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INVESTIGATION OF SOUND ABSORPTION PERFORMANCE OF THE 3D PRINTED PVDF MATERIAL WITH DIFFERENT INFILL PATTERNS USING IMPEDANCE TUBE

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Abstract:
This study investigates the sound absorption performance of 3D-printed PVDF (Polyvinylidene fluoride) materials with various infill patterns, which includes Triangles, Gyroid, Honeycomb, and Tri-hexagon, all at 50% infill density. A low-cost impedance tube was designed and fabricated with the help of Arduino Uno microcontroller board for affordability and ease of use. The Arduino Uno microcontroller is employed for frequency generation, process microphone input data, and calculate the sound absorption coefficient of materials based on sound pressure level differences. Testing the different infill patterns, using the constructed impedance tube, demonstrated that the choice of patterns significantly impact acoustic performance. Notably, Tri-hexagon and Triangles structures showed better acoustic performance than the Gyroid and Honeycomb patterns. This research underscores the critical role of infill design in optimizing the acoustic performance and suggests potential applications in noise reduction, soundproofing, and acoustic paneling. Furthermore, this method offers an accessible and cost-effective solution for evaluating the sound absorption characteristics of various materials, which will help in expanding the research possibilities in the domain of acoustic material science.
Keywords: Impedance tube, Polyvinylidene fluoride, Acoustic, Arduino Uno, 3D printing, Triangles, Gyroid, Honeycomb, and Tri-hexagon.

1. INTRODUCTION

Noise pollution is a pervasive issue exacerbated by advances in construction, industrial activities, air transportation, and commerce, necessitating effective mitigation strategies to protect human health and the environment. Prolonged exposure to noise can cause hearing loss, anxiety, and stress, significantly affecting the auditory system. Moreover, excessive noise and vibrations can damage commercial equipment, emphasizing the importance of soundproofing. Customizing acoustic experiences through boundary surfaces, geometric features, and material properties is possible, yet current measurement methods need further validation for innovative structures. Recent advancements in sound absorption leverage 3D-printed infill structures created through Fused Deposition Modelling (FDM), enabling the design of materials with complex geometries and optimized internal structures for improved acoustic performance.

Sound absorption is the process by which a material takes in sound energy when sound waves encounter it. Figure 1.1 illustrates the three processes that occur when sound waves pass through an acoustic material [7].

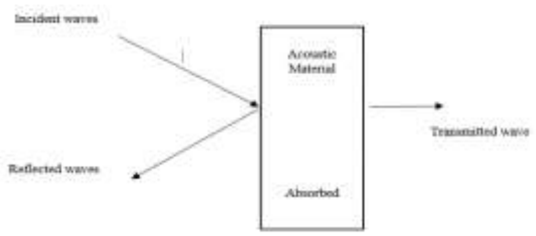

Figure 1.1 Sound absorption nature

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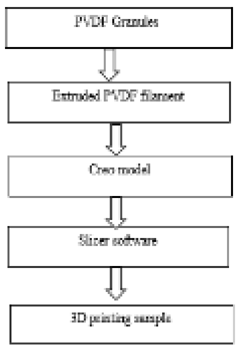
Sound absorption occurs when a material absorbs sound energy from encountering sound waves, involving processes like sound reflection, sound absorption, and sound transmission. The sound absorption coefficient (α), ranging from 0 to 1, measures the extent of sound energy absorbed by a material. A higher α value indicates better sound absorption, with $\alpha > 0.75$ denoting good sound absorbers and $\alpha < 0.25$ indicating sound-reflecting materials. Accurate determination of the α value is crucial for appropriate material application.
Three primary methodologies for determining the absorption coefficient include the Reverberation Chamber, the Reflection Method, and the Impedance Tube Method. The Reverberation Chamber method, although traditional, is space-intensive and costly, making it less suitable for research. The Reflection Method, while practical under normal room conditions, is highly sensitive to errors and thus less preferred. The Impedance Tube Method, favoured for its accuracy and practicality with smaller samples, involves a cylindrical tube with a sound source at one end and the test material at the other, measuring sound pressure at various points to calculate the sound absorption coefficient.

