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AN ORIGAMI-BASED TUNABLE HELMHOLTZ RESONATOR FOR NOISE CONTROL: INTRODUCTION OF THE CONCEPT AND PRELIMINARY RESULTS

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ABSTRACT

A Helmholtz resonator is a passive acoustic device that enables noise reduction at a given frequency. This frequency is directly related to the volume of the resonator and to the size of the neck that couples the resonator to the acoustic domain. In other words, controlling the volume of the cavity allows a real time tunability of the device, which means noise control at any desired frequency. To that end, we propose an Origami-based tunable Helmholtz resonator. The design is inspired from the well-known origami base, waterbomb. Such foldable structures offer a wide range of volume shifting which corresponds to a frequency shifting in the application of interest. The foldability of the structure is first investigated. Then, a series of numerical simulations and experimental tests were preformed are presented, in order to explore the capabilities of this origami structures in acoustic control. A shift in the frequency domain of up to 197 Hz (131-328 Hz) was achieved in an experimental testing using 3D printed rigid devices.

NOMENCLATURE

f_r The natural frequency of Helmholtz resonator.
c_0 The speed of sound in the fluid (usually air).
λ The sound wave length.
r_n The radius of the resonator's neck.
l_n The length of the resonator's neck.
l'_n The effective length of the resonator's neck.
A The cross-section of the resonator's neck.
δ Both exterior and interior ends correction.
r_c The radius of the resonator's cavity.
l_c The length of the resonator's cavity.
V The volume of the resonator's cavity.
k The length of the folding line.

INTRODUCTION

In acoustic control applications, two different methods are used. Passive noise control techniques and active noise control techniques [1]. First, passive noise control, and there are two ways for doing it: (i) the use of porous materials, which has broadband effect, but limited in amplitude, and whose effectiveness in low frequency is directly related to the thickness of the material. Or, (ii) Helmholtz resonator (a cavity with an opening and a neck), which is very effective in amplitude but has a very narrow frequency bandwidth. Furthermore, thanks to the high impedance produced by the cavity and the neck of Helmholtz resonators, The attenuation of the incident acoustic wave is attained [2]. Consequently, they are widely utilized as passive noise control devices, such as : ventilation silencers in both air

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conditioning and ventilation systems [3]. Their noise reduction ability made them the subject of study of numerous researchers and scientists [4–9]. One advantage of using Helmholtz resonators is their simplicity [10]. Moreover, unlike active devices they do not require additional energy, so the possibly of such devices to create noise rather than reducing it, is nil. On the other hand, active noise control is achieved by introducing a canceling wave (180^{o} out of phase "antinoise" wave) through an appropriate array of secondary sources [1]. The main advantage of active techniques over the passive ones is the implicit adaptability of the control system to changing excitations [10]. Since, the attenuation by Helmholtz resonator is only limited to a single narrow bandwidth [11], which corresponds to the natural frequencies of the resonator. Nonetheless, the frequency is controlled by the geometrical proprieties of the resonator [5, 6, 12]. Therefore, controlling the geometry of the device (such as the volume of the cavity), means controlling the frequency at which noise reduction is desired. Following this line of reasoning, creating an adaptive Helmholtz resonator is a valid option. There are several works in the literature that address this subject. Lamancusa et al [13], proposed a cylindrical shaped Helmholtz resonator with piston instead of the bottom wall of the cavity. The piston is needed, to adjust the volume of resonator's cavity, thus, its frequency. de Bedout et al [10] describes a cylindrical cavity made of two parts. The first part is the top end plate, the sidewall of the cylinder and an interior wall goes from the center of the cylinder to the sidewall (they called the fixed wall). The second part is the end bottom plate and another interior wall similar to the first one (the moving wall). The two interior walls (as well as the two parts) joint in the center of the cylinder, creating two separate volumes inside the cylindrical cavity. One of them has a small opening with a neck, which will act as a neck for the Helmholtz resonator. The bottom end plate is attached to a DC motor. Turning the bottom end plate turns the interior wall attached to it and changes in the process the ratio of two volumes, which shifts the natural frequency of the resonator to an appropriate value.

