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Aeroacoustic Impact of Triply Periodic Minimal Surface Porous Casings on Axial Flow Fans

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Abstract

This study investigates the effectiveness of porous casing treatments in reducing noise in axial flow fans, using various Triple Periodic Minimum Surfaces (TPMS) configurations. All TPMS-based casings outperform solid casings in minimizing radial fan noise and enhancing the casing's sound absorption capabilities. Among the structures, the Primitive type is less effective compared to the Diamond and Gyroid designs. Experimental results demonstrate that the Gyroid and Diamond casings reduce overall sound pressure levels (OASPL) by 6 dB (11%) and 8 dB (14%), respectively. They also decrease accumulated sound energy by 36% and 60%, respectively. Additionally, increasing porosity from 20% to 50% further enhances accumulated sound energy reduction by 27%. TPMS structures significantly lower sound pressure levels at Blade Passing Frequencies (BPF), with maximum noise reductions observed at BPF4 and BPF10, where noise drops by 6 dB and 7 dB, respectively. This innovative casing treatment has a marked impact on the aeroacoustic performance of axial flow fans, and the findings offer valuable insights for future noise reduction strategies using TPMS-based porous casings.

Keywords: Noise reduction, Acoustic, Experimental measurement.

1. Introduction

1.1. Literature review

An axial flow fan (AFF) is an important part of many industrial, business, and residential settings, mainly in air conditioning systems and computer cooling fans [1, 2]. Even though AFFs are very useful, they make a lot of wind noise, which is bad for both the environment and your comfort. This noise is mostly caused by things that happen when turbulent boundary layers contact with blade surfaces, like vortex shedding, boundary layer separation, and tip leakage flows. These things also make aerodynamics less effective [3, 4].

In order to reduce the noise from AFFs, many different approaches have been looked into. These include using acoustic absorbers to lower the noise [5], improving the aerodynamics of fan blades

[6], using serration techniques [7, 8], and both active and passive flow control methods [9, 10]. Recently, porous acoustic absorbers have been the focus of study that wants to find the best way to reduce noise.

Studies have shown that materials like open-cell metal foam can cut down on noise by reducing the interactions between the fan's blade and its housing, which absorbs a wide range of sound energy [11, 12]. Micro-perforated panel (MPP) dampers have also been shown to keep aerodynamic performance while significantly lowering noise levels [13-17].

Even with these improvements, Triply Periodic Minimal Surfaces (TPMS) still have a lot of untapped potential in this area. TPMS structures are known for being strong mechanically and having good acoustic qualities, such as the ability to reduce noise and vibrations that could make fan designs much better [18, 19]. Our study aims to investigate and confirm the use of TPMS-based porous covers in AFFs. We think that these designs can offer better noise reduction and aerodynamic performance.

The goal of this paper is to find new ways to use porous acoustic dampers by introducing new TPMS-based designs. These designs could set new standards for how noise is reduced in axial flow fans. This work adds to the larger conversation about improving the quality of the environment and the efficiency of fan technologies by combining advanced material science with acoustical engineering.

1.2. TPMS structures for noise reduction

Triply Periodic Minimal Surfaces (TPMS) are cellular shapes that can be told apart from each other by the way their solid and empty areas change over time. As well as having great mechanical properties like high stiffness, strength, and energy absorption, these TPMS-based systems also have great thermal and electrical conductivity, fluid permeability, and acoustic properties. Noise reduction, vibration damping, and sound absorption are some of these acoustic features [18]. According to Lin et al. [19], sandwich panels with TPMS designs are very good at blocking noise, with noise insulation levels above 20 dB across a wide frequency range. Also, Bowen et al. [20-22] looked into how TPMS-based porous leading edges could be used to lower turbulence interaction noise. According to their tests, adding porosity to the leading edge cut down on low-frequency noise by 2 to 3 decibels, but it made noise levels slightly higher above 1000 Hz. Adding a covering material to the porous leading edge, on the other hand, successfully stopped this rise in high-frequency noise.

1.3. Objectives and novelty

In axial flow fans, casings are very important for directing airflow and making sure that the flow pattern is more even. This increases the stall margin and slightly improves aerodynamic performance at both design conditions and peak efficiency [23, 24]. When a porous casing is used, it stops the tip leaking vortex and delays the start of stalling, which lowers noise levels by a lot [25]. People often use sound-absorbing materials like fibers and foams, but their weak mechanical qualities mean they can't be used in as many places [26]. When it comes to improving both the

range and efficiency of sound absorption, TPMS designs are better than traditional structures. These structures built on TPMS have better sound absorption, especially for high-frequency noise across a wide range [27, 28]. However, a search of the existing literature and earlier parts shows that the sound-absorbing properties of TPMS-based porous casings for AFFs have not been studied or used yet. Our current study aims to fill this gap by looking into how TPMS structures can be used as a new way to make AFFs less noisy. By using TPMS-based porous covers, there is a new way to lower fan noise without lowering aerodynamic performance. The design and optimization of these cases also have a lot of promise to make noise reduction technologies in AFFs better. The goal of this study is to look into the science behind these structures and how they affect the sound that fans make.

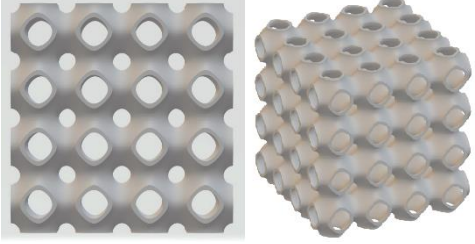
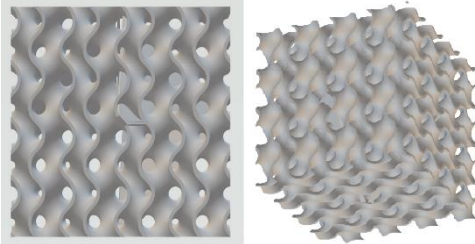
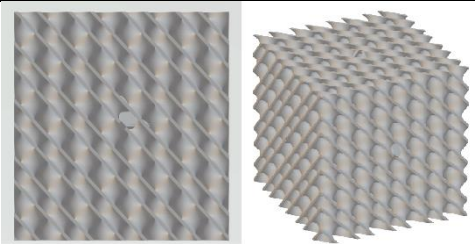
Our study helps us understand how to build and improve TPMS-based porous casings, as well as how they affect noise production and flow parameters in AFFs. Our experiment was planned so that the focus would be on the fan itself so that we could exactly test how well different TPMS-based porous casings reduced noise without having to worry about how other machine parts would affect the results. This is how the paper is put together: In Section 2, the shapes of the porous cases are described. In Section 3, the setup for the experiment is explained. Finally, in Section 4, the study's results are shown and talked about.

