# PASSIVE EQUALIZER WITH VARIABLE RESONATOR RINGS FOR MUSICAL INSTRUMENTS

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**Abstract**
Resonators are used in a variety of commercial applications to reduce or accentuate specific frequencies (e.g., acoustic absorbers, musical instruments). For most of these devices, however, the fixed geometry does not allow to variably tune the frequency response. Here we propose a device composed of multiple resonators, each mechanically tunable and in the shape of a hollow ring with variable internal volume. Together, the resonators modify the tonal content of a soundwave passing through a cylindrical pipe in similar way to a passive audio equaliser, without the need for electrical current. In this preliminary study, we use a finite element method model to analyze the propagation through the pipe with different ring configurations. We highlight the interactions between multiple rings sequentially and compare simulations with measurements. Finally, we discuss how similar devices can be used in the music industry.

**Keywords:** Equaliser, metamaterials, musical, instruments.

## 1 Introduction

Resonators are used in various commercial applications related to the reduction or selective accentuation of specific frequencies (silencers for car mufflers, acoustic absorbers, musical instruments) [15]. In the fields of sound reproduction devices and musical instruments, the concept of resonance is fundamental for the generation and control of the tonalities emitted [7]. Such characteristics are usually determined by the size, structure, and shape of the sound box of the instrument. Electronic equalizers also allow to change specific frequencies during recording and production or to intervene on unwanted audio signals inside music studios. However, traditional solutions as such often require the use of electricity; are bulky in size and heavy; or they are also expensive and prone to components failure.

The use of acoustic metamaterials for the absorption or manipulation of resonant frequencies has been the subject of countless studies in recent years. Various solutions with geometries smaller than the wavelengths have been considered, many of which exploit internal local resonances: e.g., Helmholtz resonators [4], Fabry-Perot resonators [10], perforated gradient structures [3]. For this reason, they offer much desired innovation to the creative industry. The fixed geometry of such devices however does not allow the sound emissions to be flexibly tuned to specific frequency bands [26].

In this document we propose an acoustic meta-structure consisting of a serial chain of tunable resonators (Figure 1) that allows to modify the tonal content of an acoustic beam passing through a cylindrical section tube. The purpose of this device is to intervene on the output signal in a manner like an electronic passive equalizer [10]. The introduction of tunable resonant elements aims at passively varying the flexibility of the equalization settings produced by an instrument, sound, or a speaker to control its tonal emission.
Firstly, we run simulation models with ring geometries with different diameters (60 and 90 mm) to how the AMT structure reduces an acoustic wavefront passing through cylindrical sections of different sizes. Finally, we measured the AMT performance in a solid model through a laboratory test and compared it to an identical simulation finding good agreement between the simulation and the experimental results.

Figure 1: The tunable resonator described in this study, applied to an acoustic guitar sound hole.

## 2 Model design

Extensive academic research has been focusing in recent times on creating innovative acoustic materials to increase broadband absorption while reducing geometrical footprint and weight [2],[5],[11],[12],[13],[20],[26]. Traditional porous materials have a high absorption coefficient due to viscous dissipation near the material surface and heat conduction through solids. However, such dissipation is a quadratic function of frequency and weakens at low frequencies [9]. By exploiting local resonances, acoustic metamaterials (AMMs) can be designed to obtain near-perfect absorption at subwavelength scales: however, the results are generally narrow band in nature [1],[2],[4],[12],[13].
In this work, we apply some of the learned lessons to the conceptual design of a product, with the aim of estimating how to manufacture innovative solutions to be introduced into the music audio sector at a later stage [7],[8]. Specific aspects such as underlying physics [22], complexity of the geometrical structure [24], intended and potential applications, manufacturing techniques, theoretical modelling [18],[19],[23], testing methodology and experimental results were analyzed. This exercise identified a passive equalizer (EP) as a first potential product.

The EP was performed using Sketchup Pro 2020 (Figure 1). Despite being inspired by previous solutions ([1],[2],[4],[10],[11]) the geometry of the EP presents some innovations:

1. The annular resonator's volume can be easily modified, varying the resonance frequency in real time or with preset settings.
2. A choice of interactive disks can be used to change the overall effect on the emitted frequency bands.