However, the problem with such systems is their weight, which make them unsuitable for a wide range of applications. Such as: noise reduction devices for aircrafts and automobile exhaust systems. Not to mention their complexity. Abbad et al [14, 15], proposed a new concept of a tunable Helmholtz resonator, where the top plate of the cylindrical resonator was replaced by a membrane of an Electro-Active Polymer (EAP). Their objective is to use a well-located spring to direct the deformation of the membrane caused by an applied Electric field. In other words, causing a shift in the resonators volume by changing its length. Nevertheless, the influence of the length of the resonator on its volume is still modest, compared to the influence of its radius. So, to create a significant shift in the volume (as well as in the natural frequency) of the resonator, the length of the resonator has to be greatly changed. As a result, the concept becomes somewhat limited. For this reasons, we propose the concept of the origami-based tunable Helmholtz resonator. A resonator that can be folded and unfolded gradually, thus, extensively changing the volume of its cavity, as well as, its natural frequency respectively. The main advantages of using an origami-based structure (beside its foldability), aree: the possibility of passing from a 2D fabricated structure towards a 3D functioning system, great deformation and significant volume variation. Lately we can find quite a number of origami-based structures in the literature. Onal et al [16], discussed the fabrication of a 3D robot actuated by shape memory alloys (SMA), starting from 2D polymer sheet patterned using a CO_2 laser cutter. Lee et al [17, 18], described the fabrication of a robot with deformable wheels, so it can adapt to different terrains and overcome various obstacles. The design of the wheels was based on a well-known origami pattern called waterbomb. Tolley et al [19], detailed the development of Self-folding origami, by using a shape memory composites activated by uniform heating. To meet their objective, a shape memory polymer sandwiched between two structural layers (which are made of paper) was used. Finally, Miyashita et al [20], talked about a remotely controlled Miniature Origami Robot (via an alternating external magnetic field) that Self-folds, Walks, Swims and Degrades, after accomplishing its task.

In this paper, a tunable Helmholtz resonator using the origami base, waterbomb, is presented. The origami pattern allows the somewhat cylindrically shaped resonator, to change its radius. Therefore, great shifts in volume can be accomplished, which is still true in the frequency range. Furthermore, the tunable resonator is made of a single sheet of material. Thus, it is far from being a complicated concept with a lot of moving parts. Since, using various parts, tend to be very limited in more ways than one (fabrication, assembly and actuation). The waterbomb base was already adopted by previous works, and for different applications. Kuribayashi et al [21], used the base to make a Self-deployable origami stent grafts from a SMA NiTi foil, for biomedical applications. Onal et al [16] used it for the realization of worm-like robot with a SMA actuation as well. And recently, Lee et al [17] adopted the origami base in their work, regarding the deformable wheels, already discussed above.

The aim of the paper is to propose a new concept, for tunable Helmholtz resonators. First, we present our 2D origami-based design that can be folded in 3D Helmholtz resonator (closed cavity with an opening and a neck). Next, the fold-ability of the resonator is tested and presented. Then, a numerical investigation, using finite element methods (FEM) simulations, is conducted and presented as well. Furthermore, using iron transmission tube, 3D printed rigid resonators, for different states of the folding are tested. The results (acoustic transmission loss) are compared to the 3D FEM simulation model, and then both presented. Finally some perspectives about the fabrication of the foldable resonator and its actuation are given.

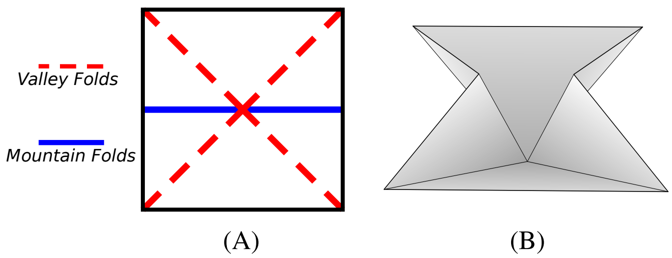


FIGURE 1. THE WATERBOMB ORIGAMI BASE, THE BLUE LINES FOR THE MOUNTAIN FOLDS AND THE RED ONES FOR THE VALLEY FOLDS (A) FLAT AND (B) FOLDED CONFIGURATIONS.

TABLE 1. A LIST OF VARIABLES.

