Design and Development of Acoustic Metamaterial and Micro-Perforated Panel by Using 3D Printing

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1 Introduction

Low-mid-frequency noise is common prevailing background noise in urban areas. Vehicles, aircraft, industrial machines, mining explosions, and air conditioning units are a common source of this low-frequency noise. Low-mid-frequency noise problems also occur in the industry presenting a different noise problem to those in homes and offices [1, 2]. The World Health Organization perceives low-frequency noise as an environmental problem [3]. It is more difficult to absorb low-frequency sounds compared to higher frequency sounds.

Metamaterials are artificially designed materials that acquire their properties from internal microstructure than from the chemical composition found in natural materials. These materials are designed to manipulate the propagation of sound much different than it is possible using conventional materials [4, 5]. There are various methods to fabricate the metamaterial, one of which is FDM (fused deposition modeling) is used for the fabrication of core and MPP structures [6].

Sound absorption is the process by which the intensity of sound waves is decreased by the conversion of the sound energy into heat due to the material structure. The sound absorption coefficient, alpha represents the sound-absorbing characteristics of a material. The absorption coefficient (α) ranges from 0 (total reflection) to 1.00 (total absorption) [7]. Frequency variation results in a significant change in the sound-absorbing characteristics of materials.

As a means of noise reduction, sound-absorbing materials have been widely used in interior architecture, transportation, and aerospace engineering. The acoustical effect of the honeycomb structure on the sound-absorbing performance of an MPP sound absorber has been studied by the authors [8, 9]. The honeycomb structure when

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coupled with the MPPs acts as Helmholtz resonators and attenuates noise in the low- and medium-frequency bands. These honeycomb structures broaden the frequency band of sound absorption, thereby making it suitable for many applications [9]. Compared to traditional sound absorption materials, MPPs are more durable, environmentally friendly, and plain in structure, so they are suitable for harsh conditions, such as in high-temperature and high-pressure applications [10]. MPPs can be usable in a severe and harsh environment. Also, they are more designable than most of the other sound-absorbing materials [8].

The principle behind using the perforated panel is enhancing the viscous and thermal losses by perforating numerous sub-millimeter diameter holes in the thin panel, leading to the desired acoustic resistance and a reduction in the mass reactance [11].

The sandwich structure comprising a honeycomb core and panels acts as a Helmholtz resonator and therefore exhibits good sound absorption in the low-mid frequency range without the need to increase the thickness of the material. It is lightweight and has excellent mechanical properties and has a high mechanical strength: weight ratio, so it is widely applied in aerospace, railway vehicle, and architectural scenarios [10]. Therefore, these metamaterials provide a lightweight solution in absorbing such low-mid-frequency noise. These can be used in office buildings, residential, and commercial environments. In aircraft, vehicle cabins, and machinery, these materials improve the structural strength and at the same time enhance the absorption frequency range into two or three-octave bands [12, 13].

2   Design and Fabrication

This paper focuses on the honeycomb structure as its lattice structure. Besides, honeycomb structure enhances the effect of the changes in MPP parameters on the sound absorption characteristics [9]. Certain variations were added to the simple hexagonal structure by adding a cylindrical part at the center of the hexagon supported by six vertical faces. To optimize the design, an octagonal structure with a cylinder and supported by eight vertical faces were designed.

The design considerations and the dimensions of the MPP were obtained from the design formulae in [14, 15]. These formulas yielded the parameters that were then used to make the MPPs and the core structures. The MPPs were designed with the following parameters:

Diameter of holes (d): 0.5, 0.6, 0.7, and 0.8 mm.
Distance between holes/perforations (b): 4.5, 5.5, and 10 mm.

The thickness of the plate (t): 1, 1.5, and 2 mm.
Diameter of MPP (D): 99.9 mm.

