ENHANCING SOUND ABSORPTION IN LABYRINTHINE METAMATERIALS: FROM STOCHASTIC NONWOVEN FIBROUS FILLERS TO 3D-PRINTED INFILL

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Abstract

This paper explores the evolution of fibrous enhancements in labyrinthine acoustic metamaterials, transitioning from stochastic fibrous fillers to programmable 3D-printed infill. While previous studies demonstrated that manual packing of natural fibres (e.g., dried dill) into labyrinthine slits significantly enhances low-frequency absorption, it suffers from manufacturing difficulties and uncertain reproducibility. Moreover, due to the uneven and random fibre distribution, analytical modelling may be inaccurate and require complex modifications. To address these limitations, we propose the use of Fused Deposition Modelling (FDM) to integrate controlled fibre networks directly into the channels. A comparative study is presented between a bio-filler reference and an engineered Cross-ply infill pattern. Experimental results from impedance tube measurements reveal a significant advantage of the engineered 30% cross-ply infill over stochastic natural fibres. While the bio-filler achieves absorption at lower frequencies, the 3D-printed infill generates a significantly broader and higher absorption peak at 1050 Hz, reaching nearly perfect absorption. Consequently, the absorption curve of the fully 3D-printed sample exhibits a broader bandwidth and a higher maximum absorption coefficient than the curve obtained for the bio-filler composite. This demonstrates enhanced broadband sound absorption combined with high manufacturing predictability. This work establishes a digital framework for the design of sub-wavelength absorbers with tunable, reproducible dissipation mechanisms.

Keywords: *acoustic metamaterials, labyrinthine structures, sound absorption, infill patterns, additive manufacturing*

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1. Introduction

The demand for compact, low-frequency noise control solutions has led to the development of labyrinthine metamaterials, which utilize space-coiling geometries to achieve sub-wavelength absorption [1], [2]. To further enhance the acoustic performance of these structures, researchers have traditionally introduced various porous fillers into the labyrinthine slits to increase viscous dissipation and broaden the absorption bandwidth [3]. Recently, however, advances in additive manufacturing have enabled a more integrated approach: directly 3D-printing the acoustic treatments using intrinsically micro-porous materials or tailored filament networks [4], [5]. For instance, standard slicer infill patterns have been effectively utilized to form a micro-porous base material for macro-perforated sound absorbers [6]. This allows for precise control over microstructural parameters and double-porosity effects, significantly improving the predictability and efficiency of sound absorption [7]. Furthermore, recent studies have demonstrated that with advanced toolpath design one can even control certain imperfections of FDM technology, such as filament stringing, and exploit them to generate highly effective micro-fibrous networks directly within slits and cavities of the main pore network [8].

The effect of "stochastic bio-fillers", such as dried organic fibres, on sound absorption of a labyrinthine metamaterial was investigated in [9]. While these natural materials successfully broaden the sound absorption curve profile and increase peak values, shifting them toward lower frequencies, their usage is rather challenging in practice. The manual packing of organic matter is inherently random, leading to variations in local porosity and tortuosity that are difficult to replicate in mass production or characterize accurately in analytical models.

The current work marks a transition from acoustic composites with traditional fibrous fillers (e.g., organic fibres) to "digitally-engineered" composites.

