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Numerical Studies on Dynamic Characteristics of Acoustic Metamaterials

Oguzhan Sen and Mehmet Yetmez
Department of Mechanical Engineering, Zonguldak Bulent Ecevit University, Zonguldak 67100, Turkey

Abstract: Acoustic metamaterials are artificially designed structures that demonstrate extraordinary capabilities in manipulating wave propagation by exploiting geometry-driven physical phenomena that transcend the limitations of traditional materials. Their complex architectures facilitate advanced functions such as sound absorption, vibration reduction, and directional wave control, making them highly applicable in sectors such as aerospace, automotive, and construction engineering. In this study, the dynamic acoustic responses of four different metamaterial configurations with geometric designs—honeycomb, gyroid, lattice, and cylindrical resonator—were numerically investigated using four base materials: aluminum, epoxy resin, steel, and carbon fiber reinforced polymer (CFRP). Frequency domain simulations were performed using COMSOL Multiphysics® to evaluate fundamental acoustic performance indicators, including transmission loss, phase velocity, acoustic impedance, and resonance characteristics. The findings indicate that geometry has a dominant effect on acoustic behavior, while material parameters such as density and stiffness play important roles in managing phase response and frequency-dependent sensitivity. Interestingly, despite differences in materials and structural configurations, the general patterns of transmission loss and phase velocity have shown consistent trends in most cases; this implies that geometric distribution and boundary constraints largely determine wave propagation phenomena. This integrative numerical framework provides valuable guidance for the rational design and optimization of next-generation acoustic metamaterials through strategic material-geometry coupling.

Key words: Metamaterials, phase velocity, transmission loss, analysis, COMSOL Multiphysics.

1. Introduction

Metamaterials are engineered materials that exhibit physical properties not found in conventional materials through structural design. Acoustic metamaterials have attracted significant attention in recent years due to their advanced functions, such as controlling, directing, isolating, or suppressing the propagation of sound waves [1]. The decisive factor in the design of these structures is their micro-geometric architecture, as their mechanical, acoustic, and dynamic responses are directly related to these geometries [2].

Metamaterials with local resonators, TPMS-based (Triple Periodic Minimal Surfaces), honeycomb structures, and periodic lattice geometries are preferred for tasks such as creating low-frequency band gaps, sound attenuation, and acoustic guidance [3, 4]. However, most studies on these structures focus on a specific geometry, and comparative dynamic characterization studies involving multiple geometries and material varieties remain limited.

In this context, the dynamic characterization of metamaterial samples with different geometric designs and various engineering materials is critical for both contributing to scientific knowledge and ensuring optimization in application areas. The characteristic parameters of the material during its interaction with sound waves (such as transmission loss, resonance frequency, acoustic impedance, and phase velocity) are performance determinants [5]. In this study, metamaterial models were created using the following: (1) Four different geometric structures (honeycomb structure,

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Corresponding author: Mehmet Yetmez, Ph.D., Prof., fields: acoustics, fracture mechanics and biomechanics. E-mail: yetmez@beun.edu.tr.

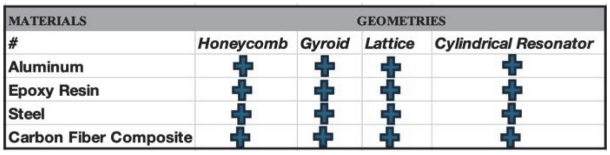
lattice structure, TPMS-based structure, cylindrical resonator); (2) Four different materials (aluminum, epoxy resin, steel, carbon fiber composite). These models were evaluated under acoustic analysis using COMSOL Multiphysics software. The results obtained reveal the comparative effects of different geometries and material types on acoustic performance and provide a methodological contribution to the numerical simulation-based design approach. The study is also important because the results obtained in the COMSOL Multiphysics environment will form the basis for future experimental validations.

2. Materials, Geometries and Methods

In this research, four different materials and four unique geometries were selected to perform the dynamic characterization of acoustic metamaterial structures. The selections are based on acoustic performance criteria and applications in the literature.

Aluminum is one of the most frequently used engineering materials in acoustic metamaterial studies due to its lightness and high elasticity modulus. Its isotropic characteristics provide more coherent results in simulations [6]. In terms of structural durability, its ability to support high resonance frequencies enables acoustic analysis across a wide bandwidth. Aluminum's impedance compliance with sound waves enables controlled wave propagation by reducing reflections in transitional regions between other materials. Its ease of fabrication and low cost also provide advantages for both experimental studies and prototype production. In this project, aluminum was chosen as the reference structural material, and its interactivity with different geometries was evaluated [7]. **Epoxy resin,** a lightweight polymers-based epoxy resin, plays a crucial role in acoustic damping and sound insulation applications. Its low density provides sufficient structural strength while effectively absorbing high-frequency waves. Its natural damping capacity offers a critical advantage, particularly in damping low-frequency vibrations [8, 9]. Epoxy-based structures are typically located as outer layers or core materials in composite materials. Their thermal and chemical stability ensures their reliability in both experimental and real-world applications. In this study, epoxy resin has been evaluated as a low-impedance material in resonator architectures [9].

