold the structure temporarily during folding. Next, a 3D printed PLA neck is glued to the folded structure. Lastly, thin flexible coating ($\approx$ 0.2 mm thick) is sprayed on top of the structed to hold the faced together as well as to make the structure airtight. Scale bars = 20 mm.

it is observed that the resonance frequency decreased as the cavity volume increased, as anticipated. Notably, despite sharing similar geometrical properties in terms of neck and cavity with the quasi-rigid resonator, the flexible resonator tended to occupy the higher end of the low-frequency domain, unlike the quasi-rigid and rigid resonators.

Furthermore, the flexible resonator demonstrated a frequency shift of its peak absorption from 431 Hz to 544 Hz, amounting to a 26% shift compared to the lowest frequency

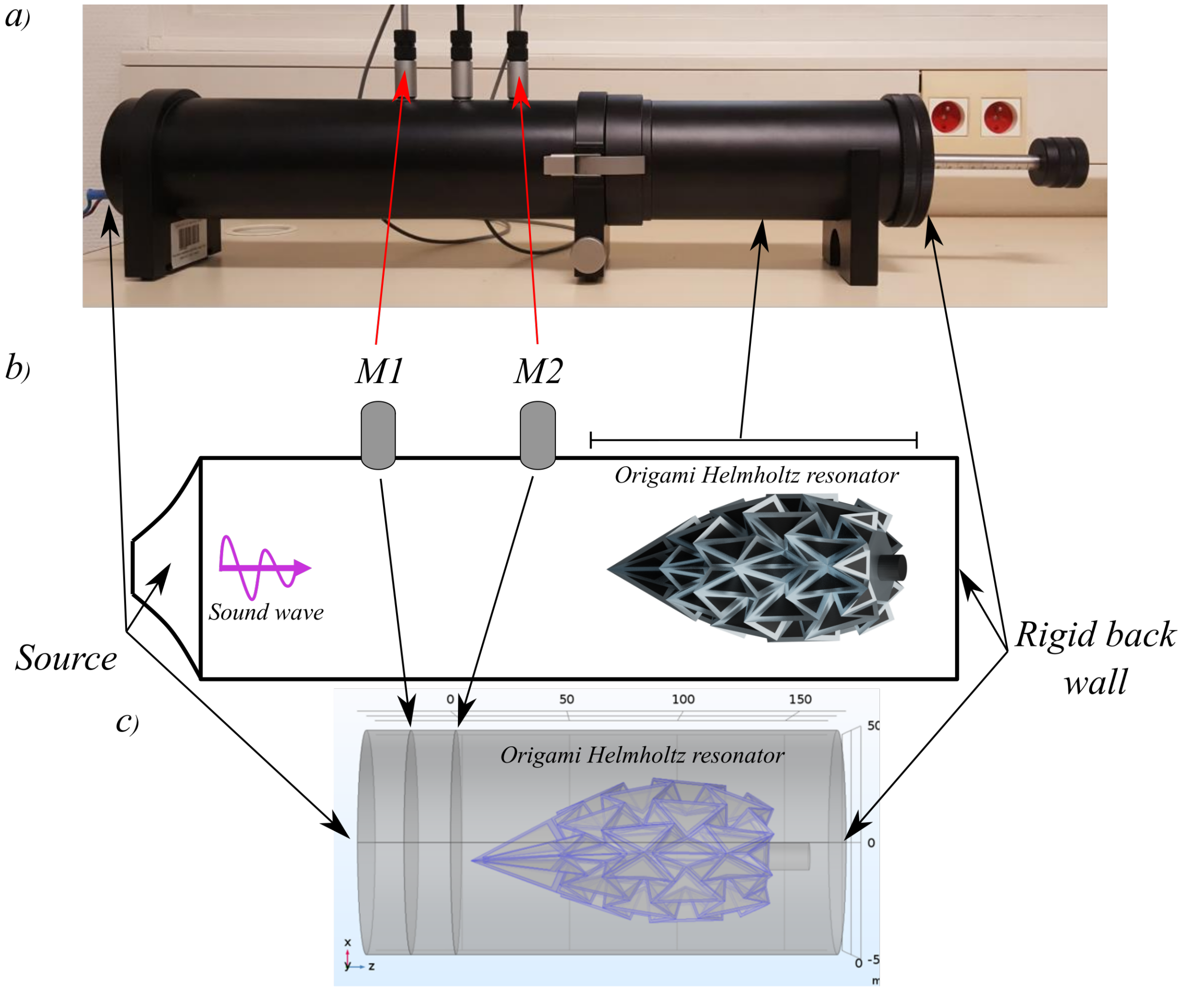

Figure 3. Experimental setup of the one load, two microphone technique [21], where the origami-based Helmholtz resonator is placed inside the impedance tube in backward position. The impedance tube contains a sound source (loudspeakers) at one end, while two microphones, referred to as 'M1', 'M2' are used to act as probes, and measure the acoustic pressure. a), b), and c) are an image of the experimental setup, its schematics, and the boundary conditions for the FE model, respectively.

point. Additionally, frequency shifts of 116, 169, and 213 Hz were observed, with average bandwidths of 47, 63, and 124 Hz for absorption rates of 95%, 90%, and 80%, respectively.