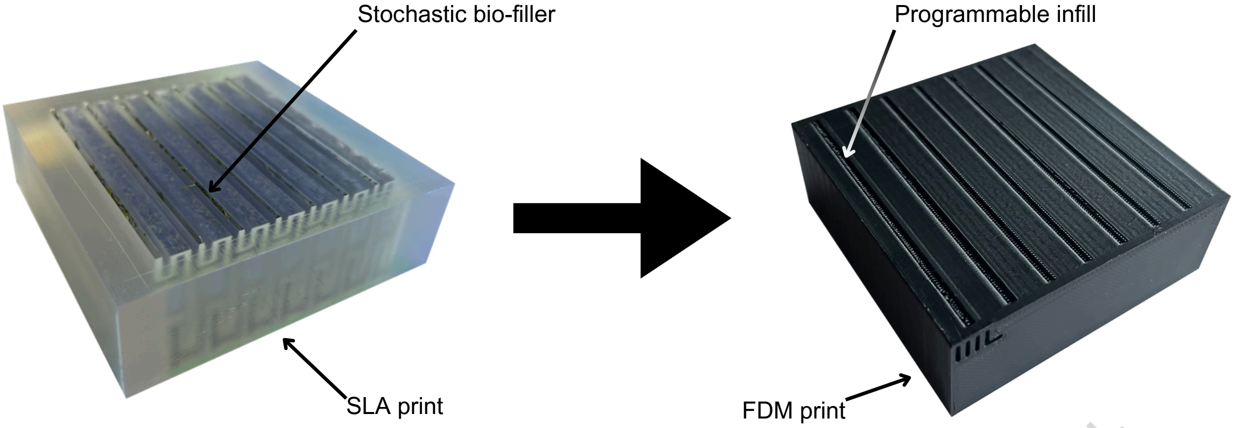

Figure 1: The conceptual evolution of labyrinthine meta-composites: transitioning from unstable, stochastic bio-fibre fillers (left) to digitally-integrated, programmable infill patterns (right).

This aligns with emerging strategies in acoustic metamaterial design, where 3D-printed fibres are seamlessly integrated within macro-scaffolds to create fibroporous structures with tailored, broadband absorption [10], [11]. By leveraging Fused Deposition Modelling (FDM) technology, we replace random organic fibres with programmable, integrated infill patterns. The significant influence of specific infill configurations on acoustic performance has been recently highlighted, demonstrating that slicer-generated geometries effectively control internal structural complexity and airflow resistivity [12]. Moreover, optimizing these internal structures, ranging from standard grids and honeycombs to custom origami inspired architectures, enables simultaneous enhancements in both broadband sound absorption and mechanical robustness [13], [14]. This approach allows for the precise control of fibre diameter, orientation, and layer distribution ratio.

Specifically, this paper compares the acoustic efficiency of the best-performing bio-fibre filler with a 3D-printed cross-ply lattice. The objective is to demonstrate that engineered infill can serve as a reproducible, predictable alternative to stochastic fibres, offering even better acoustic performance while providing a robust platform for future multi-scale optimization.

2. Materials and Experimental Methods

In this study, two kinds of labyrinthine acoustic composites were compared to assess the transition from stochastic to programmable fibrous fillers, see Fig. 1. Both composites are based on the same labyrinthine geometry, designed for low-frequency sound absorption, but differ significantly in manufacturing technology and the nature of the dissipative filler used.

2.1. Reference sample with stochastic bio-filler

The first reference sample has a labyrinthine skeleton manufactured using stereolithography (SLA) from a photopolymer resin. Its tortuous slits were manually packed with dried dill. This "bio-filler" was chosen for its high surface-to-volume ratio, efficient packing density within the narrow labyrinthine slits, and natural electrostatic adhesion to the channel walls, which allowed for more or less uniform deposition [9]. However, the manual packing process introduces inherent stochasticity in fibre orientation and local packing density, making the material reproducibility and its precise analytical modelling challenging.

2.2. Engineered sample with integrated cross-ply infill

The new composite sample represents a fully digital approach to acoustic composite design. It was manufactured using FDM with Acrylonitrile Butadiene Styrene (ABS) filament. Instead of manual filling, the fibrous structure was integrated directly into the channels during the printing process by programming the slicer's infill settings.

Based on preliminary investigations, the cross-ply infill pattern was selected for comparison. The cross-ply configuration consists of alternating layers with strands oriented at 45° and 135° relative to the build axis, creating a regular, periodic lattice. The engineered sample was printed with an infill density of $p = 30\%$ and a layer distribution rate of one fibre-infilled layer every three printed layers ($n = 3$). This monolithic integration ensures a perfect bond between the main-frame and fibres, eliminating the risk of fibre settling and degradation.

