Scientific Reports

https://doi.org/10.1038/s41598-025-34382-9

Article in Press

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Received: 30 August 2025

Accepted: 29 December 2025

Published online: 10 January 2026

Cite this article as: Meng Y. & Gu S. Aesthetic-inspired bandgap design in phononic crystal plates. *Sci Rep* (2026). https://doi.org/10.1038/s41598-025-34382-9

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Aesthetic-Inspired Bandgap Design in Phononic Crystal Plates

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Abstract

This study proposes an aesthetic-inspired design methodology for phononic crystal (PnC) plates by systematically incorporating classical aesthetic principles—such as the golden ratio, mirror symmetry, curvature smoothness, and visual balance—into the parametric modeling and simulation process. Star-shaped unit cell geometries were designed and analyzed to investigate how aesthetically inspired features affect phononic bandgap characteristics. Numerical results reveal that while curvature smoothness primarily enhances visual appeal, symmetry and visual balance significantly influence the position and width of the bandgap. Specifically, the application of the golden ratio led to wider and more visually harmonious bandgaps, while intentional symmetry-breaking enabled topological bandgap opening. Two representative unit cell

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designs are proposed that successfully integrate aesthetic considerations with functional performance. This study underscores the potential of aesthetic principles not only as a means to enhance the visual and structural coherence of phononic crystals, but also as an effective design strategy for functional optimization. By bridging geometry, aesthetics, and mechanics, the findings establish a novel pathway for creating multifunctional architected materials that combine structural integrity, acoustic performance, and visual refinement, thereby broadening the scope of applications in acoustic devices, vibration control, and structural engineering.

Keywords

Phononic crystal, Aesthetic-inspired design, Band gap, Star-shaped unit cells, Multifunctional materials

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1. Introduction

Recently, researchers have shown significant interest in elastic wave propagation within phononic crystal (PnC) structures. Such composite structures have been extensively investigated for their promising functionalities, including wave control and filtering, energy harvesting, acoustic lensing, and vibration isolation[1–7]. These properties primarily stem from the existence of phononic bandgaps, frequency ranges in which elastic waves are prohibited from propagating, significantly influenced by the microstructural characteristics and geometric parameters of the PnCs. In addition, the key factors influencing the bandgap and its tunability are also investigated. Zhang et al.[8] proposed a novel three-layer phononic crystal (PnC) composite magnetoelastic beam, in which the inclusion of a magnetoelastic layer enables tunable bandgaps by adjusting external magnetic fields across multiple scales. Hong et al.[9] proposed a novel phononic crystal model that integrates temperature effects, microstructural features, and surface energy considerations and systematically investigated various factors influencing the bandgap, including thin-walled cross-sectional shape, microstructure characteristics and so on. Kherraz et al.[10] developed a phononic crystal model that incorporates piezoelectric coupling effects, enabling effective bandgap tuning via external circuit impedance loads. Despite extensive studies optimizing phononic crystal structures for superior bandgap performance[11–14], traditional design approaches typically prioritize functional aspects while neglecting aesthetic considerations. This functional dominance often results in designs that lack visual appeal and integration, restricting their potential applications in fields where aesthetics and structural elegance are equally valued, such as architectural acoustics, sensor interfaces, and decorative functional materials. Thus, there is a growing necessity to establish design methodologies that integrate

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both bandgap performance and aesthetic qualities, enabling multifunctional PnCs that meet comprehensive performance and visual criteria.

On the other hand, With the continuous evolution of engineering design concepts, traditional approaches that prioritize functionality and performance are gradually shifting toward the integration of function and form. Aesthetics, as a crucial bridge between technology and human perception, is playing an increasingly important role in engineering. By incorporating aesthetic principles such as symmetry, proportional harmony, geometric order, and nature-inspired patterns, engineers can enhance not only the visual appeal of a product or structure but also the overall user experience and efficiency of human-machine interaction. In fields ranging from architecture and product design to transportation, interface engineering, and even functional structures like phononic or photonic crystals, aesthetic integration has been shown to improve usability, increase recognition, and in some cases, enhance performance[15,16]. As a result, aesthetics is no longer a supplementary aspect of engineering design but a driving force for innovation that unites technology, artistry, and user-centered thinking. Aesthetic effects have been increasingly recognized in PnC designs at multiple scales, bridging visual perception and structural

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functionality. Recent studies have highlighted that introducing aesthetically guided geometric patterns into phononic structures can significantly impact their bandgap properties, with the aesthetic influence becoming particularly pronounced in structures exhibiting visual symmetry or distinctive repeating patterns. Several models integrating aesthetic-driven geometry have been established to analyze this coupling in PnCs. Xin et al.[17] proposed a novel acoustic metamaterial structure incorporating an aesthetically inspired snowflake-shaped fractal geometry, and investigated its directional wave propagation characteristics. In addition, there has been growing research on expanding the bandgaps of phononic crystals through the design of aesthetic features such as symmetry. For instance, Kuang et al.[18] numerically investigated the bandgap characteristics of two-dimensional solid phononic crystals composed of lattices with varying symmetries and scatterers of different shapes, orientations, and sizes.

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This study aims to investigate a novel approach to phononic crystal plate design by systematically incorporating classical aesthetic guidelines into the parametric modeling process. In particular, we introduce aesthetic-inspired variables that have rarely been considered in previous phononic crystal studies, such as the golden ratio and curvature smoothness, thereby providing a new

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perspective on how aesthetic design choices can significantly affect bandgap properties. By leveraging these principles, we propose aesthetically informed PnC geometries and evaluate their performance using COMSOL Multiphysics (v6.2, https://cn.comsol.com/), a finite element software capable of simulating complex bandgap behaviors. Key aesthetic features are parametrically varied to examine their influence on bandgap characteristics. This paper is organized as follows: Section 2 presents the modeling approach and the aesthetic parameters under investigation. In Section 3, numerical results are used to analyze the influence of each aesthetic parameter on the bandgap characteristics. Section 4 provides a comprehensive discussion and introduces two design cases that achieve both aesthetic appeal and desirable mechanical performance. Finally, Section 5 offers conclusion.

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2. Design Methodology

During this section, PnC plates incorporating aesthetic effects are developed by systematically applying the aesthetic principles proposed in this section. To achieve this integration, parametric modeling was conducted based on classical aesthetic guidelines, including the golden ratio[19], mirror symmetry[20]. These aesthetically informed structures are then constructed and analyzed using

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COMSOL Multiphysics, a finite element software widely utilized for bandgap simulations[21-24]. Specifically, geometric features identified as visually appealing are parametrically varied to evaluate their influence on the bandgap characteristics. Through this modeling approach, we aim to quantitatively assess how aesthetic-driven geometric variations contribute to both enhanced bandgap performance and improved visual appeal, thereby providing a novel design methodology that bridges functionality and aesthetics in phononic crystal plate design. The main process is shown in Fig. 1. Firstly, the aesthetic principle is introduced into the phononic crystal. Then, the aesthetic element is optimized based on the band gap. Finally, a beautiful and practical phononic crystal design is output.

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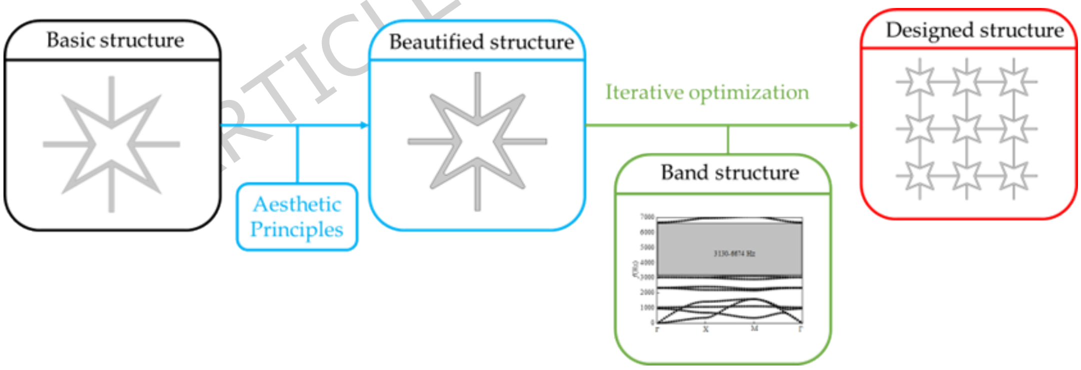

Fig. 1 Phononic crystal plate design flowchart.

