

Broadband Duct Noise Reduction Using Multi-chamber Micro-perforated Panel Absorbers

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This study explores the efficacy of Multi-chamber Micro-perforated Panel Absorbers (MC-MPPAs), a newly identified metamaterial, as a liner for attenuating noise within duct walls. The project aimed to develop MC-MPPA liners implemented across all four walls of the duct, engineered to attenuate noise over a broad frequency range from 500Hz to 4500Hz. Each of the four liners, with a depth of only 35 mm, was optimized for different, overlapping frequency ranges to maximize duct noise reduction. Experimental results demonstrated a significant noise transmission reduction, with MC-MPPA liners achieving an insertion loss of 15-20 dB on average, and a peak reduction of 40 dB at around 1500 Hz, compared to a hard-wall baseline. This substantial reduction in Sound Pressure Level (SPL) not only proves the potential of MC-MPPA as an effective sound attenuation material but also highlights its applicability in enhancing duct noise control technologies. The success of this project offers a promising solution in duct noise reduction strategies.

I. Introduction

As urbanization and industrialization advance globally, environmental noise pollution, particularly from industrial sources such as duct systems, has become a significant concern [1–3]. Duct noise, primarily caused by turbulent fluid motion and mechanical vibrations, not only disrupts the quality of life but also poses health risks [4, 5]. Addressing this noise efficiently is crucial, particularly in expansive industrial setups and HVAC (Heating, Ventilation, and Air Conditioning) applications in urban buildings. The development and optimization of effective noise control technologies, especially over a broad frequency range, remain imperative. Traditional acoustic absorbers, such as fibrous materials and foam, are effective at absorbing mid to high-frequency sounds but are less efficient at low frequencies unless they are impractically thick or dense [6–8]. Moreover, environmental and durability concerns limit their application in sensitive or harsh environments. Consequently, the exploration of alternative solutions that are effective across a wide range of frequencies, including the troublesome low frequencies, is vital.

Metamaterials, engineered composites with novel properties not found in nature, have revolutionized various scientific fields [9]. Recently, their application in acoustics, specifically for noise reduction in duct systems and aeroengines, has emerged as a promising research area [10–20]. Ross et al. [21] designed and evaluated an inlet liner a *3D printed* advanced MDOF technology/acoustic metamaterial in the Advanced Noise Control Fan (ANCF). To the author’s best knowledge, this is the first occasion results from testing *3D printed* advanced MDOF technologies in an engine nacelle have been published. Neubauer et al. [22] investigates an innovative liner design aimed at enhancing low-frequency and broadband sound attenuation. This study focuses on two variations, employing Helmholtz and plate resonators, and utilizes flexible damping materials. The research encompasses both experimental and numerical methodologies. Additionally, it addresses the design and manufacturing of curved liners, their application in jet engines, and conducts a comparative analysis of their acoustic and mechanical performance, underscoring the challenges and potential for future implementation. Kohlenberg et al. [23] proposed a novel resonator with a flexible plate dividing the back cavity, integrating the Helmholtz resonator’s damping with the flexible plate’s material damping. This design, supported by an analytic waveguide theory model and validated by wind tunnel experiments, effectively dissipates low-frequency noise. Hossain et al. [24] developed novel low frequency absorber where the eigenmodes of a flexible plate valve are coupled with a Helmholtz resonator. Sugimoto et al. [25] proposed the concept of folded cavity liners. In this study, the efficacy of these liners in attenuating mid-high frequency community noise, as well as low-frequency noise, was explored. By varying the geometry and properties of resistive layers, the performance of these liners can be optimized across a broad frequency spectrum. McKay et al. [26] introduced an innovative sound absorber, termed

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SeMSA, which utilizes the viscothermal dissipative properties of a micro-perforated plate coupled with decorated membrane resonators to effectively attenuate its frequency response. Experimental evidence indicates that this compact absorber achieves low-frequency broadband sound absorption at shallow depths, despite its subwavelength thickness [26]. Additionally, Killeen et al. [27] implemented a SeMSA liner within a fan-cooled electronics unit modeled after a server rack to assess its viability as a noise-reducing technology. Remarkably, this 15 mm-thick SeMSA liner decreased the blade pass frequency (BPF) noise by 3 dB at 620 Hz. In summary, the reduction of duct noise continues to necessitate designs that not only effectively mitigate noise but also incorporate a lightweight, structurally simple, environmentally sustainable, and compact form factor.

Micro-perforated panel (MPP) absorbers have emerged as a promising solution due to their high acoustic absorption efficiency, mechanical simplicity, and excellent environmental resilience [28–30]. MPPs absorb sound primarily through the viscous and thermal losses at the perforations when an acoustic wave interacts with the panel. However, their performance traditionally peaks at specific frequencies determined by the perforation characteristics and the backing cavity depth, which constrains their application in scenarios requiring broadband noise absorption. The concept of using multiple chambers in MPP absorbers represents an evolution in the design of acoustic treatments, allowing for targeted absorption across a broader spectrum of frequencies [31–33]. The multi-chamber design allows the differing geometric parameters of a tessellated network of chambers to be combined to maximise the sound absorption in a frequency range without compromising the absorber’s thickness and weight. The theoretical foundation for multi-chamber MPP absorbers suggests that by careful design of the chambers’ dimensions and the perforation parameters, it is possible to make multi-chamber MPPs particularly suitable for applications requiring broadband noise control.

This study advances the application of multi-chamber micro-perforated panel absorbers (MC-MPPA) to improve broadband noise absorption in duct environments, assessing their performance through experimental methods. Specifically, the primary objective is to refine the MC-MPPA design to achieve effective broadband duct noise reduction. To this end, MC-MPPA liners will be fabricated and optimized for four specific, overlapping frequency ranges. These liners will be installed on all four sides of a newly designed rectangular impedance tube, facilitating a comprehensive evaluation under conditions of grazing acoustic incidence. By individually optimizing each liner for a discrete, yet overlapping frequency band and integrating these through a quad-wall configuration, this approach aims to comprehensively attenuate noise transmission across a wide frequency spectrum, from 500 Hz to 4500 Hz.