2.3. Microstructural validation and acoustic testing

To ensure a fair comparison, both samples were subjected to microstructural characterization using an optical microscope at 50× magnification, as shown in Fig. 2. The analysis reveals a stark contrast in geometric consistency: the bio-filler (Fig. 2a) exhibits high stochasticity, with fibre diameters varying irregularly from 0.29 mm to 0.656 mm. In contrast, the engineered infill (Fig. 2b) demonstrates significantly higher precision, with measured diameters confined to a narrow range between 0.305 mm and 0.356 mm. For the engineered metamaterial, the actual fibre diame-

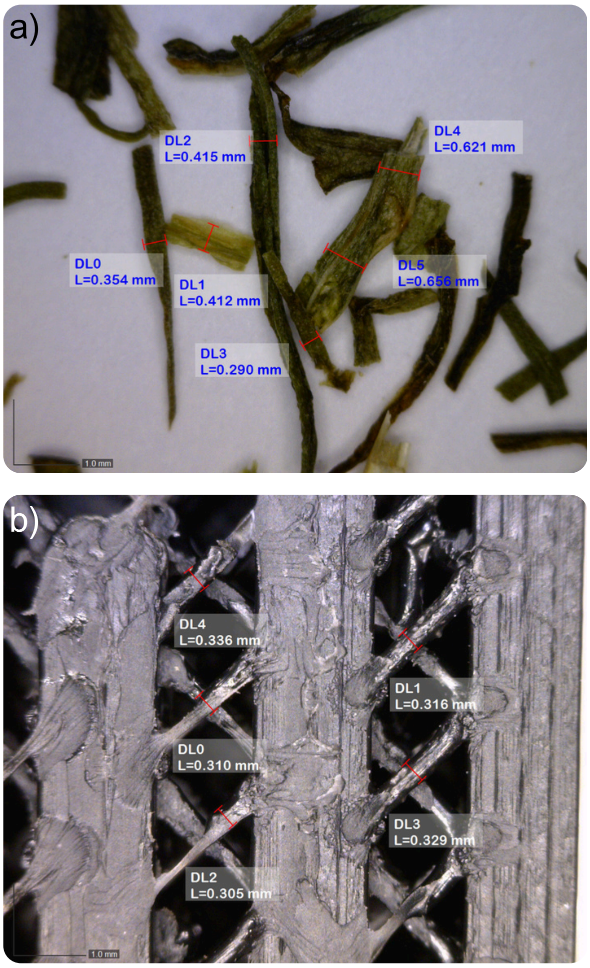

Figure 2: Micrographs (50×) of the investigated fillers: (a) organic fibres with non-uniform diameters (0.29–0.656 mm); (b) 3D-printed ABS strands with precise diameter control (0.305–0.356 mm).

ter D_f was determined by examining a representative single-layer test specimen. This ensured that manufacturing realities, such as polymer die swell, were accurately reflected in the input parameters for the analytical model.

Acoustic measurements were performed in a square impedance tube with a cross-section of 66 × 66 mm, following the ISO 10534-2 standard [15]. The testing frequency range was set from 150 Hz to 3200 Hz. All samples were carefully sealed at the edges with aluminium tape and backed by a rigid plate to ensure a hard-wall boundary condition.

3. Theoretical Framework

The acoustic response of the hybrid labyrinthine composite is modelled using the equivalent fluid approach based on the Johnson-Champoux-Allard-Lafarge (JCAL) model framework [16]. The structure is treated as a rigid-frame porous medium where the dissipative properties of the filler (organic or 3D-printed) are integrated into the effective properties of the labyrinthine channels.

3.1. Labyrinthine channel acoustics

The fundamental geometry of the labyrinthine unit cell is presented in Fig. 3. The structure is periodic with characteristic dimensions: channel width w, segment width W and height H. To determine the acoustic parameters within the JCAL analytical modelling framework, the air flow path was identified, as indicated by the red line in Fig. 3. This path is used to calculate the important parameter of the tortuosity α_∞.