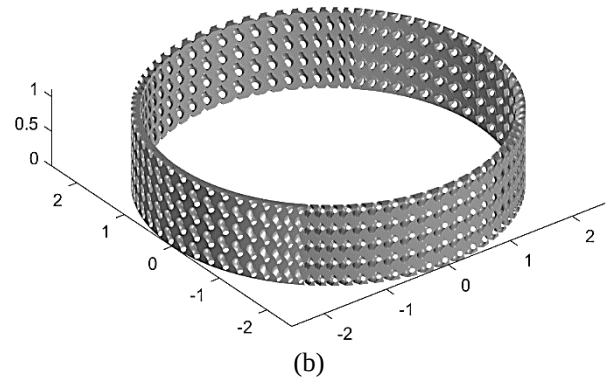
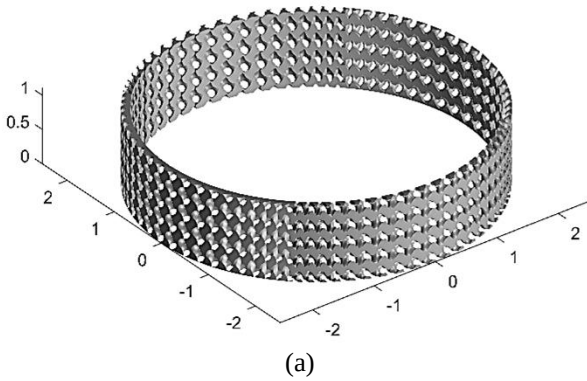
2. Casings family design

Numerous attempts have been made to create porous structures by adapting natural porous architectures. In recent years, TPMS structures have gained popularity as a means to produce porous structures with interconnected porous regions and mathematically controllable geometrical characteristics. TPMS structures can be expressed as algebraic equations using trigonometric functions [29]. The primary TPMS structures include Primitive (P), Diamond (D), and Gyroid (G), with their mathematical equations and Unite cell geometries presented in **Table 1**.

TPMS structures have two primary parameters C and $\vec{\omega}$, where C is known as the isovalue and affects the pore size and porosity of the structure. $\vec{\omega}$ is the effective geometric parameter and determines the size of the unit cell. If $\vec{\omega}$ remains constant in all three directions, the resulting TPMS structure is uniform. At the end of the section, **Figure 1** showcases various instances of TPMS-based porous casing employed in this matter, exhibiting distinct configurations and porosities.

Table 1. Mathematical formulation and microscopic detail for various types of TPMS structures.

TPMS Structure	Mathematical expression	Microscopic detail
Primitive (P)	$f(x, y, z) = \cos(\omega_x x) + \cos(\omega_y y) + \cos(\omega_z z) = C$	
Diamond (D)	$f(x, y, z) = \cos(\omega_x x) \cos(\omega_y y) \cos(\omega_z z) - \sin(\omega_x x) \sin(\omega_y y) \sin(\omega_z z) = C$	
Gyroid (G)	$f(x, y, z) = \sin(\omega_x x) \cos(\omega_y y) + \sin(\omega_z z) \cos(\omega_x x) + \sin(\omega_y y) \cos(\omega_z z) = C$	



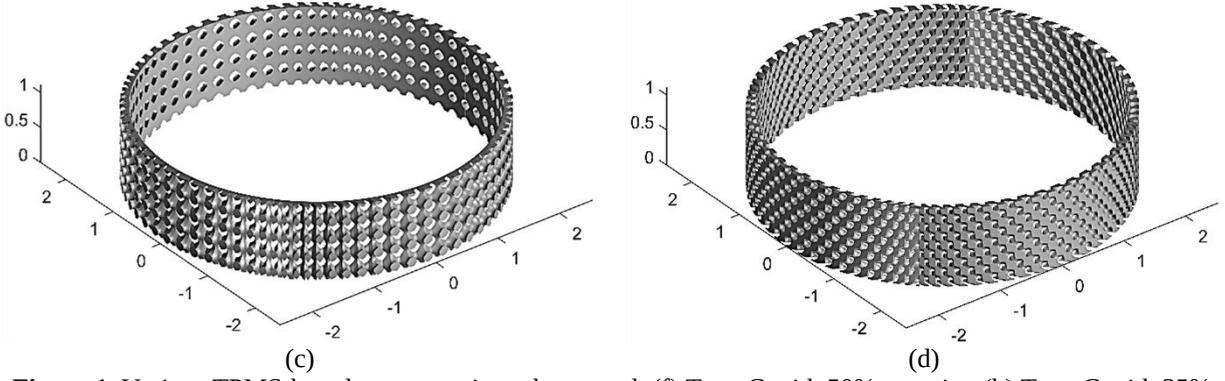


Figure 1. Various TPMS-based porous casings showcased: (f) Type G with 50% porosity, (b) Type G with 35% porosity, (c) Type P with 50% porosity, and (d) Type D with 50% porosity.

In order to create structures based on TPMS, a MATLAB code has been developed in cylindrical coordinates. Within this endeavor, an examination was conducted to understand how porosity and pore size vary with respect to the isovalue. As shown in **Table 2**, their trends were then approximated through the use of first and third-order polynomials (expressed as $ax + b$ and $ax^3 + bx^2 + cx + d$, respectively). To validate the accuracy and reliability of the findings, a comparison was made between the porosity and pore size graphs based on isovalue values and the results from the study conducted by Perez-Boerema et al [30]. As illustrated in **Figure 2a**, the results align well for porosity in Gyroid mode, and the first-order linear function estimation is accurate. However, for the Primitive mode, discrepancies emerge in the range above 75% and below 25%, and these values are excluded from the analysis. Furthermore, **Figure 2b** makes it clear that the 3rd order polynomial provides a more suitable representation of the pore size behavior.