2.1 Aesthetic Principles in PnC Plates Design

To effectively integrate aesthetic considerations into PnC structures, several fundamental principles of visual perception and aesthetic theory were employed. These include classical aesthetic guidelines such as the golden ratio, mirror symmetry, curvature

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smoothness, and visual balance, which are universally recognized to enhance visual attractiveness and structural harmony. Detailed structural design strategies incorporating these principles are outlined as follows:

Golden Ratio: Structures were proportioned according to the golden ratio (approximately 1:1.618) to achieve inherent visual harmony. Specifically, geometric parameters such as unit-cell dimensions, lattice spacing, and hole sizes were systematically determined using this ratio.

Mirror Symmetry: Designs featured symmetrical arrangements with respect to central or multiple reflective axes. By introducing mirror-symmetrical structures, uniformity and visual coherence were enhanced. For instance, unit cells were symmetrically replicated along defined axes, contributing to stable and predictable bandgap behaviors while promoting aesthetic consistency.

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Curvature Smoothness: Smooth, continuous curves were implemented instead of abrupt angles or sharp corners. Geometric features, such as circular, elliptical, or curves, were integrated into unit cells to produce flowing, organic patterns. These smooth curves reduce visual tension, enhance structural integrity, and have the potential to beneficially modulate wave propagation.

Visual Balance: Structures were arranged and distributed to

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achieve visual equilibrium, ensuring balanced visual weight across the design. Strategies included uniformly spacing unit-cell patterns, evenly distributing structural elements, and strategically placing larger geometric features opposite smaller features to maintain overall visual stability.

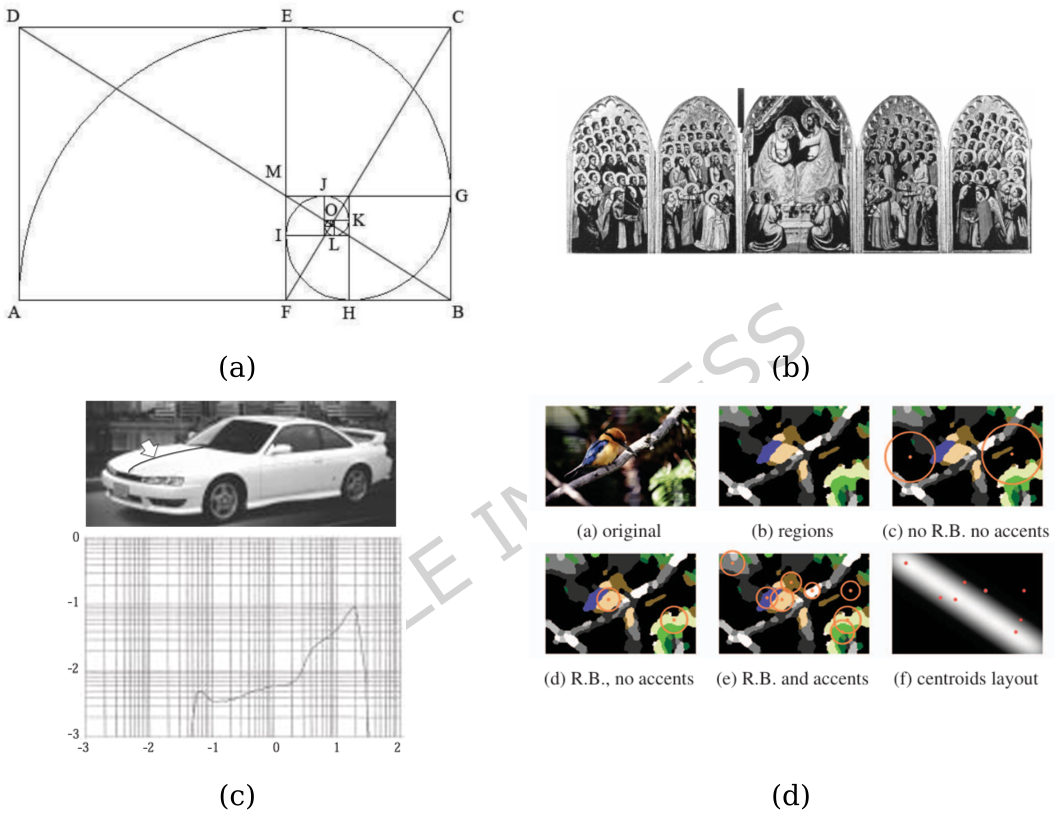

Fig. 2 Figur of (a) Golden ratio[19]; (b) Mirror Symmetry[27]. (c) Curvature Smoothness[31]; (d) Visual Balance[32].

Figure 2 illustrates the aforementioned aesthetic elements, which can be seen to greatly enhance the overall visual appeal. By methodically integrating these aesthetic principles into phononic crystal structures, the proposed designs not only demonstrate superior visual appeal but also provide a promising pathway toward

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achieving improved and customizable bandgap performance.

2.2 Generation of PnC Plates

To systematically incorporate aesthetic principles into phononic crystal (PnC) designs, parametric modeling techniques were adopted to study diverse array of visually appealing and functionally effective structural patterns.

The settings of FE plate model are shown here. A module of plates in COMSOL MULTIPHYSICS was used to build the model of the unit cell, which is specifically designed for plate structures. Within this module, the geometry can be represented by a two-dimensional model, with the plate thickness defined as a parameter, rather than requiring a full three-dimensional geometry. Therefore, although the computational model is constructed in 2D, it intrinsically represents a plate structure, and the corresponding thickness effects are included through the module settings. The wave equations are given without the body forces and body couple as

$$\nabla \cdot \boldsymbol{\sigma} = \rho \left(\frac{\partial^2 \mathbf{u}}{\partial t^2} \right) \tag{1}$$

where $\mathbf{u}$ is the displacement vector, $\boldsymbol{\sigma}$ is the stress tensor and ρ is the density.

The related boundary conditions (BCs) are denoted by:

$$\boldsymbol{\sigma}\mathbf{n} = \bar{\mathbf{f}} \text{ or } \mathbf{u} = \bar{\mathbf{u}} \tag{2}$$

where $\bar{\mathbf{f}}$ is the surface traction, $\mathbf{n}$ is the normal vector.

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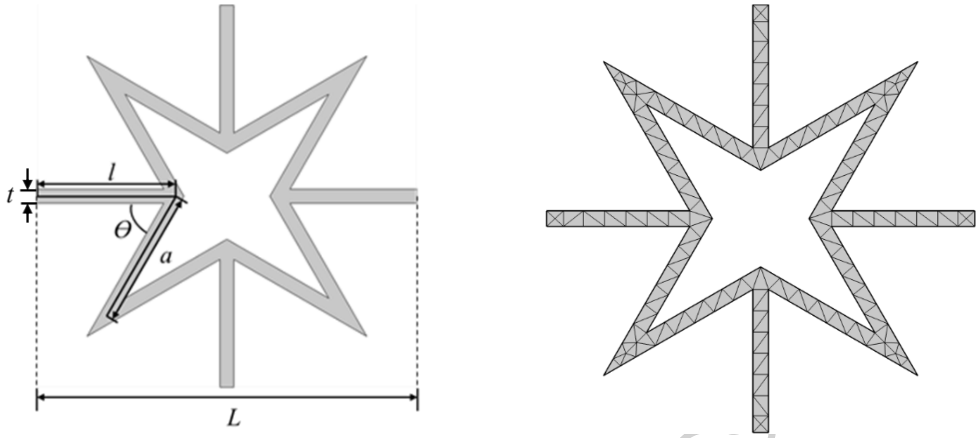
The out-of-plane thickness is uniformly set to 0.1 m, and the material does not change in the thickness direction. The unit cell is constructed in 2D as provided in Fig. 3a, and the mesh is made up of free quadrilateral cells as shown in Fig. 3b.



(a) (b)

Fig. 3 (a) Unit cell; (b) Mesh generation.