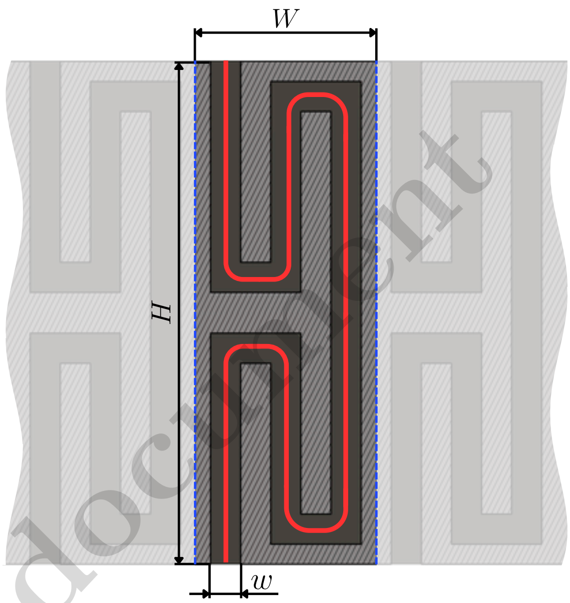

Figure 3: Periodic labyrinthine unit cell.

The labyrinthine geometry ensures a sub-wavelength absorption peak due to its high kinematic tortuosity α_∞. The labyrinthine material is modelled as an equivalent fluid with the effective density and compressibility determined from the dynamic viscous and thermal permeabilities. In a standard, empty labyrinth, these parameters are functions of the channel geometry and the properties of the air saturating the channels [7]. However, to account for the presence of the fibrous filler or infill, this baseline model must be sequentially integrated with the properties of the fibrous medium.

3.2. Modelling of the fibrous fillers

To establish the integrated model, the fibrous filler itself is first treated as an independent porous medium. The presence of fibres introduces in particular additional viscous losses. The key difference between the two studied composite materials lies in the determination of the microstructural parameters of their fibrous fillers, which are necessary to define the effective fluid acoustically equivalent to the fibrous material:

1. **Stochastic bio-filler (dill):** The fibrous filler porosity ϕ_f and viscous characteristic length Λ_{vf} are difficult to determine *a priori*. In previous works, these parameters were often roughly estimated, as the random orientation and size of organic fibres defy simple geometric description.

2. **Programmed cross-ply infill:** For the 3D-printed filler, the porosity ϕ_f is a direct function of the infill density p and the layer distribution rate of one fibre layer every n printed layers:

$$\phi_f = 1 - \frac{p\,\psi}{n} \tag{1}$$

where ψ is a small correction factor accounting for the extrusion width. The viscous characteristic length Λ_{vf} is derived from the measured fibre diameter D_f and the programmed lattice spacing. By orienting the layers in a cross-ply pattern, the structure creates a predictable network. To fully define the equivalent fluid of the 3D-printed filler, the remaining parameters were estimated using classical analytical relations for fibrous media [16]. Specifically, the tortuosity $\alpha_{\infty f}$ and the static viscous permeability K_{0f} were calculated as:

$$\alpha_{\infty f} = 2 - \phi_f \tag{2}$$

$$K_{0f} = \frac{\phi_f \Lambda_{vf}^2}{8\alpha_{\infty f}} \tag{3}$$

3.3. Integrated composite model

The essence of the multi-scale modelling approach applied in this study relies on fluid substitution. Instead of air, the labyrinthine channels are assumed to be saturated with an effective fluid equivalent to the fibrous material (which itself is saturated with air). Consequently, the hybrid structure is treated as an equivalent fluid replacing an acoustic composite with channels saturated with an equivalent fluid replacing the fibrous filler.

The surface impedance Z_s of the hard-backed composite panel of thickness H is calculated as:

$$Z_s = -\mathrm{i}Z_c \cot(k_c H) \qquad (\mathrm{i} = \sqrt{-1}) \tag{4}$$

where Z_c and k_c are the characteristic impedance and complex wavenumber of the integrated composite fluid, respectively. The normal-incidence sound absorption coefficient α is determined directly from the surface impedance using the standard relation:

$$\alpha = 1 - \left| \frac{Z_s - Z_0}{Z_s + Z_0} \right|^2 \tag{5}$$

where $Z_0 = \rho_0 c_0$ is the characteristic impedance of the surrounding air (with ρ_0 being the density of air and c_0 the speed of sound). This modelling framework allows for a direct comparison of how precisely controlled 3D-printed fibres can replicate or exceed the dissipation performance of random organic fibres.

4. Results and Discussion

The comparison between the stochastic bio-filler and the programmed cross-ply infill reveals critical insights into the scalability and predictability of labyrinthine acoustic composites.