4. Discussion

A multi-physics FE model is employed to simulate the behavior of the flexible origami resonator. This model integrates two distinct aspects of the device: its acoustic performance, akin to traditional Helmholtz resonators, and its mechanical behavior, which significantly influences the overall performance of the flexible origami resonator. In terms of acoustic behavior, a one-load two-microphone technique [21] is applied, incorporating appropriate boundary conditions. Thermo-viscous losses in the neck

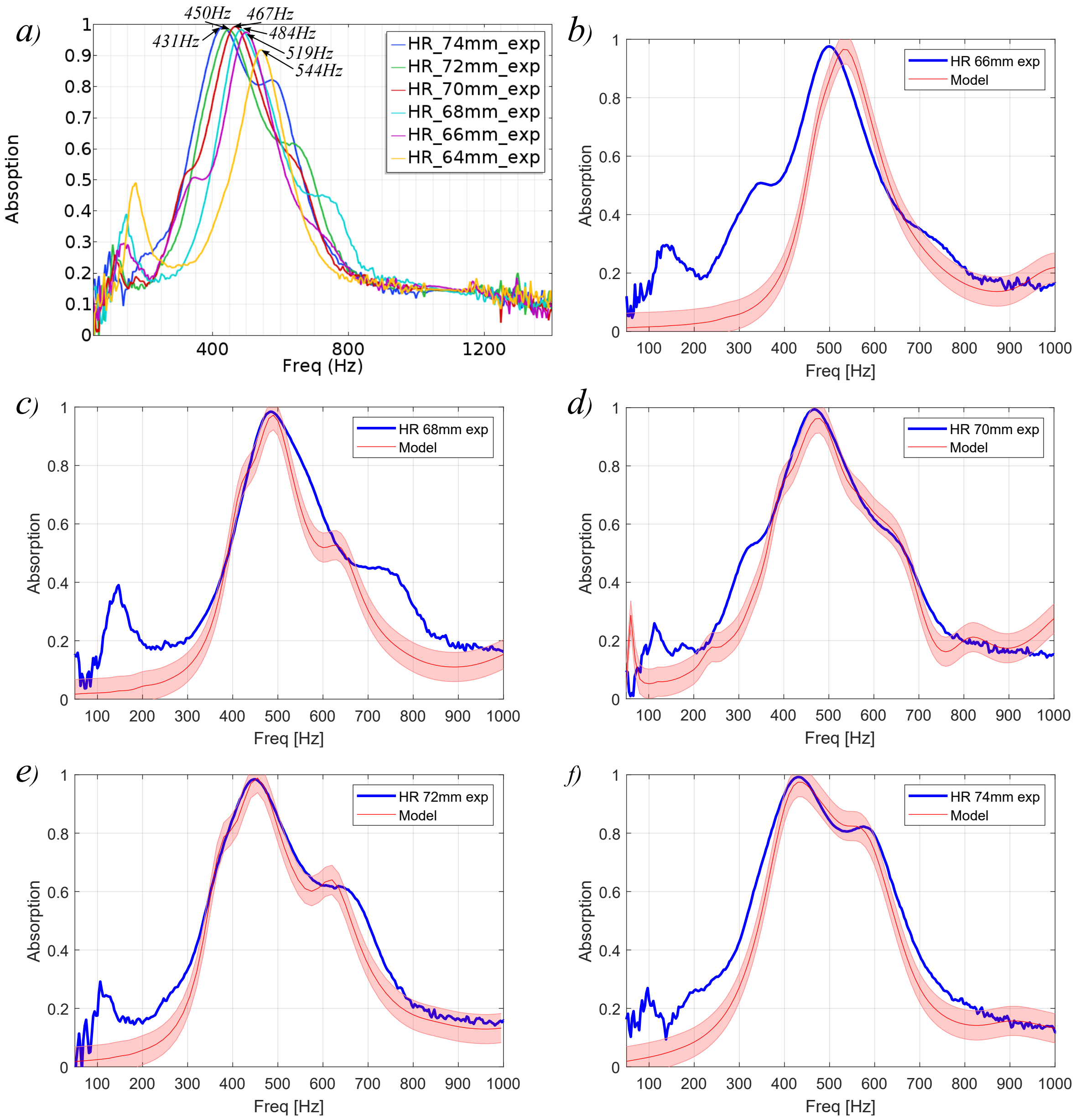

Figure 4. Comparison between the experimental results of the acoustic performance (acoustic absorption) of a flexible origami Helmholtz resonator and the corresponding FE model. a) Experimental results. Comparison between the experimental results and the model for resonator diameter openings of b) 66mm, c) 68mm, d) 70mm, e) 72mm, and f) 74mm.

and cavity are characterized using a Johnson-Champoux-Allard model. Regarding mechanical behavior, instead of assuming acoustically rigid walls for the cavity and neck, they are treated as shell structures, representing thin mechanical elements. In this scenario, the origami 3D design is divided into two components: rigid faces and flexible edges, as depicted in Figure 1. Each component is assigned appropriate material properties. The FE model, coupled with a genetic algorithm, is utilized to determine the parameters of the model, such as airflow resistivity for this structure. The model demonstrates good agreement with experimental findings, as illustrated in Figure 4. This model serves as a valuable tool for comprehending and optimizing the properties of the flexible origami resonator. Further elaboration on the FE model, its implementation, and parameterization is provided in Section II of the supplementary material.

In response to the demand for adaptive-passive noise control solutions, this study introduces, models, fabricates, and empirically assesses a flexible origami Helmholtz resonator. The flexible origami-based cavities in the Helmholtz resonator enhance its performance by introducing multiple degrees of freedom. This design allows dynamic response to acoustic excitation, with the origami structure adapting and vibrating to broaden the effective frequency range. This flexibility enables precise tuning, where small adjustments in cavity dimensions significantly impact resonance frequencies, resulting in high noise control. During experimental validation, the flexible origami resonator demonstrated a notable broad bandwidth effect, averaging 47 Hz for an acoustic absorption rate of 95%. Additionally, it exhibited a peak tunability of 11.3 Hz per mm. In contrast, the quasi-rigid resonator described in a previous study [19] exhibited a narrower bandwidth (less than 5 Hz) and a tunability of 4.1 Hz per mm.

The impact of flexible edge stiffness is investigated using the FE model, as illustrated

