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Optimizing Acoustic Materials through Surface Geometry: A Review of Engineering Strategies and Design Insights

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ABSTRACT

Optimizing the acoustic performance of materials is a crucial objective in architectural and industrial engineering, particularly for controlling sound absorption in enclosed environments. While traditional design approaches emphasize intrinsic material properties such as porosity, thickness, and density, recent advancements in material engineering highlight the significant role of surface geometry in enhancing sound absorption behaviour. This literature review synthesizes recent studies from 2009 to present. This article review explores how engineered surface shapes such as sinusoidal, pyramidal, corrugated, and conical forms can improve acoustic efficiency by promoting scattering, diffraction, and micro-resonance effects. The review examines various testing methods, including impedance tube and in-situ measurements, and discusses how geometric features interact with frequency, air gaps, and mounting configurations. It also identifies limitations in current modelling practices, where surface texture is often simplified or ignored. The insights gathered underscore the potential of geometry-driven design as a cost-effective and scalable strategy for developing high-performance acoustic panels. This review serves as a foundation for future experimental work and simulation-based optimizations aimed at integrating advanced surface design into sustainable and application-specific acoustic materials.

I. Introduction

The control of sound absorption in enclosed environments such as classrooms, studios, offices, and industrial facilities is essential for achieving desirable acoustic performance. This objective has stimulated the development of advanced materials and engineered structures designed to manipulate sound through absorption, reflection, and transmission [1]. Traditionally, porous materials are widely employed in passive noise control applications due to their inherent sound absorption capabilities. The porous material are effective at attenuating mid-to-high frequency sounds (typically above 500 Hz). However, they perform poorly in the low-frequency range, where wavelengths are longer and require absorber thicknesses comparable to one-quarter of the sound wavelength. This limitation means that achieving substantial attenuation of low-frequency noise often demands bulky and impractical absorber designs, which are unsuitable for modern space-constrained environments. The effectiveness of sound-absorbing materials has been attributed to intrinsic physical characteristics such as porosity, thickness, density, and airflow resistivity [2] [3] [4].

Recent engineering advances, however, have shifted attention toward lightweight, space-efficient materials optimized for targeted acoustic performance, particularly at low frequencies where conventional solutions often fall short [5]. Beyond intrinsic properties, surface morphology has emerged as a critical yet underexplored factor. Chen, Lee, and Chiang (2000), for instance, demonstrated that surface profiles such as triangular, semicircular, and convex rectangular forms alter the absorption behavior of porous materials, particularly in conjunction with perforated plates, underscoring the direct influence of geometry on sound and material interactions [6]. These

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mechanisms allow absorbers to extend their effectiveness into lower frequency bands without significantly increasing material thickness.

Surface modifications reshape the interaction between incident waves and material boundaries, thereby affecting absorption efficiency across frequency spectra. This influence is especially evident in micro-perforated panels (MPPs), where perforation ratio, hole geometry, and panel contour dictate airflow resistance and energy dissipation [7]. Innovations such as wavy MPPs have shown promise for low-frequency control [5], while slit-shaped perforations have been found to outperform circular ones under certain conditions[8] . More broadly, irregular and non-planar configurations including sinusoidal, pyramidal, and corrugated geometries enhance absorption by increasing effective surface area, extending propagation paths, and inducing scattering, diffraction, and local resonance [9]. Such engineered topographies not only improve energy dissipation but also promote sound diffusion, mitigate flutter echoes, and yield more uniform energy distribution in enclosed spaces[10]. Studies demonstrate that carefully tailored patterns can yield broadband absorption and tunable frequency response, presenting new opportunities for compact, lightweight, and efficient acoustic solutions.

From an engineering perspective, tailoring surface geometry represents a scalable and cost-effective strategy for enhancing acoustic performance without altering bulk composition or significantly increasing mass. This approach aligns with the development of sustainable acoustic solutions, including bio-based fibers and recycled composites. Nonetheless, systematic experimental studies isolating geometric effects remain limited, and many computational models still oversimplify or neglect surface morphology, reducing predictive accuracy in real-world design.