Variables	Value	Unit
c_0	343	$m.s^{-1}$
r_n	6	mm
l_n	20	mm
r_c	30	mm
l_c	70	mm
k	34	mm

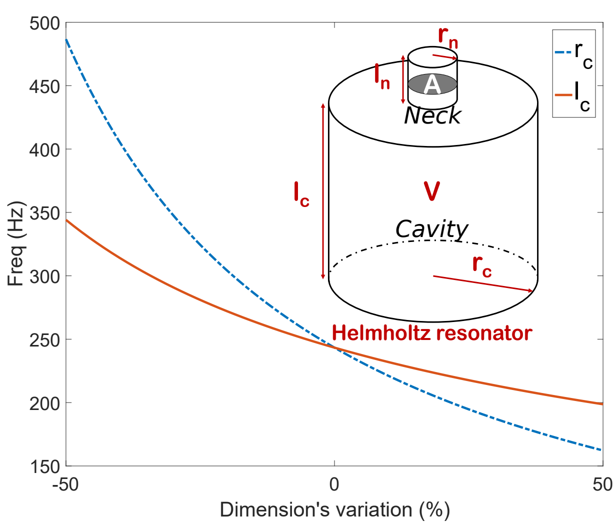


FIGURE 2. COMPARISON BETWEEN THE INFLUENCE OF THE RADIUS AND THE LENGTH OF A CYLINDRICAL CAVITY OF HELMHOLTZ RESONATOR ON ITS THEORETICAL NATURAL FREQUENCY.

CONCEPT

The concept take the shape of a number of steps. The first step is: to find the right design. Although, it can be quite challenging, considering that it should fold into a Helmholtz resonator (an origami-based closed cavity with an opening and a neck). Secondly, testing the fold-ability of the device. keeping in mind, a Helmholtz resonator made of a 2D design, doesn't guarantee that its cavity can be folded and unfolded gradually. Simply put, the fold-ability of an origami-based Helmholtz resonator is its ability to change progressively the volume of its cavity by folding, while still completely closed, except of its neck. Finally, there is the acoustic properties of the resulted device, which can be estimated using FEM simulations. Conducting the following steps properly, insures at a high degree, the fabrication of a functioning origami-based tunable Helmholtz resonator.

Design

The analytical model for calculating the natural frequency of a cavity resonator with a circular neck, was first developed by Hermann von Helmholtz [22]:

$$f_r = \frac{c_0}{2\pi}\sqrt{\frac{A}{l_n V}} \tag{1}$$

However, the Eqn. (1) does not fully agree with the experiment. The measured frequency is less than the predicted value. This was first observed by Lord Rayleigh [23], who proposed an effective neck length, $l'_n = l_n + \delta$, in which a correction was added to the physical neck length to account for ends effect. Further refinements have been made by a number of authors, which also account for different resonator geometries, including the ends effect: see, Ingard et al [12], Alster et al [24], Panton et al [5] and Chanaud et al [6]. As a results, for $\lambda >> r_n$:
Effective increase of the neck length at the cavity $\approx \frac{8r_n}{3\pi} \approx 0.85r_n$.
Effective increase of the neck length at the open end $\approx 0.61r_n$.
Which means that: $l'_n = l_n + 1.46r_n$. Thus, Eqn. (1) will be as such:

$$f_r = \frac{c_0}{2\pi}\sqrt{\frac{A}{l'_n V}} \tag{2}$$

Based on the analytical model Eqn. (2), the resonance frequency is controlled by altering the dimensions of the Helmholtz resonator, being it those of the neck, the cavity or both. Thereby, Tuning the resonator so it can cover a large frequency domain, is just a matter of adjusting the parameters of the neck and the cavity. Therefore, the design of choice must take full advantage of this fact. The design was inspired form the well-known origami base, waterbomb (Fig. 1). The reasons for choosing the waterbomb as an origami base for the design, lies in basic logic of: the bigger the shift in volume is, the wider the frequency band covered by the resonator. So, if the cavity is a cylinder, it would be better to find a design that allows the change in its radius. Since, the radius has more influence on the volume of a cylinder than its length, as shown in Fig. 2, made using the variables of Table 1. Therefore, the waterbomb base, which respects this line of reasoning is suited for an origami-based tunable Helmholtz resonator.