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In the star-shaped structure, the arm length is denoted as l, the ligament length of the connecting part is a, and the angle between the arm and the ligament is θ. The total unit cell constant L is related to these geometric parameters by the following expression:

$$L = 2\left[\frac{\sin\left(\theta - \frac{\pi}{4}\right)}{\sin\left(\frac{\pi}{4}\right)} a + l \right] \tag{3}$$

The Bloch theorem is employed to base the Bloch periodic BCs on the border of the unit cell to implement the periodic[21], yielding:

$$\mathbf{u}(\mathbf{r} + \mathbf{a}) = e^{i(\mathbf{q} \cdot \mathbf{a})} \mathbf{u}(\mathbf{r}) \tag{4}$$

where **r**, **a**, and **q** indicate the position vector at the boundary nodes, unit cell lattice constant, and Bloch wave vector, respectively.

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k is swept in the first Brillouin zone along the (0, 0, 0) - (π/L, 0, 0) - (π/L, π/L, 0) - (0, 0, 0), and dispersion curve is produced using eigenfrequency analysis.

The above-mentioned structural patterns were generated by integrating COMSOL MULTIPHYSCIS. Parametric scripts enabled systematic variation of geometric parameters, such as feature dimensions, spacing, curvature, and pattern density—to rapidly explore diverse structural configurations and evaluate their corresponding visual and bandgap performances.

A variety of structural categories—including artistically-inspired, symmetrically arranged, and non-Euclidean patterns—were generated and comparatively analyzed. Artistically-inspired structures focused on aesthetic expressiveness and complexity, whereas symmetric lattices emphasized uniformity and geometric order. Non-Euclidean patterns incorporated unconventional geometries that break traditional symmetry and periodicity, offering innovative bandgap and visual effects. By systematically comparing these structural categories, the most effective combinations of aesthetic appeal and bandgap functionality were identified.

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3. Numerical results

To demonstrate the existing model described in Section 2, this section will show examples of numerical results. In this section,

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Materials is selected to be aluminum, and Table 1 details the specific features of this material.

Table 1. Material properties of aluminum[24].

Material properties	Aluminum
ρ (kg/m^3)	2700
E (GPa)	70
ν	0.3

where ν is the Poisson's ratio, the l is set as 0.05m, θ is 60° and the line width are all 0.005m.

3.1 Validation

The existing structures in the Tang et al.[24] are reproduced and the corresponding dispersion curves are calculated to compare with the original results. The results are shown in the Fig. 4. It can be seen that the bandgap structures are almost the same, which proves the reliability of our modeling. Here, filtering was applied because flexural waves are not the primary focus of this study.

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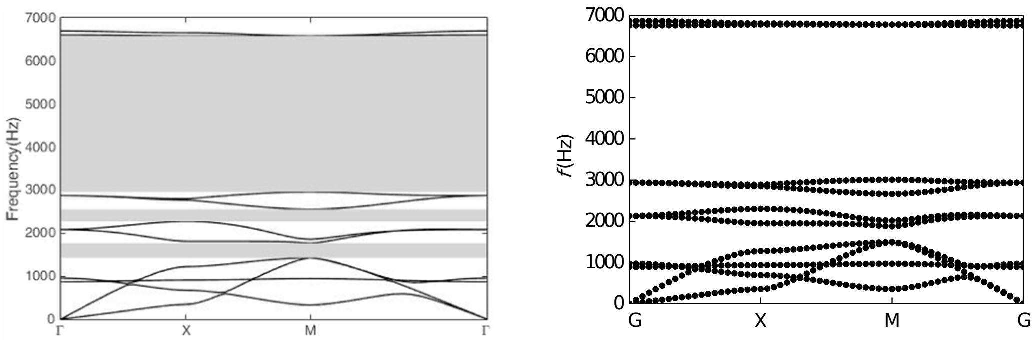

(a) (b)

Fig. 4 (a) The dispersion curves in the Tang et al.[24]; (b) The result reproduced by FEM.

In addition, the results obtained from RPWE(Read Supplementary

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Material for the detailed process) were compared with those from COMSOL to further validate their accuracy. It should be noted that, to enhance the reliability of the RPWE algorithm, the structural thickness t of ligament and arm was increased to 0.01 mm in this case. Since the analytical solution takes into account the bending wave, for ease of comparison, the results are therefore presented without filtering. The results are presented in Fig. 5. This further validates the reliability of our finite element modeling. Note that the phononic band gaps of this structure are mainly associated with in-plane waves and are essentially independent of bending waves. Therefore, most studies filter out bending-wave components to focus more clearly on the in-plane band-gap characteristics. However, the RPWE method inherently includes bending-wave solutions. To more accurately validate the results, the bending-wave branches are retained in Fig. 5 instead of being filtered out.

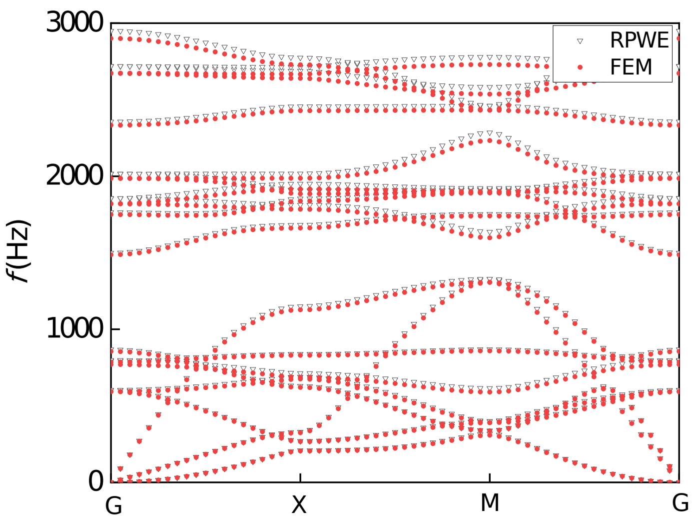

Fig. 5 Results from both RPWE and FEM.

3.2. Effects of the Golden Ratio

The golden ratio[25,26], approximately 0.618, is a proportion widely observed in nature and is regarded as one of the most aesthetically pleasing ratios to the human eye. It has been extensively applied in architecture, painting, sculpture, and modern industrial design to enhance compositional harmony and visual balance. Its significance in aesthetics lies not only in the elegance of form but also in its reflection of humanity's perception of order and structure inherent in nature.

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In the design of phononic crystals, incorporating the golden ratio is not merely an aesthetic enhancement but may also have practical implications for physical performance. The formation of band gaps in phononic crystals is highly dependent on geometric configuration, dimensional proportions, and periodic arrangement of the structural units. Applying the golden ratio to parameters such as lattice constant, scatterer size, and background medium may modifies nontrivial resonant and interference effects. Thus, the application of the golden ratio from an aesthetic perspective not only enriches the visual appeal of phononic crystal structures but also provides a novel geometric modulation guidance for band gap engineering.

Two approaches were employed to incorporate the golden ratio into the designed phononic crystal structures. In the first method,

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the lengths of the connecting rods in the star-shaped structure were set to 0.618 times the total length of the unit cell, thereby embedding the golden ratio into the geometry. The resulting unit cell configuration and its corresponding dispersion relation are shown in Fig. 6.

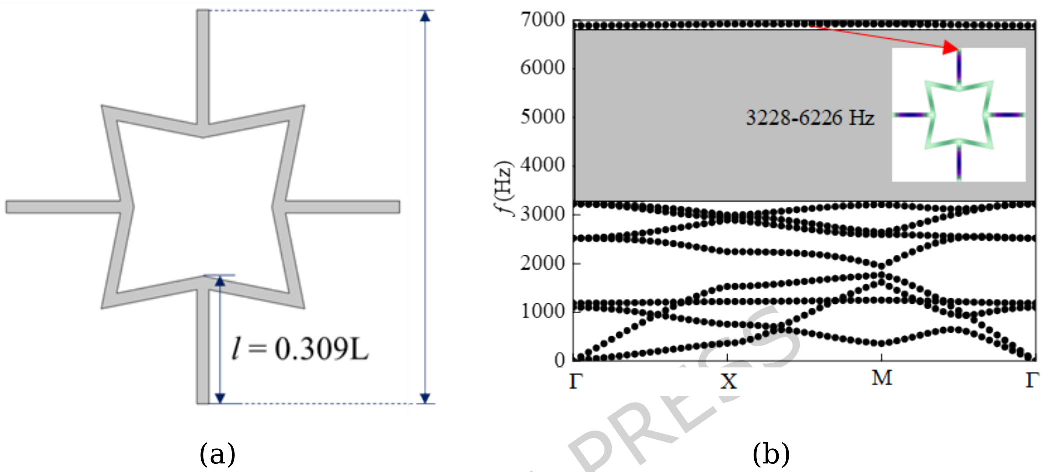

Fig. 6 (a) Structure of the unit cell incorporating the golden ratio to the rod; (b) The corresponding dispersion curve.