2. PROBLEM IDENTIFICATION

Impedance tube testing, while precise, necessitates a substantial amount of equipment, rendering it less accessible due to high associated costs. The sound absorption coefficient determined through this conventional method has not been consistently replicated using alternative innovative approaches, highlighting a gap in current testing techniques. There exists a significant demand for research on piezoelectric-based materials for acoustic applications, given their capability to convert mechanical energy into electrical energy and vice versa. However, the prohibitive costs of impedance tube testing restrict its accessibility, emphasizing the need for more affordable alternatives to thoroughly evaluate soundproofing materials. Another notable area of research pertains to the acoustic properties of 3D-printed polyvinylidene fluoride (PVDF), a piezoelectric polymer well-regarded for its chemical resilience, mechanical durability, and thermal robustness. However, the extent to which 3D-printed PVDF can effectively contribute to soundproofing applications remains largely unexplored. Investigating the capabilities of 3D-printed PVDF could yield more effective noise reduction solutions, making soundproofing more efficient and accessible. Advancing research in this field could lead to the development of innovative, cost-effective materials that address the growing demand for enhanced acoustic management across various industries, including construction and electronics.

3. MATERIAL

Piezoelectric materials generate electric charges in response to mechanical stress and undergo mechanical deformation when exposed to an electric field. These unique properties make them ideal for applications in acoustics, sensors, actuators, and energy harvesting devices. They are widely used in various industries for their ability to convert mechanical energy into electrical energy and vice versa. This dual functionality allows piezoelectric materials to play a crucial role in advanced technologies, contributing to innovations in medical devices, consumer electronics, automotive systems, and industrial equipment. Their chemical resistance, mechanical strength, and thermal stability further enhance their versatility and effectiveness.



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3.1 PVDF GRANULES

PVDF (Polyvinylidene fluoride) granules (figure 3.1) are thermoplastic polymer particles known for their piezoelectric properties, enabling conversion of mechanical stress into electrical signals. They exhibit excellent chemical resistance, mechanical strength, and thermal stability, making them suitable for diverse applications. PVDF granules are inherently non-reactive, making them ideal for use in harsh environments such as chemical processing or outdoor applications. Their high dielectric constant and low dielectric loss facilitate their use in capacitors and sensors. With a wide operating temperature range and ease of processing, PVDF granules find applications in industries ranging from electronics and aerospace to biomedical devices and energy harvesting.

Figure 3.1 PVDF granules

Table 3.1 presents the properties of PVDF granules as a piezoelectric material.

Table 3.1 Properties of PVDF granules

Properties	Value
Appearance	White Granule
Tensile strength	≥ 35 MPa
Compressive strength	14 – 172 MPa
Yield strength	4.8 – 120 MPa
Elastic modulus	0.03- 17.1 GPa
Density	0.7 – 1.89 g/cm^3
Melting point	165-175° c
Elongation at break	≥25%
Hardness	70-80
Thermal conductivity	0.2 W/m K

3.2 SINGLE-SCREW FILAMENT EXTRUDER MACHINE

Figure 3.2 is shows the single-screw filament extruder processed PVDF granules by first melting and plasticizing them. The machine's screw built pressure and sheared the molten PVDF, ensuring thorough mixing. The molten material was then conveyed to the die, where it was shaped into a filament. As the filament exited the die, it underwent cooling to solidify its form. Proper control of temperature, pressure, and screw speed was crucial throughout this process to maintain consistent filament diameter and quality. Figure 3.3 shows the PVDF filament, known for its excellent chemical resistance and mechanical properties, which makes it suitable for various high-performance applications.

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Figure 3.2 Single-screw filament extruder

Figure 3.3 PVDF Filament

3.3 MANUFACTURING PROCESS OF THE 3D-PRINTED SAMPLES

The software used to build the sample was the Cero Parametric 8.0.2.0. The geometry of the 3D (Three-dimensional printing) samples was held constant with a diameter of 99 mm and a thickness of 10 mm. After that, the file was converted to STL file type which then exported the file to Cura® software for setting the desired printing parameters. Figure 3.5 shows the 3D printed PVDF sample in Triangles, Gyroid, Honeycomb, and Tri-hexagon configurations. Table 3.2 shows the 3D printing specifications of the Creality Ender printer.