II. Design and Methods

As illustrated in Fig. 1, a rectangular MC-MPPA is characterized by adjacent panels with differing porosities and has varying depths of its sub-chambers. The investigated MC-MPPA structure is divided into nine chambers in a 3×3 configuration, where each chamber can possess unique depths and is separated by micro-perforated adjacent panels. The dimensions of the MC-MPPA are denoted by length L and width W . The thickness of the *top* MPPs in the MC-MPPA is symbolized as τ_t , whereas the thickness of the *internal* micro-perforated adjacent panels is represented by τ_i . The total height, H , of the MC-MPPA is obtained by summing τ_t and the maximum sub-chamber depth, $D_{\max}$. Throughout this paper, the overall MC-MPPA depth specifically refers to the deepest sub-chamber’s depth, $D_{\max}$. The key parameters of the investigated MC-MPPA are outlined in Table 1. We keep the perforation number n as a variable as its control is necessary to prevent an unreasonably high value inhibiting manufacture. In addition, both τ_t and τ_i are fixed with predefined thicknesses corresponding to off-the-shelf availability. Whilst both of these parameters could be allowed to vary relative to each other and as a function of sub-chamber in the optimization routine, it was decided that a constant plate thickness from chamber to chamber would be much more practical for manufacture/assembly.

The calculation of each MPP’s acoustic impedance Z_{mpp} can be conducted using Eq. (1) where the dependance on ω in this equation and in most others is omitted for brevity:

$$\frac{Z}{\rho_0 c_0} = - \left(\frac{i\omega}{c_0 \varphi} \frac{\tau + 8d\Lambda(\varphi)/3\pi}{Y_v} \right) \quad (1)$$

Here, i denotes the imaginary unit, ρ_0 is indicative of the air density, and c_0 represents the speed of sound within air. The angular frequency, ω , is formulated as $\omega = 2\pi f$, with f signifying the frequency, measured in Hertz. The equation is that used by COMSOL for its interior perforated thin panel (IPP) boundary condition which builds on the theories of Rayleigh [34] and Crandall [35]. Previous numerical studies have validated that this IPP method closely aligns with a thoroughly resolved representation of perforated holes in a COMSOL model [26].

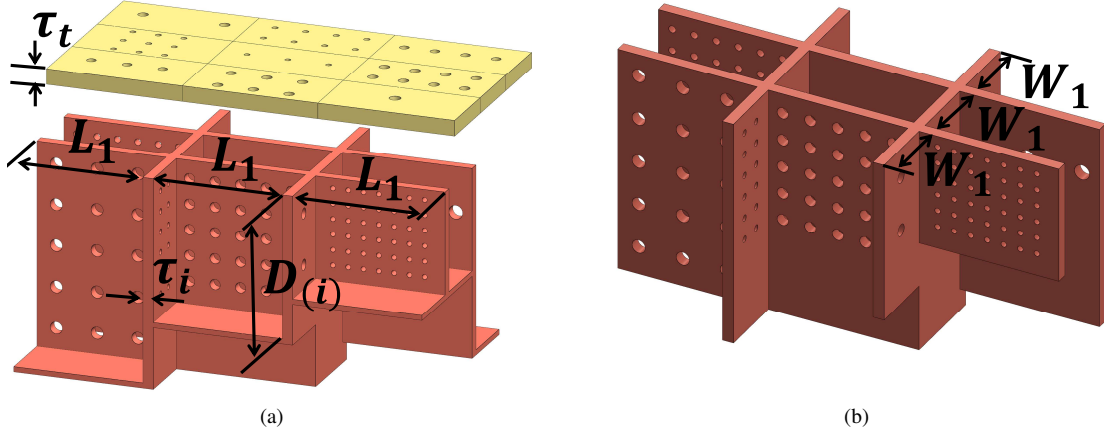


Fig. 1 Schematic of the enhanced MC-MPPA. (a) Structural arrangement of the MC-MPPA. (b) Micro-perforated adjoining panels of the MC-MPPA with varying sub-chamber depths. Solid bases and top MPP not shown for clarity.

Table 1 The parameters that define the acoustic behavior of the MC-MPPA under study.

Location of MPPs	Symbol of MPPs	Panel thickness	Perforation diameter	Perforation porosity	Perforation number	Sub-chamber depths
Top surface	MPP _{t(1)}	τ_t	$d_{t(1)}$	$\varphi_{t(1)}$	$n_{t(1)}$	$D_{(1)}$
	MPP _{t(2)}		$d_{t(2)}$	$\varphi_{t(2)}$	$n_{t(2)}$	$D_{(2)}$
	MPP _{t(3)}		$d_{t(3)}$	$\varphi_{t(3)}$	$n_{t(3)}$	$D_{(3)}$
	$\vdots$		$\vdots$	$\vdots$	$\vdots$	$\vdots$
	MPP _{t(9)}		$d_{t(9)}$	$\varphi_{t(9)}$	$n_{t(9)}$	$D_{(9)}$
Internal walls	MPP _{i(1)}	τ_i	$d_{i(1)}$	$\varphi_{i(1)}$	$n_{i(1)}$	
	MPP _{i(2)}		$d_{i(2)}$	$\varphi_{i(2)}$	$n_{i(2)}$	
	MPP _{i(3)}		$d_{i(3)}$	$\varphi_{i(3)}$	$n_{i(3)}$	
	$\vdots$		$\vdots$	$\vdots$	$\vdots$	
	MPP _{i(12)}		$d_{i(12)}$	$\varphi_{i(12)}$	$n_{i(12)}$	

The term Y_v is given by

$$Y_v = \frac{J_2(k_v d/2)}{J_0(k_v d/2)}, \quad k_v = \sqrt{-\frac{i\omega\rho_0}{\mu}} \quad (2)$$

In this equation, J_n represents the Bessel function of order n th, and μ symbolizes the dynamic viscosity of air. Any interaction between holes is ascertained by the Fok function, denoted as $\Lambda(\varphi)$, and is articulated as:

$$\Lambda(\varphi) = \sum_{n=0}^8 a_n(\sqrt{\varphi})^n \quad (3)$$

For this study, the first eight coefficients, as detailed by McKay et al. [26], can be found in McKay et al. [26] and Wang and Bennett [31].