The internal volume of each ring's resonance chamber can also be varied, if needed, stacking multiple modules into a single ring structure, therefore increasing the overall internal height by multiples of a single ring. The preliminary study aims to optimize dimensions and sound reduction values related to the range of frequencies considered. The planar section of the EP can be seen in Figure 2. The orange dotted insert highlights:

1. The passage opening between the central section of the ring and the resonator.
2. The fixed internal partition of the resonator.

In the blue solid insert one can see the movable partition, the rotation of which in relation to the fixed partition allows to change the volume of the chamber at intervals of ten degrees between 10 and 350 degrees.

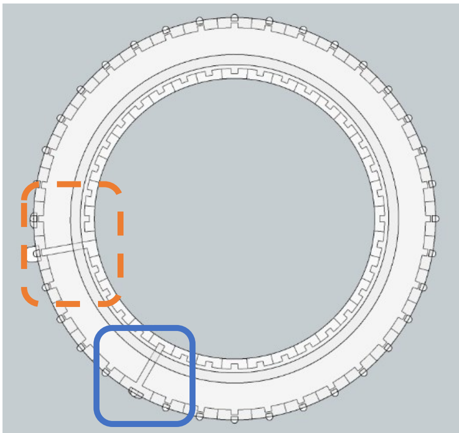

Figure 2: Plan section of the EP showing the fixed partition (blue solid line) and the fixed partition with the adjacent resonator opening (dotted orange line).

# 3 SIMULATIONS

## 1.1 Single ring model - 60 mm internal diameter

A single ring model was created for an initial simulation using COMSOL Multiphysics 5.5 Acoustics module (Figure 3). The sections constituting the central cylindrical opening, the volume of the resonator and the inlet passage of the resonator were assigned to the sound pressure physics in the frequency domain. Hard boundaries were set at the interface between the object and the air surfaces.

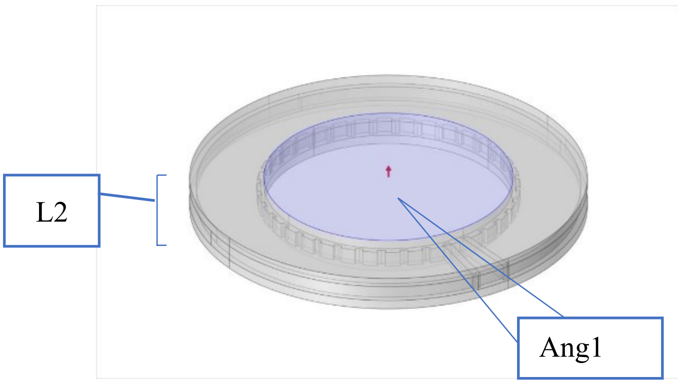


Figure 3: COMSOL model showing a port at the upper output surface of a single resonator ring.

The model was converted to a mesh with elements of maximum size λ_min/6 (where λ_min is the shortest wavelength used in the simulation). Thermo-viscous physics were disregarded in this simulation. The AMT's transmission loss values (TL) were calculated, using inlet and outlet ports, as a function of the movable partition at 10 deg intervals rotation (Ang1 parameter), for frequencies between 40 and 5000 Hz at intervals of 1/24 octaves. The resulting TL peaks for individual frequency/Ang1 combinations can be seen in Figure 4. This simulation showed that for certain specific frequency there is at least one position of maximal effect. The study was replicated by assigning variable parameter values between 1 and 8 mm to the resonator height parameter L2. The overall results of the parametric study, highlighted by the graph in Figure 5, suggest excellent potential between 1.6/2 kHz with L2 = 5 mm to be confirmed with experimental results on prototypes.

