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SOUND INSULATION IN TWO SEPARATE WIDE FREQUENCY BANDS USING LIGHTWEIGHT META-PANEL

Jiwan Kim[1] **Eunji Choi**[1] **Wonju Jeon**[1*]

[1] Department of Mechanical Engineering, Korea Advanced Institute of Science and Technology, Republic of Korea

ABSTRACT

We present a lightweight soundproofing meta-panel that can effectively block two distinct broadband sound waves in the low and high frequency ranges. The meta-panel is composed of two thin membranes sandwiching a multi-scale lattice structure, which is a multi-layered lattice structure involving different lattice sizes. By inducing negative effective material properties throughout two distinct wide bands, the meta-panel shows high transmission loss and insertion loss in those bands. With 3D printing technology, we manufacture the meta-panel sample. Then, we experimentally verified the high sound insulation performance of the meta-panel in an impedance tube and an anechoic chamber. The experimental result shows that the meta-panel can exhibit exceptional insulation performance with a lighter weight (about 5%) than a steel plate in a wide frequency range where the energy of low-frequency road noise and high-frequency motor noise is concentrated.

Keywords: *acoustic metamaterial, sound insulation, negative effective material properties, separate frequency bands*

1. INTRODUCTION

Noise reduction in the cabin must be addressed if self-driving electric cars are to provide a comfortable space for work and rest. Compared to cars with internal combustion engines, different sounds across different frequency bands will be audible more in the cabin of an electric car. While traditional soundproofing materials like urethane, fiberglass, and polyester have been employed to block such noises, their ability to insulate sound is constrained by the mass density law, which requires an increase in weight to improve insulation efficacy [1].

This study proposes a lightweight meta-panel that is based on acoustic metamaterials (AMMs) with exceptional acoustic characteristics, such as negative mass density and bulk modulus, to overcome the limits of traditional materials. The meta-panel is composed of a multi-scale lattice structure that is sandwiched between two thin membranes, and it exhibits negative effective material properties to yield high transmission loss (TL) in separate frequency bands. The experimental measurement indicated high TLs throughout a wide range of 100 - 1750 Hz after we manufactured the meta-panel. Additionally, high insertion loss (IL) was examined for both high-frequency motor noise and low-frequency road noise of an actual electric car.

2. THEORY AND EXPERIMENTS

The mass density and bulk modulus, which are acoustic material properties of a medium, affect the propagation characteristics of sound waves. Both mass density and bulk modulus are always positive in natural materials. However, acoustic metamaterials can be designed with negative effective mass density or negative effective bulk modulus, and as a result, they perform better at sound insulation than traditional materials [2-5].

Specifically, when an acoustic metamaterial has negative effective mass density or negative effective bulk modulus ($\rho_{eff} < 0$ or $B_{eff} < 0$), the speed of sound c and wavenumber k in the medium are determined as follows:

$$c = \sqrt{B_{eff}/\rho_{eff}} \text{ and}$$

*Corresponding author: wonju.jeon@kaist.ac.kr

$$k = \omega/c = \omega\sqrt{\rho_{eff}/B_{eff}} \quad (1)$$
where $\rho_{eff}/B_{eff} < 0$.

Here, ω is the angular frequency. In Eq. (1), k should be purely imaginary ($k = i\alpha$ with $\alpha > 0$), which leads the propagation energy E to meet the following relational expression for the wave pathlength x:

$$E \propto e^{-\alpha x} \quad (2)$$

According to Eq. (2), the energy is reduced exponentially along the propagation path.

In this work, a lightweight meta-panel with negative effective mass densities and negative effective bulk modulus at two distinct frequency bands has been designed. Fabrication and experimental measurements were carried out to confirm that the meta-panel can provide high TL with a small areal density over a wide range of 100 - 1750 Hz. The experimental results demonstrated that the meta-panel can reduce road noise and motor noise by over 19 dB while weighing just 5% as much as a steel plate with the same sound insulation capabilities.

3. CONCLUSIONS

We successfully designed and verified a lightweight soundproofing meta-panel with negative effective mass densities and negative effective bulk modulus based on the findings of this work, achieving substantially high transmission loss over a wide range of 100 - 1750 Hz. While having a weight that is 5% of a conventional material's weight with the same sound insulation ability, the meta-panel showed considerable noise reduction for road noise and motor noise of an actual electric car. According to our work, the meta-panel might be used in a variety of industrial domains, such as transportation, construction, and home appliances, to efficiently handle noise concerns.

4. REFERENCES

[1] L. M. Brekhovskikh: *Waves in layered media*. New York: Academic Press, 1980.

[2] Z. Liu, X. Zhang, Y. Mao, Y.Y. Zhu, Z. Yang, C.T. Chan, and P. Sheng: "Locally resonant sonic materials," *Science*, vol. 289(548), pp. 1734-1736, 2000.

[3] Z. Yang, J. Mei, M. Yang, N.H. Chan, and P. Sheng: "Membrane-type acoustic metamaterial with negative dynamic mass," *Physical Review Letters*, vol. 101(20), 204301, 2008

[4] M. Yang, G. Ma, Z. Yang, and P. Sheng: "Coupled membranes with doubly negative mass density and bulk modulus," *Physical Review Letters*, vol. 110(13), 134301, 2013.

[5] N. Sui, X. Yan, T.-Y. Huang, J. Xu, F.-G. Yuan, and Y. Jing: "A lightweight yet sound-proof honeycomb acoustic metamaterial," *Applied Physics Letters*, vol. 106(17), 171905, 2015.

[6] J. Kim, E. Choi, and W. Jeon: "Lightweight soundproofing meta-panel for separate wide frequency bands," *Mechanical Systems and Signal Processing*, vol. 184, 109647, 2023.