Concerning the air cavities present within the analyzed MC-MPPA, the acoustic impedance, designated as Z_{ac} , for each cavity is derived using Eq. (4).

$$Z_{ac} = -i\rho_0 c_0 \cot\left(\frac{\omega D}{c}\right) \quad (4)$$

In this study, the two-point impedance method (TpIM) is introduced and applied to determine the impedance of the MC-MPPA. The typically used equivalent circuit model (ECM) method uses electrical circuit analogies and can be used to characterize the operational parameters of an acoustic system [36] but only for very simple circuits. The ECM usually uses $\Delta - Y$ and $Y - \Delta$ transforms to simplify the circuit to estimate acoustic impedance[36]. However, as the complexity of the acoustic system increases, the ECM becomes unmanageable [37]. For this reason we have developed a graph-theory approach, based on the two-point impedance theory proposed by Tzeng and Wu [38] previously used in the domain of electronics, but used here instead to estimate acoustic impedance. Fig. 2 shows the investigated MC-MPPA from Fig. 1 represented schematically as bi-pyramid molecular structures where the yellow branches represent the acoustic impedances of the top MPPs, the red branches represent the acoustic impedances of internal MPPs and the green branches represent the acoustic impedances of the air cavities themselves. The objective here is to calculate the impedance of the overall system, i.e. between nodes 1 and 11. Previous studies have established the effectiveness of TpIM in calculating the impedance between any two nodes in a complex impedance network whether the circuit is planar or not [37–39].

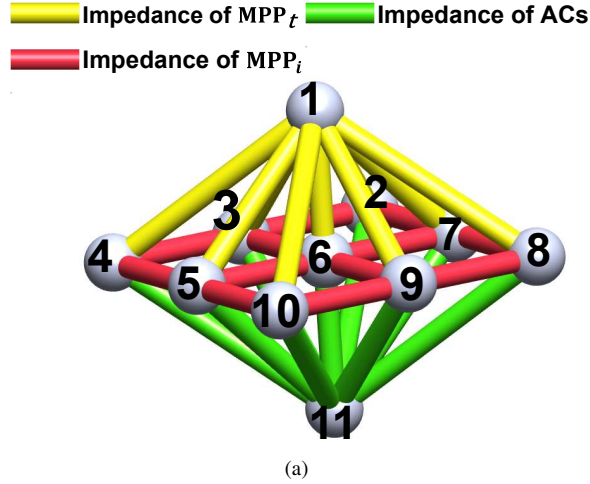


Fig. 2 Molecular model of the MC-MPPA.

From the given molecular structure, the subsequent Laplace matrix, denoted as $\mathbf{L}$, can be formulated as follows:

$$\mathbf{L} = \begin{pmatrix} y_{11} & -y_{12} & \dots & -y_{1N} \\ -y_{21} & y_{22} & \dots & -y_{2N} \\ \vdots & \vdots & \ddots & \vdots \\ -y_{N1} & -y_{N2} & \dots & y_{NN} \end{pmatrix} \quad (5)$$

Here, $N = (3 \times 3) + 2$ represents the number of nodes, y_{ij} signifies the admittance between nodes i and j , and $y_{ij} = y_{ji} = 1/Z_{ij}$ ($i \neq j$), where Z_{ij} is the acoustic impedance between nodes i and j .

The diagonal components of the Laplace matrix $\mathbf{L}$ are expressed by:

$$y_{ii} \equiv \sum_{j=1}^N y_{ij} \quad i \neq j \quad (6)$$

Employing the Laplace matrix, denoted as $\mathbf{L}$ enables the construction of the Hermitian matrix $\mathbf{L}^\dagger \mathbf{L}$, capable of being diagonalized, where † symbolizes Hermitian conjugation. To compute the impedance of the network depicted by the Laplace matrix, the ensuing eigenvalue equation is required to be resolved:

$$\mathbf{L}^\dagger \mathbf{L} \psi_\beta = \eta_\beta \psi_\beta, \quad \eta_\beta \geq 0, \quad \beta = 1, 2, \dots, N \quad (7)$$

Here, η_β and ψ_β represent the eigenvalues and eigenvectors of $\mathbf{L}^\dagger \mathbf{L}$, respectively. Consequently, there are eigenvalues of $\mathbf{L}$, which are expressed as:

$$\lambda_\beta = \psi_\beta^\dagger \mathbf{L} \psi_\beta \quad (8)$$

In conclusion, the acoustic impedance between any two nodes, represented as i and j , within the network can be determined by the equation:

$$Z_{ij} = \sum_{\beta=2}^N \frac{1}{\lambda_\beta} (\psi_\beta(i) - \psi_\beta(j))^2 \quad (9)$$

Based on this value, the specific impedance, denoted as z_{ij} , is derived from Eq. (10):

$$z_{ij} = Z_{ij} S \quad (10)$$

Here, S symbolizes the area where the sound wave incidence is normal.

The coefficient of reflection, represented by R , determined by the impedance, is expressed as:

$$R = \frac{z_{ij} - \rho_0 c_0}{z_{ij} + \rho_0 c_0} \quad (11)$$

Subsequently, utilizing this, the SAC at normal incidence, denoted by α , is computed as follows:

$$\alpha = 1 - |R|^2 \quad (12)$$

The primary objective of employing the TpIM in our MC-MPPA technology is to develop an analytical model that allows the performance of the MC-MPPA to be optimized to calculate the maximum SAC possible within a specified set of parameters. We can establish an optimization cost function that characterizes the total SAC within a specified frequency range:

$$C_\alpha = 10 \log_{10}(1 - c_\alpha) \quad (13)$$

Here, c_α represents the comprehensive SAC, proportionally balanced by the sound spectrum of the intended noise source.

$$c_\alpha = \frac{(\sum_{\omega_1}^{\omega_2} \alpha(\omega) G_{xx}(\omega))}{(\sum_{\omega_1}^{\omega_2} G_{xx}(\omega))} \quad (14)$$

Here, ω_1 is equivalent to $2\pi f_1$ and ω_2 corresponds to $2\pi f_2$, where f_1 and f_2 represent the lower and upper bounds of the frequency range under consideration. The SAC, denoted as $\alpha(\omega)$, is determined utilizing Eq. (12) and the TpIM, with the intended sound spectrum characterized by an auto-spectral density function, $G_{xx}(\omega)$. In this research, the target noise is white noise, $G_{xx}(\omega) \equiv 1$. We employed the Sequential Quadratic Programming (SQP) optimization technique to minimize the cost function.