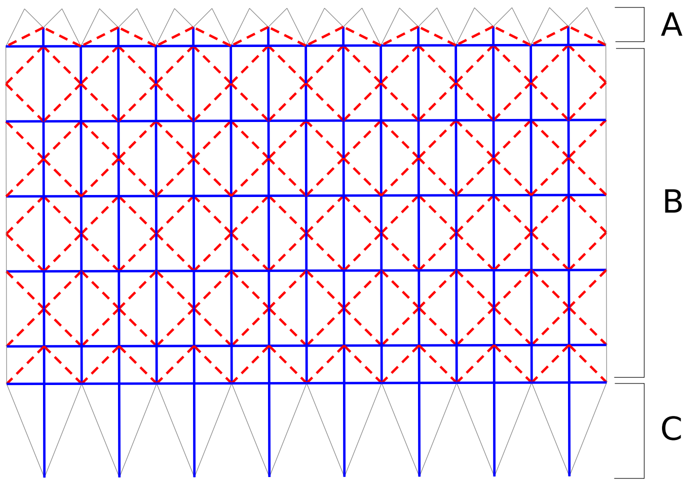


FIGURE 3. THE DESIGN OF THE ORIGAMI-BASED HELMHOLTZ RESONATOR WE MADE USING THE ORIPA SOFTWARE [25] (A) TOP END PART (B) CYLINDRICAL PART (C) BOTTOM END PART.

However, the waterbomb-based cylinder (Fig. 3.B) needs two upgrades to be called a Helmholtz resonator. First, our novel design comprises a top end part (Fig. 3.A) that allows the attachment of the neck later on. The principal used was the same as lee's et al [17] for their deformable wheels. They needed a way to add the shaft for their wheels. So, they came up with a design for both their ends, that allows the addition of the shaft without compromising the fold-ability of the wheels. Secondly, we added a bottom end part (Fig. 3.C), which was inspired from the mechanism of the umbrella. As it is required for a Helmholtz resonator to have a closed cavity.

Fold-ability

Now that the design was established, it is time to construct the Helmholtz resonator and test its fold-ability. For that purpose, an origami design software called Freeform [26] was used. The software is based on rigid origami simulation. It basically uses all the folding lines (mountain or valley, depending on the desired direction of the folding) of the predefined design as actuators for the folding. Moreover, it utilizes the crease angles of all

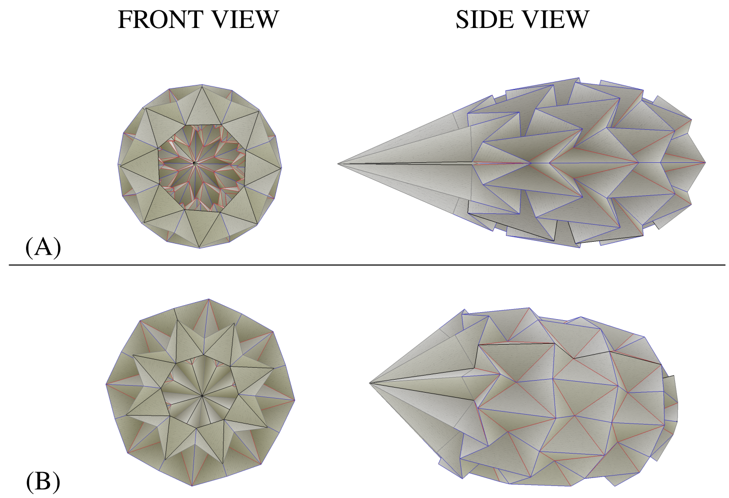


FIGURE 4. THE ORIGAMI-BASED TUNABLE HELMHOLTZ RESONATOR CONSTRUCTED USING FREEFORM (A) FOLDED (B) AND UNFOLDED STATES.

the folding lines as variables to represent configurations of the origami model. Therefore, unlike other origami design software, it is possible to simulate intermediate state of folding, which is required when gradual folding is needed (like in this case). In addition, the software is very flexible when it comes to the design, it allows the user to add and adjust folding lines (change the type: mount, valley or passive lines) during the folding simulation. That way, he can better understand his design and improve on it if needed. Furthermore, Freeform also provides a smooth and comprehensible interactive animation, from a 2D crease pattern to the 3D folded origami model. So testing the fold-ability of a device (origami model) with it is possible (as shown in Fig. 4). As for testing the fold-ability of the origami-based Helmholtz resonator, the 2D cease pattern of the folding lines (which was made according to the design) was first folded to the 3D structure (resonator). Then, the constraints on the model were added (the same constraints as a real resonator would have: a closed cavity and an undeformable zone to add the neck). Next, a folding attempt is made, first to test the fold-ability of the structure (to see if the structure folds or not). And also to obtain, the folded state (the maximum folding the structure can achieve under this constraints) and the unfolded state (the minimum folding the structure can achieve under this constraints).