2.1 Modelling of Core Structures and Micro-Perforated Panels

Three core structures and MPPs were designed in the SOLIDWORKS software by taking into account the parameters in Table 1.
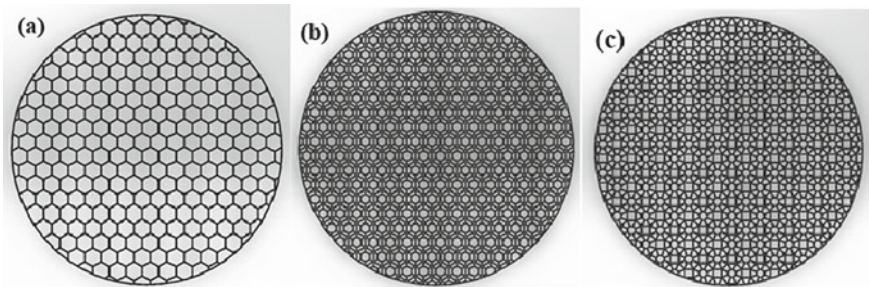

Fig. 1 CAD Model of core structures: **a** hexagonal structure, **b** lined hexagonal structure, **c** octagonal structure
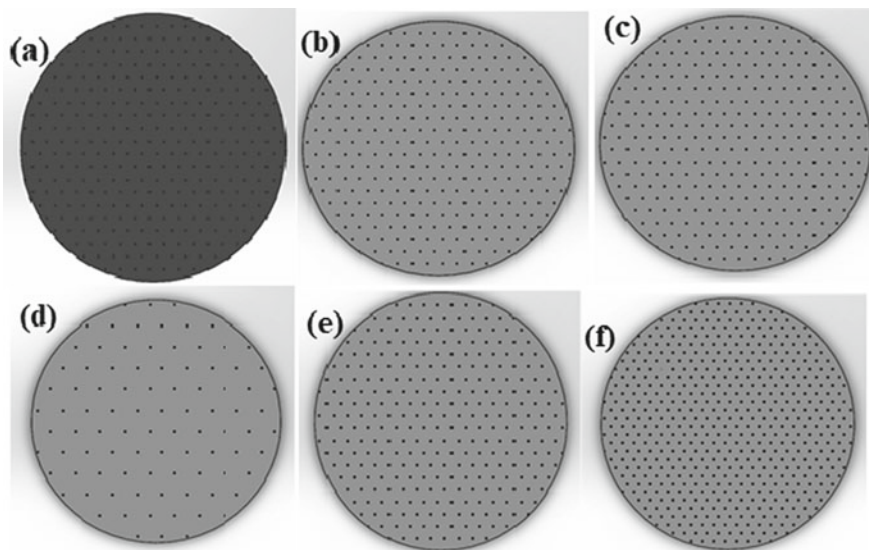

Fig. 2 CAD model Mpp with thickness t = 1 mm: **a** d = 0.5 mm, **b** t = 0.6 mm and, **c** d = 0.7 mm; CAD Model of MPPs with d = 0.8 mm: **d** b = 10 mm, **e** b = 5.5 mm, and **f** b = 4.5 mm
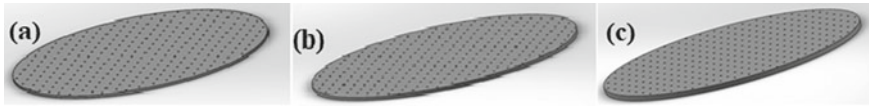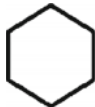
Fig. 3 Solidworks model of 0.8 mm MPP with thickness **a** t = 1 mm, **b** t = 1.5 mm, and **c** t = 2 mm

Table 1 Geometry and specifications of various structures

Structure	Geometry	Specifications
Hexagonal structure		Side of the hexagon: 3 mm
		Side of the octagon: 3 mm
		Inner circle radius: 1.36 mm
Modified hexagonal structure		Thickness of the faces and sides: 0.3 mm
		Thickness of the sample: 30 mm
Octagonal structure		