The optimization targeted four frequency ranges, each corresponding to a distinct side of the four-wall liner, with differing designs as follows: Side 1 targets 500–1500 Hz, Side 2 targets 1000–2500 Hz, Side 3 targets 2000–3500 Hz, and Side 4 targets 3000–4500 Hz. Figure 3 illustrates the overlapping frequency ranges and the four wall installation for the grazing acoustic impedance application. Other optimization geometric parameter settings can be found in Table 2.

Table 2 Optimization geometric parameter settings.

Parameters	Value
$[f_1 \ f_2]$	Side 1: 500-1500 Hz, Side 2: 1000-2000 Hz, Side 3: 2000-3000 Hz and Side 4: 3000-4500 Hz
$[d_{\min} \ d_{\max}]$	[0.5 1] mm
$[\varphi_{\min} \ \varphi_{\max}]$	[0 5] %
$[D_{\min} \ D_{\max}]$	[10 50] mm
$[L, W]$	[40, 40] mm
$[\tau_t, \tau_i]$	[2, 1] mm

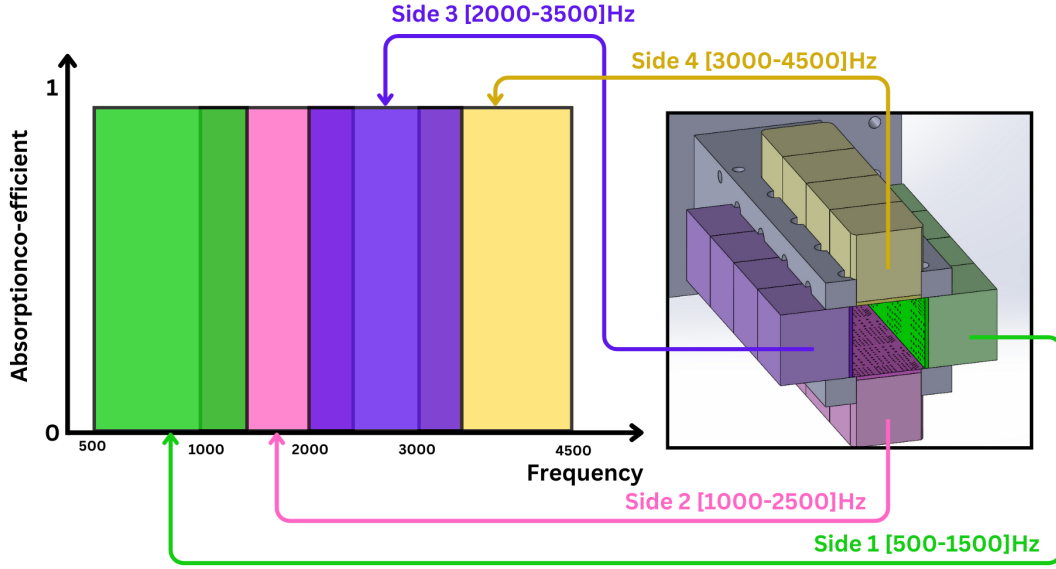


Fig. 3 Four-wall liner concept and corresponding absorption coefficient graph, showing overlapping frequency bands, providing high absorption from 500-4500Hz.

III. Experimental Validation for the Optimised Results

The optimization results for different sides are shown in Fig. 4. It is clear that each side with suitable thickness can demonstrate excellent sound absorption within its respective optimized frequency range. In this study, we aimed to achieve an optimal balance between sound absorption performance and absorber thickness while maximizing the wavelength-to-absorber thickness ratio. Accordingly, we selected a design with a maximum cavity depth of 35 mm from the optimization results presented earlier. This section will provide experimental validation of these optimized design parameters.

Figure 5 displays four optimized MC-MPPA samples, each with a maximum chamber depth of 35 mm, designed for optimal absorption across specific frequency ranges. Super glue will be employed to secure the top plate to the backing chamber, guaranteeing precise alignment of the chambers and top plates during tests under normal acoustic incidence. These samples were produced using masked stereolithography (mSLA), a 3D printing method that uses a UV laser to polymerize photopolymer resin layers sequentially. Unlike traditional stereolithography (SLA), which uses a single laser directed by mirrors to cure the resin point-by-point, mSLA utilizes an LCD screen to display each layer's shape through a semi-transparent mask, with a UV LED behind it. This technique significantly reduces the print time, as the entire layer is cured simultaneously, rather than point-by-point. The resin's exposure to UV light is controlled pixel-by-pixel via a g-code from the slicing software, enhancing the XY resolution of the print based on the LCD's pixel count. The Prusa SL1S, with an LCD resolution of 5.96 inches, 2560×1620 pixels, and a build volume of 127×80×150 mm, was used for printing. This printer optimizes print speed with a custom optics system and a UV LED panel that minimizes exposure times, enabling faster print cycles. The specific resin used was Prusament Tough Prusa Orange, designed for the Prusa SL1S.

The initial phase involves conducting experimental validation, utilizing an impedance tube to measure the absorption coefficient of the 3D printed MC-MPPA samples under normal incident sound waves. A rectangular impedance tube, featuring an 40 × 40 mm internal cross-section, was employed to determine the normal incidence sound absorption coefficients of the MC-MPPA test pieces. This experimental setup adheres to the ISO 10534-2:1998 Standard [40]. The rig's cut-off frequency is approximately 4300 Hz. Two 150 W compression drivers, positioned at the tube's end, are used to generate planar sound waves. However, due to the limited low-frequency response of the compression drivers, the lower frequency threshold for sound absorption measurements in this setup is established at 200 Hz. Figure 6(a) shows the normal incidence experimental set-up.

