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Impact of Locally Resonant Phononic Crystal Plates on Noise Reduction in Automotive Mufflers

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Abstract: This paper presents a locally resonant phononic crystal with excellent noise reduction in the low-frequency range as a soundproofing plate in mufflers. A locally resonant phononic crystal is established, and the bandgap range of the phononic crystal is analyzed by using COMSOL software. Taking the partition plate in the muffler as the object, the acoustic-solid coupling is studied to analyze the sound insulation characteristics of the locally resonant phononic crystal. A phononic crystal plate-like structure is established to analyze its noise reduction performance in the muffler. The results indicate that the locally resonant phononic crystal exhibits favorable low-frequency sound insulation performance within a bandgap range below 200 Hz. At 160 Hz, the noise reduction is 15 dB higher than that of ordinary partition plates. As the number of layers of the phononic crystal plate increases, its noise reduction effect gradually enhances, while the magnitude of the noise reduction increment tends to diminish. At 160 Hz, the single-, double- and triple-layer plates achieve peak reductions of 47, 53 and 57 dB, respectively. Compared with the double-layer phononic crystal plate, the composite of the locally resonant phononic crystal plate and the steel plate has an average noise reduction of 5 dB higher. Through research and analysis of the composite locally resonant phononic crystal plates, more feasible combined structures can be provided for future muffler structural design.

Keywords: acoustic-solid coupling; muffler; low-frequency noise reduction; locally resonant phononic crystal; bandgap characteristic

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0 Introduction

Industrialization and urbanization, particularly the growth of the automobile and transportation sectors, have significantly increased traffic noise, making urban noise

pollution^[1]. In daily life, people are frequently exposed to automotive noise, primarily exhaust noise, making the noise reduction effectiveness of mufflers a crucial factor in evaluating vehicle noise levels. As research on automotive mufflers has progressed, passive mufflers have become the most common noise reduction solution in automobiles. They are generally categorized into reactive, resistive and impedance composite types^[2].

In recent years, researchers have proposed the concept of phononic crystals by drawing an analogy with photonic crystals. Phononic crystals are artificially designed periodic materials or structures with elastic wave bandgaps. By adjusting the material and geometric parameters of phononic crystals, the propagation of elastic waves within specific frequency ranges can be significantly suppressed^[3-5].

Locally resonant phononic crystals, due to the presence of local resonance scatterers, can achieve very low-frequency bandgaps in small-sized topological structures and do not require strict periodicity^[6]. The bandgap and defect state characteristics of phononic crystals are theoretically valuable and practically useful for passive noise reduction, vibration isolation for precision mechanical platforms, and acoustic and vibration filters, offering a new theoretical approach for further vibration and noise reduction in automotive products.

The focus of phononic crystal research lies in the generation mechanisms of bandgaps and their control and regulation. Scholars have conducted extensive research in this area. Wen^[7] and Yu et al.^[8] introduced periodic phononic crystals into common engineering structures like beams and plates, and studied the bandgap and vibration isolation characteristics of typical periodic beam and plate structures. Experimental tests confirmed the existence of bandgap characteristics. Zhang et al.^[9] analyzed the impact of geometric and material parameters on the bandgap characteristics of phononic crystal plates under plane stress assumptions. The bandgap characteristics of

