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3D Labyrinthine-type Acoustical Metamaterial Proposals for Sound Control in Architectural Applications

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ABSTRACT

The purpose of this research is to develop alternative 3D labyrinthine-type acoustical metamaterials by utilizing 'space-coiling' for sound control in architectural applications. Acoustical metamaterials have a great potential on their application for building and room acoustics due to their extreme properties in sound absorption and transmission. They can be used as an interior partition, an interior surface layer, and also as a design element. They are advantageous in comparison to the traditional acoustical materials such that by tuning their physical properties more hygienic, lighter or thinner alternatives can be produced. In this research, the design ideas of acoustic metamaterials (AMMs) originate from golden ratio (GR) and web labyrinth (WL). In data collection and analysis, both experimental and theoretical methods are used. As a first step, all design alternatives are modelled in 3D, then are printed out by a CNC 3D printer, finally, the AMMs are tested in impedance tube to observe their acoustical properties. Initial results indicate that WL shows good performance in terms of transmission loss and GR has efficiency for sound absorption in low frequency range. Both options are better than Solid sample. The results indicate the potential of designed alternatives and are supportive for future optimization.

Keywords: Acoustical Metamaterials, Sound Absorption, Sound Transmission

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1. INTRODUCTION

Metamaterials (MMs) are the materials that is basically defined as composite and manufactured materials whose overall properties are quite different from their component properties that are not common in nature.[1–2] Acoustic Metamaterials (AMMs) are defined as "… artificially fabricated materials designed to control, direct, and manipulate sound in the form of sonic, infrasonic, or ultrasonic waves, as these might occur in gases, liquids, and solids."[1] Acoustic Metamaterials (AMMs) have also various application areas including subwavelength imaging, acoustic cloaking, transmission or reflection control, and surface wave manipulation.[3]

The investigations on acoustical metamaterials (AMMs) on the other hand are relatively new, and this research field necessitates many experimental data. It is mainly known that AMMs are high-tech materials with their extreme acoustical properties in comparison to the traditional acoustical materials. Another potential advantage of such materials is that due to the flexibility in material content, the output product can be environmentally sensitive. Whereas traditional ones are comparatively heavier and thicker when transmission loss is a concern, AMMs can be much lighter or even translucent. Fibrous structure is generally one component of either absorptive panel systems or they are applied within wall sections for damping. AMMs do not necessitate any fibrous backing or infill. Thus, they can be hygienic and can find further application areas in architectural acoustics.

The aim of this research is to develop a 3D labyrinthine type acoustic metamaterial within the concept of 'space-coiling' for sound control in architectural applications. For this purpose, two AMM options are designed and modelled for testing. One of the two AMMs which are proposed in this research is structured by using the principle of Fibonacci series, or golden ratio (GR). In second option, it is aimed to design a web labyrinthine (WL) to provide the coiling effect.

2. LITERATURE REVIEW

Acoustic meta-materials are mainly designed considering these two parameters which are mass density, bulk modulus to reach negative refractive index.[4–5–6] If both of the values of these two parameters becomes negative, the velocity of sound waves is predicted to behave negatively.[7] At the same time, extreme properties can be obtained by adjusting the structure or geometry of the system.[8] Thus, to construct an AMM these two are mainly studied, which are material properties and material structure.

In terms of the material properties, membrane type AMMs have great advantages in the field of acoustical metamaterials. To illustrate, they have first of all relatively simple geometries in comparison space-coiling type. They are also lightweight, compared with other AMMs, and they are particularly utilized in noise control. Also, Active AMMS are capable of actively adjusting the effective density, so resonance frequency can be adjustable. Most importantly, and uniquely, if properly designed, a broad band negative effective intensity can be observed with a very low loss of energy.[9]

AMMs can exhibit extreme properties when their geometries are designed properly, especially, labyrinthine acoustic metamaterials can provide broadband noise reduction in certain combinations and can display remarkably high effective refractive index values because of their characteristic structural properties.[10–11] For AMMs, zig-zag movement and clock wise, anti-clock wise movement is considered to manipulate sound waves.[10] So that they create ‘space-coiling’ which is also referred as labyrinthine structure.[3] The space-coiling structure of AMMs allows the propagation of sound waves only from certain intervals to the structure. Waves are weakened at specific frequencies when transmitted in structure. Also, it is possible to coil the wave using 3D perforation inside the structure because the acoustic wave has a scalar field structure.[3]

One of the research examined on labyrinthine type acoustic metamaterials in the concept of ‘space-coiling’ highlights that labyrinthine structures have high potential to be applied as sub-wavelength broadband all-angle acoustic absorbers for acoustic-noise suppression. Layer type of AMM structure has also been studied to provide ‘space-coiling’.[12]

Both negative mass density and bulk modulus lead AMMs to be different than their components. To achieve negative refractive index the structure[4] and type of the material[5] have being investigated and AMM has created a great interest in the community to explore their theories, mechanisms and practices.