An essential parameter in impedance tube measurements is the sample mounting. The sample must be installed without any air leakage. For normal incidence tests, the sample should match the tube's cross-sectional area, which in

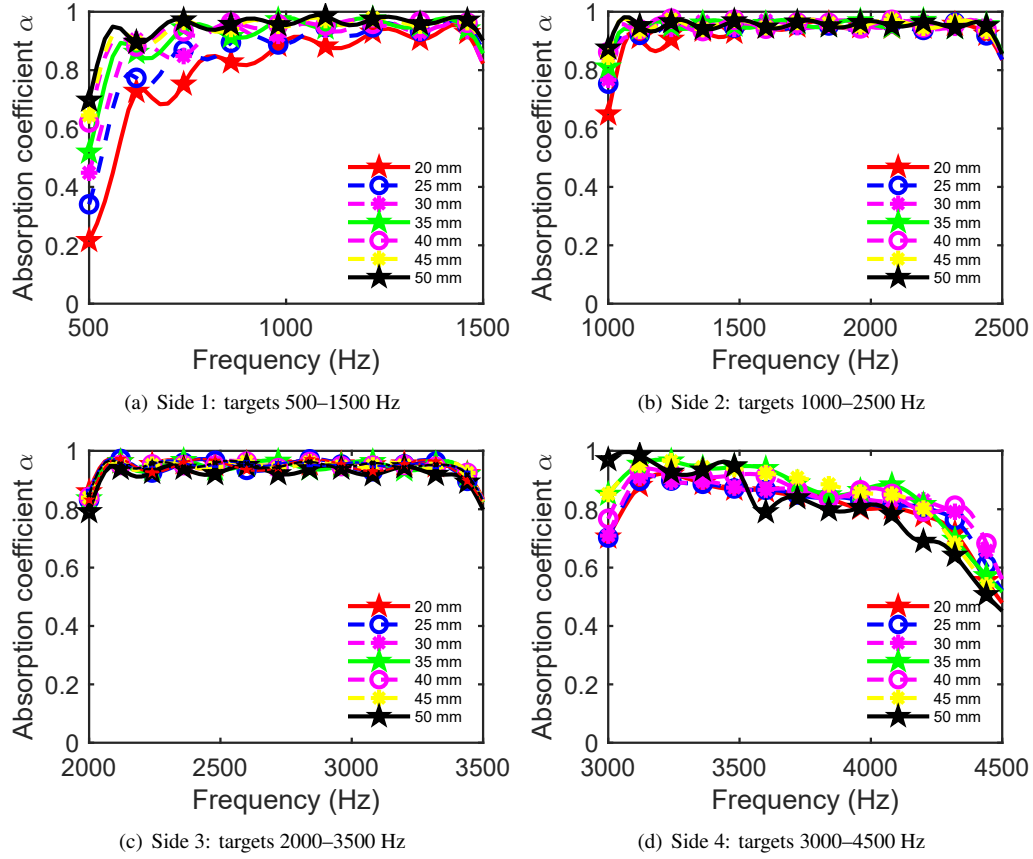


Fig. 4 Theoretical sound absorption coefficients optimised for normal impedance. Each design will occupy a distinct side of the four-wall liner, D_{max} : [20 50] mm.

this case is 40 mm × 40 mm. A holder was created via FDM 3D printing to ensure the MC-MPPA cells fit snugly within the tube and were backed by an aluminium termination that could be attached to the tube's end, as illustrated in Fig. 7. This mounting arrangement aligns the MC-MPPA surface precisely with the tube's cross-section, enabling exact alignment.

Figure 8 compares the theoretical and experimental absorption coefficient curves for each of the 3D printed MC-MPPA samples illustrated in Fig. 5. The results show acceptable discrepancies between the experimental and theoretical data, which can be attributed to manufacturing defects and errors in the experimental setup. A critical factor in the accuracy of impedance tube testing is ensuring no air leakage occurs. In this experiment, a rubber gasket and a tightly-fitted sample holder were used to seal the system, enhancing the integrity of the setup. Despite these measures, minor gaps were observed between the top plate and the holder, potentially allowing air leakage through the holder's internal structure, as shown in Fig. 9. Additionally, gaps remained between the top plate and the cell post-gluing, contributing to the observed discrepancies. In the manufacturing process, it was observed that some MC-MPPA cells exhibited tiny holes in their sidewalls due to mSLA printing defects and the removal of supports, as shown in Fig. 9. These imperfections were sealed using super glue, which, however, might have contributed to air leakage. Furthermore, it is plausible that the internal MPP walls of the MC-MPPA cells had incorrectly shaped, sized, or fully filled internal holes. Despite meticulous efforts in printing and post-processing each cell, the elimination of all errors cannot be assured. The top plates were visually inspected for any hole discrepancies, and none were detected; however, without dissecting the cell, the internal walls could not be reviewed. Additionally, the adhesive used to bond the top plate to the cell might have seeped onto the internal walls or the top plate of the MC-MPPA, inadvertently filling some holes with glue and potentially altering the cell's acoustic response. Also it should be noted that the rectangular impedance tube used in the experiment has a cutoff frequency of approximately 4300 Hz. Therefore, in Fig. 8d, when the frequency exceeds 4300 Hz, reliable experimental data cannot be obtained.