Acoustic properties simulation

Instead of constructing the device and testing, if it is really adoptable to the application of question (noise attenuation), which is easier said than done. It would be better to create a 3D FEM simulation model for its different folding states, and simulate its acoustic proprieties (specifically speaking: acoustic transmission loss). To that end, A FEM multiphysics soft-

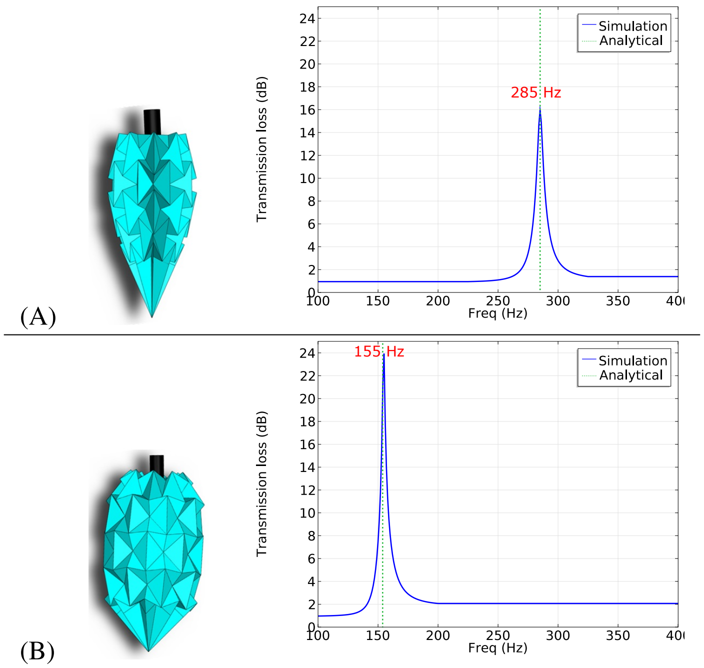
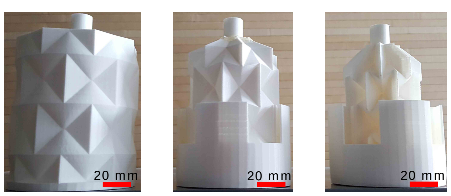


FIGURE 5. COMPARISON BETWEEN SIMULATION AND ANALYTICAL RESULTS OF THE (A) FOLDED (B) AND UNFOLDED STATES.



(A) (B) (C)

FIGURE 6. 3D PRINTED RIGID STRUCTURES OF ORIGAMI-BASED HELMHOLTZ RESONATORS (A) FOLDED (B) HALF-FOLDED (C) AND UNFOLDED .

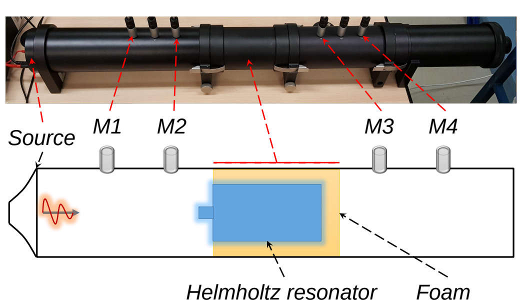
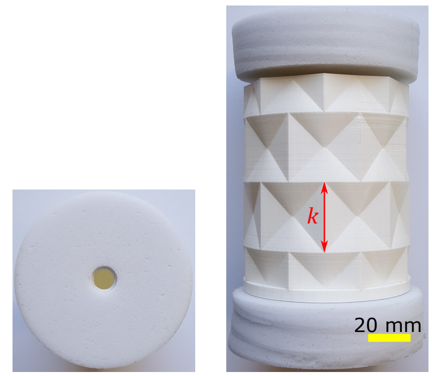


FIGURE 7. EXPERIMENTAL SETUP FOR THE ACOUSTIC ATTENUATION SYSTEM, HELMHOLTZ RESONATOR COMBINED WITH MELAMINE FOAM.