In this research, 3D labyrinthine type acoustical metamaterials are being investigated. While designing the AMM samples, structure, geometry and material properties are taken into account. Main focus is the material geometry and overall structure of the system. As for solid part of the AMMs epoxy resin is printed in model production process. Epoxy is one of the materials that is used in experiments of AMMs in many research.[6 –13] There are some advantages of using epoxy resin for AMMs. It can be transparent or semi-transparent, so can be used together with light for certain effects. On the other hand, it does not emit any particle that can be hazardous for air quality of indoors. For all that reason AMMs produced out of resin can be comparatively a much sustainable product in comparison to traditional acoustic materials applied in architecture. The details of design, production and test process of AMMs are given in following sections.

3. MATERIALS AND METHODOLOGY

3.1. Materials

In design process, based on previous research,[10 –14] possible structures are developed in the logic of an acoustic metamaterial. Particular considerations are taken into account during the design phase. For example, forming solids and voids for manipulating the path of the sound wave. The main aim is to reduce the energy of the sound, either for absorption or for transmission loss.

Although metamaterials are originally described as those materials with properties that are not found in nature, this is a very strict notation as the limits of the nature is not discernible. With the idea of bio-mimicking, the first proposal of AMM is inspired from the nature’s so called golden ratio. As it will be used in building systems, mass production is also taken into account, and modular units are proposed that will make a partition wall or panel system. Open space offices or classrooms are typical spaces, where interior design is also a concern. In GR system basically there are two units attached to each other and with one opening on the opposite sides of each unit. The spiral system is connected at the center to the other unit with another aperture. Width of the GR unit sample is 8 cm and height is 10 cm (see Fig. 1).

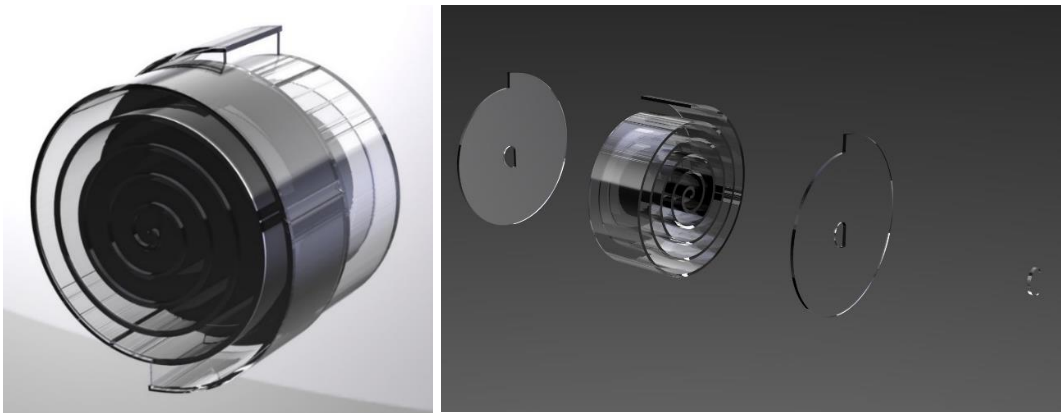


Fig. 1 Golden Ratio (GR) 3D Models two units side by side (on the left), exploded unit (on the right)

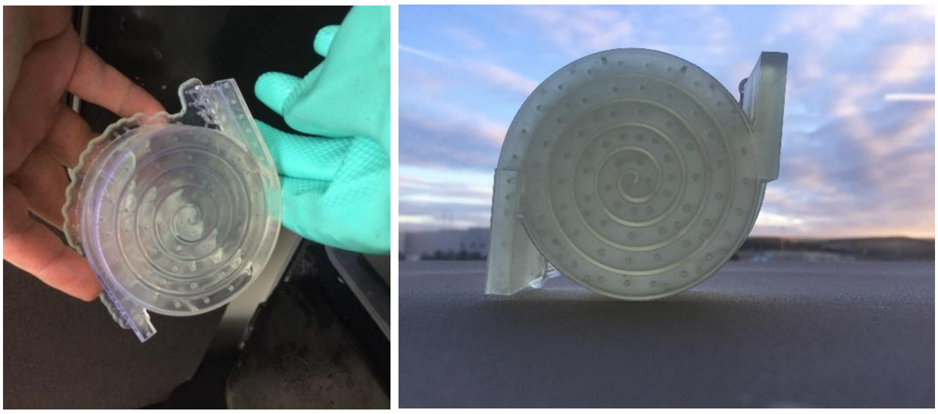


Fig. 2 Final printout of Golden Ratio (GR) sample in real size, while epoxy resin inside of the sample is being cleaned (on the left).