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locally resonant phononic crystals are closely related to the scatterers, and by designing the scatterers appropriately, the bandgap characteristics of phononic crystals can be regulated. Common scatterers include cantilever beams, single cylinders, and composite columns. Fang et al.^[10] analyzed the coupling mechanisms of two types of bandgaps in phononic crystals with beam resonators attached to aluminum plates, achieving coupling of Bragg and local resonance bandgaps in the low to mid-frequency range. Researchers^[11–14] discovered that beam-plate structures with added spring-mass systems and beam resonators exhibited excellent bandgap characteristics, with bandgap frequency ranges exceeding 200 Hz. In terms of sound insulation, Fan et al.^[15] fabricated a three-dimensional phononic crystal with rubber-coated metal spheres embedded in an epoxy resin matrix and measured their sound insulation. Li^[16] measured the sound insulation of two types of one-dimensional phononic crystals through sound insulation box tests, finding that phononic crystals increased sound insulation by about 5 dB in the 100–2 000 Hz frequency range. Assouar et al.^[17] theoretically analyzed the sound insulation mechanisms of aluminum plates with added spring-mass blocks and single rubber columns. He et al.^[18] further studied the impact of lattice constants on the sound insulation characteristics of aluminum plates with added copper-rubber composite columns, indicating that an appropriate lattice constant was needed to achieve a relatively broad sound insulation frequency range. In engineering applications, Shen et al.^[19] provided an overview of domestic and international research on the application of phononic crystals in vibration and noise reduction in ship piping systems, highlighting areas requiring further exploration. Gao et al.^[20] analyzed the sound insulation characteristics of unidirectionally periodic reinforced plate bulkheads in ship cabins at a frequency of 100–10 000 Hz. Ma et al.^[21] applied phononic crystals to the vibration and noise reduction of car roofs, reducing

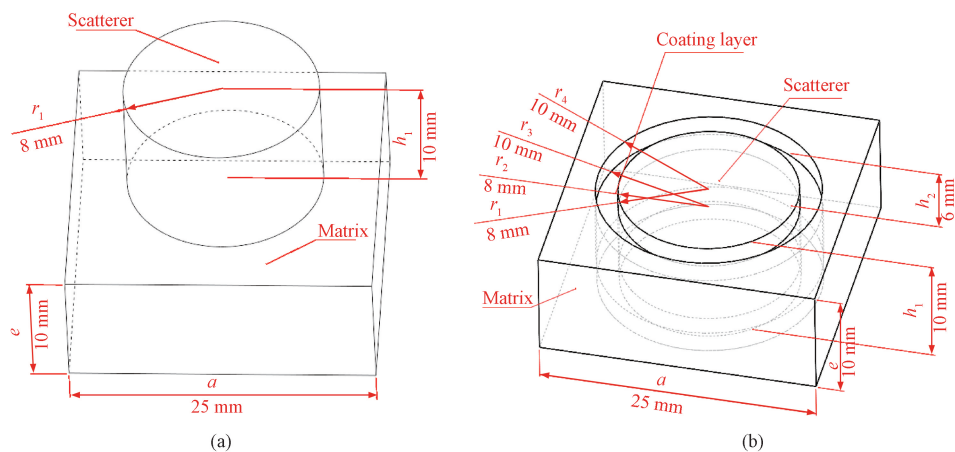
low-frequency vibration noise in car roofs. Zhang^[22] used two-dimensional (2D) phononic crystal plates to block mid-frequency noise caused by vehicle engines, effectively suppressing engine noise transmission in the 600–1200 Hz frequency range. Zhang et al.^[23] applied locally resonant phononic crystals with designed regular octagonal holes to large military aircraft cabins, achieving excellent low-frequency noise insulation with an increase of about 20 dB.

This paper designs a locally resonant phononic crystal plate structure tailored to the noise frequency characteristics of automotive mufflers. A locally resonant phononic crystal unit cell structure is modeled and analyzed by using the finite element software COMSOL to observe the bandgap characteristics and frequency ranges. Based on the bandgap ranges, a corresponding phononic crystal plate structure is applied to the muffler. The transmission loss curve of the muffler is calculated and analyzed in COMSOL to observe the noise reduction effect of the phononic crystal plate, providing a feasible plate structure application for automotive mufflers.

1 Design and Theoretical Analyses

1.1 Phononic crystal unit cell model structure

The phononic crystal unit cell model structure used in this paper is a solid-solid phononic crystal. The formation of the phononic crystal bandgap involves both Bragg scattering and locally resonant mechanisms. According to the different types of bandgaps, the phononic crystal unit cell models can be categorized into conventional phononic crystals (Fig. 1(a)) and locally resonant phononic crystals (Fig. 1(b)). Both types of phononic crystals use steel as the scatterer material and aluminum as the matrix material. The locally resonant phononic crystal features an additional coating layer made of silicone rubber. The material parameters of the phononic crystal unit cell are listed in Table 1.



a —lattice constant; r_1 —scattering radius; r_2 —inner radius of coating layer; r_3 —outer radius of coating layer; r_4 —matrix opening radius; e —matrix height; h_1 —scattering body height; h_2 —coating layer axial thickness.