Fabrication

Fabrication of the core and MPP with sub-millimeter accuracies is a challenge, especially when the holes are in the sizes of 0.5 mm diameter. Fused deposition modeling (FDM) is a type of additive manufacturing technique that is employed in this work to fabricate the required samples. FDM has been proven to be effective in printing structures with sub-millimeter dimensions [16]. The walls of the core structures have a thickness of 0.3 mm, which were printed by an FDM machine, with a 0.3 mm nozzle. PLA (Poly Lactic Acid) is a biodegradable (under the right conditions) thermoplastic derived from renewable resources such as corn starch, or sugarcane was used as the base material. PLA was the material used to print the core structures and the MPPs [17] (Table 2).
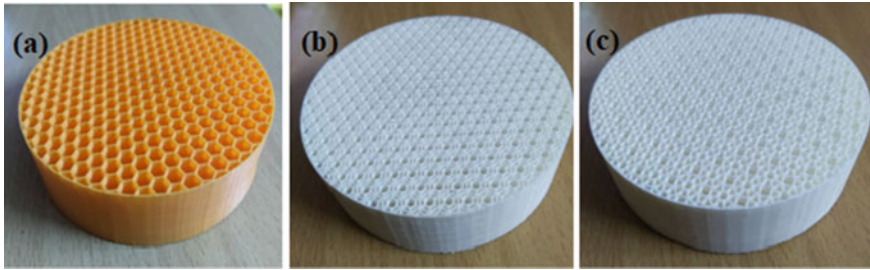
Fig. 4 3D Printed model of **a** Hexagonal core structure (C1), **b** Lined Hexagonal core structure (C2), and **c** Octagonal structure (C3)
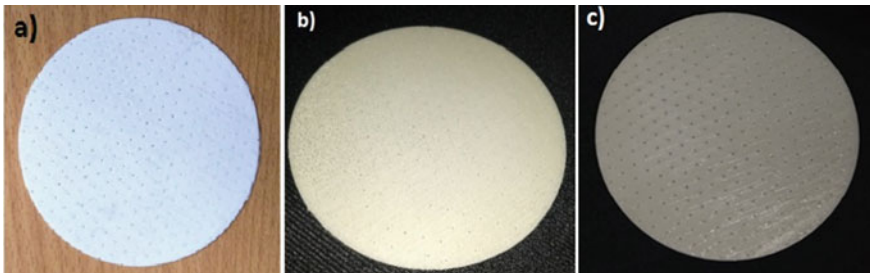

Fig. 5 3D Printed model of MPPs: MPP with **a** d = 0.5 mm, **b** d = 0.6 mm, **c** d = 0.7 mm and fixed t = 1 mm and b = 5.5 mm

3 Testing and Simulation

3.1 Impedance Tube Test

The sound absorption coefficient of the material is measured using Impedance Tube Apparatus, which is a system consisting of a glass tube containing a speaker at the one end and the material sample whose properties are to be measured at the other end [11].

The system has a pair of 1/2″ Microtech Gefell microphones separated by a fixed distance are connected to the glass tube with the help of microphone holders. These microphones are connected to a data acquisition system [11] (Figs. 1, 2, 3, 4 and 5).

A function generator is used to power the speaker in the impedance tube. For the absorption coefficient, a rigid backing is also used [6, 11].

The sound absorption coefficients of the multilayer porous absorber samples were measured with an impedance tube using the transfer function method [6, 11]. The testing setup was established according to ASTM E 1050 and is illustrated in Fig. 6a. The frequency range of interest was 50–1000 Hz.

Table 2 Specifications of impedance tube apparatus

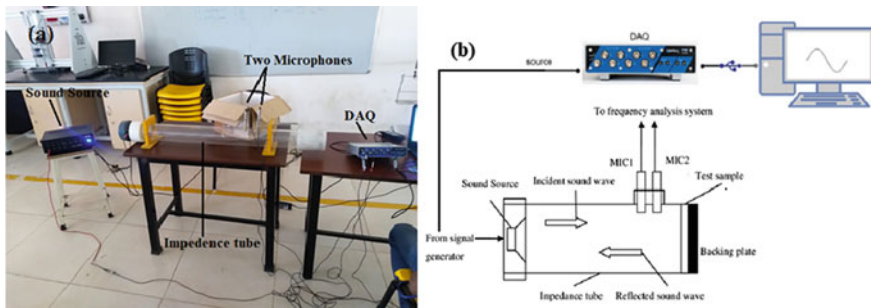| Parameter	Specifications
Impedance tube length	1000 mm
Inside diameter	100 mm
Speaker frequency response range	160–7000 Hz
Signal generator	200–6500 Hz
Sweep in	Automated
Number of microphones	2
Sample holding unit	50 mm
Controls	PC automated measurements
Software	MATLAB