Table 2. Parameters of the polynomial equations used for fitting.

TPMS	Function	isovalue variation range	Coefficients			
			a	b	c	d
Gyroid	porosity	$-1.5 < C < 1.5$	0.5	1/3	--	--
	pore size	$-1.5 < C < 1.5$	0.4281	-0.16	-0.000237	-0.0432
Primitive	porosity	$-3 < C < 3$	0.5	1/6	--	--
	pore size	$-3 < C < 3$	0.8473	-0.1631	-0.0015	-0.0103

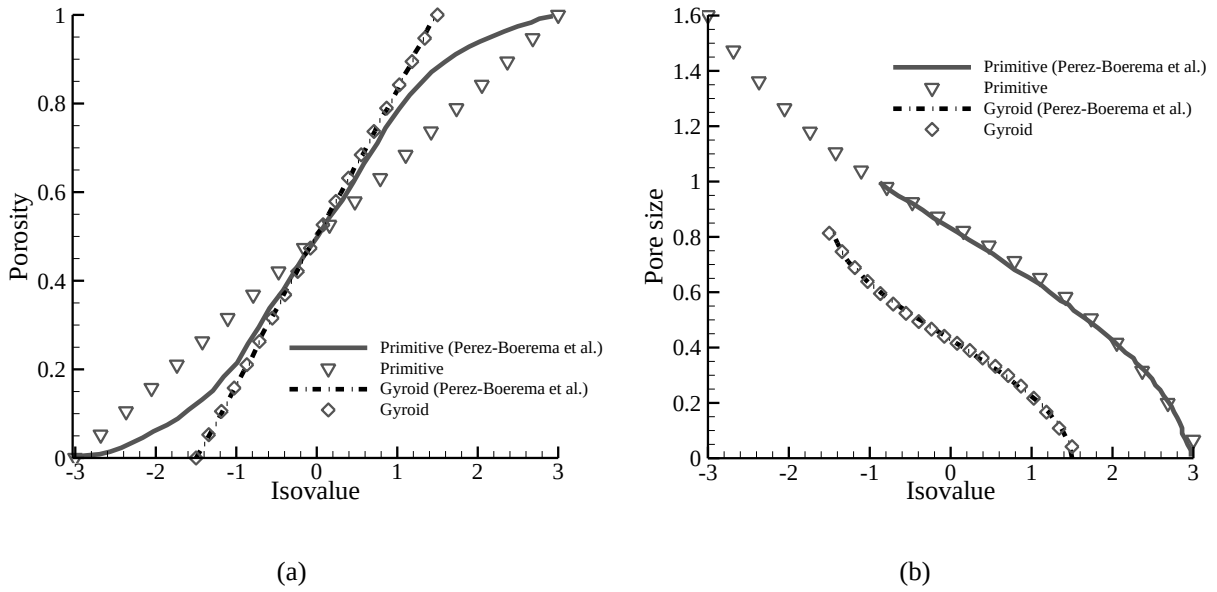


Figure 2. Contrasting the outcomes of the geometrical characteristics of Gyroid and Primitive structures with those reported by Perez-Boerema et al. [30], (a) porosity, and (b) pore size.

3. Experimental setup

3.1. The testing Axial-flow fan

In the experimental acoustic test, an axial flow fan measuring 120 mm x 120 mm x 25 mm with seven blades was utilized, as shown in **Figure 3**. The fan operates at a rotational speed of 1200 rpm, with a blade passing frequency of 140 Hz. The hub radius, tip radius, and tip clearance of the rotor blades are 23 mm, 55 mm, and 2 mm, respectively (Shown in **Table 3**). The axial flow fan being examined is utilized for computer cooling, with its casing made of plastic. After careful consideration, polylactic acid (PLA) was chosen for this research as the 3D printing material. PLA, with a density of 1250 kg/m³ and an average Young's modulus of 3.225 GPa, is highly compatible with 3D printing techniques. This compatibility enables precise control over the complex geometries required for TPMS systems, making it an ideal material for the study.

Table 3. The detailed parameters used in AFF design.

Casing axial length L (mm)	22
Hub radius h (mm)	23
Rotational speed (rpm)	1200
Casing outer radius r_o (mm)	60
Casing inner radius r_i (mm)	57
Hub axial length w (mm)	16
Tip Clearance t_c (mm)	2
Rated voltage (VDC)	12
Rated current (A)	0.06
total volume flow rate (CFM)	65

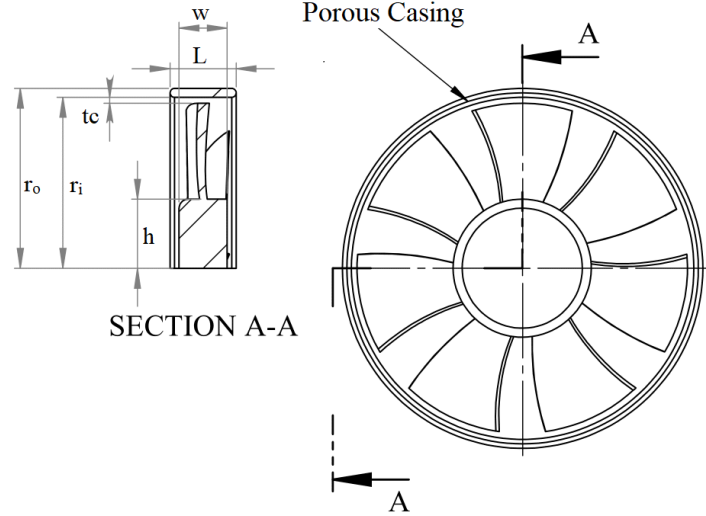


Figure 3. The AFF's geometric requirements.