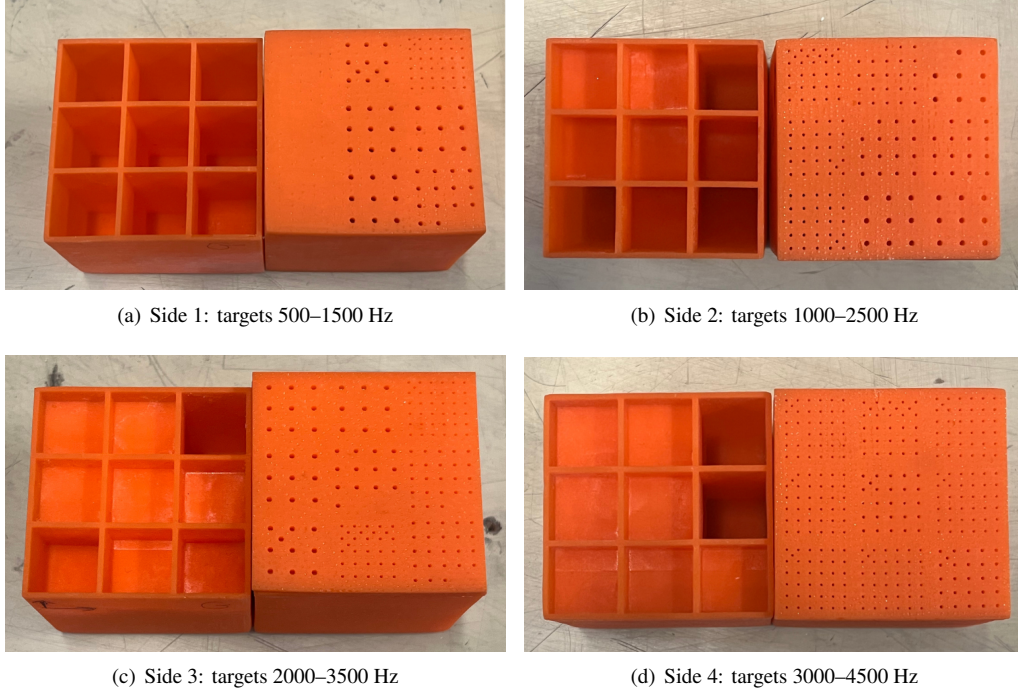


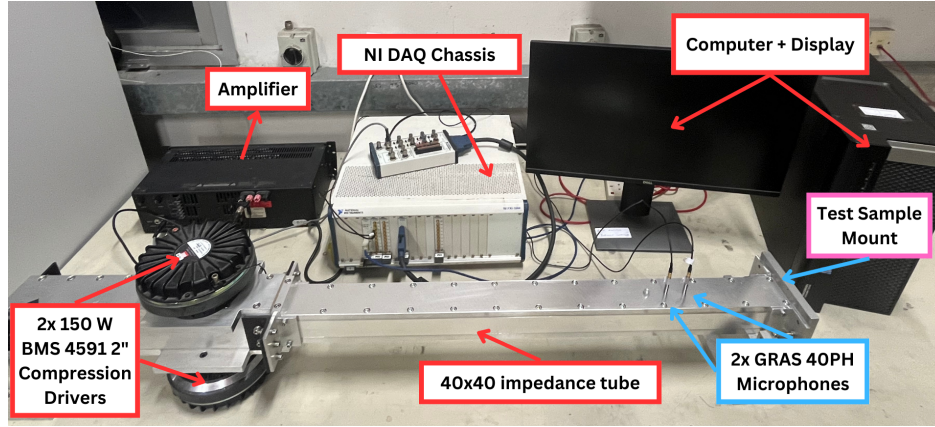
Fig. 5 MC-MPPAs (internal chambers and top plates) manufactured for normal impedance validation for all four frequency ranges.

IV. Application of MC-MPPA for Duct Noise Reduction

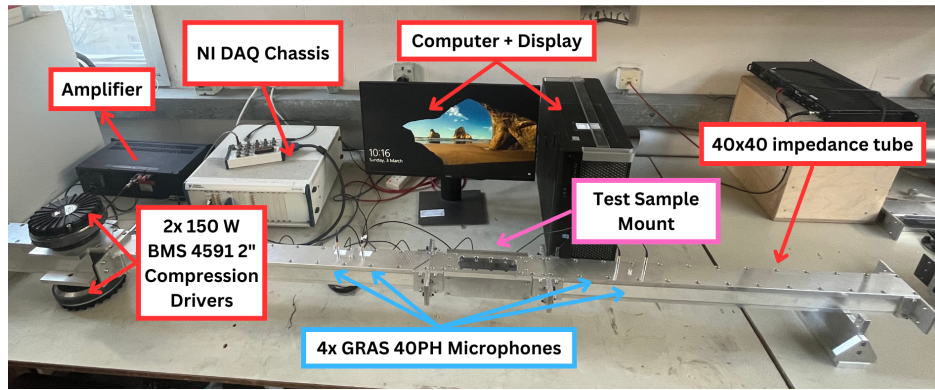
In this section, we will utilize the MC-MPPA design tested in the previous sections, manufacture the liner through 3D printing, and apply it to duct noise reduction applications. Figure 6(b) illustrates the experimental set-up. Each of the four liners examined in this study was configured as depicted in Fig. 10, consisting of four MC-MPPA cells arranged side by side with a continuous MPP plate on top. In total, 16 cells and four top plates were fabricated. The MC-MPPA cells utilized in these liners were sharing the same parameters with the MC-MPPA samples presented in Fig. 5. Each cell features a cavity depth of up to 35 mm. The design of the liners' edge cells on sides 2 and 4 required modifications due to the constraints of the conventional manufacturing techniques used for the sample holder mount, as illustrated in Fig. 10. Specifically, the outer edges of these cells were rounded with a 5mm fillet to ensure they properly fit within the sample holder mount (as show in Fig. 11). This alteration changes the volume of air within the chambers, potentially impacting the acoustic absorption characteristics of the liners. The top plates were engineered as a single continuous unit, with the top MPP of each cell (four in total) integrated on one surface to minimize air leakage between cells. Additionally, the sample holder mount included 1mm deep, 10mm radius circular tabs to support the top plates, enabling them to sit flush with the tube's interior. This configuration allows the backing chambers to exert pressure on the top plates, enhancing the alignment between the top plates and the backing chambers.

An insertion loss test was selected to demonstrate the effectiveness of the liner as a sound absorber within a duct. This test involved positioning a microphone on a retort stand 100 mm from the open end of the impedance tube and measuring the sound pressure level (SPL) when the sample was excited with white noise. The setup is depicted in Fig. 12, highlighting the microphone's placement 100 mm from the tube's end, aligned with the tube's midline. This test facilitated the generation of an SPL versus frequency graph, which was used to compare the liner's performance against a hard-wall baseline. In the hard-wall scenario, the sample holder mount was removed from the tube's center, and the tube's halves were bolted together. The insertion loss test utilized the 3D-printed samples shown in Fig. 10 and the sample holders depicted in Fig. 11.

Figure 13 presents the insertion loss results across the frequency range of [500-4500] Hz. In these results, the hard-wall baseline is depicted in red, while the liner's performance is shown in blue. The liner consistently reduces noise by 15-20 dB on average across all frequencies, with peak attenuation occurring in the mid-frequency range. Notably, there is a significant reduction of 40 dB just above 1500 Hz, suggesting possible increased resonance at this frequency.



(a) Normal acoustic incidence configuration



(b) Grazing acoustic incidence configuration

Fig. 6 Impedance tube experimental set-ups.