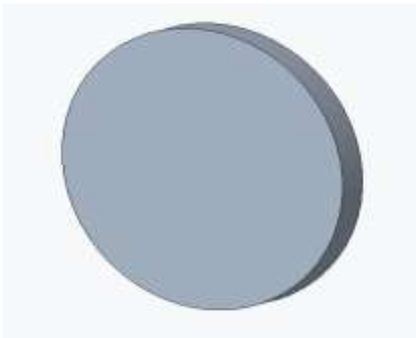

Figure 3.4 Model of sample

Table 3.2 3D printing specification

Parameter	Specification
Filaments (Ø 1.75 mm)	PVDF (polyvinylidene fluoride)
Printer Type	Fused Deposition Modeling (FDM)
Nozzle diameter	0.4 mm
Layer Height	0.2 mm
Printing speed	60 mm/s
Infill density	50%
Extrusion Temperature	220°C
Infill patterns	Gyroid, Honeycomb, Triangle, Tri hexagon

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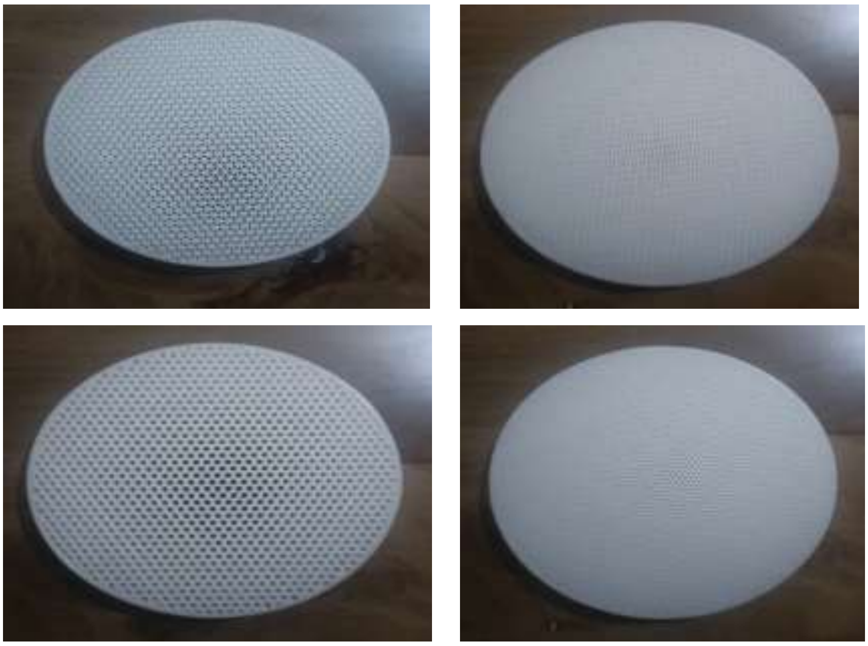

Figure 3.5 3D printed PVDF sample

4. DESIGN OF IMPEDANCE TUBE

The inner section of the tube must maintain a consistent shape throughout, whether circular or rectangular. It should remain straight with a smooth, nonporous interior surface devoid of dust to minimize sound attenuation. The tube's length should be considerable to minimize sound transmission through its walls. Materials such as cement, wood, or plastic are suitable for construction. Adequate sealing of the interior wall is essential to preserve low sound attenuation for plane waves. A loudspeaker is positioned at one end of the impedance tube, while the sample is placed at the opposite end. Following the ASTM E1050 standard, two microphones (figure 4.1) are strategically spaced within the tube to convert sound pressure into voltage signals, allowing for the calculation of absorption coefficients. To economize on setup costs, a commercially available PVC pipe has been selected, specifically a 4-inch pipe with inner diameter (Di) of 106 mm, outer diameter (Do) of 110 mm, and thickness (t) of 3 mm.