3.2. The acoustic measurement

All measurements were conducted in an anechoic chamber with dimensions of 3 m x 3 m x 4 m and a cut-off frequency of 100 Hz. As shown in **Figure 4**, the sound was measured by manually placing a microphone at 12 different points on a sphere, positioned 0.8 meters from the center of the rotor, with an angular interval of 45 degrees between each point.

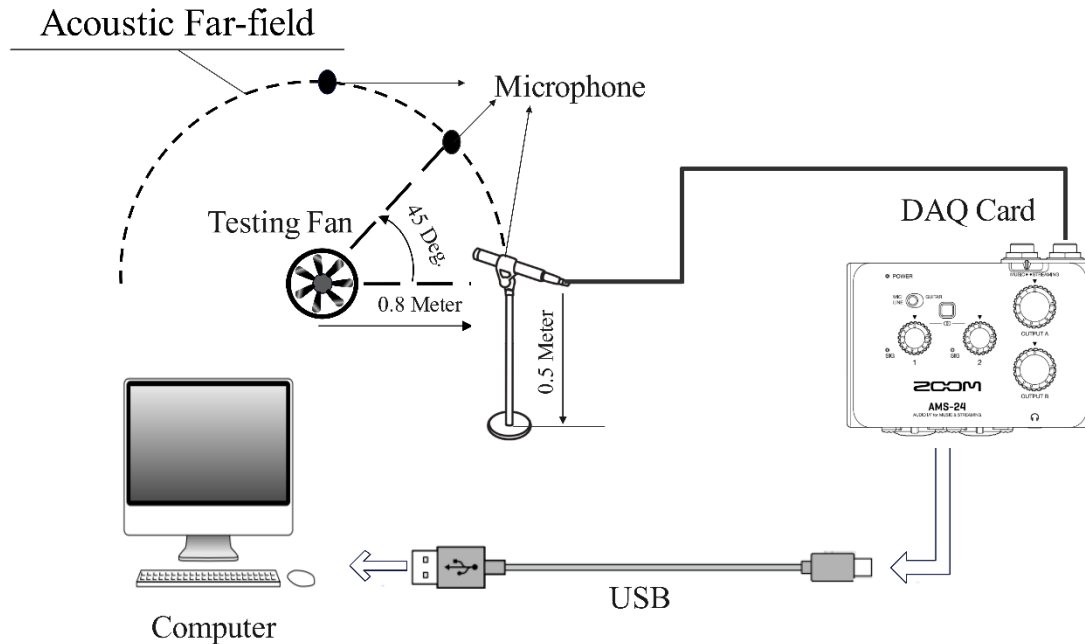


Figure 4. Schematic representation of experimental setup and microphone array.

The experimental setup and its components are illustrated in **Figure 5**. The components are shown schematically, and during the main test, the power supply and laptop were positioned outside the

acoustic room. Additionally, **Figure 5c** shows the TPMS-based porous casings, which were produced using 3D printing technology. The microphone was placed at a standard distance from the chamber's absorbing wedges to minimize the impact of wall reflections. The procedure followed the Iranian national standard ISIRI 6184: Acoustics – Determination of sound power levels of noise. A PreSonus® PRM1 microphone, with a frequency range of 20 Hz to 20 kHz and a sensitivity of 14 mV/Pa, was used for the measurements. Noise data was sampled at 44.1 kHz using a Zoom AMS-24 USB Audio Interface (24-bit). Each data acquisition lasted for 20 seconds. The recorded signals were processed on a personal computer using MATLAB software, and the average sound spectrum was calculated and presented as sound pressure level (SPL in dB). Additionally, background noise was measured, which refers to the ambient sounds present when the fan is off, including noises from the operator, equipment movements, and room ambience.