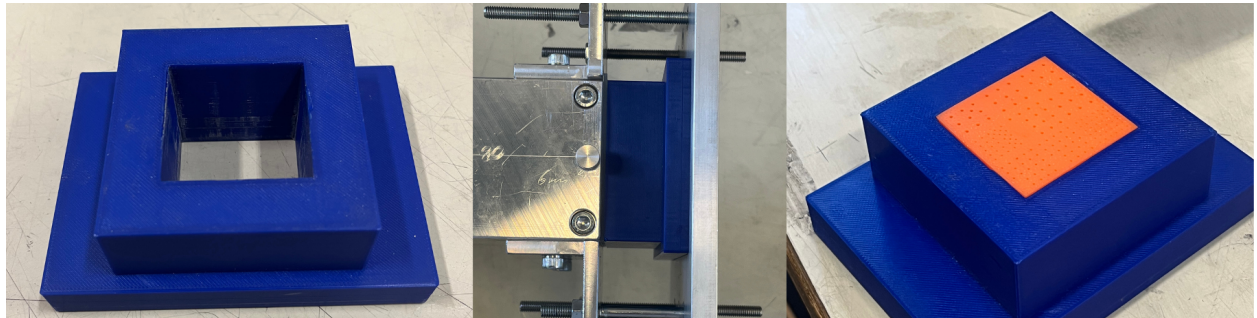


Fig. 7 Normal incidence sample holder.

The design of the liner, particularly the continuous top plates, has room for improvement; similar to the smaller top plates, they exhibited warping. Enhancing the liner's design by securing the top plate to the cells with adhesive could mitigate this issue. Additionally, the potential for air leakage at the top plate within the sample holder mount, as indicated in Fig. 9, should be addressed in future tests, which should include proper calibration of the microphones.

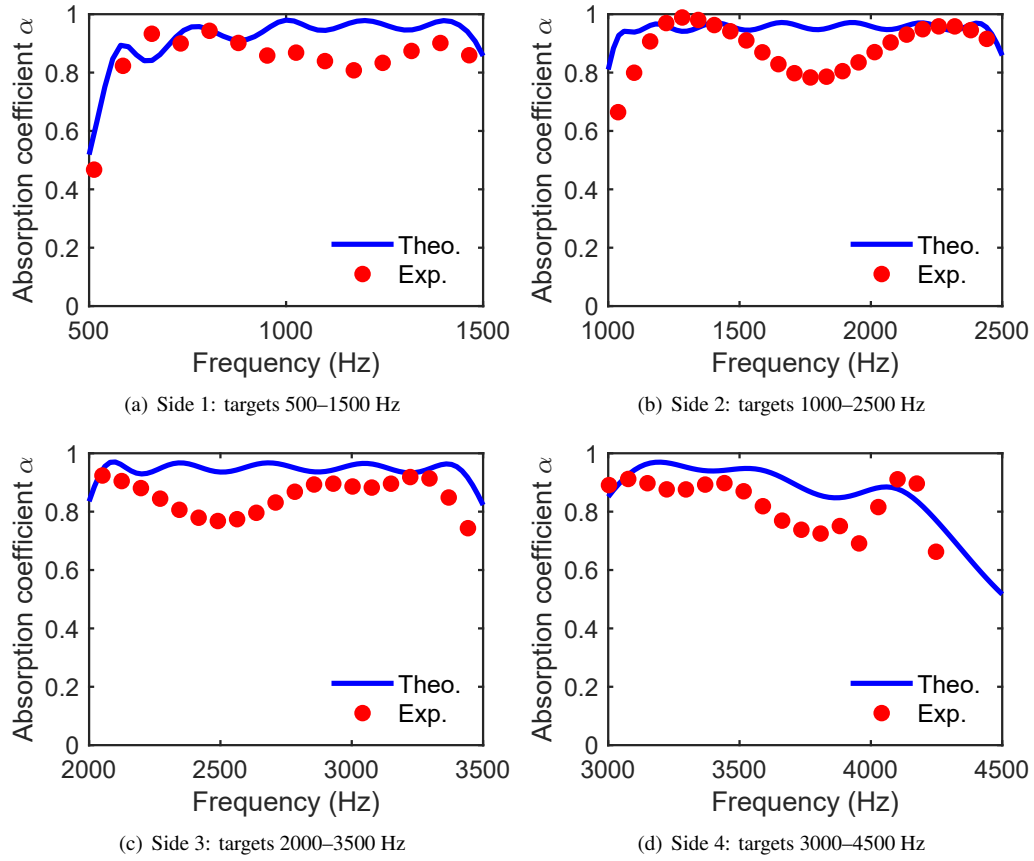


Fig. 8 Comparison of the theoretical and experimental normal impedance absorption coefficient curves for each of the 3D printed MC-MPPA samples illustrated in Fig. 5.

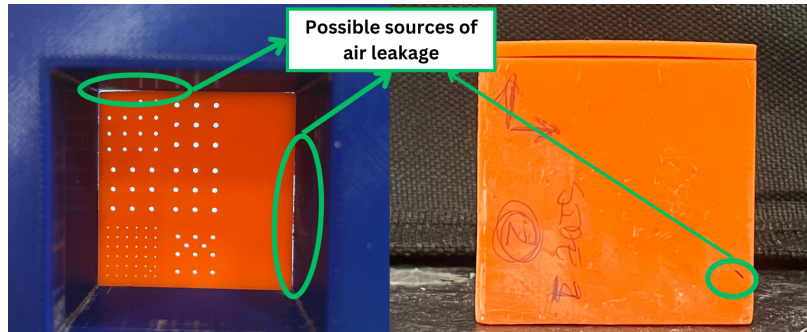


Fig. 9 Possible sources of error due to air leakage.