4.1. Microstructural contrast

Optical microscopy analysis revealed the fundamental differences in fibre morphology. The bio-filler (dried dill) contains fibres of various diameters and often irregular shapes and surface texture. Furthermore, the manual packing leads to non-homogeneous fibre distribution and random orientation inside the labyrinthine slits, which complicates the determination of the viscous characteristic length Λ_{vf}. In contrast, the cross-ply infill presents a perfectly regular geometry with a highly representative and measurable average fibre diameter $D_f \approx 319$ μm. This value is smaller than the nominal 400 μm nozzle diameter, which can be attributed to the stretching of the polymer melt during deposition and subsequent thermal shrinkage. This regularity of the 3D printed fibrous filler allowed for a more precise calibration of the corresponding JCAL model, as the porosity ϕ_f and characteristic length Λ_{vf} could be derived directly from the manufacturing parameters.

4.2. Sound absorption comparison

Figure 4 shows the sound absorption coefficients for the empty labyrinth material, the corresponding bio-filler composite, and the engineered cross-ply infill composite.

- **Bio-filler composite:** The addition of natural fibres significantly shifts the absorption peak from 1150 Hz (no fibres in the slits) down to approximately 1000 Hz (bio-fibres in the slits). While effective, the peak magnitude and width were sensitive to the manual packing density.

- **Cross-ply infill composite:** The engineered sample demonstrated a stable primary absorption peak at 1050 Hz. Most notably, the cross-ply infill achieved nearly perfect sound absorption and a significantly broader bandwidth, yielding higher absorption coefficients across the evaluated frequency range compared to the narrower curve of the bio-filler.

4.3. Discussion on engineering control

The results demonstrate that the programmed cross-ply lattice effectively mimics the viscous dissipation mechanisms occurring in the complex mesh of natural fibres. By orienting the layers at 45°/135°, the structure creates a series of micro-obstacles that maximize the drag forces acting on the oscillating air particles. The primary advantage of the FDM-integrated approach is reproducibility and durability. While the composite samples with bio-fibrous filler showed a variation in peak position across different manufacturing batches, the cross-ply infill samples remained stable. This transition from "stochastic fibrous fillers" to "programmed fibres" enables the design of sub-wavelength absorbers with precisely tuned performance, a crucial requirement for industrial noise control applications.