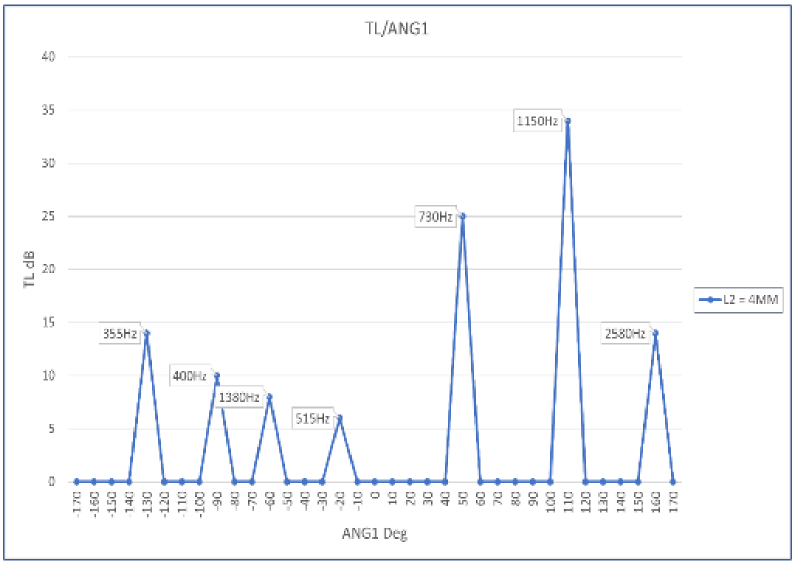


Figure 4: TL value peaks at relative frequencies with fixed height parameter L2 = 4 mm

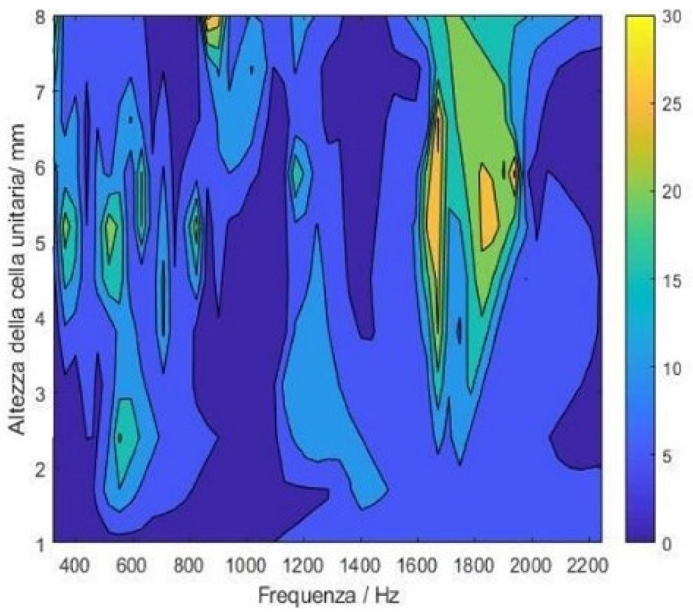


Figure 5: TL values (0-30 dBs) with parameter L2 (resonator's height) between 1 and 8 mm (Y axis) and parameter Ang1 between -170 and 170 degrees (not shown)

## 1.2 Double ring 90 mm internal diameter

It was then decided to manufacture a prototype for experimental testing and compare the results with an identical model simulation. To simulate the average dimensions of an acoustic guitar sound hole, a 90 mm diameter dimensions was chosen for the internal air passage cylinder. The Sketchup 2020 Pro layout (Figure 6) was turned into a solid object using a 500 mm long acrylic pipe section with 90 mm internal diameter to channel the emission of a car speaker model JVC CSJ520X speaker sound source through the AMT central opening. A base with slotted supports was manufactured using a laser cutter, preventing the test system from moving; a double ring metamaterial composed of three 3d printed plastic parts, externally sealed with adhesive acoustic tape. To guarantee acoustic leakage-free results, acoustic tape was also attached to the metamaterial's pipe connectors faces, the interface between the acrylic pipe and the supports, the gap between the enclosure and the speaker mounting plate.

### 1.2.1 Experimental Test

An omni-directional microphone (1/2'' free field, model Norsonic, type 1201/30323) was attached to a 3d-printer adapted for noise mapping and used to scan the acoustic sound pressure levels (SPL) generated by the speaker through the AMT. Received signals were acquired using a Picoscope 2200b and acquisition software developed for the purpose. An arbitrary wavefront generator (AWG) was used to generate a 20 μs square pulse source signals, recorded with a resolution of 0.7 μs for 5.7 ms. A program compiled in Matlab was developed to compute the transfer function between the measurements.
To limit the rear dipolar transmission effects, the speaker was enclosed with a box utilizing internal metabricks [21] (Figure 6). We measured a SPL difference of 33 dBs at 6 kHz between the cylinder outlet front and the rear of the metamaterial enclosure using a calibrated DIGI++ Analyzer app. The test was run positioning the microphone at 10 mm along the Y axis centered on the metamaterial outlet, at frequencies between 300 Hz and 20 kHz. Results with and without the metasurface were compared to obtain TL values generated at the AMT outlet level.