The maximum operational frequency of the system can be determined using the following formula

$$f_u < \frac{KC}{d}$$

$$f_u < \frac{0.58*343*1000}{106}$$

$$f_u = 1876.79 \text{ Hz}$$

K = 0.586, C = speed of the sound = 343 m/s

4 inch impedance tube can have the upper most working frequency of 2000 Hz

$$f_l < f < f_u$$

The tube's length must exceed three times its diameter (L > 3d). To accommodate the microphones, two holes are drilled in the PVC tube. The distance between the sample and the first microphone, denoted as X2, should surpass half the tube's diameter to ensure a flat sample surface. The spacing between the microphones can be calculated using the following formula

$$S << \frac{C}{2f}$$

$$S << \frac{343*1000}{2*1876.79}$$

$$S = 91.34 \text{ mm}$$

C= speed of sound, f= upper most working frequency

Lowest frequency response of the system is found out by the formula

$$f_l = \frac{0.1C}{2s}$$

$$f_l = \frac{34300}{182.68}$$

$$f_l = 187.76$$

The 4-inch impedance tube enables the analysis of acoustic materials within a frequency range spanning from 200 Hz to 2000 Hz. A commercially available end cap is employed as the sample holder, with reflective foil paper affixed inside to enhance its reflective characteristics. The impedance tube is constructed (Figure 4.2) from a PVC pipe, maintaining a uniform circular cross-section along its entire length. The main design parameters of the tube are summarized in Table 4.1.

Table 4.1 Parameters of the impedance tube

Parameter	Value
Inner diameter of the tube d	0.106 m
Tube wall thickness t	0.003 m
Tube length L	0.856 m
Distance X_2 of nearest microphone and sample	0.100 m
Distance s between microphone positions 2 and 1	0.09 m
Lower frequency f_l of the tube	200 Hz
Upper frequency f_u of the tube	2000 Hz

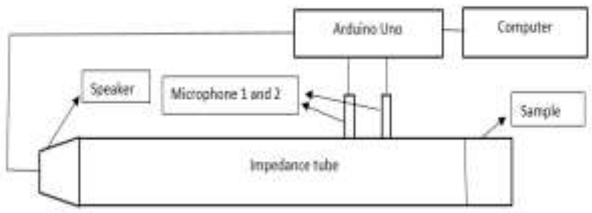

Figure 4.1 Two microphone setup


Figure 4.2 Impedance tube setup

4.1 MEASURING THE SOUND ABSORPTION COEFFICIENT USING AN ARDUINO UNO

Arduino code measures the sound absorption coefficient at various frequencies. Figure 4.3 uses two microphones connected to analog pins A0 and A1, and a speaker connected to digital pin 9. The program generates sound tones from 200 Hz to 2000 Hz in 10 Hz steps, each lasting 500 milliseconds. For each tone, the sound intensity is read from both microphones. These readings are then converted to voltage. The reflection coefficient is calculated as the ratio of the voltages obtained from the two microphones. The absorption coefficient is then calculated as one minus the square of the reflection coefficient, ensuring it remains within the range of 0 to 1.The results, including the frequency, voltages, reflection coefficient, and absorption coefficient, are printed to the serial monitor. This process provides a comprehensive overview of the material's acoustic properties across a range of frequencies, facilitating the evaluation of its soundproofing effectiveness.

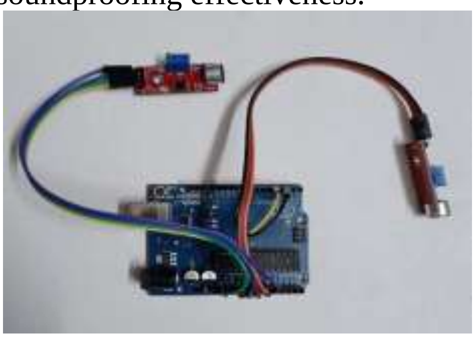
Figure 4.3 Microphone with Arduino Uno

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5. RESULT AND DISCUSSIONS

An experiment was conducted with an empty tube lined with aluminum foil. The output voltages from two microphones were measured at various frequencies. The absorption coefficient of the empty tube was then calculated using Arduino Uno programming. Now the Graph is plotted between frequency and absorption coefficient. Figure 5.1 shows variation of absorption coefficient of empty tube for various frequency.