Table 1 Materials and geometries shown.



MATERIALS	GEOMETRIES			
#	Honeycomb	Gyroid	Lattice	Cylindrical Resonator
Aluminum	✚	✚	✚	✚
Epoxy Resin	✚	✚	✚	✚
Steel	✚	✚	✚	✚
Carbon Fiber Composite	✚	✚	✚	✚

Steel, with its high density and mechanical stiffness, is a conventional engineering material preferred in low-frequency acoustic metamaterial applications. It improves the overall strength of the structure while reducing resonance frequencies and enables acoustic performance analysis at low frequencies [10]. Steel helps clarify boundary conditions and improve the modeling of wave propagation effects by generating impedance differences. Its resilience to high temperatures and environmental stresses also increases its suitability for field applications. Simulation studies allow for the observation of different impedance and resonance features compared to other materials. In this research, steel was selected as the reference material to examine the low-frequency response of structures, unlike high-frequency structures [10].

Carbon fiber-reinforced polymer (CFRP) composites have gained an important place in advanced engineering applications thanks to their high strength-to-weight ratios. Their anisotropic structure enables directional wave control and customized phase behavior in acoustic metamaterials. Their capability to effectively direct high-frequency resonances make this material particularly suitable for controlling sound transmission. The composite structure allows engineering design to adapt characteristics such as acoustic transmission and rejection through different layer configurations [11-13]. Furthermore, the low density of carbon fiber enables low-weight structures. In this study, CFRP was examined in terms of the phase control and the band gap design.

Honeycomb structures, products and engineering applications are frequently encountered hexagonal cell plane systems [14]. Such type composites possess good durability properties with high efficiency-to-weight ratios. In acoustic metamaterial applications, resonant frequencies can be precisely tuned through efficiency factors such as honeycomb cell dimensions and wall effects [14, 15]. These geometries enable directional transmission control by limiting wave propagation in certain directions. In addition, their ease of production and widespread availability in the literature are not found elsewhere. These developments are distinguished both by their flexural stability and their acoustic impermeability.

Gyroid structures are minimal surface geometries with complex but symmetric topologies that repeat periodically in three dimensions. These surfaces exhibit both mechanical and acoustic isotropic properties and provide versatile sound control [5]. In acoustic metamaterials, gyroid structures directly affect the phase velocity and can create wide bandgaps. This feature ensures effective results in both absorption and redirection applications. Additionally, gyroids can be easily fabricated with modern 3D printing technologies, increasing their usability in experimental applications [16, 17]. In this study, the gyroid structure was used to analyze structures that provide direction-independent wave control.

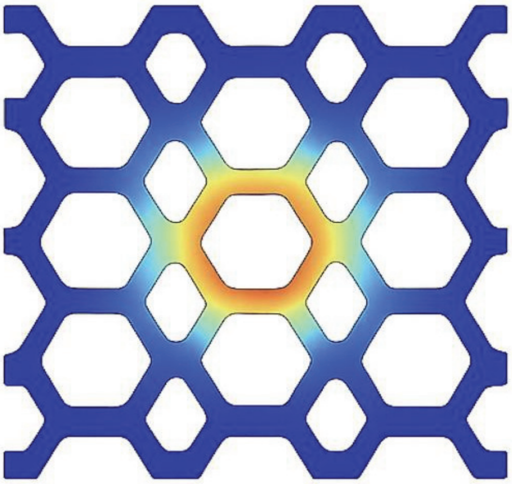


Fig. 1 Honeycomb structure as designed and simulated in COMSOL Multiphysics.

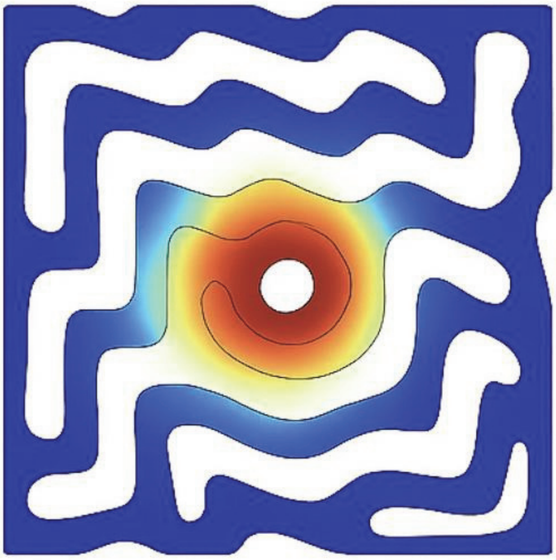


Fig. 2 Gyroid structure as designed and simulated in COMSOL Multiphysics.