The second design proposal is web labyrinth (WL), which has the same logic with Golden Ratio basically. There are openings on the opposite sides of the material. Middle part of the structure is for coiling the sound waves up and to extend the sound path. Different from GR, it has a layered structure. There are four types of layers in total with top (first) and bottom (fourth) layers. The second is the one with the opening in the middle, the third one is the one with the opening on the sides (see Fig. 3). Due to the openings on the sides and at the centre of the structure, one layer connects with another upper and lower layers through these openings. The two layers of the same type cannot overlap when the layers are combined, each layer must be different from the previous and the next one. There is no limitation for the number of the repetition of layers. It depends on the need and width of the desired place to be applied. Height of the WL sample is 10 cm, width is adjustable depending up on the number of the layers (see Fig.4)

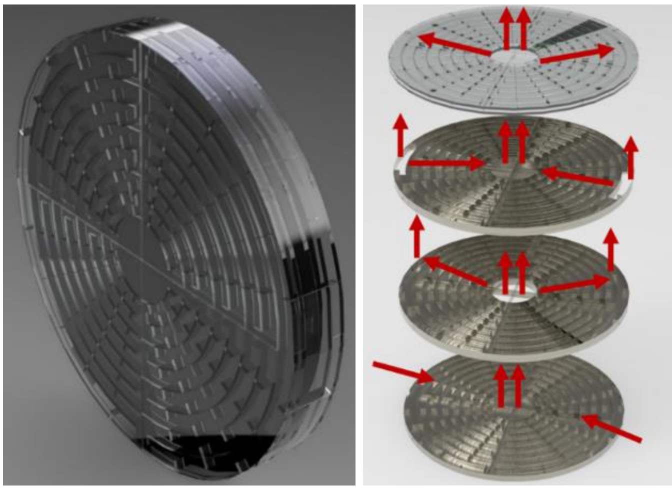


Fig. 3 Web Labyrinth (WL) 3D Models, one unit composed of 4 layers (on the left), exploded unit indicating apertures on the sides and at the center (on the right)

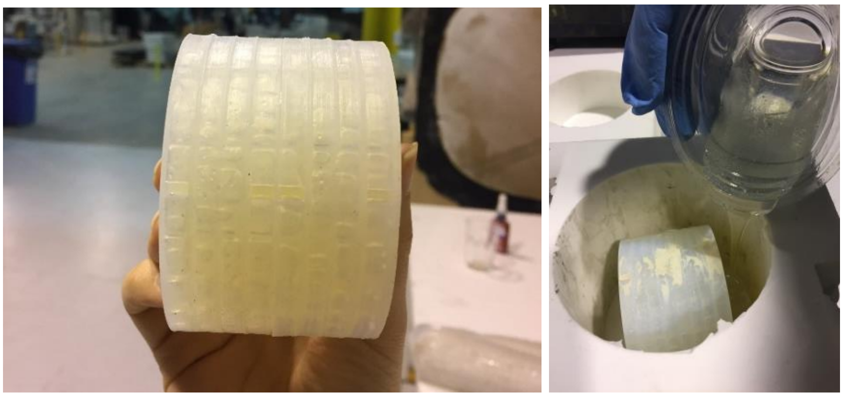


Fig. 4 Final printout of Web Labyrinth (WL) sample in real size (on the left), while epoxy resin is being cast to the mould to have the final version suitable for Kundt tube measurements. (on the right)

In both AMM options, open apertures on both sides are more likely to be used for sound transmission loss. While the openings on the back side of the units are closed, AMMs work in a similar way to the Helmholtz.[15–3]

3.2. Methodology

3.2.1. Production

In addition to the acoustical and aesthetic concerns, production is also an important phase for the smooth realization of designed products. Coiling the space with various forms of labyrinth and spirals is a challenging idea in terms of manufacture. In today's technology, 3D CNC printers has been started to be utilized in small scale construction. Printing the designed units at the moment takes a significant time (12 hours per sample), however, it is assumed that this technology will boost in the future so it will be much easier to design, model and test such AMM samples under research.