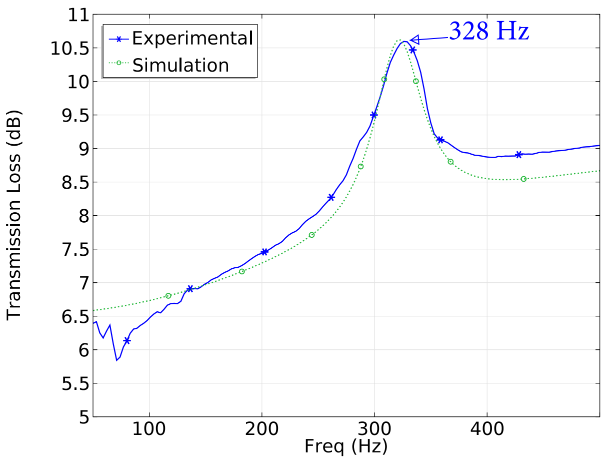
(A) (B)

FIGURE 8. ACOUSTIC ATTENUATION SYSTEM, HELMHOLTZ RESONATOR COMBINED WITH MELAMINE FOAM (A) FRONT VIEW AND (B) SIDE VIEW.

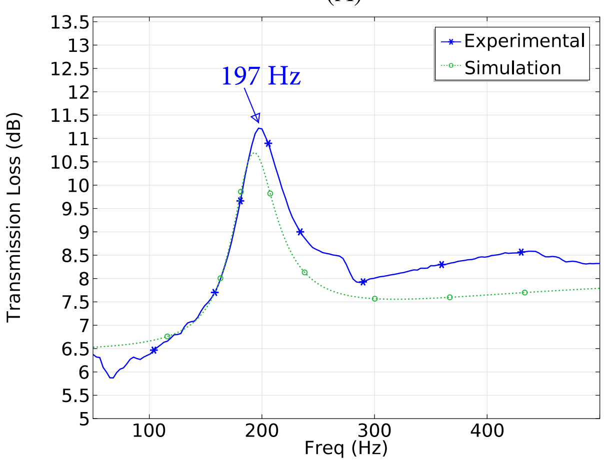
ware was utilized. The resonators were coupled with a melamine foam. A Johnson-Champoux-Allard equivalent fluid model was used to simulate the melamine foam behavior and the viscous loss in the neck [27]. Helmholtz resonators are usually used for low frequency noise reduction. While, foams are better for handling the high frequency end. Hence, coupling the two will result in a better system for noise control. The couple was integrated into a tube (called transmission tube). One of the tube's ends was replaced with a sound source in order to generate acoustic plane waves (called inlet in the model). The other end was selected as a outlet. The chosen frequency band for the study is 50-500 Hz (a low frequency range). Next, the physics was established (incident acoustic plane wave with a pressure of 1 Pa). Then, the model was meshed with the appropriate size mesh (which depends on the used frequency band). Finally, the study was launched, and the results can be seen in Fig. 5. The results are given in form of the acoustic Transmission loss by the frequency. The Transmission loss is the incident acoustic power (the power in the inlet), minus the acoustic power transmitted through the system (outlet), and it is specified in dB. The transmission loss, quantifies how efficient is our system, in noise reduction.

RESULTS AND DISCUSSION

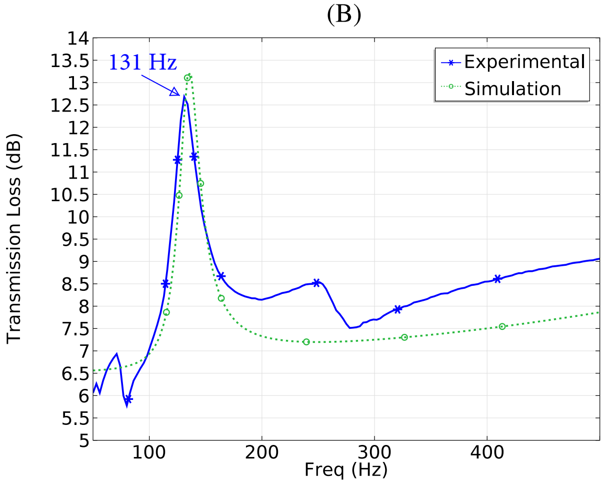
Just as a proof of concept, 3 rigid structures of 3 different states of folding (folded, hlaf-folded and unfolded) were 3D printed (see Fig. 6). Then, an experiment in a iron Transmission tube was mounted. As discussed above, a sound source was added to one end of the iron tube (loudspeakers). In addition, Four microphones, referred to as "M1", "M2", "M3" and "M4" were also add to act as probes, and measure the acoustic pressure inside the tube (as shown in Fig. 7). Finally, the sample (3D printed Helmholtz resonator combined with the melamine foam, same as above) was add in order to calculate the Transmission



(A)



(B)



(C)

FIGURE 9. COMPARISON BETWEEN EXPERIMENTAL AND SIMULATION RESULTS OF (A) FOLDED (B) HALF-FOLDED (C) AND UNFOLDED STRUCTURES.