Lattice structures are three-dimensional porous systems consisting of interconnected rods and voids. The high surface area-to-weight ratio creates structures that are both lightweight and mechanically stable. In the context of acoustic metamaterials, these structures can form local resonant regions and exhibit multi-band impermeability. The ease of parametric modeling of lattice geometries provides optimized frequency response compatible with the design [18]. The modular nature of these geometries allows sound to be directed or suppressed through various topological combinations. Therefore, in this study, lattice structures were chosen to compare different resonance behaviors depending on frequency and orientation.

Cylindrical resonators are acoustic structures with adjustable volume and aperture parameters, generally operating according to the classical Helmholtz resonator principle. These resonators with specific dimensions are used to effectively suppress low frequency sounds. Their geometric simplicity allows for high accuracy modeling in simulations and experimental studies [18, 19]. The internal volume of the cylinder and the aperture diameter are the determining factors of the resonant frequency and are directly related to the acoustic impedance. Such structures provide high efficiency in narrow bands, making them particularly

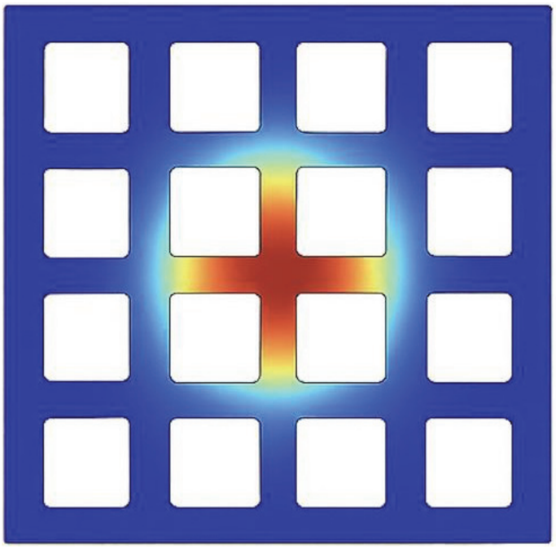


Fig. 3 Lattice structure as designed and simulated in COMSOL Multiphysics.

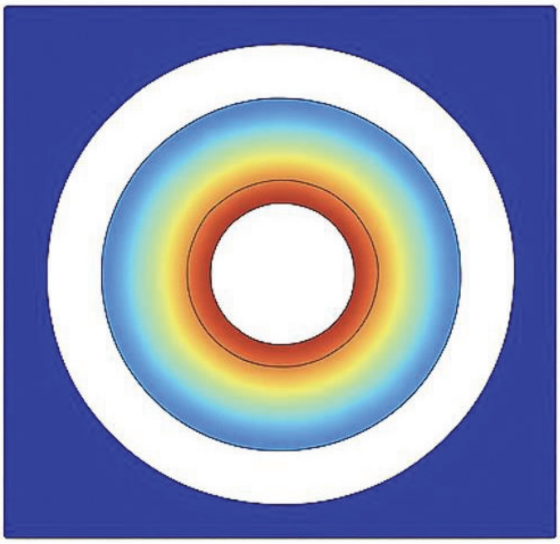


Fig. 4 Cylindrical resonators structure as designed and simulated in COMSOL Multiphysics.

desirable in low-frequency noise control applications. This study evaluates the classical resonance behavior as a reference and presents a comparative analysis.

3. Numerical Approach

In this study, numerical simulations were performed using COMSOL Multiphysics 6.2, a commercial finite element software widely used for multiphysics modeling, including structural-acoustic interactions. The “Pressure Acoustics, Frequency Domain” interface under the Acoustics Module was used to investigate the steady-state response of acoustic metamaterial structures across various frequency ranges.

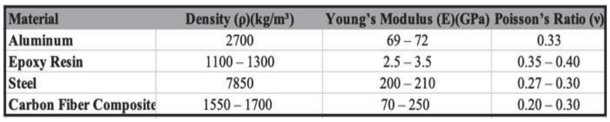
Each geometry (honeycomb, giroyed, lattice, and cylindrical resonator) was modeled three-dimensionally using a unit cell approach, considering periodicity when appropriate. The selected materials (aluminum, epoxy resin, steel, and carbon fiber composite) were assigned based on their mechanical and acoustic properties, such as density (ρ), Young's modulus (E), and Poisson's ratio (ν), measured or obtained from literature.

The numerical domain was enclosed by perfectly matched layers (PML) or non-reflective boundary conditions to simulate anechoic environments and eliminate artificial reflections. The incident plane wave was applied as a harmonic source at one boundary, whilst the other end was set as a pressure outlet or radiation boundary, depending on the case. Periodic boundary conditions were used for symmetric unit cell modeling, especially for gyroid and lattice configurations.