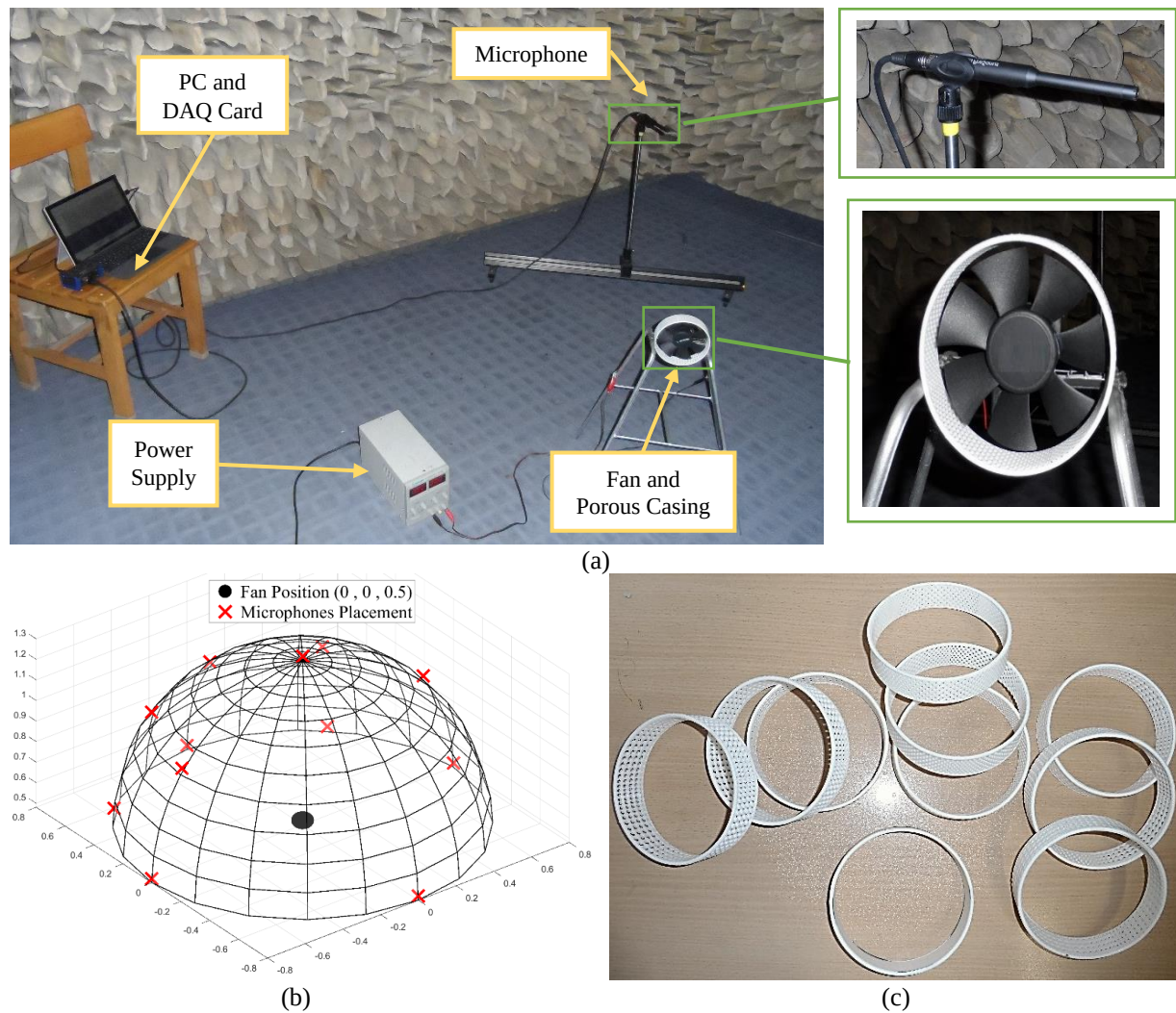


Figure 5. A schematic of the experimental setup for measuring axial flow fan noise using a single microphone: (a) Overall view of the acoustic chamber apparatus, (b) Microphones position on sphere surface and (c) the casings under investigation.

4. Results and discussion

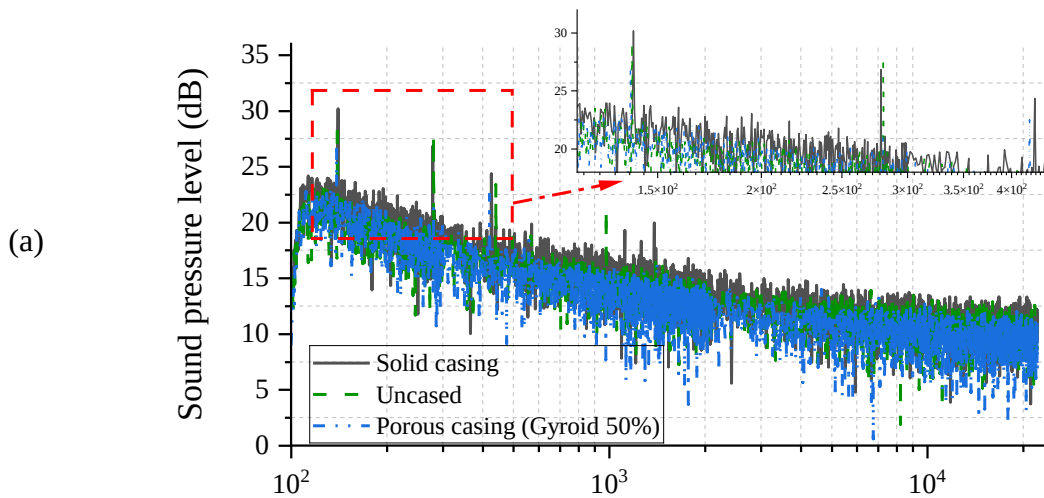
4.1. Spectral analysis of AFF noise

Figure 6 presents a comparative analysis of (a) the sound pressure level (SPL) and (b) the accumulated sound energy spectrum for an axial flow fan with three different casing configurations: solid casing, uncased, and porous casing (Gyroid 50%). The SPL curve alone is insufficient for depicting sound energy distribution, so the accumulated sound energy (ASE) curve is used for clarity. The accumulated sound energy spectrum is defined as:

$$E = \int p^2 df \quad (1)$$

Where p^2 represents the power spectral density of the received acoustic pressure. The porous casing consistently outperforms the solid casing in both SPL and ASE. While the uncased configuration provides moderate noise reduction, it is generally more efficient than the solid casing but less effective than the porous casing. Overall, the porous casing treatment significantly reduces fan noise, as shown in **Figure 6a**, where it decreases SPL by 3 to 4 decibels across most frequencies. As shown by the area under the curve in **Figure 6b**, the porous casing reduces the accumulated acoustic energy by roughly $36\% \pm 3\%$. The SPL curve in **Figure 6a** highlights a marked reduction in the first three dominant tones, and the ASE curve in **Figure 6b** confirms a significant decrease in sound energy in these frequency ranges. Although the porous casing's sound absorption performance weakens at the blade passing frequencies (BPFs), it still enhances noise reduction in general.

Figure 7 shows the overall sound pressure level (OASPL) distribution for the three casing configurations. The porous casing reduces noise across all radial directions of the fan, resulting in an average OASPL reduction of 6 dB ($11\% \pm 1.5\%$). However, selected points on the left side of the fan exhibit higher noise levels, likely due to the fan's counterclockwise rotation and the interaction between the separation vortex and the tip vortex of the next blade.