Moreover, absorption is further influenced by boundary conditions, including panel placement relative to reflective surfaces, air gaps, and layer thickness, as well as excitation frequency and incidence angle[11]. This SLR is essential as it consolidates fragmented knowledge on surface geometry, an often overlooked yet critical parameter in acoustic design. By mapping consistent findings, methodological shortcomings, and future research directions, it advances the development of efficient, application-specific, and sustainable acoustic materials.

II. Method

This study employs a structured literature review approach to investigate the role of surface geometry in optimizing the sound absorption capabilities of acoustic materials. The review focuses on peer-reviewed articles published from 2000 to 2025 which examine the influence of geometric surface modifications such as sinusoidal, pyramidal, conical, and corrugated forms on sound absorption behavior.

2.1 Search Strategy

A systematic search was performed across several reputable academic databases (Scopus, ScienceDirect, and Google Scholar were used to collect relevant studies). These databases were selected because they provide comprehensive coverage of peer-reviewed journals, conference proceedings, and high-impact publications in the fields of acoustics, materials science, and Combination of keywords used such as: "sound absorption"; "surface geometry", "material texture", "acoustic performance", "impedance tube method", "non-planar surface absorbers", "room acoustics modeling", and "angle-dependent absorption coefficient". The initial screening was based on titles and abstracts, followed by full-text evaluation.

2.2 Selection criteria

To ensure the relevance and quality of the sources, the following inclusion criteria were applied: Peer-reviewed journal articles, conference papers, and academic theses, Publications from the last 25 years (2000–2025), with an emphasis on the past five years. The decision to narrow the timeframe is based on the rapid development of computational modeling techniques, additive manufacturing, and acoustic metamaterials, which have significantly advanced research into surface geometry and sound absorption. Older studies often emphasize traditional porous absorbers, whereas more recent works provide novel insights into engineered geometries such as sinusoidal, corrugated, pyramidal, or perforated structures. By emphasizing the most recent literature, this review ensures that the analysis reflects the current state of the art, highlights emerging design strategies, and captures ongoing research trends relevant to modern acoustic challenges. The identified studies were analyzed in terms of material type, geometric profile, testing methods, frequency range, and acoustic performance outcomes.

This article review also examines how geometric variables interact with other design parameters, such as air gap size, material thickness, excitation frequency, and boundary conditions. Gaps in comparative studies, measurement consistency, and integration with predictive modeling tools are identified to outline future research directions.

2.3 Data Extraction and Thematic Analysis

Key information was extracted from each selected study, including:

1. Material type and surface configuration (flat, corrugated, pyramidal, wavy, sinusoidal, etc.).
2. Testing methodology (e.g., impedance tube, reverberation room, in situ measurements).
3. Frequency range analyzed and its relevance to human auditory perception.
4. Quantitative data such as absorption coefficients and surface area-to-volume ratios.
5. Reported mechanisms (e.g., scattering, diffraction, micro-resonance).

The literature was then categorized into thematic clusters: Intrinsic Properties of Acoustic Materials Influence of Surface Geometry, Modeling and Simulation Techniques, Experimental Measurement Methods, and Applications in Room Acoustics and Industrial Design.

2.4 Quality Assessment

To ensure academic rigor, each article was evaluated for:

1. Research design and methodology clarity,
2. Data transparency and repeatability of results,
3. Relevance to surface geometry as a variable in sound absorption
4. Citation count and journal impact factor (for additional weight in interpretation).

This methodological approach to the literature review has enabled a structured understanding of current advances and persisting challenges in the study of surface geometry in sound-absorbing materials. The synthesis forms the basis for defining the scope, experimental design, and contribution of the present research.

III. Results and Discussion

3.1 Results

The literature review reveals a consistent pattern that surface geometry plays a decisive role in shaping the sound absorption performance of acoustic materials, particularly in the mid-to high-frequency ranges. Numerous studies demonstrate that non-flat configurations such as wavy, pyramidal, and sinusoidal textures significantly enhance absorption coefficients compared to flat surfaces. The improvement in acoustic absorption due to engineered surface geometry can be attributed to several physical mechanisms:

1. *Diffraction and Scattering*
   Structured surfaces such as sinusoidal or corrugated geometries promote multiple scattering and diffraction of incident sound waves. This process increases the effective path length within the absorbing medium, thereby enhancing the probability of energy dissipation.
2. *Local Resonance Effects*
   Geometries that incorporate cavities, perforations, or periodic patterns can function as locally resonant units, like Helmholtz resonators. These localized resonances allow for targeted absorption at specific frequency bands, particularly in the low- to mid-frequency range, where traditional porous absorbers are less effective.
3. *Impedance Matching*
   Surface texturing modifies the acoustic impedance profile at the material–air interface, reducing reflection and facilitating greater sound transmission into the absorber. This mechanism is particularly important for achieving broadband absorption.
4. *Coupled Airflow and Viscous Losses*
   Micro-structured surfaces (e.g., micro-perforations, grooves) enhance viscous and thermal boundary layer interactions, increasing energy dissipation as sound waves travel through constricted channels.

