Effect of Perforation Volume on Acoustic Absorption of the 3D Printed Micro-Perforated Panels made of Polylactic Acid reinforced with Wood Fibers

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Abstract. In recent times, Additive Manufacturing (AM) has been applied rapidly in almost all fields. This study was conducted to apply the additive manufacturing into an acoustic application by 3D printing the Micro-Perforated Panels (MPP) through Fused Deposition Modelling (FDM) made of Polylactic Acid (PLA) reinforced with wood fibers. MPP were fabricated by altering its perforation volume. Later, the effect of perforation volume on acoustic absorption of the fabricated MPP was measured using the two-microphone impedance tube method as per ISO 10534-2 standard. The result shows altering the perforation volume affects the acoustic absorption of the MPP. MPP with a thickness of 2 mm and a perforation diameter of 0.2 mm shows the maximum sound absorption coefficient of 0.93 at 2173 Hz. It is made possible to absorb the 3D printed MPP made of natural fiber reinforced composite at different spectrums by altering the perforation volume.

1. Introduction

In recent times, the fast expansion of transit, industrialization, and urbanization has made the increase in noise pollution, which is evident in urban areas. Noise pollution is detrimental to human health and behavior patterns, as it can cause disorders and psychological disturbances. Hence, noise regulation is critical and must be addressed immediately [1]. Micro-perforated panels (MPP) could be a viable commercial solution for noise reduction. The concept of MPP having sub-millimeter holes in it backed by an air gap, and a rigid wall was published by Maa [2], as shown in Figure.1. Each micro-perforation functions as a single Helmholtz resonator, dissipating sound energy primarily through resonance and viscous loss in the perforation's neck. The absorption is caused by the acoustic impedance of an MPP, which is mainly composed of resistance and reactance components [3].

Maa recommended a model to predict the acoustic properties of the MPP with an error of less than 5%. In the Maa model, the acoustic impedance Z_{pM} can be calculated using Eq. (1) [2].
\[ Z_{PM} = R_{PM} + jX_{PM} \] (1)

\[ R_{PM} = C_1 t \times 10^{-5} \frac{1 + \frac{xd\sqrt{2}}{8t}}{pd^2} \] (2)

\[ X_{PM} = 0.0185 \frac{tf}{p} \left( 1 + \frac{1}{\sqrt{9 + \frac{x^2}{2}}} + \frac{0.85d}{t} \right) \] (3)

\[ x = C_2 \times 10^{-3} d \sqrt{f} \] (4)

where, \( R_{PM} \) represents the resistance of the MPP (real part), while \( X_{PM} \) represents the reactance of the MPP (imaginary part). For non-metal MPP, \( C_1 \) and \( C_2 \) are the constant values, which are 0.147 and 0.316. The frequency is represented by the symbol \( f \), \( t \) is the thickness of the panel, while \( d \) represents the diameter of the perforated hole, and \( p \) is the perforation ratio. Finally, the sound absorption coefficient \( \alpha \) can be calculated using Eq. (5) [5].

\[ \alpha = \frac{4R_{PM}}{(1+R_{PM})^2 + [\omega \times X_{PM} - \cot (\frac{\omega D}{C_0})]^2} \] (5)

where \( \omega \) is the angular frequency of sound, \( D \) is the depth of the air gap, and \( C_0 \) is the speed of sound.