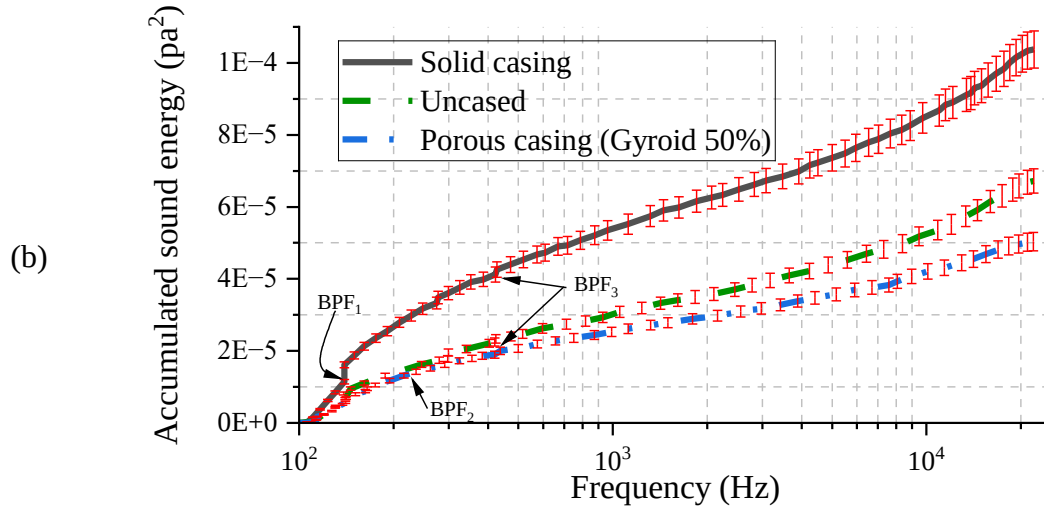


Figure 6. Comparative analysis of sound pressure level and accumulated sound energy spectra for fan with solid casing, uncased, and Gyroid porous casing under identical operating conditions.

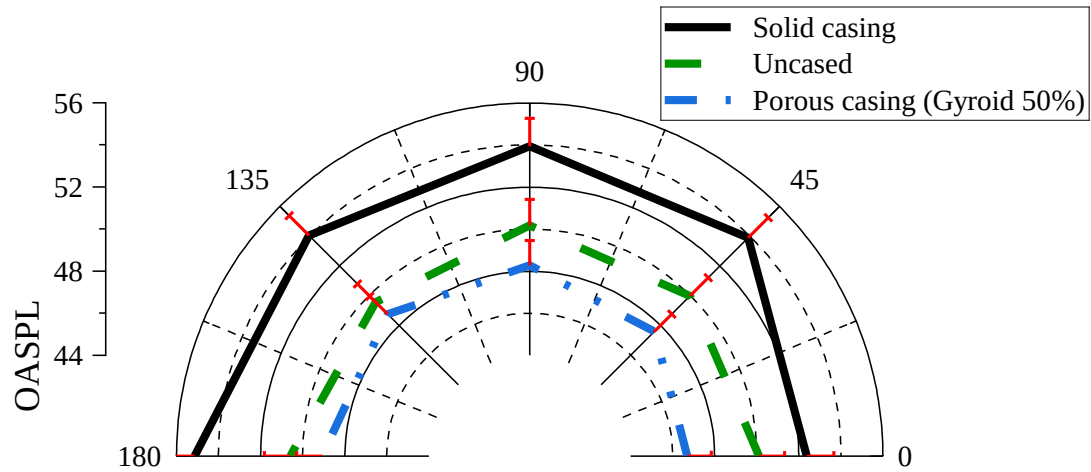


Figure 7. OASPL distribution curve for fan with solid casing, uncased, and Gyroid porous casing under identical operating conditions.

When evaluating data from this measurement system, it's essential to account for repeatability error to determine the significance of any observed differences or trends. The **Figure 8** displays the repeatability error curve for acoustic measurements, specifically the sound pressure level (SPL). As shown, the error is minimal across most frequencies, typically below ± 1 dB (the average error rate is 1.5%). The error appears random, with no discernible pattern or trend, indicating that the fluctuations in the data are likely due to inherent noise within the measurement system or slight variations in testing conditions.

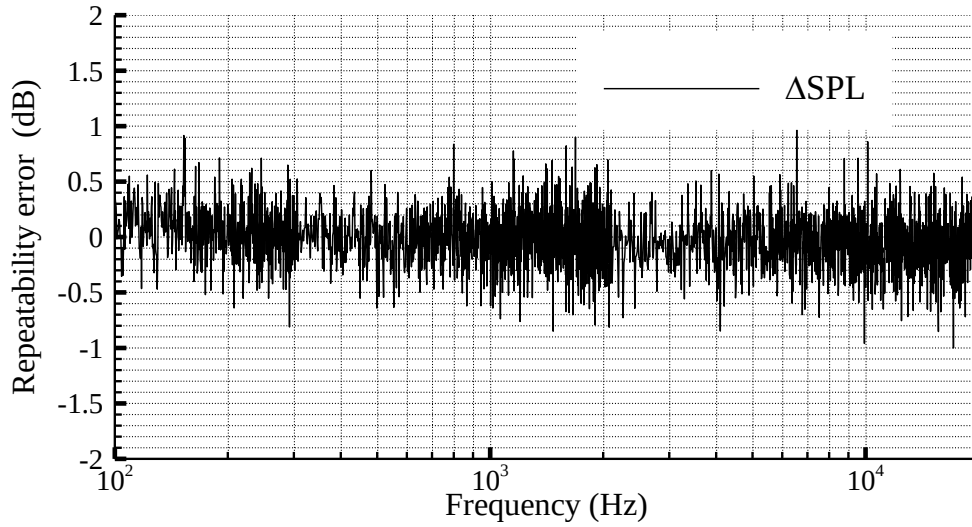


Figure 8. Repeatability error curve in acoustic measurement.

4.2. Effect of the porous casing type

The **Figure 9** illustrate a comparative analysis of the sound pressure level (SPL) and accumulated sound energy spectra for an axial flow fan equipped with three different TPMS-based porous casings: Primitive, Diamond, and Gyroid. As shown in **Figure 9** and supported by the data in **Table 4**, the Diamond casing generally exhibits the lowest SPL across most frequencies. Additionally, all three casings, particularly the Diamond, demonstrate a notable impact in reducing noise, especially at higher frequencies. Based on the accumulated sound energy spectra, both the Gyroid and Diamond casings outperform the Primitive casing in noise reduction, lowering radial noise from the fan by an average of 2 to 4 decibels per frequency. Furthermore, at frequencies above 1000 Hz, the sound energy difference between the Primitive and Diamond casings surpasses $1\text{E-}05$. Additionally, the Diamond casing achieves a $24\% \pm 2.5\%$ greater noise reduction compared to the Gyroid structure. This is a notable distinction, as reflected in the curve, highlighting the superior performance of the Diamond casing in noise reduction at higher frequencies. the Diamond structure is defined by its intricate network of interconnected cells with sharp angles and varying cross-sectional areas, which effectively scatter sound waves through angular transitions and edges. The sharp edges also create a thicker boundary layer, resulting in a more viscous region and greater viscous damping, which enhances sound energy dissipation near the casing wall. Additionally, its high surface area-to-volume ratio promotes sound absorption by increasing wave-material interaction, while its labyrinthine pore pathways further enhance scattering efficiency. In comparison, the Gyroid structure is isotropic with smooth, curvilinear surfaces. Although its moderate surface area reduces scattering efficiency relative to the Diamond, it still provides notable sound absorption. the Primitive structure, with simple ellipsoidal pores, features fewer sharp edges, a lower surface area-to-volume ratio, and more direct, less intricate pore pathways, resulting in reduced scattering and absorption capabilities compared to the Diamond and Gyroid configurations. As shown in **Table 4**, using any type of porous casing provides a clear benefit by