In the second approach, the total width of the star-shaped structure was set to 0.618 times the lattice constant of the unit cell, as illustrated in Fig. 7(a). The corresponding dispersion curve for this configuration is presented in Fig. 7(b).

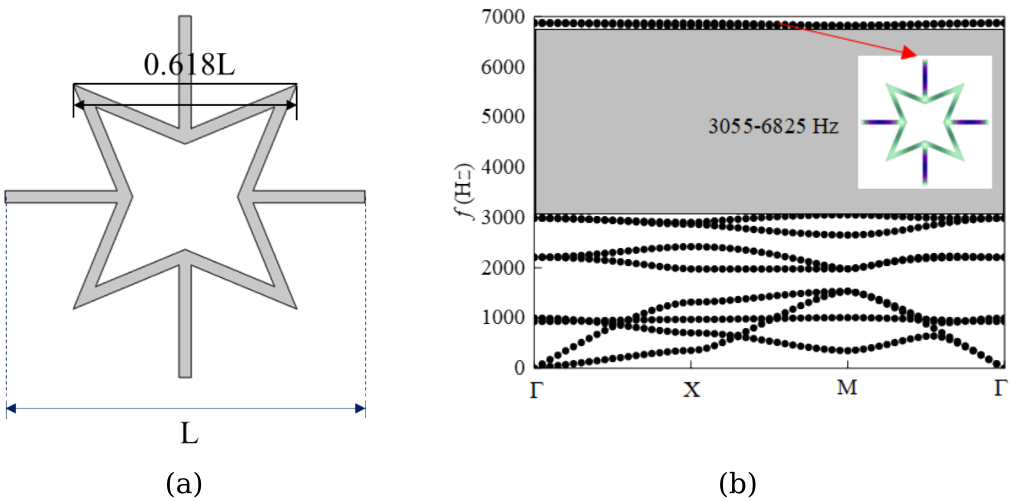

Fig. 7 (a) Structure of the unit cell incorporating the golden ratio to the unit cell; (b) The corresponding dispersion curve.

After incorporating the golden ratio, modifications to the unit cell geometry led to corresponding changes in the phononic band gap characteristics. A comparison of the two implementation strategies reveals that setting the width of the star-shaped structure to 0.618 times the total unit cell width results in a visually more balanced and aesthetically pleasing design. Moreover, this configuration yields a wider band gap, suggesting that it achieves a more effective balance between aesthetic form and functional acoustic performance.

3.3 Effects of the Mirror Symmetry

Symmetry is a fundamental element in aesthetics[27], often associated with balance, harmony, and order. Throughout art, architecture, and design, symmetrical compositions are perceived as more pleasing and stable by the human eye, as they reflect a natural sense of coherence and structural integrity. This aesthetic preference is rooted not only in visual psychology but also in the widespread presence of symmetry in natural forms—from snowflakes and flowers to animal bodies—reinforcing the perception of beauty through regularity and repetition.

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In the realm of phononic crystals, symmetry is not only an aesthetic feature but also a critical determinant of physical and topological properties. From a topological perspective, the symmetry of a phononic crystal's unit cell governs the fundamental

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classification of its band structure and the possible emergence of nontrivial topological phases[28,29]. For instance, certain crystalline symmetries—such as inversion, mirror, and rotational symmetries—can protect degeneracies at high-symmetry points in the Brillouin zone, giving rise to Dirac or Weyl-like cones. Breaking or modifying these symmetries can lead to topological band gap openings, associated with robust edge states that are immune to defects or backscattering.

Furthermore, the intentional design of symmetry-protected topological phases (e.g., valley Hall, quantum spin Hall[30] analogs in acoustics) relies on precise control over the spatial symmetry of the structure. By manipulating symmetries within the unit cell—such as breaking mirror symmetry while preserving rotational invariance—designers can induce pseudo-spin degrees of freedom and achieve directional edge transport. These topologically nontrivial features offer new functionalities beyond conventional band gap engineering, enabling robust waveguiding and defect-insensitive signal transmission. Therefore, symmetry in phononic crystals serves a dual function: aesthetically enhancing the structure's visual form, while enabling the exploration and realization of rich topological phenomena with promising applications in acoustic control and device design.

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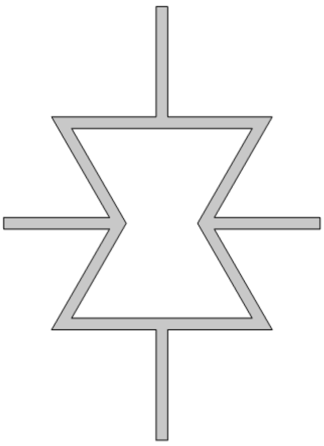
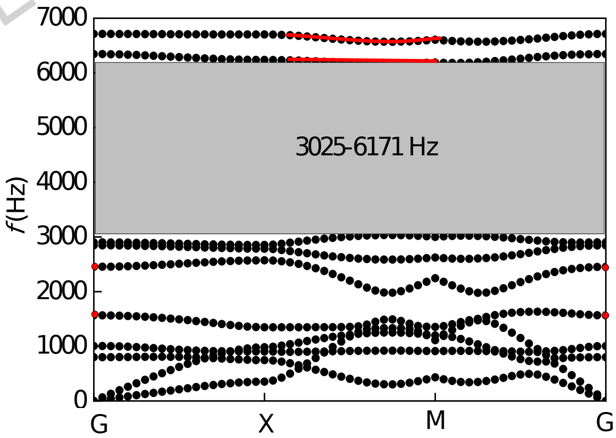
To break the symmetry, the following modification was implemented, effectively breaking the fourfold rotational symmetry (C_4 symmetry), as shown in the Fig. 8(a). The corresponding dispersion relation is presented in Fig. 8(b). After breaking the C_4 rotational symmetry, the unit cell loses its high symmetry, which theoretically enlarges the irreducible Brillouin zone and would require a broader sweep of wave vectors. However, since our focus is on how symmetry breaking affects the original band gap rather than exploring entirely new dispersion features, we limit the calculation to the original high-symmetry path. This allows for a clear and direct comparison while maintaining computational efficiency and relevance to the initial design





(a) (b)

Fig. 8 (a) Unit cell breaking C_4 symmetry; (b) The corresponding dispersion curve.

The results indicate that the change in symmetry primarily leads to the opening of a bandgap. More importantly, the originally

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degenerate dispersion curves at high-symmetry points are lifted due to the symmetry breaking. As highlighted in red along the X–M path and at the Γ point in the Fig. 8(b), these band splittings are indicative of topological phase transitions, where symmetry-protected degeneracies are removed, enabling nontrivial band topology to emerge. While this direction holds considerable research potential, the present study focuses on the influence of aesthetic parameters on band structure, and therefore does not delve into the topological aspects in detail.