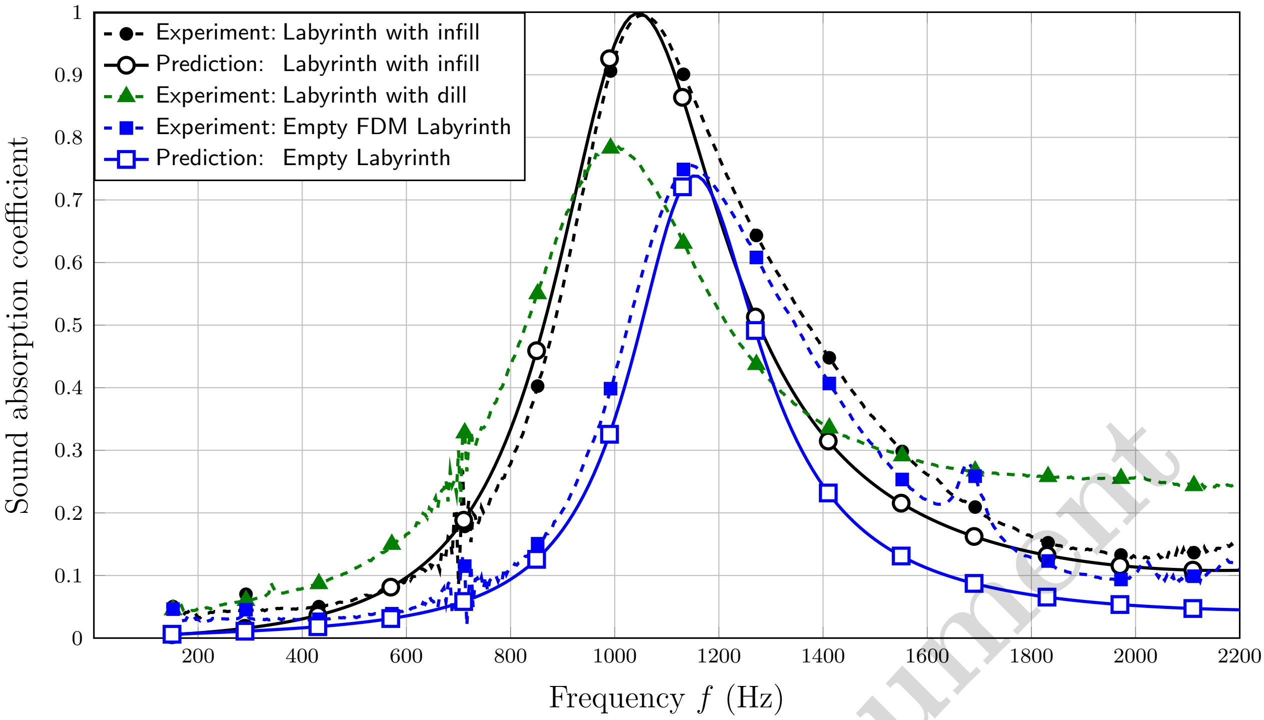

Figure 4: Measured and predicted acoustic absorption coefficients for labyrinthine composites. The transition from stochastic bio-fillers (green triangles) to programmable 3D-printed infill (black circles) is shown, with experimental results (dashed lines, filled markers) compared against JCAL analytical predictions (solid lines, hollow markers).

5. Conclusions

This study demonstrated the transition from stochastic organic fillers to programmable 3D-printed infill in labyrinthine acoustic composites. By comparing the results obtained for the reference composite with bio-fibre filler (dried dill) with the results for the composite with an integrated cross-ply lattice, the following conclusions were drawn:

- **Enhanced sound absorption:** The engineered 30% cross-ply infill provides an acoustic enhancement far better than that of stochastic fibres, shifting the absorption peak to the low-frequency range without increasing the total thickness of the absorber. This superior performance stems from the ability to 3D-print a dense, regular array of fibres with a smaller diameter than the natural bio-fibres. Consequently, this precise control over the viscous characteristic length Λ_{vf} and porosity ϕ_f made it possible to design the composite for near-perfect sound absorption at the peak.

- **Predictability and control:** Unlike the stochastic bio-filler, the cross-ply infill parameters can be directly derived from manufacturing data and microscopic validation. This leads to greater model reliability and overall better agreement between the analytical modelling and experimental results.

- **Reproducibility:** The monolithic integration of the filler during the FDM process eliminates the variability associated with manual packing. As a result, the engineered infill means strict structural repeatability, ensuring a highly reproducible acoustic performance that stochastic natural fibres cannot guarantee.

- **Durability:** Transitioning from a reference composite sample to a thermoplastic material (ABS) for both the skeleton and the filler ensures long-term structural integrity and eliminates the risk of biological degradation inherent in organic materials.

In conclusion, FDM-integrated infill fibres offer a robust, digital alternative to traditional fibrous fillers. This approach transforms the labyrinthine absorber into a fully programmable acoustic treatment, opening new possibilities for multi-scale topology optimization in sub-wavelength noise control.

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References

[1] Y. Li and B. M. Assouar, "Acoustic metasurface-based perfect absorber with deep subwavelength thickness," *Applied Physics Letters*, vol. 108, no. 6, p. 063 502, Feb. 2016, ISSN: 0003-6951. DOI: 10.1063/1.4941338

[2] X. Cai, Q. Guo, G. Hu, and J. Yang, "Ultra-thin low-frequency sound absorbing panels based on coplanar spiral tubes or coplanar helmholtz resonators," *Applied Physics Letters*, vol. 105, no. 12, p. 121 901, Sep. 2014, ISSN: 0003-6951. DOI: 10.1063/1.4895617

[3] I. Prasetiyo, I. Sihar, F. Brahmana, and Gunawan, "Enhancing nonwoven fabric material sound absorption using embedded labyrinthine rigid structures," *Applied Acoustics*, vol. 195, p. 108 852, 2022, ISSN: 0003-682X. DOI: https://doi.org/10.1016/j.apacoust.2022.108852