During the 3D printing process the design has been revised several times as some samples were unsuccessful. It is found out that the printer is not sensitive enough to print certain forms with very small dimensions, so the design and the 3D model is revised again to be on a larger scale. After approximately of 20 hours of drying process, the products become hard and stable to be tested in the impedance tube.

3.2.2. Impedance Tube Measurements

Measurements are performed with S.C.S. Kundt Tube. 'Kundt Tube' configuration represents the basic, standard system set up for absorption coefficient and acoustic impedance measurements (2 microphones - transfer function method), according to ISO 10534-2:1998. 'TL tubes' configuration represents the tube arrangement scheme, which allows Transmission Loss measurements (4 microphones method). The double tube set up of sound absorption and transmission loss measurements include small and large tubes. Large tube is utilized for AMM tests in this study, which is made up of Ø100mm tubes for measurements in the low frequency range (50Hz to 1200Hz).

Samples of the AMMs are manufactured to fit into the impedance tube with a diameter of 10 cm proper for measuring acoustical properties for the frequency range below 1200 Hz. As it is comparatively easier to handle with sound waves in high frequency range, this research mainly focus on the sound activities in low frequencies.

Each composition is measured approximately 10 times for checking repeatability. The tested samples for transmission loss estimations are WL, GR, and a Solid sample with 8 cm thickness for comparative evaluations (Fig. 3). For sound absorption analysis, more configurations are tested in order to check the difference between one side closed versus two sides open units. The tested compositions of sound absorption tests are WL 2 sides open and 1 side closed, GR 2 sides open and 1 side closed. Also, because the developed units are considered to be applied in building systems, the cavity behind the AMM is an option. Therefore, WL absorption with and without 5 cm gap behind, GR absorption with and without 5 cm gap behind, 8 cm Solid sample with and without 5 cm gap behind are tested in alpha measurements (Table 1).

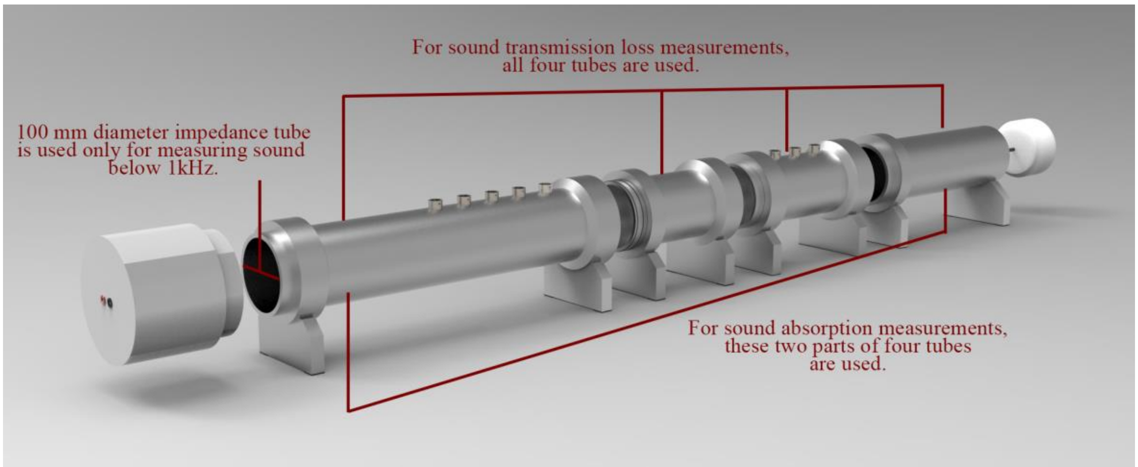


Fig.5 3D model of impedance tube set up for sound absorption and transmission loss measurements (prepared by the author).