significantly reducing noise at the primary dominant tones, particularly at the blade passing frequency (BPF). For example, at BPF2, noise levels are lowered by 18% and 21%, respectively. Visual analysis further highlights a considerable decrease in SPL for fans with TPMS-based porous casings when compared to those with solid casings. The TPMS-based porous casing fans demonstrated more pronounced SPL fluctuations, particularly at higher frequencies. This could be attributed to the interaction between sound waves and the porous casing structure.

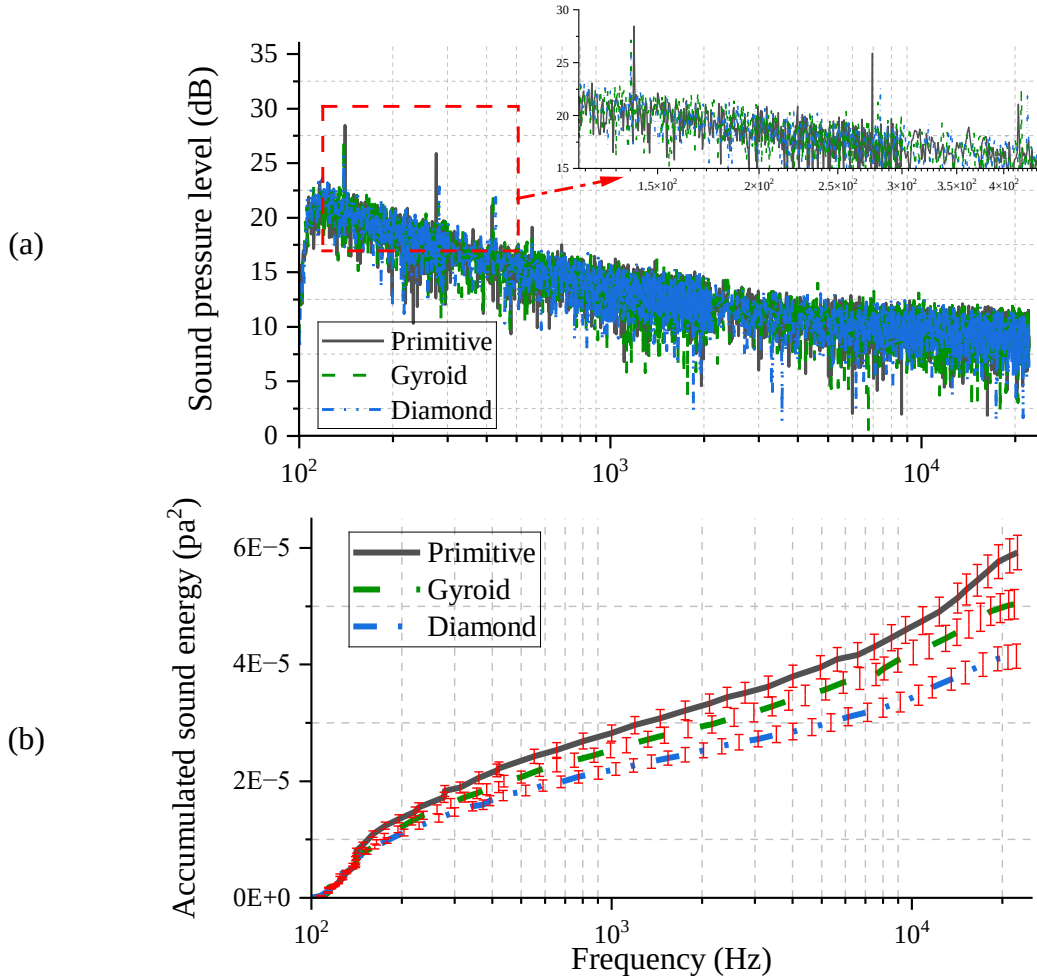


Figure 9. Comparative analysis of sound pressure levels and normalized accumulated sound energy spectra for fans with TPMS-based porous casings (Primitive, Diamond, and Gyroid) under identical operating conditions.

Table 4. Acoustic benefits of TPMS-based porous casings at blade passing frequencies.

	Blade Passing Frequency (Hz)	BPF ₁ 140 Hz	BPF ₂ 280 Hz	BPF ₃ 420 Hz
Solid Casing	SPL (dB)	30.21	26.85	24.37
Gyroid	SPL (dB)	27.12	22.03	22.50
	benefit (dB)	3.09	4.82	1.87
Diamond	SPL (dB)	25.77	21.23	20.82
	benefit (dB)	4.44	5.62	3.55
Primitive	SPL (dB)	28.45	24.68	21.08
	benefit (dB)	1.76	2.17	3.29

4.3. Effect of casing porosity percentage

The figures provide a comparative analysis of the accumulated sound energy spectra for an axial flow fan using three different Gyroid porous casings—20%, 35%, and 50%—operating under identical conditions (**Figure 10**). The analysis is presented both in the frequency domain and through acoustic benefits curves (**Figure 11**), demonstrating how various Gyroid casings affect noise reduction in axial flow fans. All three Gyroid casings outperform the solid casing in noise reduction, with the 50% Gyroid casing offering the most substantial noise reduction across all frequencies. Higher porosity indicates a larger volume of interconnected, air-filled pores within the structure. As sound waves travel through these pores, they dissipate energy due to viscous and thermal losses caused by the complex, tortuous pathways of the material. As frequency increases, the accumulated sound energy generally rises for all configurations, but the 50% Gyroid casing consistently maintains the lowest accumulated sound energy. In higher frequencies, the 50% casing reduces sound energy by over $27\% \pm 2\%$ compared to the 20% porous casing. At lower frequencies, the 50% Gyroid casing provides the greatest acoustic benefit, though this diminishes as frequency increases. However, the 50% casing may still show an acoustic benefit at higher frequencies. While higher porosity casings generally perform better at lower frequencies, between 700–1000 Hz, lower porosity casings may have a benefit. According to **Figure 11**, despite potential noise increases at certain BPFs, porous casings with any porosity level are preferable to solid casings for noise reduction.