3.4 Effects of the Curvature Smoothness

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Curvature smoothness[31] was explored as a design principle by introducing smooth, continuous curves into the unit cell geometry, replacing sharp corners and abrupt transitions. Geometric elements such as circular arcs, ellipses, and organic curves were deliberately integrated to create more fluid and visually harmonious structures. Beyond their aesthetic appeal, these smooth contours can improve mechanical stability by reducing stress concentrations at geometric discontinuities. More importantly, from a phononic perspective, curvature smoothness can modulate local resonances and scattering behavior, potentially leading to more controlled wave propagation and tunable band gap characteristics. Additionally, the use of smooth curves facilitates fabrication, especially in high-resolution

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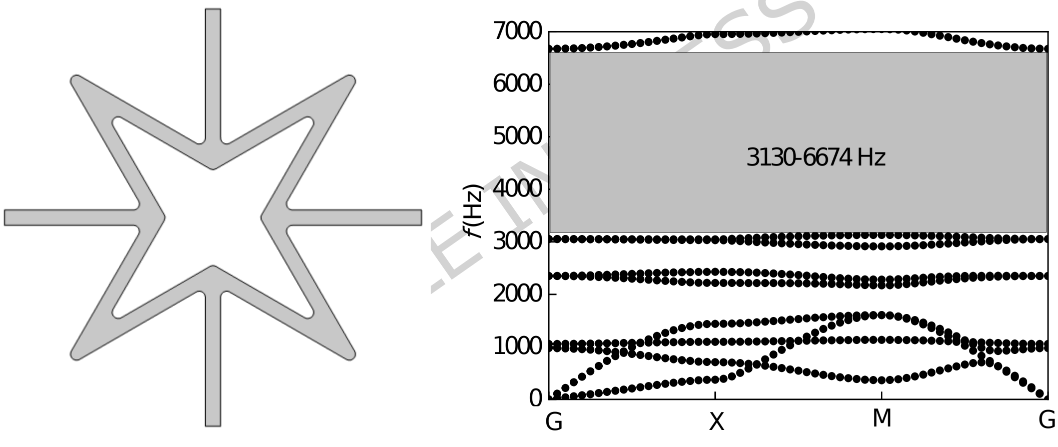
manufacturing methods such as 3D printing, where sharp edges may introduce errors or defects. This section investigates how introducing curvature-driven design influences the phononic band structure and the acoustic performance of the resulting crystal.

As a first step, a minor modification was applied to the phononic crystal unit cell by introducing fillets at sharp edges. This rounding operation was performed using the built-in fillet tool in the design software, with the radius set to 0.002 m. The modified unit cell and its corresponding dispersion curve are shown in Fig. 9.



(a) (b)

Fig. 9 (a) Phononic crystal unit cell after fillet operation; (b) The corresponding dispersion curve.

The introduction of fillets at sharp edges produced no significant changes in the phononic band gap characteristics, indicating that the curvature smoothing had minimal impact on wave propagation in this specific configuration. However, from an aesthetic standpoint, the addition of rounded edges enhanced the overall visual appeal of

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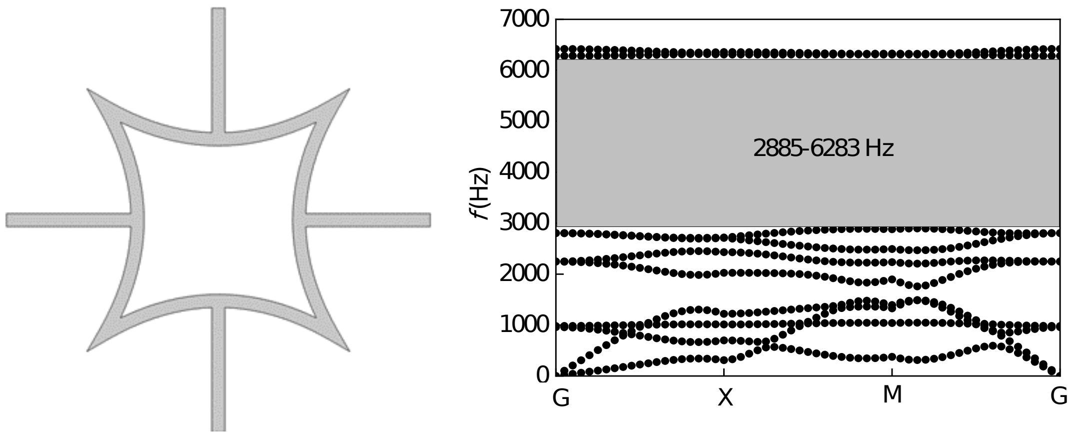
the unit cell by creating a softer, more refined geometry.

Next, an attempt was made to replace the straight-line segments of the star-shaped structure with curves, in order to enhance the smoothness and visual softness of the design. Quadratic Bézier curves were employed for this purpose, with the endpoint weights fixed at 1, while the control point weight was treated as a tunable parameter to adjust the curvature of the resulting shape. The modified structures and corresponding results are shown in Figs. 10, 11 and 12.

In this work, the edge profile is generated with COMSOL's built-in quadratic Bézier curve, defined by three control points $\mathbf{P}_0 = (x_0, y_0)$, $\mathbf{P}_1 = (x_1, y_1)$, and $\mathbf{P}_2 = (x_2, y_2)$. The polynomial (weighted) form is:

$$\mathbf{B}(t) = \frac{(1-t)^2 w_0 \mathbf{P}_0 + 2(1-t)t w_1 \mathbf{P}_1 + t^2 w_2 \mathbf{P}_2}{(1-t)^2 w_0 + 2(1-t)t w_1 + t^2 w_2} \tag{5}$$

where ω_i are the weights of the P_i.



(a) (b)

Fig. 10 (a) Unit cell structure using a Bézier curve with control point weight of 1; (b) The corresponding dispersion curve.

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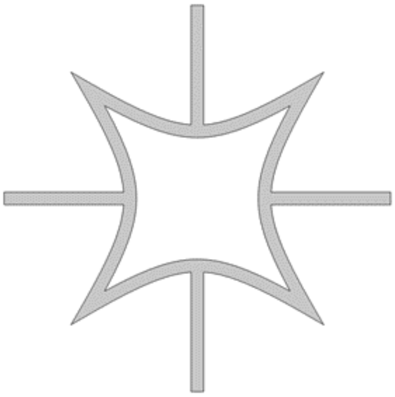
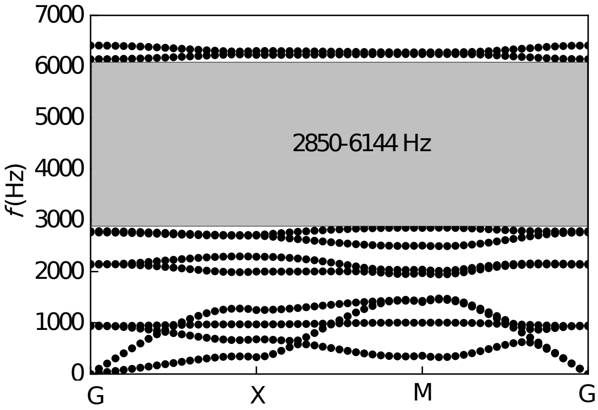
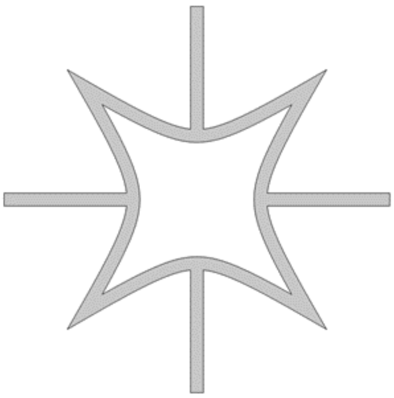
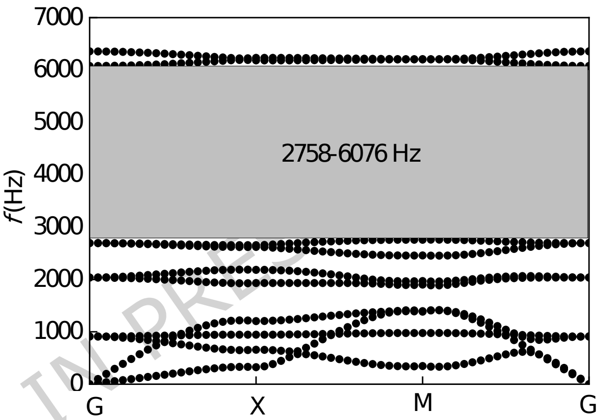




(a) (b)

Fig. 11 (a) Unit cell structure using a Bézier curve with control point weight of 2; (b) The corresponding dispersion curve.





(a) (b)

Fig. 12 (a) Unit cell structure using a Bézier curve with control point weight of 3; (b) The corresponding dispersion curve.

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The results show that as the control point weight increases—corresponding to greater curvature along the edges of the star-shaped structure—the phononic band gap shifts progressively toward lower frequencies. Notably, even geometrical changes that appear minor from a visual perspective can lead to significant variations in the band structure. This observation highlights that aesthetic features influencing visual perception can also exert substantial effects on the physical performance of phononic crystals. Therefore, achieving a thoughtful balance between visual aesthetics and functional performance is of particular importance in the design process.