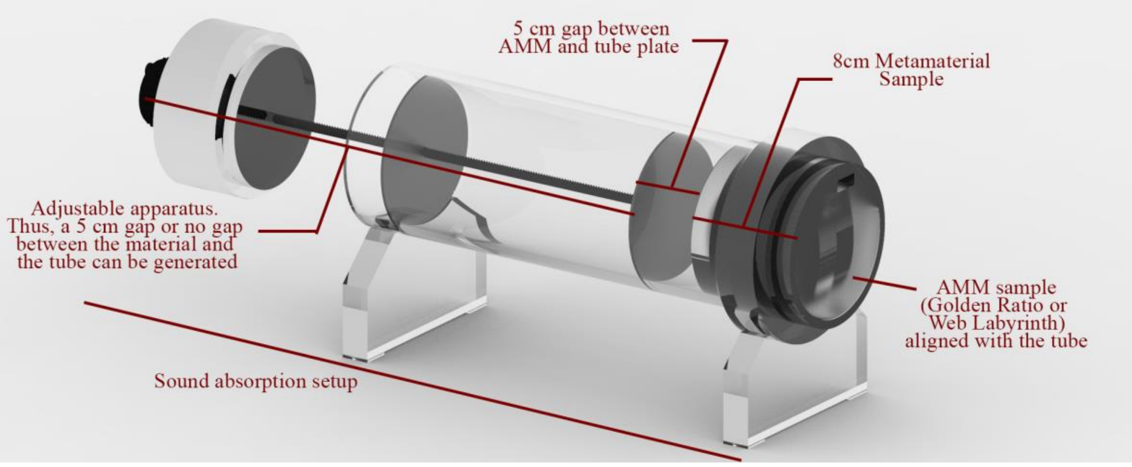
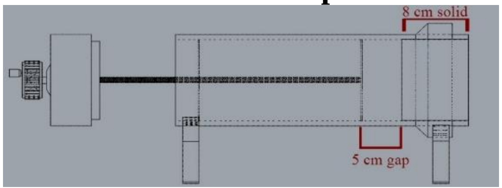
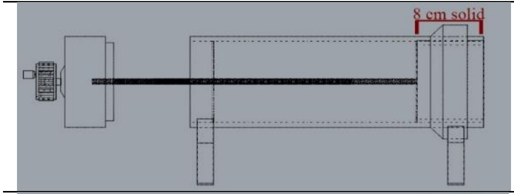
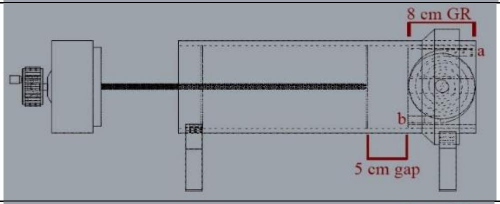
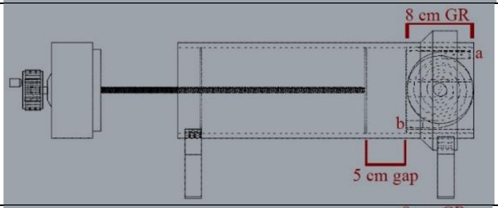
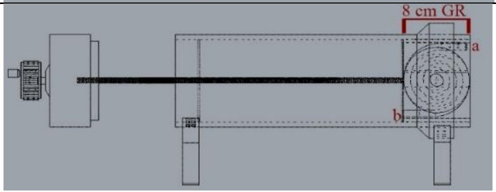
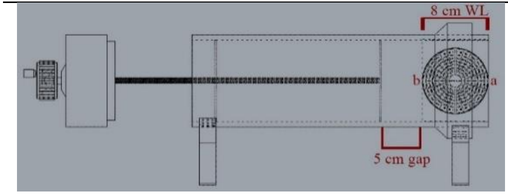
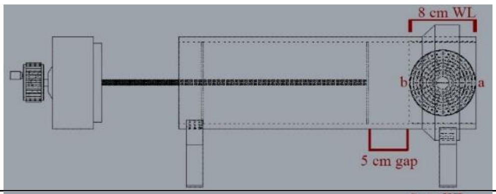
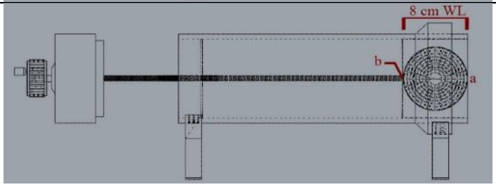


Fig.6 Abstracted 3D Model of Impedance Tube with AMM sample located in predefined position. In this placement, only sound absorption coefficients are tested (prepared by the author).