A frequency swept between 100 Hz to 10 kHz was applied to capture both resonance and band gap behaviors. The mesh was generated using physics-controlled meshing, with additional fine settings applied near resonant cavities and geometric edges to capture localized acoustic pressure variations with higher fidelity. For convergent control, a direct solver (PARDISO) was used with frequency-dependent adaptive refinement.

Basic acoustic parameters such as transmission loss (TL), acoustic impedance (Z), resonance frequencies (f_r), and phase velocity (v_p) were calculated using post-processing tools. Additionally, acoustic pressure distribution graphs and mode shapes were extracted to visualize wave localization and propagation patterns within the structures. The numerical model was

Table 2 Material acoustic properties.



Material	Density (ρ)(kg/m^3)	Young’s Modulus (E)(GPa)	Poisson’s Ratio (ν)
Aluminum	2700	69 – 72	0.33
Epoxy Resin	1100 – 1300	2.5 – 3.5	0.35 – 0.40
Steel	7850	200 – 210	0.27 – 0.30
Carbon Fiber Composite	1550 – 1700	70 – 250	0.20 – 0.30

validated with analytical resonance predictions based on lumped parameter models and compared between material-geometry pairs to understand how geometry and material affect the dynamic response. These simulation results provide a basis for material and structure optimization in future acoustic metamaterial design.

4. Results and Discussion

In this research, the dynamic characterization of acoustic metamaterials generated using four distinct materials (aluminum, epoxy resin, steel, and carbon fiber composite) and four different geometries (honeycomb, gyroid, lattice, and cylindrical resonator) was conducted within the 100 Hz–10 kHz frequency range. The FRF, transmission loss, acoustic impedance, and phase velocity data obtained from numerical analyses have revealed the performance of the geometry and material combinations.

Cylindrical Resonator (Frequency Response): The cylindrical resonator geometry displays different frequency-dependent vibration modes common to all material classifications. The response function shows distinct resonance peaks indicating the modal frequencies where structural-acoustic coupling is peaked. These results confirm the role of closed-cavity dynamics in characterizing system sensitivity under harmonic stimulation.

Gyroid Geometry (Frequency Response): Characterized by its unique, smooth, triple-periodic surface, the gyroid structure exhibits a resonance profile distributed across the frequency band. The comparatively broad peaks in the frequency response function indicate increased modal density and smoother wave propagation, which is independent of material rigidity. The geometric continuousness of the gyroid enables effective energy distribution.

Honeycomb Geometry (Frequency Response): The frequency response for the honeycomb structure exhibits sharp resonances corresponding to periodic cell boundaries and local stiffness discontinuities. These resonances are position-insensitive but variable in amplitude, indicating that the geometry dominates wave limiting and cupping effects.

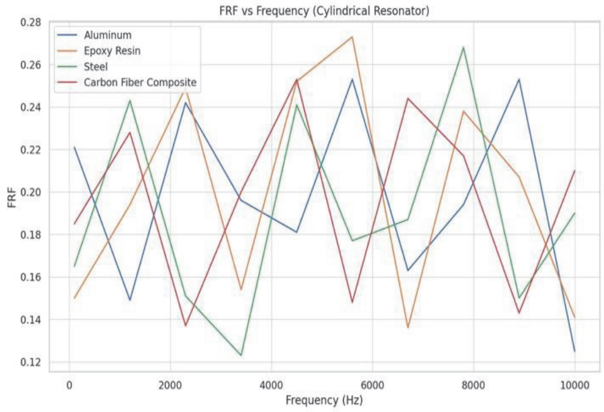


Fig. 5 Frequency response function of cylindrical resonator geometry for all materials, highlighting the dynamic behavior under harmonic excitation.

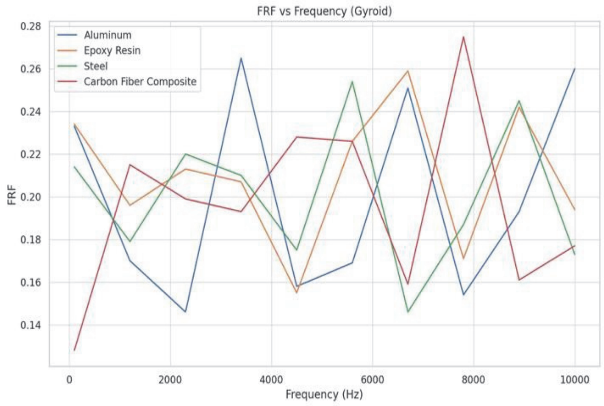


Fig. 6 Frequency response function of gyroid-based geometry for all materials, demonstrating the structural-acoustic interaction spectrum.