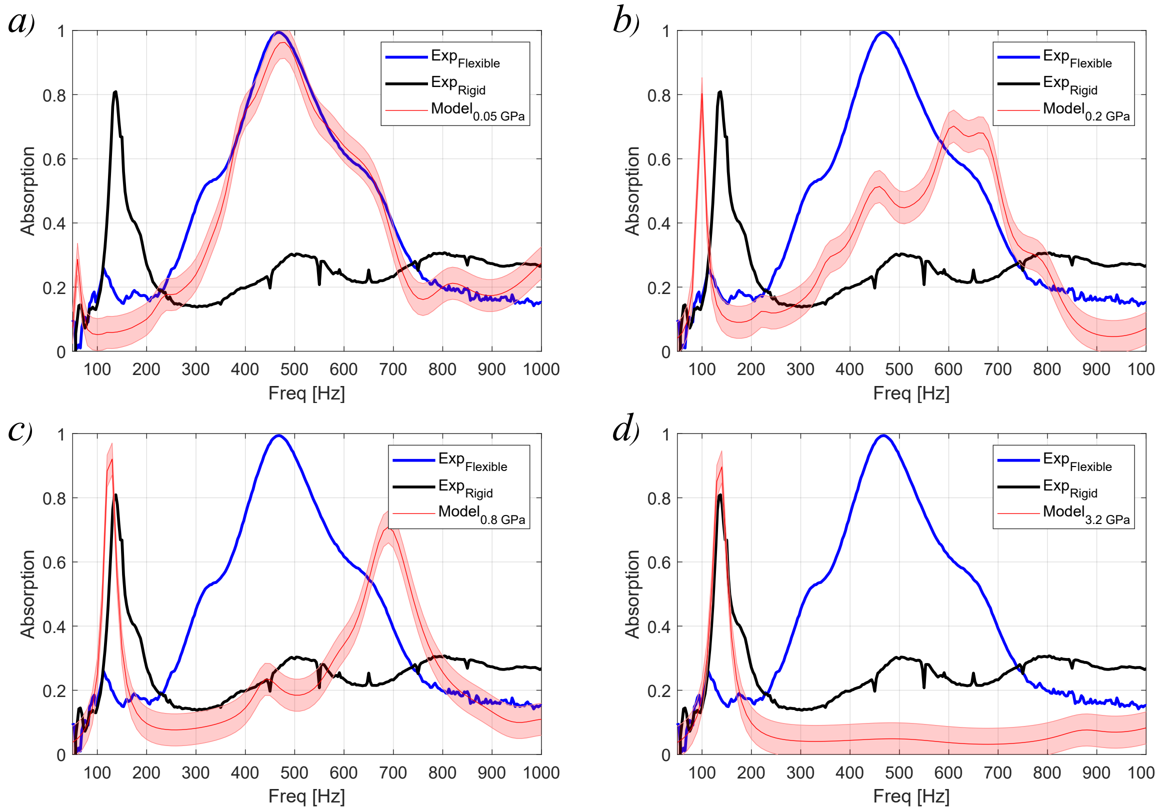

Figure 5. Comparison between FE model and experimental results for a 70mm diameter origami resonator. Transitioning from flexible edges to rigid edges (with stiffness equivalent to the facets) of the origami Helmholtz resonator, starting from edge stiffness values of: a) 0.05 GPa, b) 0.2 GPa, c) 0.8 GPa, to d) 3.2 GPa.

in Figs. 5, S2 and S3. The study encompasses a range of edge rigidities, spanning from flexible (reflecting their actual properties) to rigid (matching the rigidity of the facet, thereby transforming into a single-material resonator). Essentially, Figs. 5 demonstrates the transition from a flexible origami Helmholtz resonator (with rigid facets and flexible edges) to a rigid origami resonator (where facets and edges are made from the same material) using the FE model. Initially, sound attenuation is dominated by the flexible origami cavity. As the edges become more rigid, attenuation by the resonator neck becomes prominent, evolving into the primary mechanism for sound control, similar to traditional Helmholtz resonators.

Initially, the study reveals that as stiffness increases, the broad bandwidth associated with the resonator shifts towards higher frequencies before eventually vanishing in the medium frequency range. Simultaneously, a narrow peak bandwidth emerges, with its magnitude amplifying in the low end of the low-frequency spectrum.

Movie S2 showcases the transition from the flexible origami resonator (characterized by broad bandwidth) to the quasi-rigid origami resonator (with narrow bandwidth), maintaining identical geometrical properties and folding diameter (70 mm). This transition is elucidated by the behavior of the small cavities within the origami design, which initially function as subsystems, vibrating to absorb acoustic energy and collectively generating the broad bandwidth effect. However, with increasing stiffness, there is reduced vibration among the subsystems, akin to the effect of folding, ultimately resulting in a stiffer system. Once the edges reach the rigidity level of the facets, the transition is complete, and the resonator operates predominantly through the neck, akin to traditional Helmholtz resonators. Consequently, the model demonstrates good alignment with quasi-rigid resonator outcomes (refer to Fig. S2).