In the past, synthetic and metallic materials were used in the fabrication of MPP. However, considering the environmental impacts, sustainability and cost, PLA reinforced with natural fibers has been used in the fabrication of MPP in recent times [6]. PLA is a biodegradable polymer that has negligible environmental effect [7] which can be incorporated with natural fibers which are available in abundant [8]. These natural fibers have already proven to be suitable for acoustic applications [9]. Acoustic absorption of the MPP is influenced by factors like thickness and density of the MPP, size, the shape of the MPP, and its perforations and air gap behind the panel. Hamdan et al., investigated the effect of acoustic absorption of the MPP by altering the diameter of the perforations. The diameter of...
the micro-perforated panel is usually less than 1 mm, and the diameter of the macro perforated panel usually ranges from 1 mm to 1 cm. Membranes with different thicknesses and densities were considered as MPP. They have selected three diameters of perforations for the membranes; 0.65 mm, 2.7 mm, and 5.7 mm. The results revealed that the perforation size affects the width of the frequency range and the sound absorption coefficient of the material. An increase in the size of the perforations shifts the acoustic absorption peaks toward the high-frequency region and also improves the acoustic absorption coefficient. However, when the size of the perforation increases further, acoustic absorption peaks become low. They concluded that when the size of the perforations is too small, it will be difficult for the acoustic waves to enter them, and thus, few waves are reflected back. If the size of the perforation is too large, acoustic resistance and reactance become smaller. Hence, in both cases, the acoustic absorption of the MPP will not be satisfied. Therefore, it is recommended to optimize the size of the perforations, which can allow for acoustic waves with good acoustic resistance and reactance. The membrane with a perforation diameter of 2.7 mm records the highest acoustic absorption coefficient of 0.98 in the range between 2500 Hz to 2900Hz [10]. Liu et al., explored the effect of acoustic absorption of the MPP by varying the distance between the perforations. They have 3D-printed MPP with a constant thickness of around 1 mm, and the diameter of the perforations is 0.8 mm. A non-woven porous material has been backed along with the MPP. The distance between the perforations of the MPP considered was 5 mm, 4 mm, 3 mm, 2 mm, and its acoustic absorption has been recorded. It was seen that MPP with a larger spacing of 5 mm backed with a porous material could control the acoustic absorption at a lower frequency, and MPP backed with porous material with a smaller spacing of 2 mm can absorb well in the higher frequency spectrum. They have concluded that a decrease in spacing between the perforations results in a decrease in the acoustic mass of all the holes, thereby increasing the resonant frequency at which maximum acoustic absorption happens [11].

The effect of the perforation ratio on acoustic absorption of the MPP was studied by Liu et al. MPP backed with porous material with a thickness of around 1 mm, and the perforation diameter of 0.6 mm had been 3D printed. The perforation ratio can be altered either by changing the diameter or the distance between the perforations. They have considered perforation ratios of 0.90%, 1.59%, 2.63%, and 5.90% by altering the distance between the perforations and measuring their acoustic absorption. They found that MPP backed by a porous material with a smaller perforation ratio provides a better sound absorption coefficient at lower frequencies, and MPP backed by a porous material having a higher perforation ratio gives better sound absorption at higher frequencies. They have concluded that an increase in the perforation ratio results in a decrease in the total acoustic mass of all the holes and thereby increases the resonant frequency at which the peak sound absorption coefficient takes place [12]. The thickness of the MPP will usually be less than 1 mm. MPP with lesser thickness can offer optimistic acoustic resistance responsible for increased acoustic absorption. However, these thin MPP’s are not suitable for practical applications because of their decreased strength. Hence, research has been done in order to increase the acoustical performance of the thick MPP. Sakagami et al., provided some numerical examples of acoustical performances of MPP having a thickness of 0.4 mm, and 10 mm with the perforation diameter being 0.4 mm. It was found that the acoustic absorption peak shifts to a lower frequency when the thickness is increased. The value of acoustic absorption is drastically reduced when the thickness is increased. However, with a further increase in the size of the perforation to 10 mm, an increase in acoustic absorption was noted, but the peaks were found to be narrow. This is because of the higher reactance produced by the long throat of the thicker MPP. Hence, it is necessary to fix the thickness of MPP, which can provide optimistic acoustic reactance and resistance for effective acoustic absorption [13]. Desmond et al., studied the effect of acoustic absorption by varying the density of MPP. PLA reinforced with Kenaf fibers was used in developing the MPP. The density of MPP was varied by changing the fiber content in it. MPP with fiber contents of 5 wt.% to 30 wt.% was used, and its respective acoustic absorption had been recorded. It was seen that the MPP with less fiber content (5 wt.%) exhibits slightly lesser acoustic absorption than the other compositions. It was suspected that the lesser amount of fiber content might not be enough to spread
over the entire area of the MPP, whereas the acoustic absorption coefficient of the MPP made of other compositions was almost similar to the difference in the peak sound absorption coefficient, being comparatively small. There is not a big difference in resonance frequency recorded since the acoustic mass of the MPP was almost the same. MPP with a fiber content of 30 wt.% shows the highest peak acoustic absorption coefficient of 0.987 at 1521.02 Hz [14]. Table 1 summarizes the most recent research into the factors influencing the acoustic absorption of the MPP.