Loss of the system.
The first thing to do was, to investigate the best configuration of the foam. The foam configuration has to respect two condition: (i) it can be combined the 3 different printed structures (folded, hlaf-folded and unfolded) of the resonator. (ii) The system has to generat attenuation peaks with at least 10 dB of amplitude (the amplitude found in the literature [28]). The investigation was handled by the trial and error technique, and the results (the most effective configuration found) can be seen in Fig. 8. Finally, a series of experimental test, were done of the different states of the resonator, and the results (as shown in Fig. 9) were compared to the adjusted simulation model (a model which takes into account the new configuration of the foam).

The results of the Fig. 9 show that the 3D printed structure produce a shift in the frequency domain of almost 200 Hz (131 Hz to 328 Hz). Also, while achieving a noise attenuation more than 10 dB. Comparing this results with those of the structures made by freeform (Fig. 5), where only a shift of 130 Hz (155-285 Hz) was produced, there is a difference of 70 Hz (equal to 35% difference). However, that is what to be expected, since the 3D printed structures(Fig. 6) are considered somewhat a perfect foldabe cylinder. Meaning, that it unfolds completely into a cylinder, and in the same time it folds to the point where it can not be folded anymore, which is unrealistic (the fold-ability is not considered here). On the other hand, the structures made by freeform (Fig. 4) have a limited folding/unfolding, thanks to both its top and bottom end parts. The parts needed so that the structure can have a the fold-ability, while allowing it to keep the classic form of a Helmholtz resonator (a closed cavity with an opening and a neck). From the 70 Hz difference in the produced results, there is 20 Hz (10%) lost in the unfolding (the difference between the unfolded 3D printed structure, Fig. 9.C and the unfolded freeform structure, Fig. 5.B), which is not all that bad, considering that it is compared to an almost perfect cylinder. Moreover, 50 Hz (25%) this time were lost in the folding (the difference between Fig. 9.A and Fig. 5.A). The big difference in the frequency shift, is mostly due to the top end part. The resonator has to keep a big rigid opening (for the neck to be added) while being folded. Thereby, its folding is very limited. One way to optimize the design: the top end part must be replaced, so that the rigid opening is as small as possible.

CONCLUSION

During this study, the concept of making use of the intermediate folding states of the origami structures was established. Unlike the classic origami structures where only the folded and unfolded states matter (have a functionality), here every folding state between the two, act as Helmholtz resonator. As a results, the advantages offered by such structures were fully exploited.
Also, a 2D Origami design that can be transformed in 3D tun-

able Helmholtz resonator, was introduced and validated. Furthermore, a fold-ability with sufficient volume variation (a one that can generate a shift of atleast 100 Hz in the frequency range, the same as the ones found in the literature [10,28]) was proved using Freeform. Finally, 3D FEM simulation model of the system (the couple: resonator, plus the foam) was likewise established and validated using experimental testing of 3D rigid origami structures. All and all, a concept that starts from making an origami design, all the way to simulating the behavior of the resulted origami structure in the designated field of application, was established and validated.
As for the future work, the first step would be to upgrade the simulation model, so it will take into account the forces needed for the folding of the origami structure. Then, investigating the best way to fabricate a foldable structure. Either, by using bi-material 3D printing or by machining 2D sheet of martial. Finally, figuring out a way to integrate the actuators, been it SMA actuators or EAP actuators.