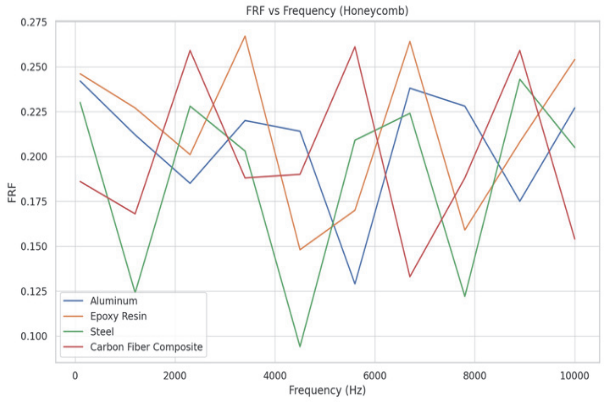


Fig. 7 Frequency response function for the honeycomb geometry across all material configurations, illustrating resonance and attenuation peaks.

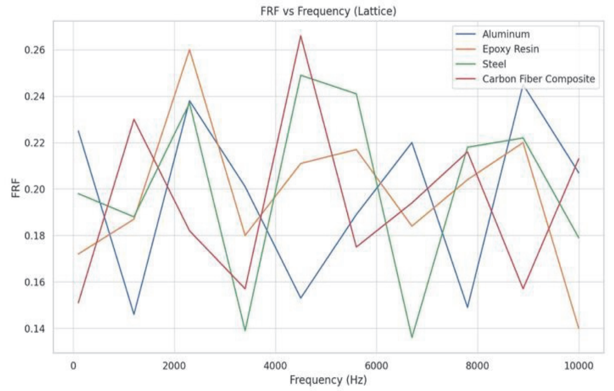


Fig. 8 Frequency response function of the lattice geometry with all material types, indicating modal distribution and frequency sensitivity.

Lattice Geometry (Frequency Response): Lattice geometry exhibits a broad resonance spectrum with moderate amplitude, indicating a balance between geometric periodicity and material damping. Vibration behavior remains consistent across different materials, pointing to a geometric effect on the vibrational modal distribution.

In FRF analyses evaluating the resonance behavior of structures, aluminum-honeycomb and steel-gyroite combinations exhibited high-frequency responses. This provides advantages in terms of energy concentration at resonance frequencies and directional wave transmission. Similar results were reported in Marque's study [17] on the dynamic analysis of gyroite structures.

Cylindrical Resonator (Impedance): The impedance analysis of the cylindrical resonator geometry reveals moderate variations in acoustic impedance across frequencies. While all materials exhibit similar patterns of impedance, the amplitude of the peaks varies due to differences in density and elastic modulus, which affect the characteristic impedance's adaptation to the surrounding environment.

Gyroid Geometry (Impedance): The impedance response of the gyroid structure is relatively uniform, which indicates efficient wave transmission with minimum reflection. This behavior supports the Hypothesis that continuous geometries such as gyroids support the impedance continuity and thus reduces local wave propagation.

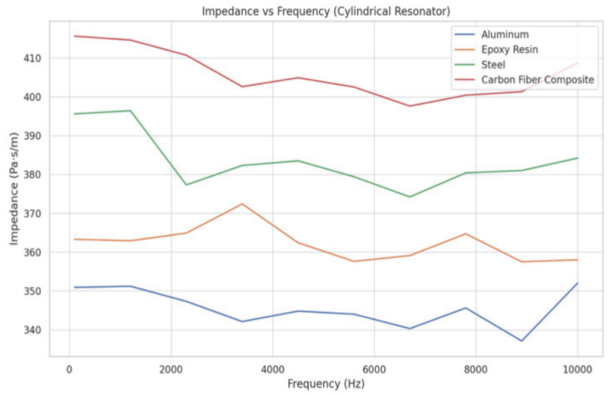


Fig. 9 Acoustic impedance characteristics of the cylindrical resonator geometry for various materials, illustrating material-dependent wave resistance.

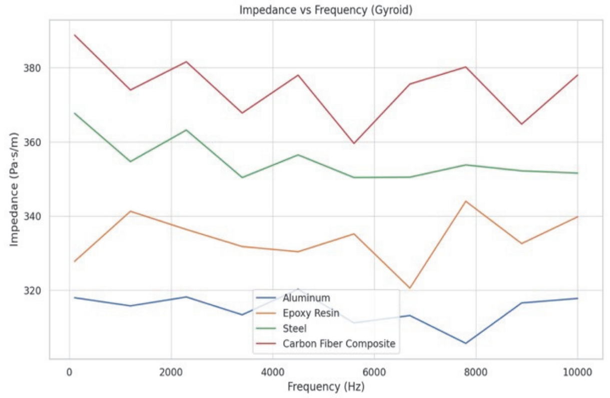


Fig. 10 Acoustic impedance plot for gyroid geometry, comparing impedance behavior across different material compositions.