3.5. Effects of the Visual Balance

Visual balance[32,33] is a fundamental principle in aesthetics, referring to the perception of stability and equilibrium within a visual composition. A well-balanced design guides the viewer's eye comfortably across the structure, avoiding a sense of visual tension or asymmetry. In artistic and architectural contexts, visual balance is often achieved by carefully distributing visual weight—determined by factors such as shape, size, color, and spatial arrangement.

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In phononic crystal design, visual balance may seem unrelated to physical performance at first glance; however, the same structural features that influence perceived balance—such as proportion, symmetry, and spatial density—can also affect the dynamic response of the system. For instance, imbalanced geometry may lead to uneven mass distribution or stiffness, which in turn can alter the local resonance characteristics or modify the dispersion behavior of acoustic waves.

In the present study, structural thickness is identified as the primary factor influencing the visual balance of the unit cell. Thickness directly impacts the mass density and stiffness of the medium, which are crucial parameters governing the formation and

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width of phononic band gaps. Therefore, this section focuses on investigating how variations in structural thickness influence both the visual balance and the acoustic band structure of the designed phononic crystal. Note that the same order bandgap as in the earlier analysis are studied in this section.

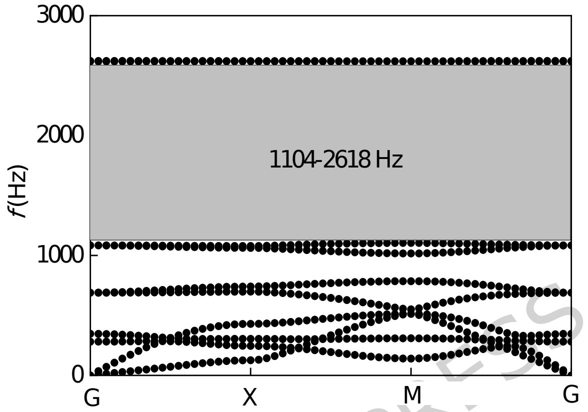

Fig. 13 The dispersion curve with thickness of 0.002m.

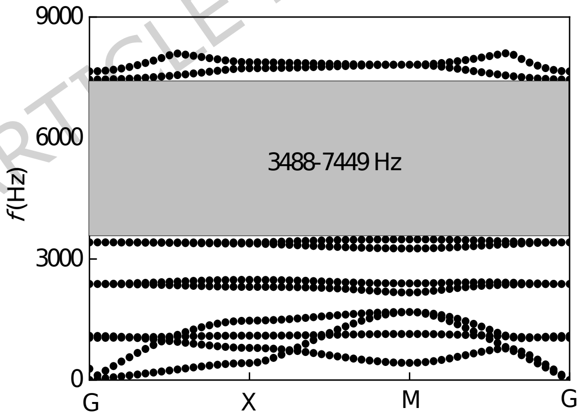

Fig. 14 The dispersion curve with thickness of 0.006m.

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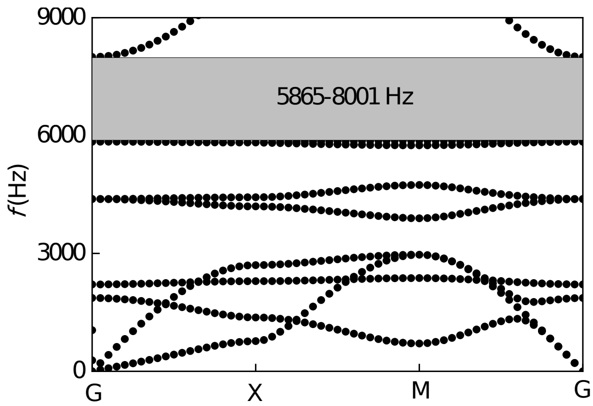

Fig. 15 The dispersion curve with thickness of 0.01m.

Figs. 13, 14 and 15 show the bandgap structures at different thicknesses *t*. As observed, increasing the thickness results in a shift of the band gap toward higher frequencies. This trend can be attributed to the increase in local stiffness and effective wave velocity, which raises the natural frequencies of the system and thus moves the band gap boundaries upward. Additionally, the band gap width first increases and then decreases with increasing thickness. This non-monotonic behavior may result from the fact that moderate increases in thickness enhance acoustic scattering and local resonances, which favor band gap formation. However, beyond a certain point, the structure becomes overly rigid, reducing mode coupling and weakening the mechanisms that sustain a wide band gap. These results indicate that the thickness plays a crucial role in determining the phononic band structure, and careful tuning of this parameter is essential to strike a balance between aesthetic considerations and functional performance.

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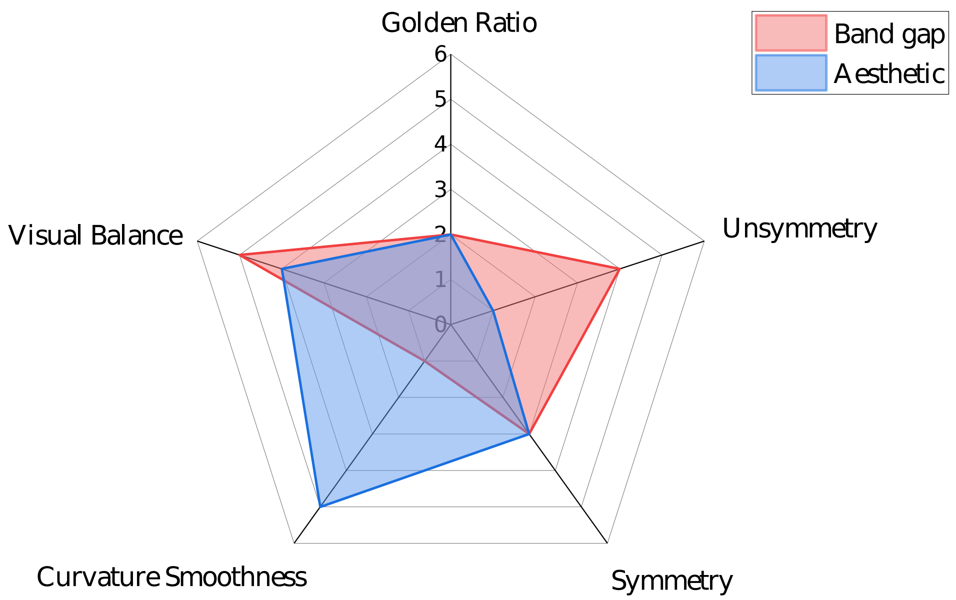

Fig. 16 The radar chart of the influences on the band gap and the aesthetic quality.

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Furthermore, Fig. 16 was plotted to illustrate the influence of different factors on the band gap and the aesthetic quality of phononic crystals. The radar-chart scoring was performed by ranking the influence of each factor on the two elements using a 1–5 scale. The radar chart reveals distinct differences between the influences on the phononic crystal band gap and the aesthetic quality of the unit cell. The aesthetic evaluation in this study is primarily based on visual harmony and perceived attractiveness, including proportional balance (e.g., the golden ratio), smoothness of geometric curves, and overall structural symmetry and balance. These criteria provide a consistent and intuitive standard for assessing aesthetic quality. The band gap is more strongly associated with structural asymmetry, while aesthetics depends

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primarily on symmetry and curvature smoothness; the golden ratio plays only a minor role in both aspects. Visual balance contributes to both band gap and aesthetics but is not a decisive factor. Overall, there is a trade-off between performance and aesthetics: achieving a larger band gap often requires introducing asymmetry, whereas enhancing aesthetics relies more on symmetry and smooth curves. Therefore, the design of phononic crystals should balance functional performance and visual appeal according to specific requirements.

4. Discussion and application design

Different aesthetic parameters exert varying degrees of influence on the band gap characteristics of phononic crystals. Some parameters, such as fillet operations, have minimal impact on the band gap but significantly enhance the visual appearance by smoothing sharp edges and reducing visual tension, resulting in a more fluid and refined geometry. In contrast, other factors—such as visual balance—not only improve the aesthetic appeal of the unit cell but also substantially affect the position and width of the phononic band gap. Therefore, achieving an appropriate balance between aesthetics and performance across multiple design parameters is essential in the optimization of phononic crystal structures. Based on these findings, the following section presents two phononic crystal designs developed from the results discussed in Section 3.