[4] J. Boulvert, T. Cavalieri, J. Costa-Baptista, L. Schwan, V. Romero-García, G. Gabard, E. R. Fotsing, A. Ross, J. Mardjono, and J.-P. Groby, "Optimally graded porous material for broadband perfect absorption of sound," *Journal of Applied Physics*, vol. 126, no. 17, p. 175 101, Nov. 2019, ISSN: 0021-8979. DOI: 10.1063/1.5119715

[5] W. Johnston and B. Sharma, "Additive manufacturing of fibrous sound absorbers," *Additive Manufacturing*, vol. 41, p. 101 984, 2021, ISSN: 2214-8604. DOI: https://doi.org/10.1016/j.addma.2021.101984

[6] J. Carbajo, J. Molina-Jordá, L. Maiorano, and N. Fang, "Sound absorption of macro-perforated additively manufactured media," *Applied Acoustics*, vol. 182, p. 108 204, 2021, ISSN: 0003-682X. DOI: https://doi.org/10.1016/j.apacoust.2021.108204

[7] T. G. Zieliński, K. C. Opiela, N. Dauchez, T. Boutin, M.-A. Galland, and K. Attenborough, "Extremely tortuous sound absorbers with labyrinthine channels in non-porous and microporous solid skeletons," *Applied Acoustics*, vol. 217, p. 109 816, 2024, ISSN: 0003-682X. DOI: 10.1016/j.apacoust.2023.109816

[8] T. G. Zieliński, M. D'Agostini, A. Gleadall, R. Venegas, P. Colombo, and G. Franchin, "Improving sound absorption through the filament stringing effect in 3D printed acoustic materials," *Applied Acoustics*, vol. 240, p. 110 892, 2025, ISSN: 0003-682X. DOI: https://doi.org/10.1016/j.apacoust.2025.110892

[9] M. Niedzielczyk, M.-A. Galland, and T. G. Zieliński, "An acoustic material with tortuous slits filled with fibres," in *Proceedings of ISMA 2024 - International Conference on Noise and Vibration Engineering and USD 2024 - International Conference on Uncertainty in Structural Dynamics*, 2024, pp. 323–336.

[10] W. Johnston, J. Godakawela, C. Gatti, S. Keshavanarayana, and B. Sharma, "Fibro-porous materials: 3D-printed hybrid porous materials for multifunctional applications," *Additive Manufacturing*, vol. 94, p. 104 470, 2024, ISSN: 2214-8604. DOI: https://doi.org/10.1016/j.addma.2024.104470

[11] W. Johnston, J. Godakawela, and B. Sharma, "Gradient fibro-porous materials for tailored sound absorption," *Proceedings of Meetings on Acoustics*, vol. 57, no. 1, p. 065 012, Nov. 2025. DOI: 10.1121/2.0002148

[12] M. F. K. Bin Norrifin, N. B. C. Din, M. N. Bin Yahya, and D. D. C. Vui Sheng, "Influence of infill pattern on sound absorption performance of 3d-printed microperforated panels," *Journal of Physics: Conference Series*, vol. 3156, no. 1, p. 012 009, 2025. DOI: 10.1088/1742-6596/3156/1/012009

[13] W. Shen, W. Li, and H. Qin, "Dual-function infill design in fused deposition modeling for mechanical and acoustic optimization," *Smart Materials and Structures*, vol. 34, no. 8, p. 085 026, 2025. DOI: 10.1088/1361-665X/adfbb4

[14] W. Shen, X. Jiang, and H. Qin, "Acoustic absorption performance investigation in standard and custom infill patterns for FFF 3D printing with PLA material," *Manufacturing Letters*, vol. 44, pp. 1113–1122, 2025, 53rd SME North American Manufacturing Research Conference (NAMRC 53), ISSN: 2213-8463. DOI: https://doi.org/10.1016/j.mfglet.2025.06.131

[15] International Organisation for Standardization, *ISO 10534-2: Determination of sound absorption coefficient and impedance in impedance tubes.* 1998.

[16] J. F. Allard and N. Atalla, *Propagation of Sound in Porous Media: Modeling Sound Absorbing Materials, 2nd ed.* Chichester: John Wiley & Sons, 2009. DOI: 10.1002/9780470747339