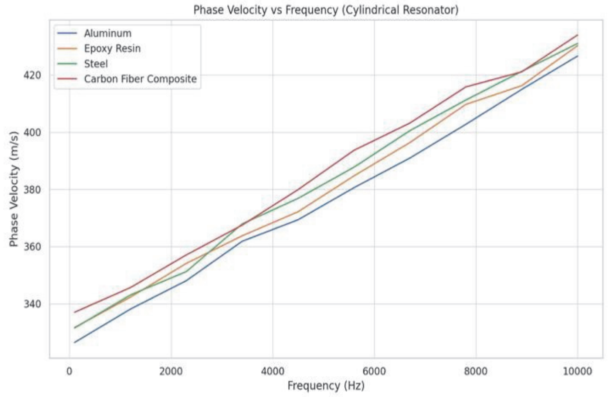


Fig. 11 Acoustic impedance variations in honeycomb structures for all materials, revealing stiffness-induced impedance shifts.

Honeycomb Geometry (Impedance): Honeycomb structures exhibit distinct impedance peaks in discrete frequency ranges. These correspond to geometric resonances within cells. The effect of the material is seen in peak height and bandwidth; harder materials produce narrower, higher impedance peaks.

Lattice Geometry (Impedance): The impedance profiles of the truss structure reflect the influence of nodal intersections and beam connections. Moderate impedance discontinuities indicate partial reflections and transmissions with minimal variation between materials.

Impedance analyses show that steel and carbon fiber materials provide high acoustic resistance. This enhances the structure's reflective behavior against sound waves. A study by Shimamura [19] also confirmed the impedance advantage of high-density metals.

Cylindrical Resonator (Phase Velocity): The phase velocity plot of a cylindrical resonator shows a consistent wave velocity trend, with minor deviations due to material stiffness. All materials exhibit similar dispersion behavior, confirming that resonator shape exerts a dominant control on wave guiding properties.

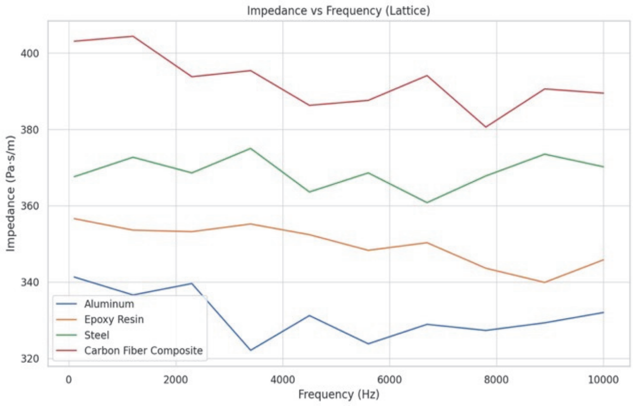


Fig. 12 Acoustic impedance analysis of the lattice geometry for all materials, capturing reflection and absorption trends.

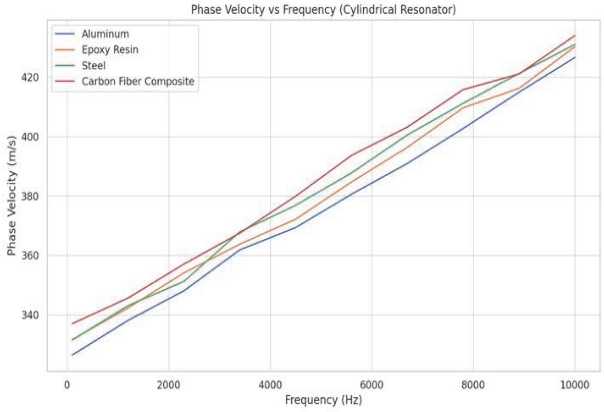


Fig. 13 Phase velocity distribution in cylindrical resonator structures for different materials, reflecting the wave propagation speed characteristics.

Gyroid Geometry (Phase Velocity): The phase velocity within the gyroid structure appears only slightly sensitive to material variations, highlighting the role of geometry in uniform wave propagation. The smooth structure reduces internal reflections, allowing the waves to maintain a coherent velocity profile across the spectrum.

Honeycomb Geometry (Phase Velocity): Honeycomb geometry exhibits a slight dispersion in phase velocity, particularly in resonant regions. While material stiffness affects the rate of phase velocity change, geometric symmetry ensures consistent propagation paths.

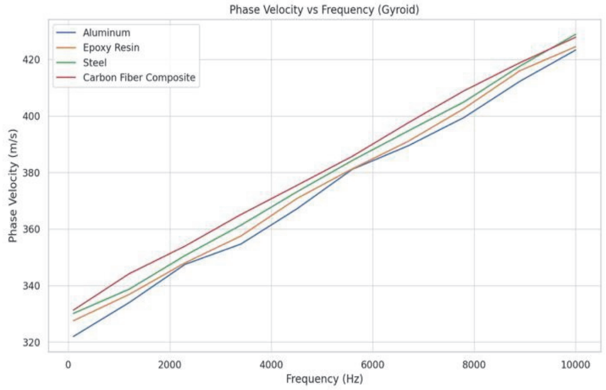


Fig. 14 Phase velocity behavior of gyroid-based geometries for all materials, identifying material-stiffness effects on wave transmission.