Notably, for a folding diameter of 70 mm and an 80% acoustic absorption rate, the bandwidth initiates at 123 Hz and diminishes with increasing stiffness until stabilizing at less than 15 Hz (see to Fig. S3). For further insights, refer to supplementary materials, Section III.

Ultimately, the flexible origami resonator represents a groundbreaking advancement in low-frequency noise control, offering genuine passive operation while retaining tunability if necessary. It stands out as an exceptionally effective solution for noise control, especially in the realm of acoustics.

5. Conclusion

In essence, this study presents an innovative approach to broaden the bandwidth of tunable Helmholtz resonators. Overcoming the longstanding limitations of traditional Helmholtz resonators, our method combines auxetic origami-based design with a compliant multi-material structure. This novel system not only expands the design possibilities for tunable Helmholtz resonators but also holds promise for adaptive-passive acoustic devices in general. Through adjustments in origami design, dimensions, and mechanical properties—such as material stiffness—we can precisely define and control the position, bandwidth, and tunability of origami-based Helmholtz resonators. Our proposed system achieves an average bandwidth of 47 Hz for 95% acoustic absorption, along with a peak tunability of 113 Hz (from 431 to 544 Hz) for a mere 10 mm diameter variation, equivalent to 11.3 Hz per mm. Furthermore, our future endeavors will focus on integrating smart materials, such as shape memory alloys (SMA) [22] or shape memory polymers (SMP), to actuate these acoustic systems. Preliminary investigations into the actuation mechanism and its outcomes are detailed in Section IV of the supplementary material, along with Movies S3 and S4. Lastly, acoustic systems based on compliant origami hold the potential to disrupt the realm of low-frequency acoustics, offering new avenues for designing and implementing adaptive-passive noise control devices.