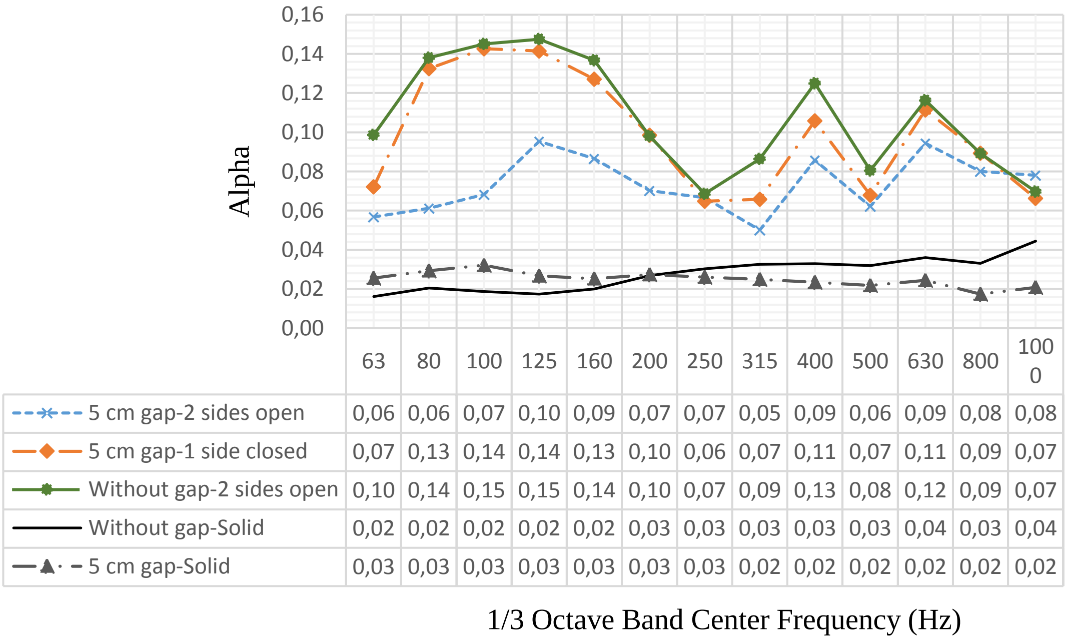
Table 1, Explanation of tested configurations in alpha measurements

Tube set-up	**Composition Description**
	8 cm Solid sample + 5 cm air gap
	8cm Solid sample without air gap
	8 cm GR + 5 cm air gap, two sides open, (a and b open)
	8 cm GR + 5 cm air gap, 1 side closed (a is open b is closed)
	8 cm GR without air gap, two sides open, (a and b open)
	8 cm WL + 5 cm air gap, two sides open, (a and b open)

	8 cm WL + 5 cm air gap, 1 side closed (a is open b is closed)
	8 cm WL without air gap, two sides open, (a and b open)