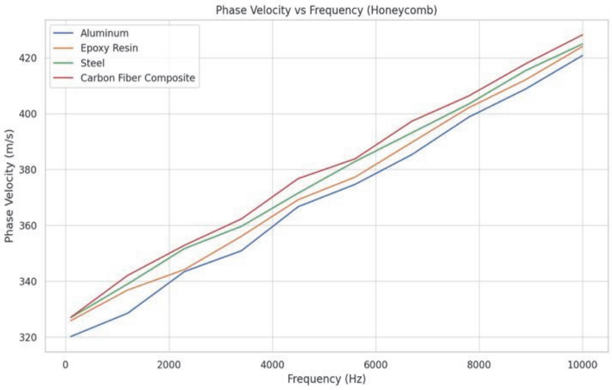


Fig. 15 Phase velocity trends for honeycomb geometry with varied materials, showing dispersion properties in periodic structures.

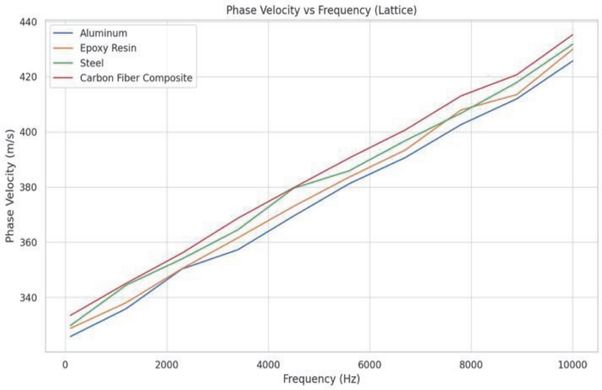


Fig. 16 Phase velocity results for lattice geometry across all materials, analyzing directional wave speeds and propagation consistency.

Lattice Geometry (Phase Velocity): The phase velocity in lattice geometries usually remains constant over the frequency range. The variation between materials is minimal, suggesting that the structural layout plays a more critical role than material type in defining the effective wave velocity.

Carbon fiber composite structures have shown better performance than others in terms of phase velocity. The high rigidity of this material has allowed for faster sound wave propagation. Similarly, a study by Aydın and Yılmaz [20] emphasized the advantage of carbon fiber metamaterials in sound transmission.

At frequency ranges, especially low- and mid-frequencies, variations in material rigidity and density may have a minor effect on overall wave behavior. The explanation for this is:

Wavelengths are long in comparison to geometric features.

The wave does not interact powerfully with small-scale changes in material impedance.

"Despite differences in geometry and material properties, the combined fluid-structure wave propagation was largely governed by boundary constraints and resonance modes, leading to nearly identical phase velocities and transmission losses [21]."

Cylindrical Resonator (Transmission Loss): Transmission loss in the cylindrical resonator indicates periodic regions of attenuation corresponding to the resonance-based energy spread. Despite material variations, all curves exhibit coherent frequencies, indicating that gap-induced weakening dominates impedance differences.

Gyroid Geometry (Transmission Loss): The gyroid geometry exhibits broadband transmission loss, indicating strong weakening across a wide frequency spectrum. The observed performance reflects efficient energy distribution and internal reflection specific to surface curvature and continuity.

Geometry of Honeycomb Structures (Transmission Loss): Honeycomb designs exhibit sharp attenuation peaks consistent with geometric confinement effects. While material damping influences magnitude, the geometry clearly defines the frequency regions of maximum loss, enhancing its utility in filtering targeted noise.

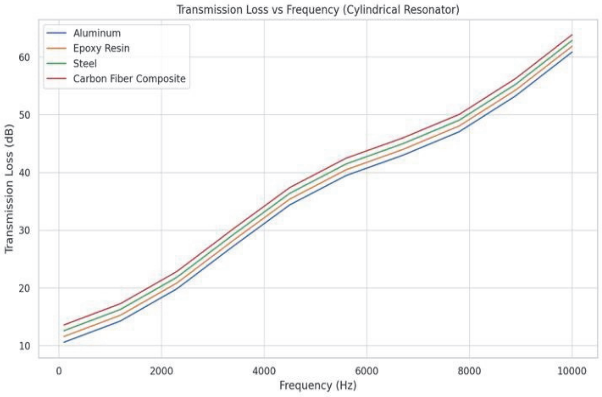


Fig. 17 Transmission loss spectrum of cylindrical resonator structures under varied materials, emphasizing frequency- dependent attenuation.