By leveraging these mechanisms, engineered surface geometries provide a versatile design approach that overcomes the limitations of conventional porous materials, especially for compact structures intended to mitigate low-frequency noise. These findings underscore the strong potential of geometry-informed design to deliver efficient, application-specific, and sustainable acoustic materials [12]. A summary of representative studies is presented in Table 1.

Table 1. Literature Review Findings

No.	***Author (Year)***	***Material Type***	***Surface Geometry***	***Testing Method***	***Frequency Range (Hz)***	***Key Findings***
1	Cox & D'Antonio (2016) [2]	Porous absorber	Pyramidal, sinusoidal	Impedance Tube	125 – 4000	Irregular surfaces enhance high-frequency absorption via diffraction and scattering
2	Zhang et al. (2020) [9]	Polyurethane foam	Wavy, 3D structured	Kundt's Tube & FEM	100 – 5000	Sinusoidal geometry increases effective surface area and absorption efficiency
3	Alonso & Martellotta (2015) [11]	Perforated absorber	Flat + microperforated	Numerical simulation	125 – 4000	Shape and distance from wall interact to affect overall acoustic performance
4	Cai et al. (2017) [13]	Micro lattice porous	Tuned regular pore size and spacing	Impedance tube / model	~500 – 5000	Optimized pore size (~2× viscous boundary layer) maximizes absorption via viscous dissipation
5	Comandini et al. (2021) [14]	Fractal / metamaterial	Hilbert-fractal and coiled geometries	Impedance tube + FEM modeling	Resonant peaks, ~few kHz	Tortuous fractal channels enhance absorption at targeted

						resonant frequencies
6.	Pitchaimani et al. (2024) [15]	Metal or 3D printed inhomogeneous multi-cavity MPP	Variable hole sizes, cavity backing	Impedance tube	500–3000	Multi-cavity improves midband absorption
7.	Zhang et al. (2024) [16]	Polymer / metal curved micro-perforated metamaterial	Curved MPP with resonator cavity	Reverberation or tube	low-mid frequencies	Curvature enhances low-frequency absorption via resonator coupling
9.	Zieliński (2025) [17]	3D printed foam	Surface texture from filament stringing	Impedance tube	100–4000	Unintended geometry affects low-mid performance
11.	Mohammadi (2025) [10]	Standard MPPs	Flat, variable porosity and hole diameters	Reverberation chamber	500–5000	Porosity and hole diameter key to tuning absorption
12.	Krishna (2024) [18]	Fractal resonator	Hilbert curve + coiled cavities	Impedance tube	200–1500	Compact deep-subwavelength absorption

3.2 Discussion

The studies summarized in Table 1 consistently demonstrate that surface geometry exerts a decisive influence on the acoustic performance of absorptive materials, particularly in the mid-to high-frequency ranges. Across diverse investigations, modifications of surface profiles such as sinusoidal, pyramidal, corrugated, or perforated geometries have been shown to increase absorption coefficients relative to flat configurations. These improvements are underpinned by several mechanisms: geometrically structured surfaces expand the effective area available for sound and material interactions; irregular profiles promote multiple scattering and diffraction, extending propagation paths within or near the material; and localized resonance phenomena further amplify energy dissipation.