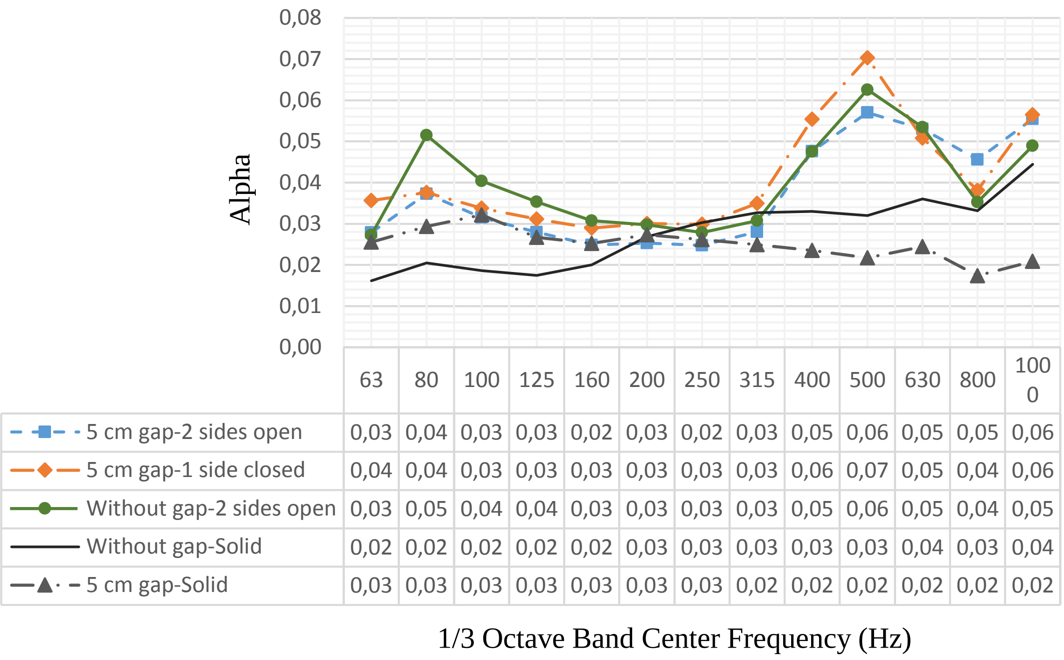
4. MEASUREMENT RESULTS

In this section sound absorption coefficient measurement results of GR and WL samples are initially presented by comparing different configurations as listed in Table 1. In Fig. 5 the effectiveness of the GR sample in sound absorption is evaluated. It can be observed that all three options have a better performance than Solid sample. The alpha values vary between 0.02 and 0.04 in the Solid sample, and ranges in between 0.05 and 0.14 in the GR sample. When GR compositions are interpreted among themselves, although "5 cm gap, 2 sides open" is better than the Solid sample for the same air gap behind, the results show that this condition is the least efficient condition in overall GR configurations. "5 cm gap, 1 side closed" shows higher sound absorption values in between 63 and 200 Hz at low frequencies. Generally, it has average absorption among three compositions of GR. "Without gap, 2 sides open" condition indicates the best overall results.



	63	80	100	125	160	200	250	315	400	500	630	800	1000
5 cm gap-2 sides open	0,06	0,06	0,07	0,10	0,09	0,07	0,07	0,05	0,09	0,06	0,09	0,08	0,08
5 cm gap-1 side closed	0,07	0,13	0,14	0,14	0,13	0,10	0,06	0,07	0,11	0,07	0,11	0,09	0,07
Without gap-2 sides open	0,10	0,14	0,15	0,15	0,14	0,10	0,07	0,09	0,13	0,08	0,12	0,09	0,07
Without gap-Solid	0,02	0,02	0,02	0,02	0,02	0,03	0,03	0,03	0,03	0,03	0,04	0,03	0,04
5 cm gap-Solid	0,03	0,03	0,03	0,03	0,03	0,03	0,03	0,02	0,02	0,02	0,02	0,02	0,02

Fig. 5 GR sound absorption coefficients measurement results for a) 5 cm gap-2 sides open, b) 5 cm gap-1 side closed, c) without gap-2 sides open, d) without gap-solid, e) 5 cm gap-solid



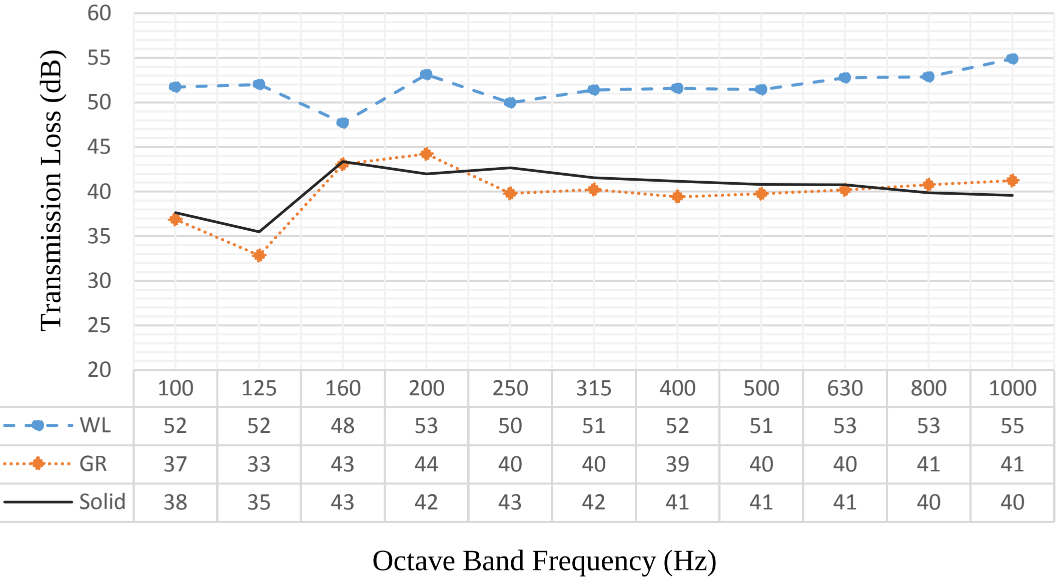
	63	80	100	125	160	200	250	315	400	500	630	800	1000
5 cm gap-2 sides open	0,03	0,04	0,03	0,03	0,02	0,03	0,02	0,03	0,05	0,06	0,05	0,05	0,06
5 cm gap-1 side closed	0,04	0,04	0,03	0,03	0,03	0,03	0,03	0,03	0,06	0,07	0,05	0,04	0,06
Without gap-2 sides open	0,03	0,05	0,04	0,04	0,03	0,03	0,03	0,03	0,05	0,06	0,05	0,04	0,05
Without gap-Solid	0,02	0,02	0,02	0,02	0,02	0,03	0,03	0,03	0,03	0,03	0,04	0,03	0,04
5 cm gap-Solid	0,03	0,03	0,03	0,03	0,03	0,03	0,03	0,02	0,02	0,02	0,02	0,02	0,02