Fig. 1 Phononic crystal unit cell model: (a) ordinary phononic crystal; (b) locally resonant phononic crystal

Table 1 Material parameters of phononic crystal unit cell

Part	Material	Density/(kg/m ³)	Elastic modulus/Pa	Poisson's ratio
Scatterer	Steel	7 850	2.1×10^{11}	0.28
Matrix	Aluminium	2 702	7.2×10^{10}	0.33
Coating layer	Silicone rubber	1 300	1.175×10^5	0.47

1.2 Theoretical calculation of phononic bandgap in phononic crystals

The finite element method is used to compute phononic crystals. Floquet periodic boundary conditions are applied at the unit cell boundaries, and the Bloch wave vector is introduced. This approach allows the band gap characteristics of an infinite phononic crystal to be analyzed by using a representative unit cell structure.

In the solid mechanics module, Floquet periodic boundary conditions are selected and applied to the adjacent boundary surfaces of the unit cell. The periodic boundary condition function is defined as follows:

$$\begin{cases} \mathbf{u}(x+a, y) = \mathbf{u}(x, y) e^{i(k_x \cdot a)}, \\ \mathbf{u}(x, y+a) = \mathbf{u}(x, y) e^{i(k_y \cdot a)}, \end{cases} \quad (1)$$

where \mathbf{u} stands for the nodal displacement; a is the lattice constant of the unit cell in the phononic crystal plate structure; \mathbf{k} is the Bloch wave vector confined to the irreducible Brillouin zone, its components in the x and y directions are denoted by k_x and k_y , respectively.

After setting the boundary conditions, the unit cell structure of the phononic crystal is meshed by using a standard mesh size. This results in a finite number of connected elements composed of nodes. The characteristic equation within the unit cell is

$$(\mathbf{K} - \omega^2 \mathbf{M}) \mathbf{u} = 0, \quad (2)$$

where \mathbf{K} represents the equivalent stiffness matrix; ω is the fluctuating angular frequency; \mathbf{M} denotes the mass matrix.

The Floquet periodic boundary settings in COMSOL software can constrain the boundary displacement of periodic structures to achieve Bloch boundary conditions, which satisfy the following equation:

$$\mathbf{u}_d = \mathbf{u}_s e^{-ik_F \cdot (r_d - r_s)}, \quad (3)$$

where k_F represents the wave vector; \mathbf{u}_s and \mathbf{u}_d represent the target displacement and the initial displacement of the Floquet periodic boundary, respectively. In the phononic crystal structure, r_d and r_s are defined as two characteristic positional parameters. The lattice constant a is given by the difference between them ($a = r_d - r_s$).

In the COMSOL finite element software, characteristic frequencies are added for research, and the step size of the parametric scan is selected. Due to the point group symmetry characteristics of phononic crystals, the Bloch wave vector \mathbf{k} is scanned along the symmetric boundaries of the irreducible Brillouin zone shown in Fig. 2. The scanning path follows the radial direction $M \rightarrow \Gamma \rightarrow X \rightarrow M$. By scanning the Bloch wave

vector \mathbf{k} to obtain its characteristic frequencies and referring to Eqs. (1) and (2), the band structure of the phononic crystal can be determined.