Table 1. Recent researches on factors influencing the acoustic absorption of the MPP

| Factors varied                  | Material of the MPP                          | Method of developing MPP | References |
|--------------------------------|---------------------------------------------|--------------------------|------------|
| Density of the MPP             | PLA reinforced with coir and kenaf fibers   | Compression molding      | [6], [14] |
| Diameter of the perforation    | Latex membrane                              | Needle technique         | [10]       |
| Thickness of the MPP           | Latex membrane                              | Needle technique         | [10]       |
| Distance between the perforations | VisiJet-SL (Polymer)                       | 3D printing              | [12]       |
| Perforation ratio              | VisiJet-SL (Polymer)                        | 3D printing              | [11]       |
| Perforation volume             | PLA-wood fiber                              | 3D printing              | This study |

It can be seen from the above Table 1 that MPP were developed using methodologies like molding and needle techniques. In general, customization or varying the parameters, developing inner porosity in the acoustic absorber by compression molding was considered to be tedious [15]. To overcome this problem, Additive manufacturing (AM) or 3D printing technology can be used as a tool since the technology directly 3D prints the porous structure from the design where variation in parameters or customization of the acoustic absorbers can be done [16]. AM has no doubt demonstrated its potential as a commercial manufacturing process in various applications. As compared to conventional methods, AM has the upper hand in terms of less material wastage [17] and the ability to produce complex parts that are extremely difficult to be manufactured by conventional methods [18]. There have been a few attempts to develop acoustic absorbers through 3D printing using different polymers and materials. However, developing an MPP made of a natural fiber-reinforced composite by additive manufacturing hasn’t been explored. Hence, this study aims to develop MPP made of natural fiber-reinforced composites and to investigate its acoustic absorption by varying the perforation volume.

2. Materials and Methods

2.1. Design

MPP were designed using the CAD software SolidWorks as per the dimensions in Table 2. The diameter of the MPP was set to be 33.4 mm, which is the inner diameter of the impedance tube. The volume of the perforation is dependent on the thickness of the MPP and the size of the perforation. Altering either of the parameters solely would alter the volume of the perforation. However, the results on altering the thickness of the MPP and the size of the perforations separately have already been discussed by previous researchers [10]. Hence, the volume of the perforation is varied by altering both the diameter of the perforations and the thickness of the MPP simultaneously. Each perforation is considered as a cylindrical hole, and its volume is calculated by the formula $\pi r^2h$. The total volume of the perforations is calculated by multiplying the number of perforations by the volume of a single perforation. After designing, all CAD models were later converted to an STL file format and transferred to 3D printing and laser cutting host software.
Table 2. Design Dimensions of MPP

| Sample ID | Thickness (mm) | Perforation size (mm) | Distance between perforations (mm) | Total volume of the perforations (mm$^3$) |
|-----------|----------------|-----------------------|-----------------------------------|------------------------------------------|
| MPP 2     | 2.00           | 0.20                  | 4.00                              | 3.57                                     |
| MPP 3     | 3.00           | 0.30                  | 4.00                              | 12.08                                    |
| MPP 4     | 4.00           | 0.40                  | 4.00                              | 28.63                                    |
| MPP 5     | 5.00           | 0.50                  | 4.00                              | 48.08                                    |

2.2. 3D Printing
Panels were 3D printed using a Raise 3D N2 Plus printer, which works with FDM technology, and perforations were made using a laser cutting machine. Commercial PLA-wood fiber filament with a standard diameter of 1.75 ± 0.05 mm, outsourced from ColorFabb, was used. The filament contains 70 wt.% of PLA and 30 wt.% of recycled fine wood fibers obtained from pine. The density of the filament is 1.15 g/cm$^3$. Panels were 3D printed with a printing temperature of 215°C at a rate of 70 mm/s. Panels were 3D printed at an infill density of 100%, default grid type infill pattern with a constant distance between the perforations of 4 mm. 3D printed MPP shows a product tolerance of ± 0.1 mm compared to the design. Figure 2 shows the 3D printed MPP with a varying diameter of the perforations and thickness of the MPP simultaneously.