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References

[1] H. Von Helmholtz, On the Sensations of Tone as a Physiological Basis for the Theory of Music, Longmans, Green, 1912.

[2] E. S. Webster, C. E. Davies, The use of helmholtz resonance for measuring the volume of liquids and solids, Sensors 10 (12) (2010) 10663–10672.

[3] J. S. Anderson, M. Bratos-Anderson, Noise: Its measurement, analysis, rating and control, Gower Technical, 1993.

[4] M. L. Munjal, Acoustics of ducts and mufflers with application to exhaust and ventilation system design, John Wiley & Sons, 1987.

[5] R. L. Panton, J. M. Miller, Resonant frequencies of cylindrical helmholtz resonators, The Journal of the Acoustical Society of America 57 (6) (1975) 1533–1535.

[6] R. Chanaud, Effects of geometry on the resonance frequency of helmholtz resonators, Journal of Sound and Vibration 178 (3) (1994) 337–348.

[7] U. Ingard, On the theory and design of acoustic resonators, The Journal of the acoustical society of America 25 (6) (1953) 1037–1061.

[8] J. M. De Bedout, Adaptive-passive noise control with self-tuning helmholtz resonators, Ph.D. thesis, Purdue University (1996).

[9] J. M. de Bedout, M. A. Franchek, R. J. Bernhard, L. Mongeau, Adaptive-passive noise control with self-tuning helmholtz resonators, Journal of Sound and Vibration 202 (1) (1997) 109–123.

[10] X. Yu, Z. Lu, F. Cui, L. Cheng, Y. Cui, Tunable acoustic metamaterial with an array of resonators actuated by dielectric elastomer, Extreme Mechanics Letters 12 (2017) 37–40.

[11] A. Abbad, N. Atalla, M. Ouisse, O. Doutres, Numerical and experimental investigations on the acoustic performances of membraned helmholtz resonators embedded in a porous matrix, Journal of Sound and Vibration (2019) 114873.

[12] A. Abbad, K. Rabenorosoa, M. Ouisse, N. Atalla, Adaptive helmholtz resonator based on electroactive polymers: modeling, characterization, and control, Smart Materials and Structures 27 (10) (2018) 105029.

[13] Z. Yan, F. Zhang, J. Wang, F. Liu, X. Guo, K. Nan, Q. Lin, M. Gao, D. Xiao, Y. Shi, et al., Controlled mechanical buckling for origami-inspired construction of 3d microstructures in advanced materials, Advanced functional materials 26 (16) (2016) 2629–2639.

[14] K. Hu, T. Jeannin, J. Berre, M. Ouisse, K. Rabenorosoa, Toward actuation of kresling pattern-based origami robots, Smart Materials and Structures 31 (10) (2022) 105025.

[15] J. Mitani, Oripa (origami pattern editor), available at: http://mitani. cs. tsukuba. ac. jp/floripa (2005).

[16] S. S. Nudehi, G. S. Duncan, U. Farooq, Modeling and experimental investigation of a helmholtz resonator with a flexible plate, Journal of vibration and acoustics 135 (4) (2013) 041102.

[17] M. H. Kurdi, G. Scott Duncan, S. S. Nudehi, Optimal design of a helmholtz resonator with a flexible end plate, Journal of vibration and acoustics 136 (3) (2014) 031004.

[18] Z. Lu, Y. Cui, J. Zhu, M. Debiasi, A novel duct silencer using dielectric elastomer absorbers, in: Electroactive Polymer Actuators and Devices (EAPAD) 2014, Vol. 9056, SPIE, 2014, pp. 658–670.

[19] A. Benouhiba, P. Rougeot, N. Andreff, K. Rabenorosoa, M. Ouisse, Origami-based auxetic tunable helmholtz resonator for noise control, Smart Materials and Structures 30 (3) (2021) 035029.

[20] D.-Y. Lee, J.-S. Kim, S.-R. Kim, J.-S. Koh, K.-J. Cho, The deformable wheel robot using magic-ball origami structure, in: ASME 2013 international design engineering technical conferences and computers and information in engineering conference, American Society of Mechanical Engineers, 2013, pp. V06BT07A040–V06BT07A040.

[21] A. E-1050, Standard test method for impedance and absorption of acoustical materials using a tube, two microphones and a digital frequency analysis system (2012).

[22] K. Hu, K. Rabenorosoa, M. Ouisse, A review of sma-based actuators for bidirectional rotational

motion: application to origami robots, Frontiers in Robotics and AI 8 (2021) 678486.