Fig. 6 a Experimental setup of Impedance tube setup, **b** Schematic diagram of Impedance tube setup

Simulation

The Absorption coefficient simulation is carried out in the COMSOL 5.5 Multiphysics software. The porous absorber model is solved in the frequency domain and provides the absorption coefficient in a frequency range of 50–1000 Hz in steps of 2 Hz.

The inbuilt model can be used to perform simulations by changing different parameters such as the thickness of the plate, the diameter of holes in the plate, the distance between the holes, and porosity.

Input Parameters:

Model type: Thin Plate (PLA Material); Hole diameter: Varying from 0.5 mm to 0.8 mm; Plate Thickness: 1 mm; Air Domain height: 30 mm; Fluid Material: Air.

4   Results and Discussion

4.1   Impedance Tube Test

The following graph was obtained by experimenting on the samples: C1, C2, C3, C1P, C2P, and C3P. C1P, C2P, and, C3P are C1, C2, and, C3 each coupled with a d = 0.5 mm, t = 1 mm MPP, respectively.

Figure 7 shows that the core structures C1, C2, and C3 do not offer good acoustic shielding. The sound absorption through a metamaterial is achieved by viscous and thermal losses, through an MPP by resonant behavior. Thus, a wide range of frequencies was absorbed when the MPP was coupled with a porous material. For an MPP with a fixed perforation ratio of 1.1%, Fig. 7 provides a comparison between the three porous structures and their acoustic performance when accompanied by an MPP. These single units (C1P, C2P, and C3P) that behave as Helmholtz resonators are quite effective in broadening the peak over a range of frequencies.

AFoam sample was used as a standard to compare the performance of the test samples. The acoustic performance of C3P was found to be better than C2P, followed by C1P and foam for the frequency range of 400–700 Hz. For instance, at 550 Hz, the value of the absorption coefficient by C3P was 0.756, by C2P was 0.6, and by C1P, it was 0.37. The intricacy of the porous structure contributes to a better acoustic performance that is evident from the octagonal porous structure (C2P) as well.
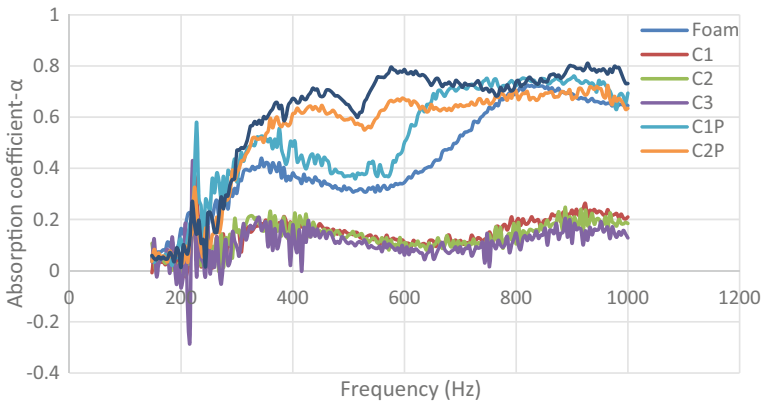