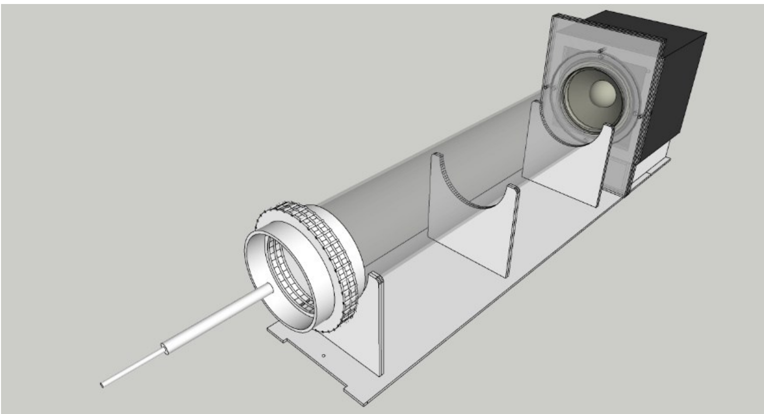

Figure 6: Experimental test layout, showing the speaker, the enclosure, the pipe, the AMT, and the microphone locations.

The AMT's internal partition were set in the A/J configurations shown on Table 1. The resonators inlet passages relative locations can be seen in Figure 7, while the individual rings Ang = 0 deg reference points are shown in Figure 9. It can be noted that, as the angle between the two inlet passages changes accordingly to the Ang1 and Ang2 values, the interaction between the two passages creates a peak resonance at 3114 Hz with Ang2 = 90 deg (blue solid insert in Figure 10).

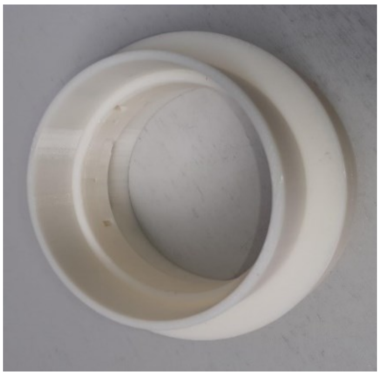

Figure 7:  Resonator rings inlet passages at Ang1 = 90 deg and Ang2 = 90 deg (Table 1/A)

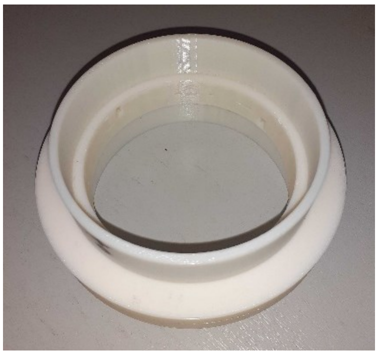

Figure 8: Resonator rings inlet passages at Ang1 = 270 deg and Ang2 = 90 deg (Table 1/F)

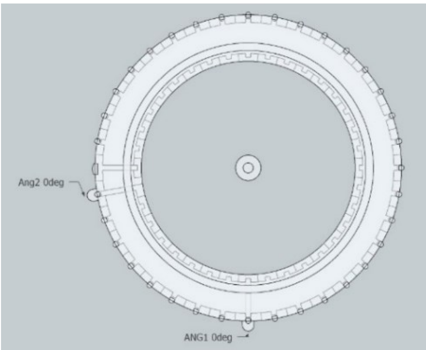


Figure 9: Ang1 and Ang2 0 deg reference positions with Table 1/A values

Table 1

| | ANG2 deg | ANG1 deg |
|---|---|---|
| A | 10 | 90 |
| B | 10 | 180 |
| C | 10 | 270 |
| D | 90 | 90 |
| E | 90 | 180 |
| F | 90 | 270 |
| G | 100 | 280 |
| H | 180 | 90 |
| I | 180 | 180 |
| J | 180 | 270 |

The TL values, indicated in Figure 10, show some indicative results at 778.5 Hz with Ang1 = 270 deg / Ang2 = 90 deg and Ang1 = 90 deg / Ang2 = 10 deg. This result was investigated running a COMSOL simulation on a model with similar geometry (Figure 11): although significantly lower in TL value (1.4 dB against 8 dB), the comparison between the laboratory test and the FEM simulation showed close agreement at 775 Hz.