Fig. 6 Web Labyrinth sound absorption coefficients over octave bands for a) 5 cm gap-2 sides open, b) 5 cm gap-1 side closed, c) without gap-2 sides open, d) without gap-solid, e) 5 cm gap-solid

Although the sound absorption coefficient of the WL is not as good as the GR. there are specific frequency ranges that show relatively higher absorption in comparison to the Solid sample. In general, the values of all WL compositions range from 0.03 to 0.07. Different compositions in WL option are not clearly separated from each other like GR. There are different frequencies in which all three conditions are effective. For example, while the condition "without gap, 2 sides open" reaches 0.05 alpha at 80 Hz, which is the highest value at this frequency compared to three conditions, at the 500 Hz, "5 cm gap 1 side closed" gives the best result with 0.07 alpha value.

Although the differences in between absorption coefficients for both GR and WL is not that radical, when compared to its real scale from 0 to 1, or to call these cells as absorptive units, the absolute differences give hint on the effect of form or geometry and the behaviour of sound when exposed to such AMM units. So, further optimizations should follow these initial studies in order to increase the efficiency of AMM samples in sound absorption.

In terms of sound transmission loss, GR has no remarkable difference in comparison to the Solid sample. GR and Solid sample almost have same values at all frequencies. The values of the GR and Solid sample for 8 cm thickness in transmission loss ranges from 33 to 44 dB on average. On the other hand, the transmission loss values of WL for frequency range below 1 kHz as tested, shows a significant improvement in comparison to the Solid sample. For instance, the values of Solid sample range from 35 dB at 125 Hz to 43dB while transmission loss of WL values are in between 48 to 55 dB. There is an average of 12 dB increase in TL values of WL sample when compared to the Solid sample with the same thickness. These results indicate that WL proposal has a potential to be applied in noise control applications in architecture. Especially, when the units are placed in a lattice like structure, as an interior partition or interior surface layer, the overall performance would be even higher.



	100	125	160	200	250	315	400	500	630	800	1000
WL	52	52	48	53	50	51	52	51	53	53	55
GR	37	33	43	44	40	40	39	40	40	41	41
Solid	38	35	43	42	43	42	41	41	41	40	40

Fig.7 Golden Ratio – Web Labyrinth and 8 cm solid sample Transmission Loss (dB) measurement results.

5. CONCLUSION

In this research, two types of AMMs are designed and modelled then printed out in a 3D CNC printer. In order to understand the effectiveness of the metamaterial samples, besides the AMM options, Solid sample with the same thickness and material properties are tested and compared. All measurements are done in S.C.S. Kundt impedance tube for absorption coefficient and transmission loss assessments below 1250 Hz of designed AMMs.

Findings of this research indicates that for sound absorption Golden Ratio (GR) model has more potential in comparison to Web Labyrinth (WL) option and also to the Solid sample. As the sample is produced to fit into the 100mm diameter tube for low frequency assessment, the size is still limited to perform its full potential in a real application such as a partition with multiple units laid in two directions. When one side of the AMMs' models is closed, energy of sound waves oscillate with the help of sound resonance of the cavity like Helmholtz Resonator.

When all compositions of WL option are considered, in practice, it does not give as good results as the GR in terms of sound absorption. On the other hand, WL has significant efficiency in sound transmission loss value reaching almost 12 dB more than a Solid sample. Particularly, when they are aligned in a structure side by side as an interior partition or interior surface layer they can show better results.

The intention of this research, is to contribute ongoing scientific field and research area of metamaterials by focusing on its architectural applications, disposition and optimization of architectural and physical variables of metamaterial systems supported by experimental data. Another objective is to improve their acoustical performances specifically in low frequency range. Accordingly, a multi-use acoustical metamaterial units are investigated for both sound absorption and transmission loss depending on their configuration. Besides, the study focuses on searching after and proposing sustainable acoustical material solutions. The absolute absorption coefficients are not that high for even GR, so it still necessitates an optimization of geometry and layout. While, WL option will be also investigated for improving its transmission loss potential with more alternative design solutions in the following phases of this research. Experimental stage of this study will be supported by the numeric validation of the results for better understanding of input and output parameters, the process of which is still ongoing.

6. ACKNOWLEDGEMENTS

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