Fig. 7 Comparison of curves of the samples from the sound absorption test
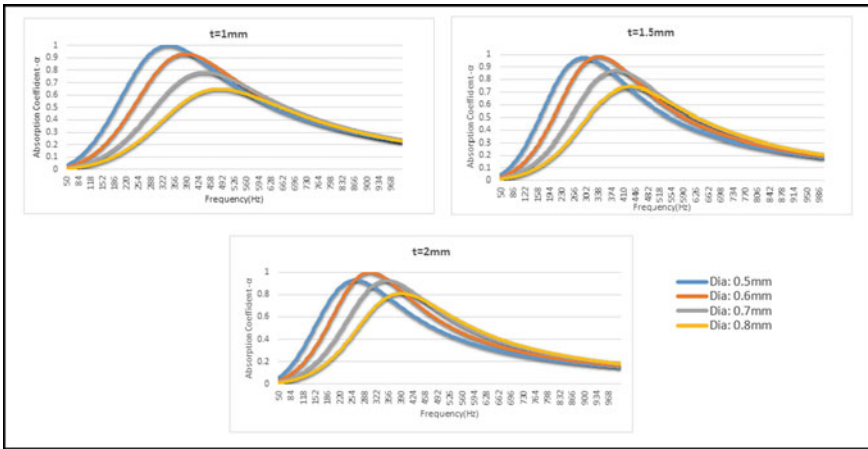
Fig. 8 Comparison of the absorption coefficient with a change in perforation diameter (d) for t = 1 mm, t = 2 mm, and t = 3 mm and a constant pitch, b = 5.5 mm

Effect of perforation diameter and plate thickness on the absorption coefficient.

Effect of pitch/number of holes on the absorption coefficient.

From Fig. 8 it can be said that, with the increase in the thickness of the MPP, the absorption coefficient increases and the absorption frequency falls, hence attenuating lower frequencies better.

It can be observed from Fig. 9 that MPPs with shorter pitch absorb a larger frequency range compared to, b = 10 mm MPP. With the increase in the diameter of holes, the absorption efficiency of lower pitch MPPs decreases. With the increase in the diameter of holes, the curve for lower pitch MPPs flattens.

The higher pitch boosts the absorption for larger diameter MPPs corresponding to lower frequencies. The MPP with b = 10 mm exhibits a high absorption coefficient
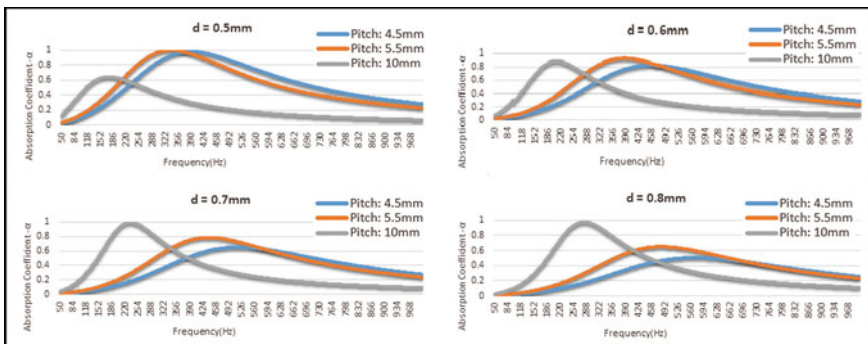

Fig. 9 Comparison of the absorption coefficient with a change in perforation diameter (d) and pitch (b)

(~0.97), but the absorption curve is steep; therefore, a small band of frequencies is absorbed. The objective of the larger diameter MPPs is to absorb the sound in the low-mid-frequency range, which is effectively being done by the low pitch MPP, especially 5.5 mm. Also, as we increase the pitch, the absorption coefficient reaches 0 at the higher end of the low-frequency band, but on the other hand, the lower pitch MPPs have a broad range of absorption.

5   Conclusion

The study showed that the simple hexagonal structured metamaterial when coupled with an MPP exhibited good sound absorption with an absorption coefficient ~0.8. The low-mid-frequency range was absorbed effectively and the absorption coefficient was between 0.6 and 0.8 for this range. The Octagonal structure was found to be better than the modified hexagonal structure in terms of sound absorption.

The simulation study gives the right choice of parameters for fixing the MPP to be coupled with the metamaterial, so that the combination yields maximum absorption coefficient, It can be told that, with the increase in the thickness of the MPP, the absorption coefficient increases, the frequency corresponding to maximum absorption falls, hence attenuating the lower frequencies is better. It is observed that MPP with a higher pitch offered a higher absorption coefficient for different hole diameters, but the curve was steep and therefore attenuating a narrow frequency band. Hence, MPPs with shorter pitch (b = 5.5, 4.5 mm) though exhibiting less absorption coefficient are preferable since the frequency band is broader. The design can be improved further to achieve better results.

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