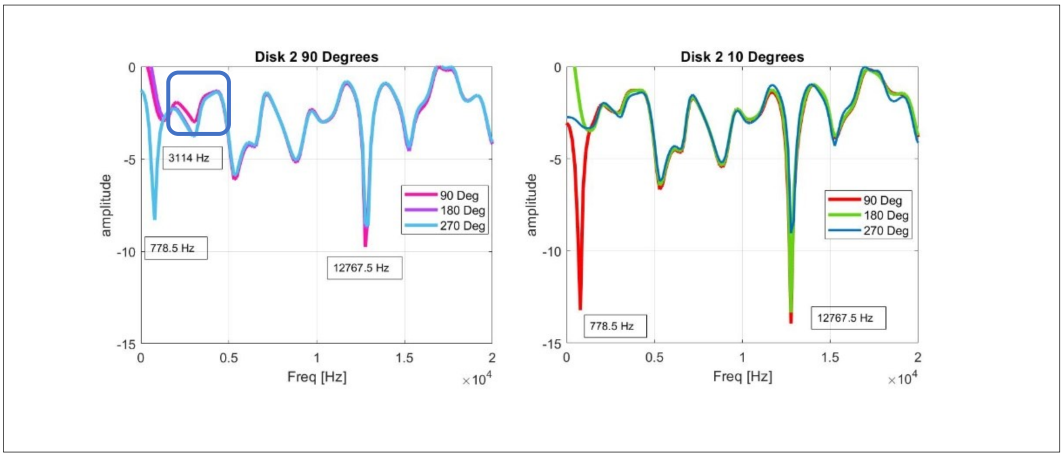


Figure 10: TL dB values with Ang2 = 90 deg and 10 deg, Ang1 = 90/180/270 deg. The blue solid insert indicates different TL values at 3114 Hz with changes in the resonators' inlets relative positions.

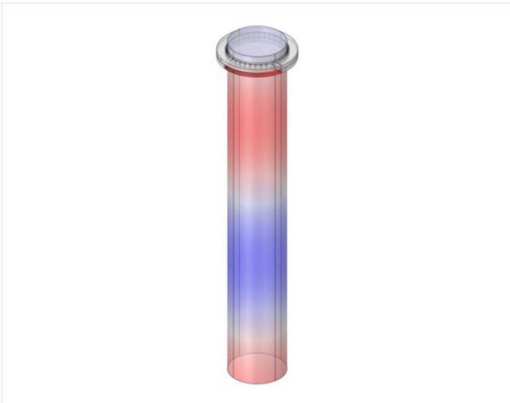

Figure 11: COMSOL model replicating experiment test setup at 775 Hz.

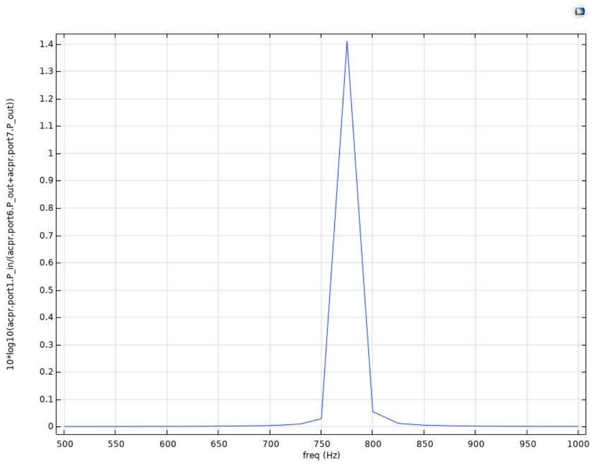


Figure 12: TL value peak at 775 Hz in COMSOL model.

# 4 Conclusions

In this project, we explored how acoustic metamaterials can be incorporated into creative tools used in recording studios and music venues (e.g., music instruments, speakers, amplifiers, stage monitors) to control the frequency range in acoustic instruments, focus or direct their projection and increase their volume, and improving clarity at distance. At present, more complex models are being developed. Further studies will be carried out on multiple disk systems, with elongated wave guide, etc. Combined geometries will be explored in future studies through the incorporation of flexible labyrinthine internal structures, intercommunicating openings, and baffles. The metamaterial structure could potentially be able to intervene on a music instrument or audio speaker output signal in a similar way to a passive audio equalizer without the use of electric current (Figure 13). The interaction between multiple rings with variable parameters would benefit from the creation of an analytical model to allow the optimization of the geometric dimensions used according to the required results in terms of attenuation levels on specific frequencies.