![Figure 2. 3D printed MPP](image)

2.3. Acoustic Testing
The Sound Absorption Coefficient (SAC) of the MPP was measured using a two-microphone impedance tube method as per the ISO 10534-2 standard [19]. Figure 3 shows the setup of the acoustic testing used in this study. The results were obtained within the frequency range of 500 Hz to 4500 Hz. Frequencies ranging from 500 Hz to 2500 Hz are termed as the low to mid-frequency spectrum, and frequencies ranging from 2500 Hz to 4500 Hz are termed as the mid to high-frequency spectrum.
3. Results and Discussions
Acoustic absorption of the MPP is due to the combination of both resistance (friction between air and the inner surface of the perforation) and reactance (inertial motion of the air inside the perforation). For the MPP absorber, the most important element that causes the dissipation of sound is the perforated hole itself. The perforation volume comprises both the perforation diameter and the thickness of the panel collectively. Figure 4 shows the effect of varying the perforation volume on the acoustic absorption of the MPP. MPP 2 shows the typical MPP trend with a better SAC in the mid-frequency spectrum. For the other MPP, it can be noted that an increase in perforation volume causes the first peaks of acoustic absorption to be reduced, narrower, and shift towards the low-frequency spectrum.

![Figure 3. Set up of acoustic testing used in this study.](image)

![Figure 4. Effect of perforation volume on acoustic absorption of the MPP at an air gap of 5 mm.](image)
When the volume of a perforation increases, so does the mass of air inside the perforation. Since the air gap was unchanged, the stiffness remained constant. Hence, the resonant frequency decreases as acoustic mass increases. Also, acoustic waves find it harder to enter the structure in the thicker panels, causing a decrease in SAC. Smaller acoustic reactance and higher acoustic resistance are required for an MPP to have a wider peak [20]. Increasing the perforation volume allows acoustic waves to pass through the perforations, lowering acoustic resistance and increasing reactance. As a result, increasing the perforation volume narrows the peaks of acoustic absorption. Previous studies have shown that the effect of the thickness of the MPP and the diameter of the perforation can affect the reactance and resistance of the MPP [10]. In this study, perforation volume (both the thickness of the MPP and the diameter of the perforations) is collectively involved in affecting the acoustic absorption of the MPP. MPP 2 records the highest SAC of 0.93 at 2173 Hz. Table 3 shows the highest SAC at the corresponding resonant frequency. The second peak of acoustic absorption could be caused by sound-induced vibration [18].

| Sample ID | Highest SAC, Frequency (Hz) |
|-----------|-----------------------------|
| MPP 2     | 0.93, 2173                  |
| MPP 3     | 0.73, 1461                  |
| MPP 4     | 0.72, 1449                  |
| MPP 5     | 0.64, 1410                  |

4. Conclusion
Micro-Perforated Panels made of PLA reinforced with wood fibers were successfully fabricated using additive manufacturing through FDM technology. The effect of altering the perforation volume on the acoustic absorption of the MPP was studied. An increase in perforation volume causes the first peaks of acoustic absorption to be reduced, narrower, and shift towards the low-frequency spectrum. The thickness of the MPP and the diameter of the perforations are collectively involved in altering the volume of the perforation, which in turn affects the acoustic absorption of the MPP. This research could help acousticians fine-tune acoustic absorption at specific frequency spectrums. These acoustic absorbers made of natural fiber reinforced composite along with the features of additive manufacturing will be a great turning point in the field of acoustics. Further investigation of other product parameters and process parameters will be extended for future study.

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