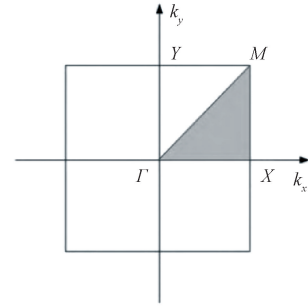


Fig. 2 Brillouin zone of 2D phononic crystal unit cell

1.3 Analysis of bandgap in phononic crystal unit cell structure

By using COMSOL, a simulation analysis was conducted for both regular phononic crystals and locally resonant phononic crystals. Figures 3 and 4 show the Floquet periodic boundary settings for the two types of phononic crystal unit cells, respectively. The unit cell matrix is made of aluminum with a height of 10 mm, while the scatterer is made of steel with a radius of 8 mm and a height of 10 mm. The lattice constant is 25 mm. The Floquet periodic boundary settings for the locally resonant phononic crystal unit cell are the same as those for the regular phononic crystal unit cell. The locally resonant phononic crystal features an embedded structure as shown in Fig. 1(b), with a silicone rubber coating surrounding the scatterer. The radial thickness of the coating layer is 2 mm, and the axial thickness is 6 mm. The other structural material parameters are the same as those of the regular phononic crystal.

The mesh is defined by using COMSOL's built-in meshing tools, and the mesh refinement meets the requirements for phononic crystal simulation. The bandgap for the regular phononic crystal and the locally resonant phononic crystal unit cells are shown in Fig. 5, in which the horizontal coordinate represents the bandgap period and the vertical coordinate represents the start and end frequencies of the bandgap. It can be observed that the bandgap frequencies of the regular phononic crystal are relatively high, starting at about 40 000 Hz, whereas the bandgap frequencies of the locally resonant phononic crystal start at about 100 Hz. Since typical automotive noise occurs in the low-frequency range, the locally resonant phononic crystal is selected as a muffler baffle for studying its noise reduction performance.

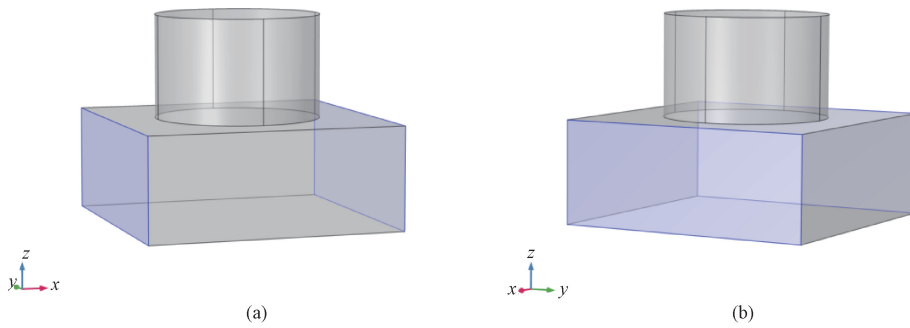


Fig. 3 Floquet periodic boundary settings of regular phononic crystal unit cell; (a) x periodic boundary; (b) y periodic boundary

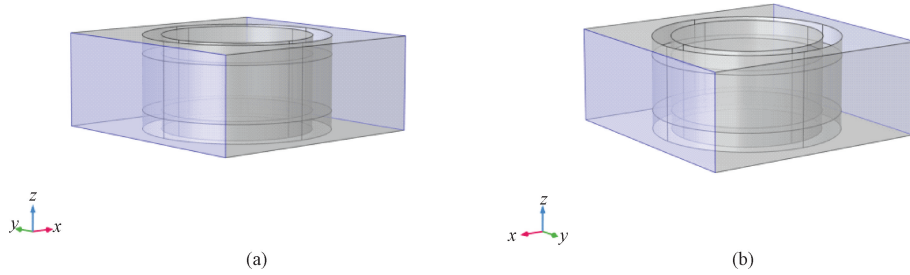


Fig. 4 Floquet periodic boundary settings of locally resonant phononic crystal unit cell; (a) x periodic boundary; (b) y periodic boundary