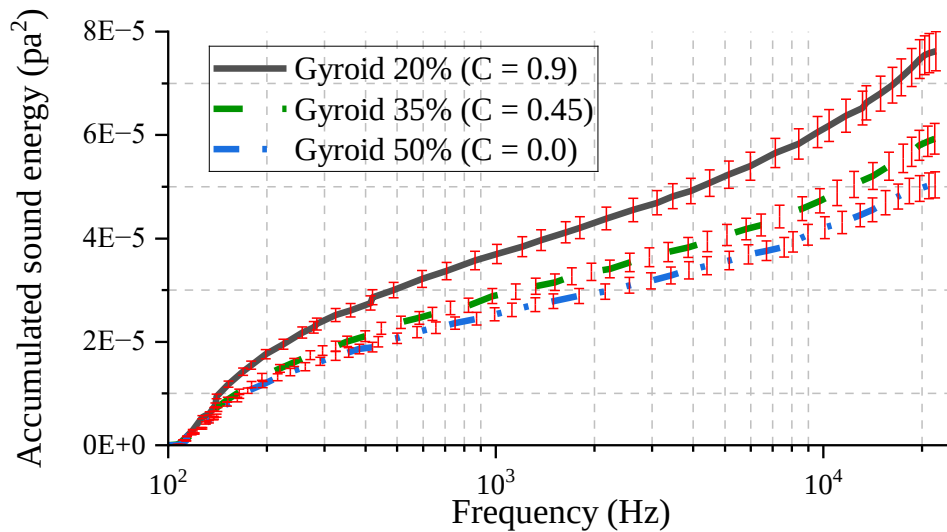


Figure 10. Comparative analysis accumulated sound energy spectra for fans with Gyroid porous casings (20, 35, and 50%) under identical operating conditions.

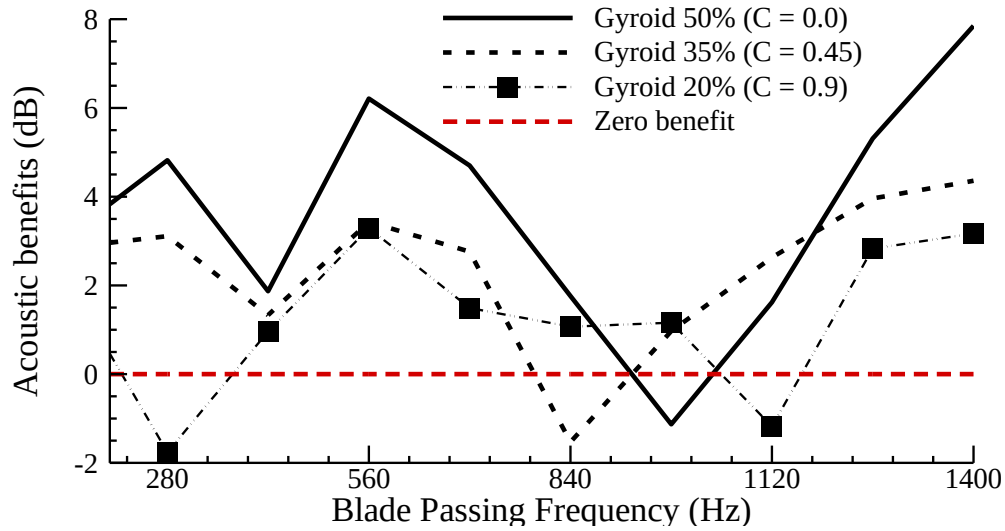


Figure 11. Acoustic benefits curves based on blade passing frequency for various percentages of Gyroid porous casings.

5. Conclusion

The study serves as a foundation for understanding how TPMS structures can be used to reduce noise in axial flow fans. Given that fans are a critical component in air conditioning systems and are often located near people, minimizing their noise is essential. All TPMS casings demonstrated superior noise reduction compared to solid casings, with the Diamond casing performing the best, particularly at lower frequencies. While the Primitive and Gyroid casings were also effective, they did not perform as well as the Diamond structure.

The research yielded the following key findings:

1. The type of TPMS structure significantly influences noise reduction. The Gyroid and Diamond structures reduced overall sound pressure level (OASPL) by 6 dB (11%) and 8 dB (14%), respectively. Additionally, they lowered accumulated sound energy by 36% and 60%, according to the area under the curve, thereby enhancing the casing's sound absorption capabilities. Any TPMS structure effectively reduces SPL at dominant frequencies.
2. Porosity percentage plays a crucial role in noise reduction. Increasing porosity (void volume) from 20% to 50% led to a 27% greater reduction in accumulated sound energy. In general, TPMS structures with any porosity level offer significant acoustic benefits across most dominant frequencies when compared to solid casings.
3. This paper suggests that TPMS structures offer a novel casing treatment for reducing noise in axial flow fans. Additionally, these structures have potential for broader industrial applications, as they can be adapted using scaling approaches and aeroacoustic similarity parameters [31].

272 **Data Availability**

273 The data used to support the findings of this study are available from the corresponding author
274 upon request.

275 **Conflicts of Interest**

276 The authors declare that there is no conflict of interest regarding the publication of this paper.

277 **Funding Statement**

278 The authors have no relevant financial or non-financial interests to disclose.

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