Empirical evidence reinforces these mechanisms. Zhang et al. (2020) [9] reported that sinusoidal surfaces not only enhanced overall absorption but also shifted peak performance toward lower frequencies through resonance effects, while corrugated and multi-scale roughness structures yielded broadband absorption suitable for general-purpose room treatments. Similarly, Cox and D'Antonio (2016) [2] emphasized that surface irregularities enhance absorption via scattering and impedance variations without altering bulk material properties. These findings suggest that surface modification represents a scalable, cost-effective strategy for improving acoustic efficiency without increasing mass or changing base composition. Overall, the review highlights the need for systematic, controlled experimentation using identical base materials with varied surface geometries. In addition, integrating these findings into simulation models for room acoustics remains limited. Many current acoustic prediction tools still rely on simplified or flat surface assumptions, which can lead to suboptimal design outcomes in architectural and industrial applications.

The insights from these studies underscore the potential of surface shape as a cost-effective design parameter in acoustic material engineering. By optimizing surface geometries, it is possible to enhance sound absorption without significantly altering material composition or increasing production costs. This opens opportunities for the development of high-performance, sustainable acoustic panels suitable for a wide range of environments. Nevertheless, methodological inconsistencies remain a challenge. Variations in material type, sample thickness, mounting conditions, and measurement techniques (e.g., impedance tube vs. reverberation chamber) complicate direct comparisons, while many studies fail to isolate geometry from other parameters such as porosity or backing conditions. Moreover, most computational models still adopt oversimplified or planar assumptions, limiting predictive accuracy in architectural and industrial applications. This highlights the need for systematic experiments using identical base materials with controlled geometric variations, coupled with advanced modelling tools that explicitly account for surface morphology.

Recent advances in material design further underscore the importance of integrating microstructural features with geometric modifications. An optimal relation between pore size and the viscous boundary layer thickness, showing that carefully tuned pore geometry and by extension, surface configuration can maximize absorption efficiency [13]. Pitchaimani et al. (2024) showed that functionally graded perforations in 3D-printed biodegradable panels simultaneously improved absorption and transmission loss, particularly at low frequencies. Inhomogeneous micro-perforated panels with multiple back cavities achieve superior performance, with pore diameter, perforation ratio, and cavity length emerging as dominant parameters [15]. Likewise, Van Damme et al. (2024) reported that introducing perforations, microcracks, and surface roughness into closed-cell foams markedly enhanced low-frequency absorption even in ultrathin samples. This configurations achieving substantial performance gains despite limited thickness [19]. Surface shape is effective in improving the absorption performance of these types of adsorbents [20]. Collectively, these studies illustrate that the synergy between surface geometry and microstructural tuning offers a powerful pathway to optimize acoustic performance across wide frequency ranges.

Overall, this review confirms that surface geometry is a critical yet underutilized parameter in acoustic material engineering. Beyond traditional factors such as porosity, thickness, and density, engineered surface configurations can significantly enhance sound absorption, promote diffusion, and improve acoustic comfort in enclosed spaces. Future work should prioritize standardized experimental comparisons and simulation frameworks that explicitly integrate geometric effects. Such efforts are expected to accelerate the development of cost-effective, application-specific, and sustainable acoustic materials tailored to modern built environments.

The insights gained from recent studies on surface geometry and acoustic absorption have significant implications for practical applications. In the construction industry, engineered absorbers with optimized surface patterns can be integrated into wall panels, ceilings, and partitions to improve indoor acoustic comfort in classrooms, offices, and residential buildings. In the automotive sector, lightweight geometrically engineered materials offer an effective solution for reducing engine and road noise while maintaining compact design requirements. Furthermore, in the context of urban planning and environmental noise control, surface-structured panels can be deployed in noise barriers and public infrastructure to mitigate traffic and industrial noise in densely populated areas. These applications demonstrate that advancing the design of surface geometry is not only a scientific pursuit but also a strategic response to the growing demand for sustainable and efficient noise-control technologies.

IV. Conclusion

Based on the literature review conducted, several key conclusions can be drawn:

1. Surface geometry is a decisive factor in sound absorption, particularly in the mid- to high-frequency ranges where traditional porous absorbers are less effective.
2. Engineered geometries such as sinusoidal, pyramidal, corrugated, and perforated forms improve acoustic performance by expanding surface area, promoting scattering and diffraction, and inducing local resonance effects.

3. Geometry-informed design offers a cost-effective pathway to optimize acoustic efficiency without major changes in material composition or mass, making it compatible with bio-based and recycled materials.
4. Systematic experimentation with controlled geometrical variations and advanced computational models that integrate surface morphology are essential to achieve more accurate predictions and broader practical applications.

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