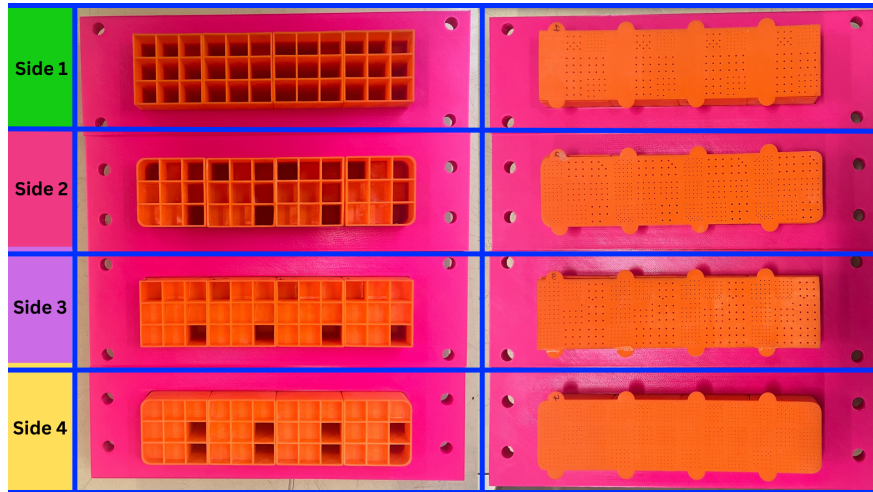
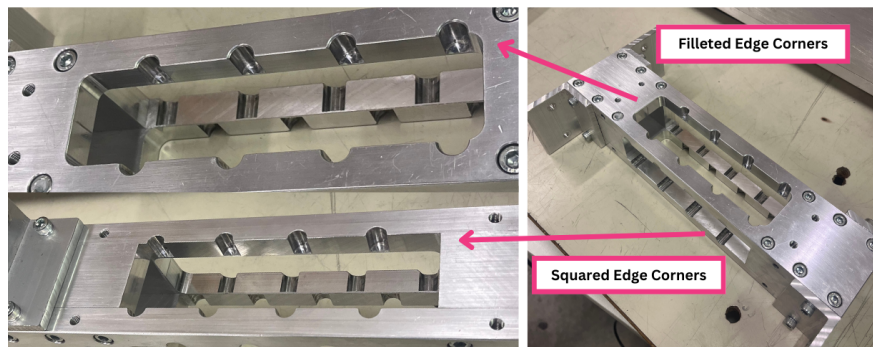
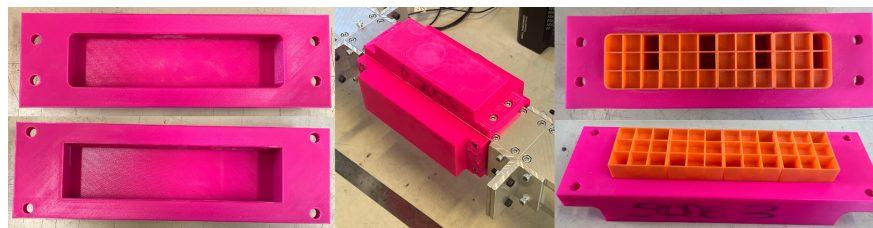


Fig. 10 Four sets of liners for sides 1-4 of the grazing impedance tube and their accompanying top perforated faceplates.



(a) Grazing impedance tube test section.



(b) Sample holder and liner inserts.

Fig. 11 Quad-wall test section.



(a)

(b)

Fig. 12 Set-up for the insertion loss test.

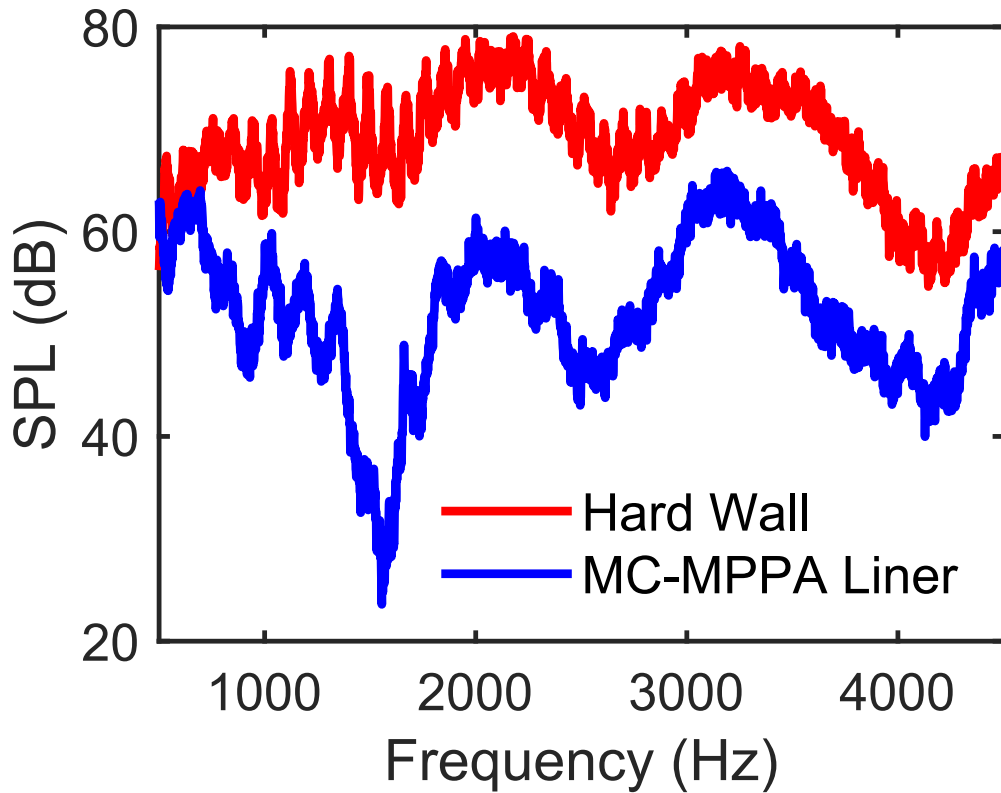


Fig. 13 Insertion loss result for quad-wall MC-MPPA liner [500-4500]Hz, comparing it to hard wall case.

V. Conclusion

It is evident that mitigating duct noise significantly contributes to addressing our current environmental noise challenges. Given the extensive use of ducts across various industries including aeronautics, automotive, and construction, it is crucial to develop more effective duct noise attenuation solutions. This paper demonstrated the potential of MC-MPPA, a metamaterial, used as a liner on duct walls to reduce noise. The liner design applied to all four walls, aimed to cover a broad frequency range from 500Hz to 4500Hz. Experimental results confirmed that each liner, optimized for different overlapping frequency bands, achieved an average Sound Pressure Level (SPL) reduction of 15-20dB, when compared to a hard-wall baseline. Specifically, there was a peak reduction of 40 dB at around 1500 Hz. This was achieved with a liner of total depth equal to 35 mm. These findings not only underscore the efficacy of MC-MPPA as a sound attenuation material but also highlight its practical applications in enhancing industry-standard duct noise control methods.

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