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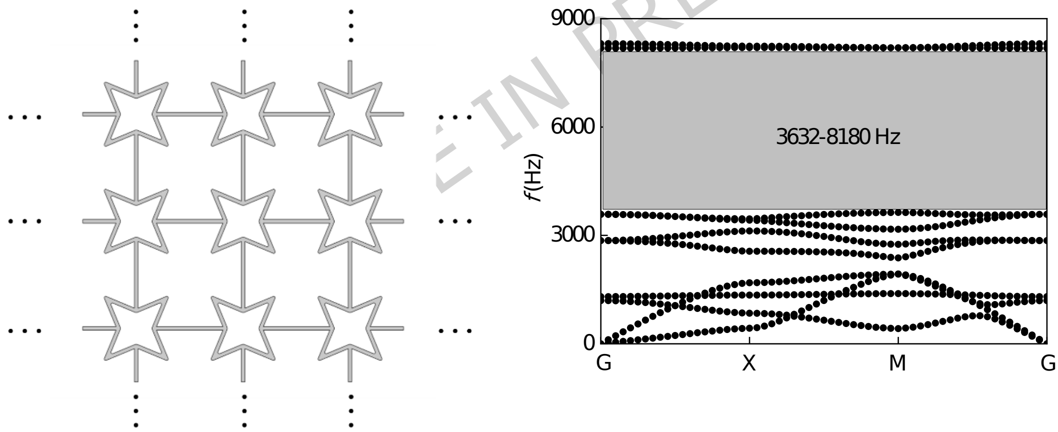
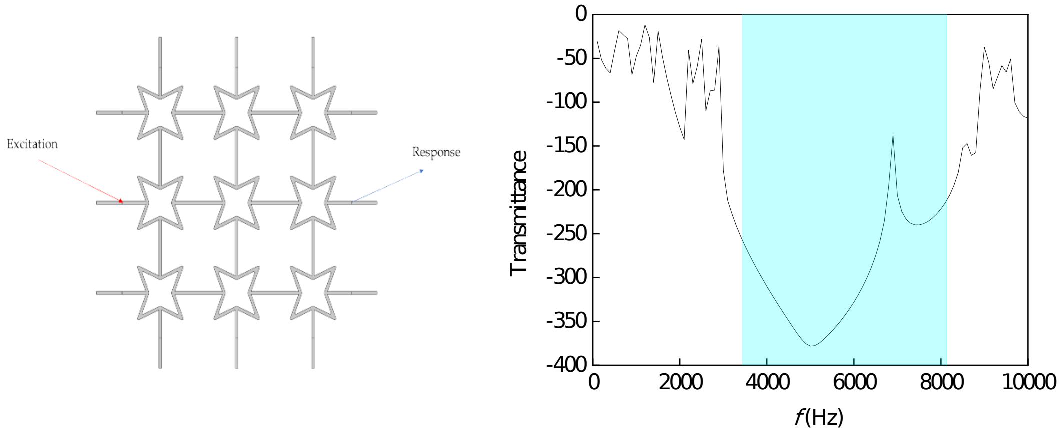
These structures were carefully crafted to harmonize both functional performance and visual appeal, demonstrating an integrated approach to aesthetic-functional design.

The first structure presented combines fillet operations with the application of the golden ratio. In addition, the visual balance of the structure was adjusted to a more aesthetically pleasing state, further enhancing the overall harmony of the design. This design enhances visual aesthetics while maintaining geometric harmony. The unit cell configuration and its corresponding band gap characteristics are shown in Fig. 17.



(a) (b)

Fig. 17 (a) One phononic crystal plate designed with both aesthetic and mechanical considerations; (b) The corresponding dispersion curve.



(a) (b)

Fig. 18 (a) Finite phononic crystal plate model; (b) The corresponding frequency response curve.

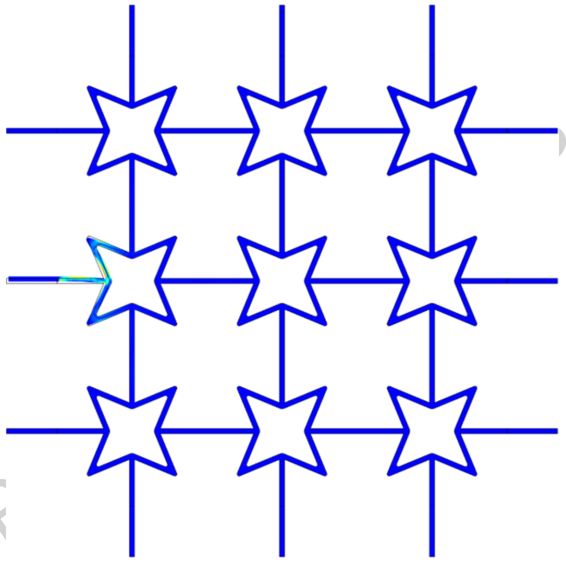


Fig. 19 The mode shape at frequency 6000 Hz.

In addition, the frequency response curve of the finite structure (Fig. 18(a)) was calculated, as illustrated in Fig. 18(b). The band gaps of the infinite structure are highlighted in light blue shading. It can be observed that the effective vibration attenuation frequency range of the finite structure closely matches the band gaps predicted for the infinite structure, further confirming the accuracy of the modeling approach and the effectiveness of the structural vibration

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attenuation. And the vibration mode at a frequency of 6000 Hz—located within the bandgap of the finite phononic structure—is presented in Fig. 19. The displacement field clearly shows that the oscillation is strongly localized within the first unit cell adjacent to the excitation source, while the vibration amplitude in subsequent cells decays rapidly to nearly negligible values. This strong spatial confinement of vibrational energy provides direct evidence of the effectiveness of the designed bandgap in suppressing wave propagation. Such behavior highlights the ability of the proposed structure to serve as an efficient vibration isolation and attenuation system, with potential applications in noise control, structural protection, and acoustic filtering.

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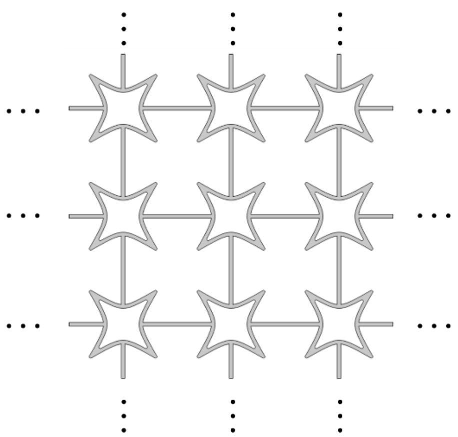
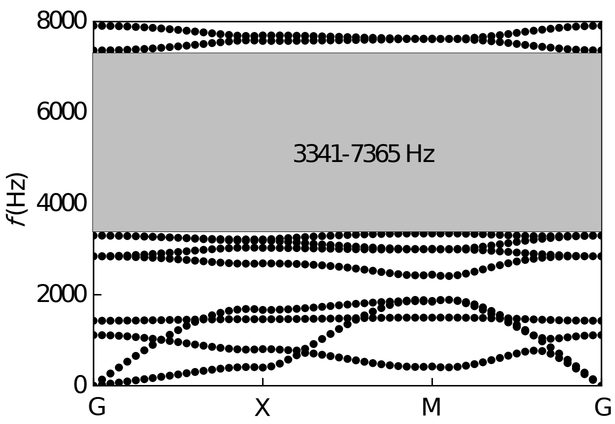
The next structure presented incorporates fillet operations, golden ratio geometry, and considerations of visual balance. The unit cell configuration and its corresponding band gap characteristics are shown in Fig. 20.