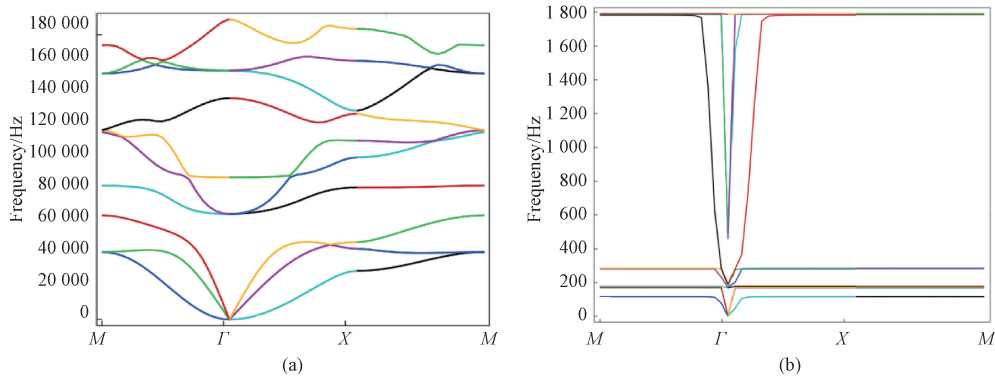


Fig. 5 Bandgap curves of phononic crystal unit cells; (a) regular phononic crystal; (b) locally resonant phononic crystal

1.4 Analysis of noise reduction characteristics of locally resonant phononic crystals

By using the acoustics-structural coupling module in COMSOL, the sound insulation properties of the phononic crystal structure can be calculated. Since both bandgap characteristics and sound insulation properties are based on the ideal phononic crystal (an infinite periodic structure), Floquet periodic boundary conditions can be applied to the surrounding boundaries of the phononic crystal structure. This allows for sound insulation calculations by using the structure of the phononic crystal unit cell and subsequently determines the sound insulation performance of the infinite phononic crystal periodic structure.

A noise reduction finite element model is established in COMSOL, as shown in Fig. 6. On both sides of the phononic crystal unit cell are air domains. The lower air domain is modeled as a background pressure field and is excited by an incident plane wave with a sound pressure amplitude of 1 Pa. Perfectly matched layers (PMLs) are configured at the ends of the air layers. Here, the PMLs

serve to simulate a non-reflective boundary for the sound field. The finite element mesh for the PML must be subdivided into at least 8 layers. The sound insulation properties of the phononic crystal structure and a standard aluminum plate are calculated by using COMSOL with the MUMPS direct solver. The frequency range for the solution is 10–2 000 Hz, with a calculation step size of 50 Hz.

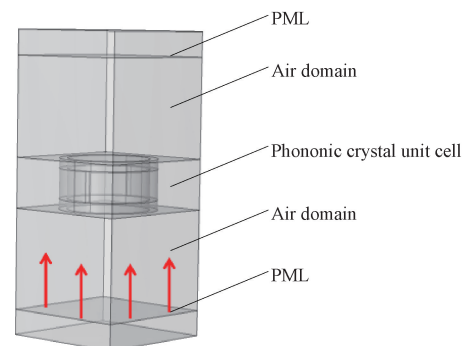


Fig. 6 Noise reduction finite element model

2 Simulation Experiment

2.1 Impact of muffler baffle structure on noise reduction performance

In automotive muffler noise reduction structures, commonly used designs such as high-temperature-resistant and aluminum-foam-based impedance composite mufflers. However, compared to phononic crystals, these

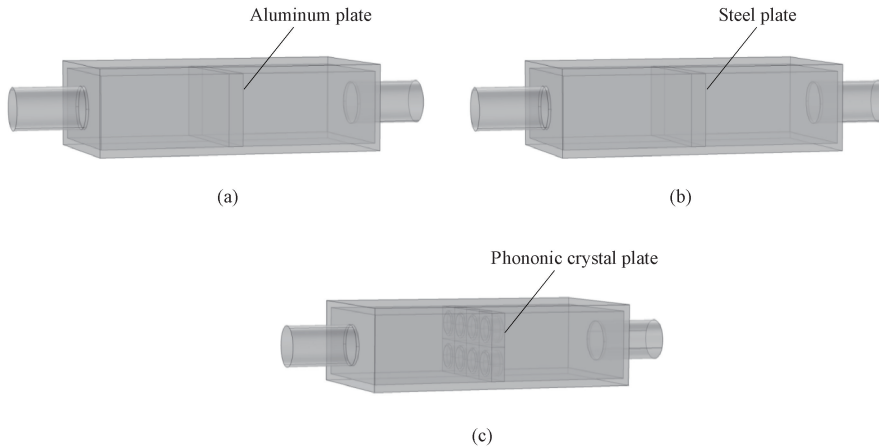


Fig. 7 Muffler models: (a) aluminum plate muffler; (b) steel plate muffler; (c) phononic crystal plate muffler

The transmission loss for these three models was observed at specific frequencies, as illustrated in Fig. 8.