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REFERENCES

[1] Kuo, S. M., and Morgan, D. R., 1999. “Active noise control: a tutorial review”. *Proceedings of the IEEE,* ***87***(6), pp. 943–973.
[2] Allard, J., and Atalla, N., 2009. *Propagation of sound in porous media: modelling sound absorbing materials 2e*. John Wiley & Sons.
[3] Chen, K., Chen, Y., Lin, K., and Weng, C., 1998. “The improvement on the transmission loss of a duct by adding helmholtz resonators”. *Applied Acoustics,* ***54***(1), pp. 71–82.
[4] Tang, P., and Sirignano, W., 1973. “Theory of a generalized helmholtz resonator”. *Journal of Sound and Vibration,* ***26***(2), pp. 247–262.
[5] Panton, R. L., and Miller, J. M., 1975. “Resonant frequencies of cylindrical helmholtz resonators”. *The Journal of the Acoustical Society of America,* ***57***(6), pp. 1533–1535.
[6] Chanaud, R., 1994. “Effects of geometry on the resonance frequency of helmholtz resonators”. *Journal of Sound and Vibration,* ***178***(3), pp. 337–348.
[7] Dickey, N., and Selamet, A., 1996. Helmholtz resonators: one-dimensional limit for small cavity length-to-diameter ratios.
[8] Selamet, A., and Lee, I., 2003. “Helmholtz resonator with extended neck”. *The Journal of the Acoustical Society of America,* ***113***(4), pp. 1975–1985.
[9] Tang, S., 2005. “On helmholtz resonators with tapered necks”. *Journal of Sound and Vibration,* ***279***(3), pp. 1085–1096.
[10] De Bedout, J. M., 1996. “Adaptive-passive noise control with self-tuning helmholtz resonators”. PhD thesis, Purdue University.
[11] Lane, S. A., and Huybrechts, S., 2001. “Coupled helmholtz resonators for acoustic attenuation”. *Journal of Vibration and Acoustics*.
[12] Ingard, U., 1953. “On the theory and design of acoustic resonators”. *The Journal of the acoustical society of America,* ***25***(6), pp. 1037–1061.
[13] Lamancusa, J. S., 1987. “An actively tuned, passive muffler system for engine silencing.”.
[14] Abbad, A., 2016. Numerical investigations on a tunable helmholtz resonator: Integration of a passive polymer membrane in a helmholtz resonator. Tech. rep., SAE Technical Paper.
[15] Abbad, A., Rabenorosoa, K., Ouisse, M., and Atalla, N., 2017. “Investigations on an electroactive polymer based tunable helmholtz resonator”. In SPIE Smart Structures and Materials+ Nondestructive Evaluation and Health Monitoring, International Society for Optics and Photonics, pp. 101640P–101640P.
[16] Onal, C. D., Wood, R. J., and Rus, D., 2011. “Towards printable robotics: Origami-inspired planar fabrication of three-dimensional mechanisms”. In Robotics and Automation (ICRA), 2011 IEEE International Conference on, IEEE, pp. 4608–4613.
[17] Lee, D.-Y., Kim, J.-S., Kim, S.-R., Koh, J.-S., and Cho, K.-J., 2013. “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, pp. V06BT07A040–V06BT07A040.
[18] Lee, D.-Y., Kim, J.-S., Park, J.-J., Kim, S.-R., and Cho, K.-J., 2014. “Fabrication of origami wheel using pattern embedded fabric and its application to a deformable mobile robot”. In Robotics and Automation (ICRA), 2014 IEEE International Conference on, IEEE, pp. 2565–2565.
[19] Tolley, M. T., Felton, S. M., Miyashita, S., Aukes, D., Rus, D., and Wood, R. J., 2014. “Self-folding origami: shape memory composites activated by uniform heating”. *Smart Materials and Structures,* ***23***(9), p. 094006.
[20] Miyashita, S., Guitron, S., Ludersdorfer, M., Sung, C. R., and Rus, D., 2015. “An untethered miniature origami robot that self-folds, walks, swims, and degrades”. In Robotics and Automation (ICRA), 2015 IEEE International Conference on, IEEE, pp. 1490–1496.
[21] Kuribayashi, K., Tsuchiya, K., You, Z., Tomus, D., Umemoto, M., Ito, T., and Sasaki, M., 2006. “Self-deployable origami stent grafts as a biomedical application of ni-rich

tini shape memory alloy foil". *Materials Science and Engineering: A, **419***(1), pp. 131–137.

[22] Helmholtz, H. v., 1860. "Theorie der luftschwingungen in röhren mit offenen enden.". *Journal für die reine und angewandte Mathematik, **57***, pp. 1–72.

[23] Rayleigh, J., 1945. The theory of sound,(1945).

[24] Alster, M., 1972. "Improved calculation of resonant frequencies of helmholtz resonators". *Journal of Sound and Vibration, **24***(1), pp. 63–85.

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

[26] Tachi, T., 2010. "Freeform origami". *TSG, University of Tokyo College of Arts and Sciences, Komaba, Tokyo, Japan available at: http://www.tsg.ne.jp/TT/software/.*

[27] Doutres, O., Atalla, N., and Osman, H., 2014. "Modeling and experimental validation of cellular porous material with large resonant inclusions". In Inter-noise and noise-CON Congress and conference proceedings, Vol. 249, p. 122.

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