The COMSOL simulations were coherent in terms of transmission loss values, although the results greatly vary between the 60 mm and 90 mm diameter models. This will be the subject of future studies: However, the laboratory comparative test showed reasonable agreement, although the interaction mechanisms between the resonators rings need further investigation.

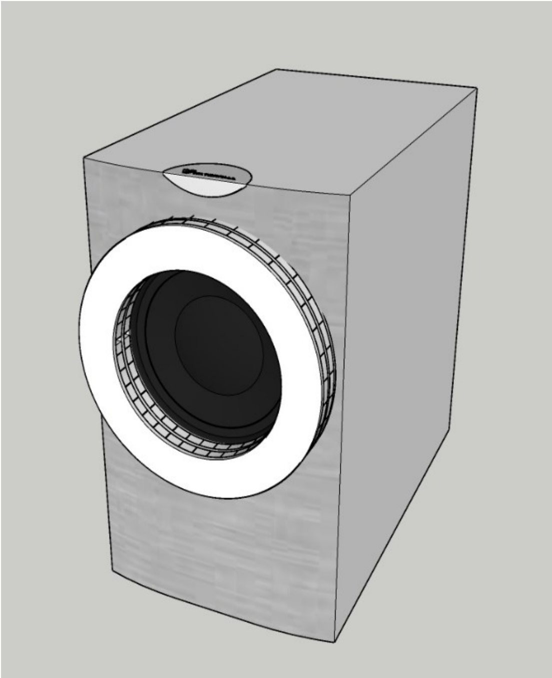

Figure 13

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# 5 Bibliography

[1] Y. Zhu and B. Assouar, “Multifunctional acoustic metasurface based on an array of Helmholtz resonators,” *Physical Review B,* vol. 99, no. 17, p. 174109, 2019.

[2] M. Yang, S. Chen, C. Fu and P. Sheng, “Optimal sound absorbing structures,” *Journal of the Acoustical Society of America,* vol. 32, no. 1, pp. 3575-3575, 2017.

[3] Y. Ye, M. Ke, Y. Li, T. Wang and Z. Liu, “Focusing of spoof surface-acoustic-waves by a gradient-index structure,” *Journal of Applied Physics,* vol. 114, no. 15, p. 154504, 2013.

[4] L. Zhao and S. Zhou, “Compact Acoustic Rainbow Trapping in a Bioinspired Spiral Array of Graded Locally Resonant Metamaterials,” *Sensors,* vol. 19, no. 4, p. 788, 2019.

[5] S. Huang, Z. Zhou, D. Li, T. Liu, X. Wang, J. Zhu and Y. Li, “Compact broadband acoustic sink with coherently coupled weak resonances,” *Chinese Science Bulletin,* 2019.

[6] C. Casarini, B. Tiller, C. Mineo, C. MacLeod, J. F. C. Windmill and J. C. Jackson, “Enhancing the Sound Absorption of Small-Scale 3-D Printed Acoustic Metamaterials Based on Helmholtz Resonators,” *IEEE Sensors Journal,* vol. 18, no. 19, pp. 7949-7955, 2018.

[7] T. Liu, S. Liang, F. Chen and J. Zhu, “Inherent losses induced absorptive acoustic rainbow trapping with a gradient metasurface,” *Journal of Applied Physics,* vol. 123, no. 9, p. 091702, 2018.

[8] S., Degraeve; J., Oclee-Brown, “Metamaterial Absorber for Loudspeaker Enclosures,” *AES 148th Convention, Online,* pp. 1-9, 2020 June 2-5.

[9] M. Planitz, W. H. Press, B. P. Flannery, S. A. Teukolsky and W. T. Vetterling, “Numerical Recipes: The Art of Scientific Computing,” *The Mathematical Gazette,* vol. 71, no. 456, pp. 167-168, 1987.