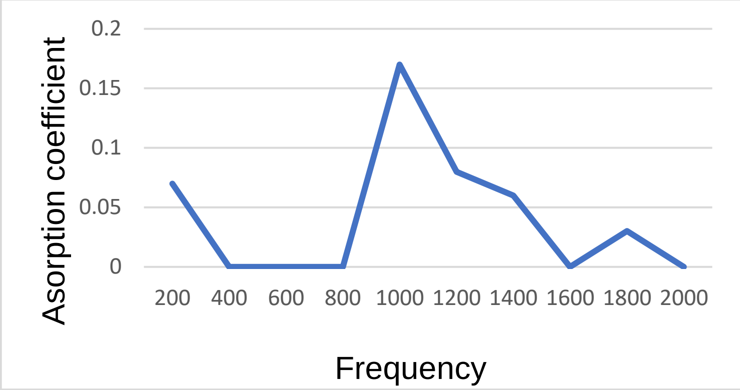

Figure 5.1 Absorption coefficient vs Frequency

Figure 5.2 shows a graph of the absorption coefficient versus frequency for an impedance tube with a 3D-printed Tri-Hexagon sample. The absorption coefficient 0.47 peaks at around 600 Hz, indicating maximum sound absorption at this frequency. It decreases sharply beyond 600 Hz, with minor fluctuations between 1000 Hz and 1800 Hz, and a significant drop near 2000 Hz.

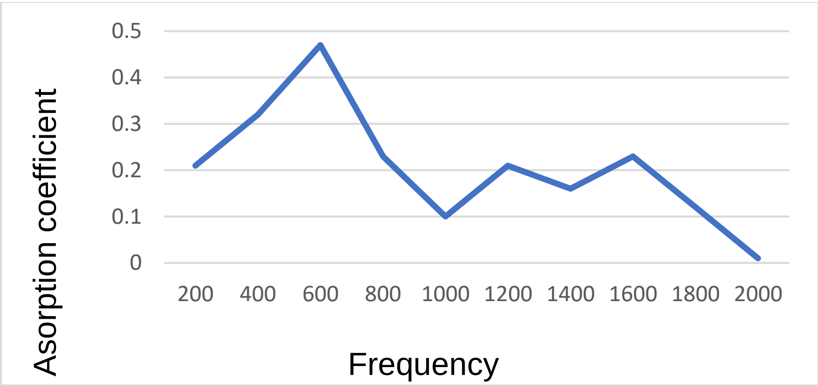

Figure 5.2 Absorption coefficient vs Frequency for Tri- hexagon sample

Figure 5.3 shows a graph of the absorption coefficient of a triangular sample across frequencies from 200 Hz to 2000 Hz. It peaks at 0.4 around 600 Hz, drops sharply near 900 Hz, fluctuates between 1000 Hz and 1800 Hz, and significantly decreases to 0.15 near 2000 Hz.

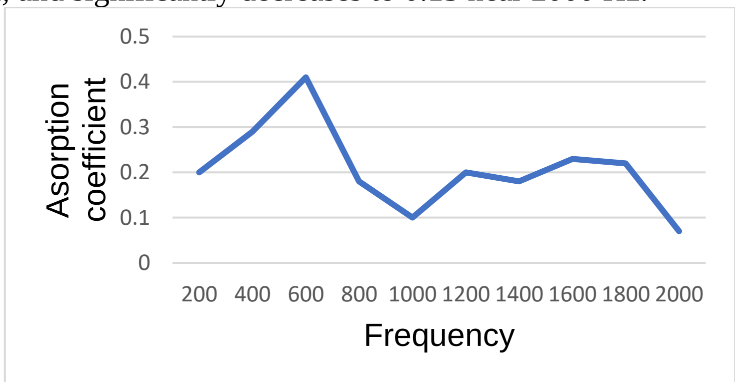

Figure 5.3 Absorption coefficient vs Frequency for Triangular sample

Figure 5.4 shows a graph of the absorption coefficient versus frequency for an impedance tube with a 3D-printed honeycomb sample. The absorption coefficient 0.25 peaks at around 600 Hz, indicating

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maximum sound absorption at this frequency. It decreases sharply beyond 600 Hz, with minor fluctuations between 900 Hz and 1800 Hz.