(a)



(b)

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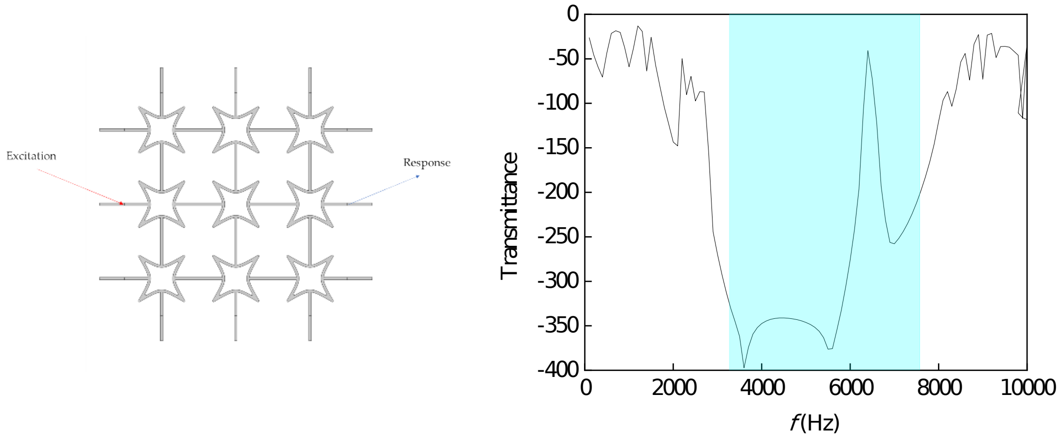
Fig. 20 (a) Another phononic crystal plate designed with both aesthetic and mechanical considerations; (b) The corresponding dispersion curve.



(a) (b)

Fig. 21 (a) Another finite phononic crystal plate model; (b) The corresponding frequency response curve.

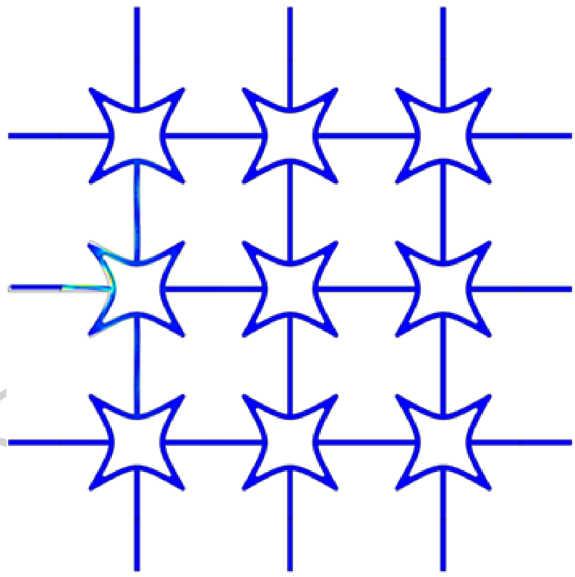


Fig. 22 The mode shape at frequency 6000 Hz.

Similarly, the frequency response curve (Fig. 21) and the vibration mode at a frequency of 6000 Hz (Fig. 22) is depicted. The effective vibration attenuation frequency range of the finite structure still closely matches the band gaps predicted for the infinite structure and the mode shape indicates that the vibrational energy is again strongly localized, with the displacement confined to

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the vicinity of the excited unit cell and rapidly decaying along the propagation direction. This consistent confinement behavior across different structural configurations further verifies the robustness of the designed bandgap, confirming that the phononic plate can reliably suppress vibration transmission at targeted frequencies. Such results highlight the structure ’ s potential for practical vibration isolation and noise reduction applications in engineering systems.

In addition, anomalous peaks were observed within the band-gap range, and the corresponding mode shape at such a peak was plotted, as shown in Fig. 23. The results indicate that the waves propagate primarily along the edges of the phononic crystal plate. A possible explanation is that different forms of coupling occur, giving rise to a special wave modes that enable transmission, whereas the band-gap analysis only considers in-plane waves. This phenomenon is therefore an interesting topic for further investigation in future research.

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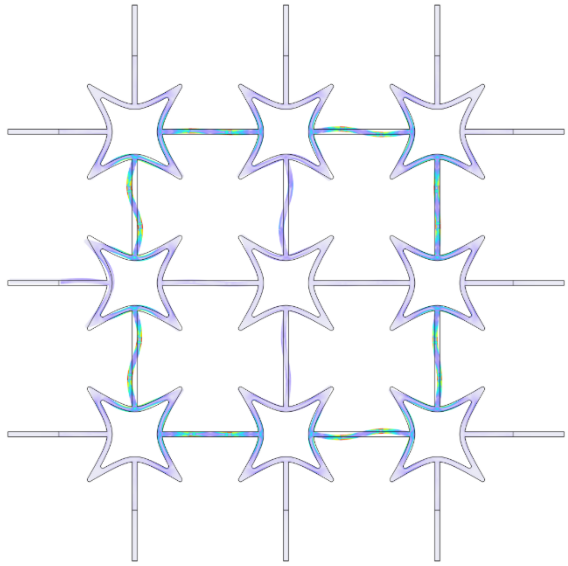

Fig. 23 The mode shapes of anomalous peaks

The vibration transmission characteristics of the two-dimensional periodic structure show discrepancies with the predicted bandgap behavior. The differences mainly arise from the inherent contrast between finite and infinite periodic structures. In an ideal infinite system, Bloch–Floquet conditions strictly govern wave propagation and clearly define the bandgap regions. In a finite structure, however, surface effects and boundary reflections play a significant role. Waves may partially transmit through edge regions or interfere constructively/destructively after reflecting from the boundaries, leading to local resonances or leakage of energy into modes not captured by the infinite periodic model.

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Through the analysis of phononic crystal structures designed with both aesthetic and mechanical performance in mind, this study demonstrates that a balance between visual appeal and functional

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effectiveness can indeed be achieved. By systematically exploring the influence of aesthetic factors—such as the golden ratio, curvature smoothness, and visual balance—on band gap characteristics, it is shown that beauty and performance need not be mutually exclusive in material design.

5. Conclusions and Outlook

In this work, several aesthetic principles were systematically integrated into the design of PnC plates to explore their dual roles in visual appeal and bandgap performance. The numerical results reveal that different aesthetic attributes contribute in distinct ways: curvature smoothness enhances geometric elegance without significantly altering the dispersion relations, while symmetry and visual balance strongly modulate the width and position of phononic bandgaps. Notably, the use of the golden ratio produces not only more visually harmonious geometries but also broader and more robust bandgaps, confirming that aesthetic rules can directly guide functional optimization.

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More broadly, this work highlights the transformative potential of integrating aesthetic considerations into the rational design of architected materials. Rather than serving as mere visual embellishment, aesthetics emerge here as a functional design tool that can complement or even substitute traditional performancedriven optimization. Such an approach opens new opportunities for engineering multifunctional systems that are structurally efficient, acoustically optimized, and visually refined. Extending this paradigm to related domains—such as acoustic metamaterials, vibration control devices, architectural acoustics, and adaptive structural systems—may enable the creation of materials and structures that operate at the intersection of science, engineering, and design. In this way, the findings establish aesthetics-inspired design as a generalizable and forward-looking methodology for the next generation of multifunctional materials. More importantly, embedding aesthetic considerations into the early stages of material and structural design opens new avenues for creating systems that are not only efficient and tunable, but also visually coherent and contextually harmonious. This aesthetics-informed paradigm thus provides a novel framework for next-generation multifunctional materials, bridging engineering performance with design elegance.

Looking forward, experiments of more complicated and functional PnC plates will be conducted to further substantiate the theoretical and numerical findings of this work. Specifically, the proposed phononic crystal structures will be fabricated using 3D printing techniques, and vibration tests will be carried out with a shaker–accelerometer setup to obtain frequency response curves.

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Such experiments will enable us to directly verify how aesthetic parameters not only alter the visual appearance of the structures but also influence their vibration attenuation performance. This approach will provide a more comprehensive understanding of the interplay between aesthetic design and functional characteristics, and serve as a foundation for future practical applications of aesthetically informed phononic crystals.

Author contributions: Yue Meng: Formal analysis, Methodology, Writing—original draft. Shuitao Gu: Supervision, Writing—review & editing, Conceptualization, and Writing—review & editing.

Data Availability Statement: The original contributions presented in this study are included in the article. Further inquiries can be directed to the corresponding author.

Conflicts of Interest: The authors declare no conflicts of interest.

Funding: This research received no external funding.

Competing interests: The authors declare no competing interests.

Conflict of interest: Authors declare that they do not have any conflicts of interest.

Data availability: The datasets used and/or analyzed during the current study available from the corresponding author on reasonable request.

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