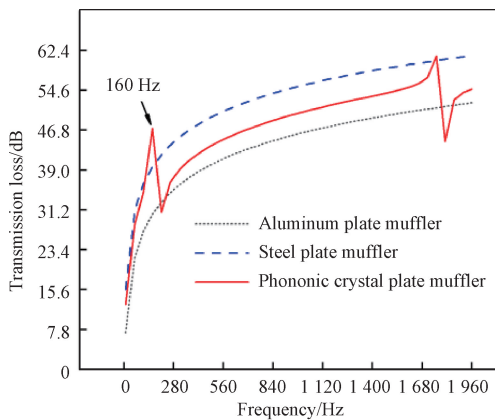


Fig. 8 Muffler transmission loss curve

Figure 8 shows that within the low frequency range of 0–280 Hz, the phononic crystal plate exhibits better noise reduction performance at 160 Hz. However, as the frequency increases, the noise reduction effectiveness of the phononic crystal plate is not as superior as that of the steel plate in the 300–1700 Hz range. In comparison, the phononic crystal plate outperforms the aluminum plate in terms of the transmission loss below 2000 Hz. Given that a steel structure would make mufflers heavier, the locally resonant phononic crystal plate is thus a better choice when all factors are considered.

composite mufflers are relatively complex and are not well-suited for creating thinner designs. Therefore, using phononic crystal plates for sound insulation to reduce noise in automotive mufflers is a simpler and more effective noise reduction approach.

To effectively compare the noise reduction performance of phononic crystal mufflers, three muffler models were established as shown in Fig. 7.

2.2 Effect of the number of phononic crystal plates on noise reduction performance

When studying the noise reduction performance of locally resonant phononic crystal plates in mufflers, it is also important to investigate the effect of the number of phononic crystal plates on noise reduction. By comparing the noise reduction performance of two and three stacked plates to that of a single plate, we can assess the performance enhancement achieved by the multi-layer phononic crystal plate structure. The structural models are shown in Fig. 9. The length, width and height of the plates are 100, 50 and 30 mm, respectively, and the transmission loss results obtained from simulation analysis are depicted in Fig. 10.

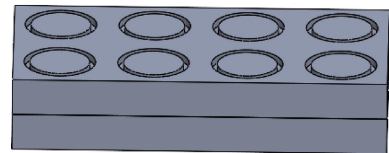


Fig. 9 Structure diagram of a multi-layer phononic crystal plate

Figure 10 shows that transmission loss increases with the number of photonic crystal layers. However, the peak frequencies of the curves remain unchanged, with peaks still occurring at 160 and 1760 Hz. This indicates that the peak frequencies (or inherent vibrational frequencies) of the multi-layer structure remain unchanged. At the first peak of 160 Hz, the maximum noise reduction values for the single-, double- and triple-layer phononic crystal plates are 47, 53 and 57 dB, respectively. The higher number of layers results in higher transmission loss, but

the incremental benefit of additional layers decreases. Moreover, increasing the number of layers also raises material costs and the overall weight of mufflers. Therefore, selecting an optimal number of layers is crucial for achieving the best noise reduction performance.

