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ULTRA-THIN AND ULTRA-LIGHTWEIGHT META-PANEL FOR BROADBAND NOISE INSULATION

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ABSTRACT

This study presents an ultra-thin and ultra-lightweight meta-panel for broadband noise insulation. The meta-panel consists of a multi-scale lattice structure sandwiched between two thin membranes, engineered to induce negative effective material properties for high sound transmission loss (STL) across a wide frequency range. A theoretical model is developed for fast and accurate prediction of the meta-panel's STL by integrating the effective impedances of membranes under elastic boundary restraints and wave propagation through the multi-scale lattice structure. This model facilitates a systematic inverse design process to maximize STL over the 100-1500 Hz range while simultaneously minimizing the meta-panel's thickness and weight. The meta-panel is fabricated via 3D printing, and its insulation performance is experimentally validated through impedance tube tests. Experimental results demonstrate an STL improvement of up to 30 dB compared to a same-weight plate, highlighting the meta-panel's superior weight-to-performance efficiency.

Keywords: *acoustic metamaterial, sound insulation, negative effective material properties, multi-scale lattice structure, meta-panel*

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1. INTRODUCTION

The development of ultra-thin and ultra-lightweight soundproofing solutions for low-frequency broadband noise remains a important challenge across a range of industries, including transportation, home appliances, industrial machinery, and architectural structures. Conventional materials such as rubber sheets and gypsum boards are still widely used for noise insulation, but their effectiveness is limited by the mass law [1], which requires increased weight to achieve adequate sound insulation. To address this limitation, this study presents an ultra-thin and ultra-lightweight meta-panel designed to achieve low-frequency broadband noise insulation, by inducing negative effective material properties. The proposed meta-panel incorporates a multi-scale lattice structure sandwiched between two thin membranes, utilizing hierarchical design concepts to enhance broadband sound insulation. A theoretical model is developed to provide fast and accurate predictions of the meta-panel's sound transmission loss (STL), along with a systematic design approach aimed at achieving high STL performance over a broad frequency range of 100–1500 Hz. Finally, the sound insulation performance of the meta-panel is validated through fabrication and experimental testing.

2. THEORY AND EXPERIMENTS

The propagation behavior of sound waves is governed by the acoustic properties of a medium—mass density and bulk modulus. In conventional materials, both of those parameters are inherently positive. However, through the use of acoustic metamaterials, it is possible to engineer either the effective mass density or the effective bulk modulus to take on negative values, enabling significantly enhanced sound insulation performance compared to traditional acoustic materials [2–5].

When an acoustic metamaterial exhibits a negative effective mass density ($\rho_{eff} < 0$) or a negative effective bulk modulus ($B_{eff} < 0$), the resulting speed of sound c and wavenumber k in the medium are given by:

$$c = \sqrt{\frac{B_{eff}}{\rho_{eff}}}, \quad (1)$$

$$k = \frac{\omega}{c} = \omega\sqrt{\frac{\rho_{eff}}{B_{eff}}}, \quad (2)$$

where the condition is:

$$\frac{\rho_{eff}}{B_{eff}} < 0. \quad (3)$$

Under this condition, the wavenumber k becomes purely imaginary (i.e., $k = i\alpha$ with $\alpha < 0$), leading to an exponential decay of the propagation energy E along the wave path x:

$$E \propto e^{-\alpha x}. \quad (4)$$

This relationship implies that as sound waves propagate through the medium, their energy diminishes exponentially, thereby enabling highly efficient sound insulation using thin and lightweight structures.

Expanding upon the theoretical foundation, this study presents a comprehensive methodology for both predicting and enhancing the sound insulation performance of the proposed meta-panel. To this end, a theoretical model is developed that rapidly and accurately predicts the STL by accounting for the effective acoustic impedance of the membranes and the wave propagation characteristics within the multi-scale lattice channels. Based on this model, a design framework is established to optimize STL performance across a wide frequency range of 100–1500 Hz, all while minimizing structural thickness and overall mass.

Compared to a previous design benchmark [6], the newly optimized meta-panel achieves a 64% reduction in thickness and a 26% decrease in weight. The meta-panel was fabricated via 3D printing, and its acoustic performance was validated experimentally using impedance tube testing. The results revealed that the meta-panel outperformed a reference plate with the same mass by approximately 30 dB in STL. Particularly in the low-frequency range of 100–500 Hz, the panel exhibited high broadband insulation capabilities. Within this range, its performance matched that of a 9 mm thick steel plate, despite weighing only 1/40 as much—demonstrating outstanding insulation performance relative to its weight.

3. CONCLUSION

This study presents an ultra-thin and ultra-lightweight meta-panel designed for broadband sound insulation in the low-frequency regime. The meta-panel features a multi-scale lattice structure sandwiched between two thin membranes, and it is tailored to exhibit negative effective material properties, enabling high STL across a wide frequency range of 100–1500 Hz. A theoretical model was formulated to predict STL, serving as the foundation for a systematic inverse design strategy aimed at maximizing STL while minimizing both thickness and mass. The meta-panel was fabricated using 3D printing techniques, and its sound insulation performance was experimentally evaluated through impedance tube measurements. Experimental results showed an STL improvement of approximately 30 dB compared to a plate of equal weight. These findings confirm that the proposed meta-panel delivers outstanding sound insulation despite its compact and lightweight form factor. Based on its excellent weight-to-performance ratio, the proposed meta-panel offers strong potential as a lightweight soundproofing solution for diverse applications, including electric vehicles, urban air mobility (UAM), drones, consumer electronics, and architectural acoustics.

4. REFERENCES

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