[10] C. Zhou, B. Yuan, Y. Cheng, Y. Cheng, X. Liu and X. Liu, “Precise rainbow trapping for low-frequency acoustic waves with micro Mie resonance-based structures,” *Applied Physics Letters,* vol. 108, no. 6, p. 063501, 2016.

[11] J. Yang, J. S. Lee, H. R. Lee, Y. J. Kang and Y. Y. Kim, “Slow-wave metamaterial open panels for efficient reduction of low-frequency sound transmission,” *Applied Physics Letters,* vol. 112, no. 9, p. 091901, 2018.

[12] M. R. Stinson, “The propagation of plane sound waves in narrow and wide circular tubes, and generalization to uniform tubes of arbitrary cross-sectional shape,” *Journal of the Acoustical Society of America,* vol. 89, no. 2, pp. 550-558, 1991.

[13] R. Ghaffarivardavagh, J. Nikolajczyk, S. W. Anderson and X. Zhang, “Ultra-open acoustic metamaterial silencer,” *Journal of the Acoustical Society of America,* vol. 145, no. 3, pp. 1726-1726, 2019.

[14] Z. Yifan, F. Shi-Wang, C. Liyun, D. Krupali and B. Assouar, “Acoustic Meta-Equalizer,” *Phys. Rev. Applied,* vol. 14, p. 014038, 2020.

[15] C. Christabel, B. Shubhi, M. Niko and S. Sriram, “Fabricating and Assembling Acoustic Metamaterials and phononic crystals,” *advanced engineering materials,* vol. 23, no. 2, 2021.

[16] “Metamaterials: how can the UK develop successful supply chains and deliver next generation products?,” 2019. [Online]. Available: https://ktn-uk.co.uk/news/metamaterials-how-can-the-uk-develop-successful-supply-chains-and-deliver-next-generation-products.. [Accessed Metamaterials: how can the UK develop successful supply chains and deliver next generation products? 1 2020].

[17] N., Jiménez; V., Romero-García; V., Pagneux; J.-P., Groby, “Rainbow-trapping absorbers: Broadband, perfect and asymmetric sound absorption by subwavelength panels for transmission problems,” *Scientific Reports,* no. 7, 2017.

[18] J. W. Creswell, Research Design, Thousand Oaks: SAGE Publications, 2014.

[19] O. Quevedo-Teruel, C. Hongsheng, D.-R. Ana, G. Gurkan, G. Anthony, M. Gabriele, M. Enrica, M. Stefano, E. George V, C. Michael, Z. Nikolay, P. Nikitas and C. Sajid, “Roadmap on metasurfaces,” *Journal of optics,* vol. 21, no. 7, 2019.

[20] N., Jiménez; W., Huang; V., Romero-García; V., Pagneux; J.-P., Groby, “Ultra-thin metamaterial for perfect and quasi-omnidirectional sound absorption,” *AIP,* vol. 109, no. 12, 2016.

[21] G., Memoli; L., Chisari; J.P., Eccles; M., Caleap; B.W., Drinkwater; S., Subramanian, “Vari-Sound:a varifocal lens for sound,” in *CHI 2019*, Glasgow, 2019.

[22] D. W., Herrin, “Vibro-Acoustic Design in Mechanical Systems,” [Online]. Available: http://web.engr.uky.edu/~dherrin/ME510_Old/Chapter_10_6_Slides.pdf. [Accessed 7 3 2021].

[23] M. Gianluca, C. Mihai, A. Michihiro, S. Deepak R, D. Bruce W and S. Sriram, “Metamaterial bricks and quantization of metasurfaces,” *Nature Communications,* vol. 8., no. a14608, 2017.

[24] M. Yang and P. Sheng, “Sound Absorption Structures: From Porous Media to Acoustic Metamaterials,” *Annual Review of Materials Research,* vol. 47, no. 1, pp. 83-114, 2017.

[25] E., Redon; A., Dhia; S. Bonnet-Ben; J.-F., Mercier; S., Poernomo, “Non-reflecting boundary conditions for acoustic propagation in ducts with acoustic treatment and mean flow,” *International Journal for Numerical Methods in Engineering,* vol. 86, no. 11, pp. 1360-1378, 2011.

[26] Y. Li, Y. Li, S. Qi, S. Qi and M. B. Assouar, “Theory of metascreen-based acoustic passive phased array,” *New Journal of Physics,* vol. 18, no. 4, p. 043024, 2016.