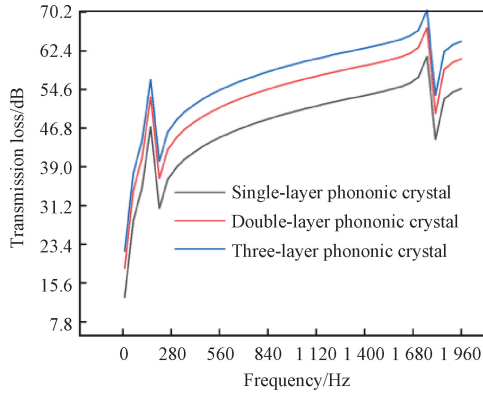


Fig. 10 Transmission loss of phononic crystal plates from simulation analysis

2.3 Analysis of sound insulation characteristics of composite phononic crystal plate

The noise reduction performance of a single phononic crystal plate, as shown in Fig. 8, is inferior to that of a single steel plate at certain frequencies, so we combined standard sound insulation plates with phononic crystal plates to study the noise reduction performance of these composite phononic crystal plates. We used combinations of aluminum plates with phononic crystal plates (aluminum-phononic crystal plate) and steel plates with phononic crystal plates (steel-phononic crystal plate), and compared these plates with a double-layer phononic crystal plate (double-phononic crystal plate). The resulting transmission loss curves are shown in Fig. 11.

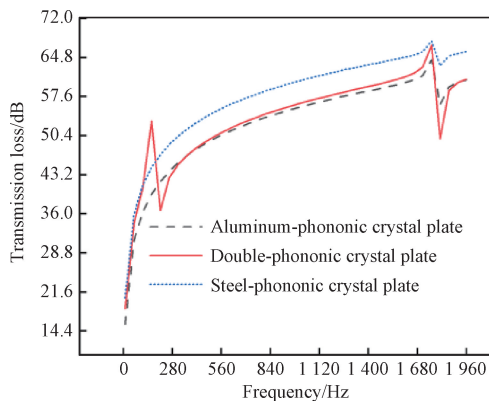


Fig. 11 Transmission loss of composite phononic crystal plates

Figure 11 shows that the double-layer phononic crystal plate exhibits the best noise reduction performance at 160 Hz, reaching 53 dB. However, within a frequency range of 280 – 2 000 Hz, the noise reduction of the

double-layer phononic crystal plate approaches that of the aluminum-phononic crystal plates. The steel-phononic crystal plate shows an average noise reduction improvement of about 5 dB over the double-layer phononic crystal plate. Therefore, when using composite phononic crystal plates, it is advisable to appropriately combine standard sound insulation plates with phononic crystal plates to achieve optimal sound isolation performance.

3 Conclusions

In this study, a locally resonant phononic crystal model was established by using COMSOL and employing acoustic-structural coupling simulation methods. The locally resonant phononic crystals offer superior low-frequency bandgap characteristics compared to conventional phononic crystals, with noticeable noise reduction at specific frequencies and stable performance in the low-frequency range. The locally resonant phononic crystal plate demonstrates certain advantages over aluminum and steel plates in terms of noise reduction. Additionally, when using composite structures, combining a standard plate with good sound insulation properties and phononic crystal plates achieves better noise reduction compared to a double-layer phononic crystal plate. Therefore, phononic crystal plates can be applied in automotive mufflers to achieve effective low-frequency noise reduction.

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局域共振声子晶体板对汽车消声器降噪的影响

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摘要: 提出了一种在低频范围具有良好降噪效果的局域共振声子晶体并应用于消声器隔声板。首先, 建立一种局域共振声子晶体, 使用 COMSOL 软件对声子晶体的带隙范围进行分析。其次, 以消声器隔板为研究对象, 通过声固耦合研究, 分析局域共振声子晶体的隔声特性。最后, 建立声子晶体板状结构, 分析其在消声器中的降噪性能。研究表明: 局域共振声子晶体的带隙范围在 200 Hz 以下可产生较好的低频隔声效果。在 160 Hz 时比普通隔板降噪高出 15 dB; 随着声子晶体板层数增加, 其降噪效果逐渐增强, 但降噪幅度逐渐减小。在 160 Hz 时, 单层、双层和三层声子晶体板的峰值降噪分别为 47、53 和 57 dB。与双层声子晶体板相比, 钢复合局域共振声子晶体板平均降噪高出 5 dB。研究分析复合局域共振声子晶体板可为未来消声器结构设计提供更可行的组合结构。

关键词: 声固耦合; 消声器; 低频降噪; 局域共振声子晶体; 带隙特性