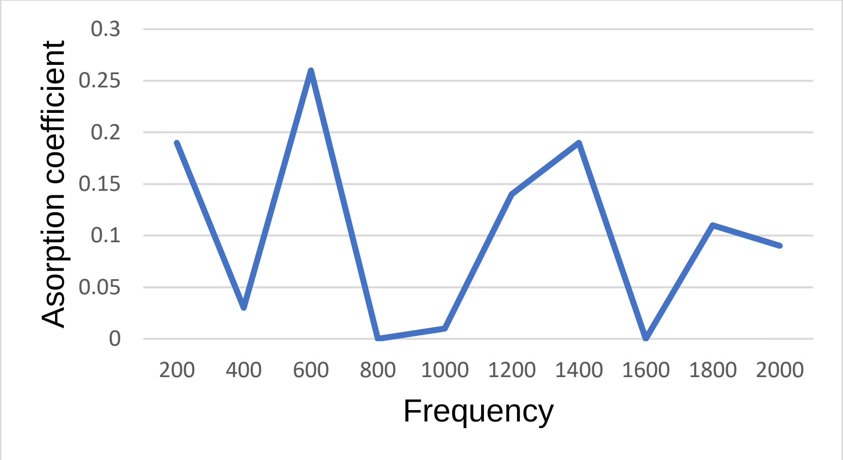

Figure 5.4 Absorption coefficient vs Frequency for Honeycomb sample

Figure 5.5 shows a graph of the absorption coefficient of a gyroid sample across different frequencies. The highest absorption coefficients, about 0.27, occur near 700 Hz and 1400 Hz. The lowest absorption, near 0, happens around 900 Hz and 1600 Hz, indicating varying absorption efficiency at different frequencies.

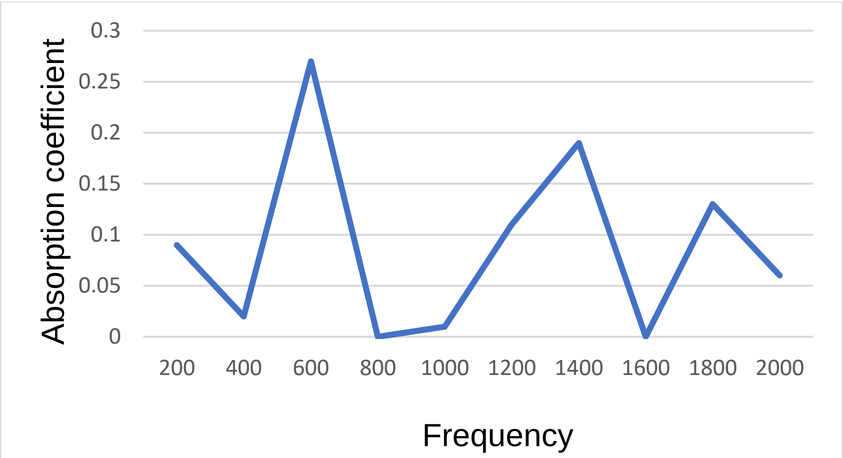

Figure 5.5 Absorption coefficient vs Frequency for Gyroid sample

6. CONCLUSION

In this work, a cost-effective impedance tube system was developed to measure the sound absorption coefficient of 3D-printed PVDF samples with four internal configurations (tri-hexagon, triangular pattern, gyroid, and honeycomb) at 50% infill density. The study found that the tri-hexagon and triangular pattern samples, which are fully dense, demonstrated superior acoustic performance compared to the partially dense gyroid and honeycomb patterns. The custom-designed PVC impedance tube and Arduino Uno-based measurement system ensured precise and reliable data collection. Additionally, the utilization of PVDF's piezoelectric properties expands the potential for advanced acoustic materials. This study highlights a novel approach to acoustic material testing by combining 3D printing with an efficient impedance tube system, significantly contributing to noise reduction technology innovations

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