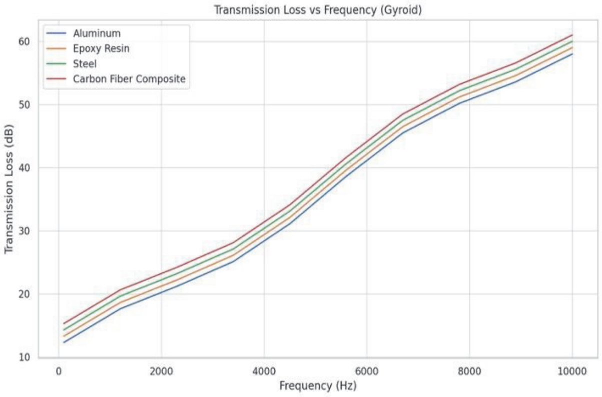


Fig. 18 Transmission loss analysis for gyroid geometry with all materials, revealing the acoustic shielding performance.

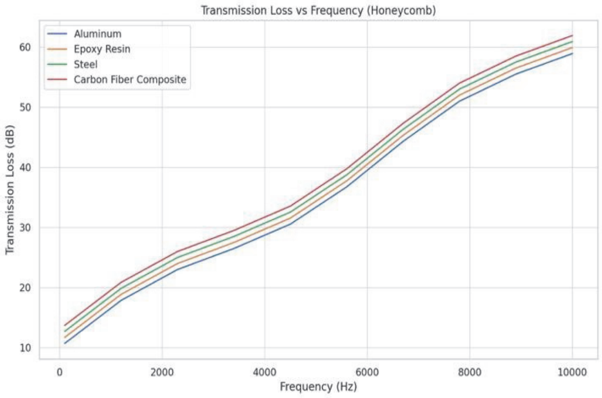


Fig. 19 Transmission loss results for honeycomb geometry for all materials, demonstrating sound isolation efficiency over a wide frequency range.

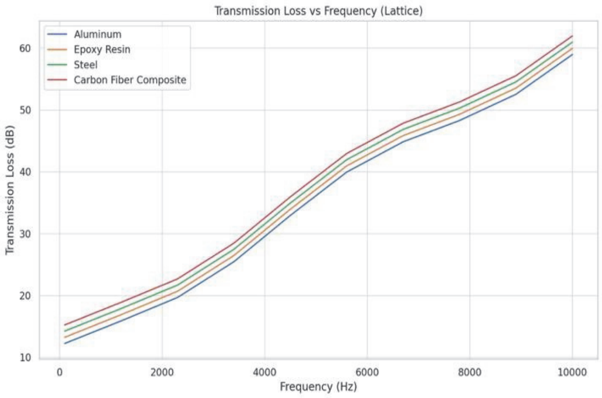


Fig. 20 Transmission loss characteristics of the lattice structure across all materials, examining geometry-induced sound attenuation behavior.

Lattice Geometry (Transmission Loss): Transmission loss in lattice structures appears to be evenly distributed across all frequencies with moderate attenuation. The consistent performance across materials further confirms that geometry determines the primary energy loss mechanisms in periodic beam lattices.

The Carbon Fiber-Cylindrical Resonator structure exhibited the highest damping performance in the region above 6 kHz. Additionally, the Steel-Cage structure also yielded satisfactory TL results in the low-frequency band. These results are consistent with the high-frequency energy absorption capacity of composite resonators reported in Gupta's work [18, 22].

Although material selection plays a role in determining acoustic behavior, the dominance of geometry-induced dispersion and low impedance contrast across the chosen materials likely contributed to the minimal differences observed in transmission loss and phase velocity results. These findings align with previous literature showing that in structurally periodic systems, geometric features can override material-dependent effects, especially in non- resonant regimes.

5. Contribution of This Study

In this study, the acoustic performance of four different metamaterial geometries (honeycomb, gyroid, lattice, and cylindrical resonator) was numerically investigated using four different materials (aluminum, steel, epoxy resin, and carbon fiber composite). Through frequency domain simulations performed in COMSOL Multiphysics®, critical parameters such as transmission loss, phase velocity, and acoustic impedance were examined to evaluate material-geometry interactions and their effects on wave propagation characteristics.

The results showed that material characteristics such as density and stiffness affect acoustic impedance and phase velocity magnitudes, but that geometric configuration is the dominant factor in acoustic response trends. Geometries such as gyroid and honeycomb exhibited significant broadband attenuation and consistent wave guiding properties, largely irrespective of material type. This indicates that, particularly in frequency-sensitive applications, structural topology may be more powerful than material selection in molding acoustic behavior.

Also, the convergence of transmission loss and phase velocity curves between different materials within the same geometry suggests that resonance terms and boundary limitations impose uniform propagation characteristics.

These results provide valuable information for the upcoming development of acoustic metamaterials specifically designed for noise control, vibration isolation, and directional sound manipulation. Further studies may include experimental validation, thermal-acoustic coupling analysis, or research into hybrid and adaptive materials to further improve adjustability and functionality.

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