

SOUND TRANSMISSION LOSS BY A HEXAGONAL ACOUSTIC METAPANEL UNDER RANDOM INCIDENCE

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ABSTRACT

Investigating sound attenuation in subwavelength regimes remains challenging with conventional materials. Previous studies have examined locally resonant acoustic metamaterials (AMMs) with a negative bulk modulus, achieved through multiple in-parallel Helmholtz resonators, which generate bandgaps that enhance acoustic transmission loss. Here, we extend the analysis of a hexagonal AMM by predicting sound transmission loss (STL) under random incidence, further broadening its applicability in practical acoustic engineering.

1. Introduction

In acoustics, the ability to manipulate sound wave propagation at low frequencies has been the focus of numerous scientific studies. In recent years, significant efforts have been made to develop acoustic metamaterials (AMMs) to achieve this, enabling novel physical behaviours beyond those found in natural materials.

Advances in material science, particularly in AMMs, have enabled the exploration of novel physical properties. These include single-negative AMMs with an effective bulk modulus or negative density, as well as double-negative or negative refractive index AMMs, which result from frequency-dependent local resonance mechanisms.

Previous research [1] has explored the development of AMMs with in-parallel resonator inclusions to achieve broadband perfect sound absorption. Building on this work, rigid-frame fluid-equivalent approaches have been used to evaluate the model and determine its effective properties [2].

This study examines the effects of random incidence, facilitating the formation of a metapanel and expanding possibilities for acoustic systems with significant sound transmission loss while maintaining passive airflow. A brief validation of the finite element model is performed using an analytical description based on the Johnson-Champoux-Allard fluid-equivalent model for a rigid frame [2, 3].

2. Proposed Design

Figure 1 shows a printed sample of the axially symmetric acoustic metamaterial panel. It consists of six Helmholtz resonators tuned at same resonance frequency, laterally arranged around the symmetry axis of the waveguide, which has a radius r_w and length L , representing the lattice constant of the periodic system along the z -axis. The structure extends infinitely in the xy -plane within the Cartesian coordinate system (x, y, z) . The resonator dimensions are defined by the neck parameters $l_{\text{neck}}^{[n]}$ and $w_{\text{neck}}^{[n]}$, representing its length and the width, respectively. The resonant cavity volume $V_{\text{cav}}^{[n]}$ is determined using $l_{\text{cav}}^{[n]}$ and $w_{\text{cav}}^{[n]}$, which denote the length and width of the cavity, respectively. At the circular inner boundary, the cross-sectional shape

is defined by the radius r_t . The superscript $[n]$ denotes the order of the included resonator.

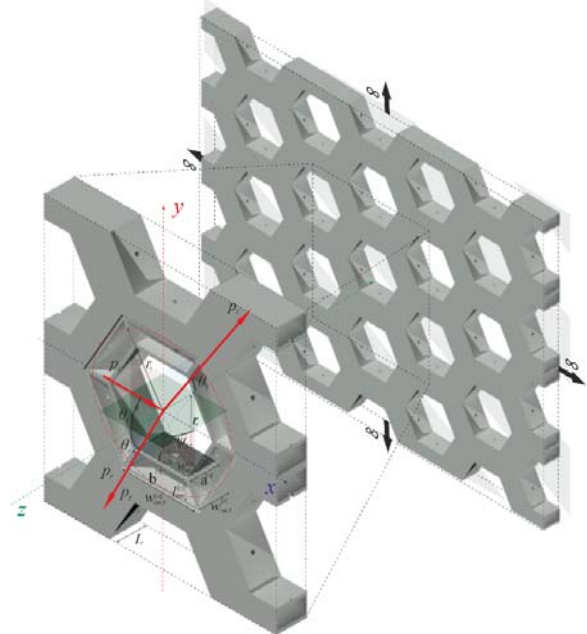


Figure 1 - The conceptual diagram of an infinite hexagonal resonant metapanel under acoustic excitation of a random incident plane wave p_i .

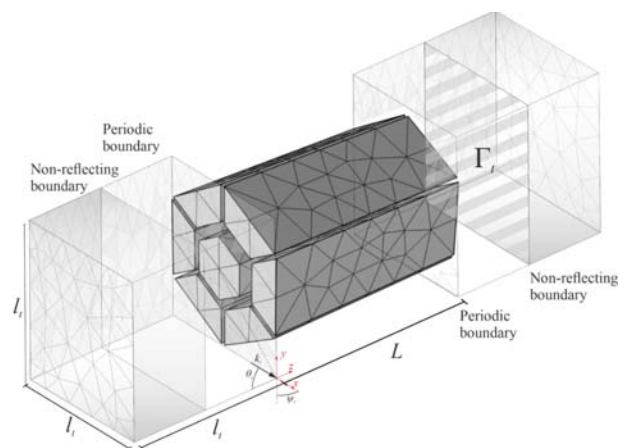


Figure 2 – Schematic illustration of the numerical model of the unit cell used to calculate the random STL.

3. FEM Modelling

To predict the acoustic behavior of the proposed AMM under random incidence, all numerical calculations were performed using COMSOL Multiphysics. Figure 2 presents a schematic of the unit cell's numerical model, consisting of two rectangular domains ($l_y = l_x = 37.5$ mm) placed on either side of the AMM. The main domain is defined as air, with a mass density ($\rho_0 = 1.23$ kg/m³), dynamic viscosity ($\eta = 1.82 \times 10^{-5}$ Pa·s), and ambient pressure $P_0 = 101325$ Pa.

Acoustic excitation is applied at the left side using a plane wave with unitary amplitude (1 Pa) at an oblique incidence angle θ_{in} . Bloch-Floquet periodic boundary conditions are imposed on all lateral boundaries to account for the unit cell being part of an infinite planar array. For simplification, the Bloch-Floquet wavevector k_B is assumed to match the incident wave vector k_i . To minimize reflections, non-reflecting boundary conditions are imposed on each side.

To ensure accuracy, viscous and thermal losses in narrow regions, such as the resonator necks, are considered to model acoustic energy dissipation within the boundary layer. These losses are incorporated using the Johnson-Champoux-Allard model, as described in Refs. [1, 2].

4. Results

4.1 Normal and Oblique incidence

To analyse random incidence in the proposed metamaterial we consider a symmetric system comprising six identical axially coupled Helmholtz resonators, each tuned to $f_1 = 1000$ Hz. To assess the influence of wave attenuation in distinct directions, the incidence angle θ_{in} is varied between 0°, 15°, 30°, 45°, 60°, and 75°, while the azimuth angle ψ_i remains constant.

Figure 3 presents the numerical and analytical results for oblique incidence. The analysis reveals minimal variations in both the local resonance frequency and the STL peak value. However, a significant reduction in STL is observed outside the resonance peak, attributed to the reflection phase caused by panel discontinuity. In summary, the overall sound transmission loss (STL) increases as the incidence angle decreases.

4.2 Diffuse incidence

To investigate the performance of the hexagonal acoustic metamaterial under conditions other than normal incidence, additional simulations were conducted to calculate the diffuse incidence STL. As mentioned in Ref. [3], this was achieved by simulating the STL for various incidence angles from $\theta_{in} = 0^\circ$ to 78° and integrating the resulting STL values across the frequency range.

Figure 4 presents the initial attempts to compute the numerical diffuse STL values for the hexagonal AMM based on a single resonant unit cell. The blue lines represent the analytical results, while the blue markers correspond to the numerical values. For comparison, the grey lines show the STL of the AMM for various incidence angles, ranging from 0 to $\pi/2$. The proposed AMM demonstrates significant transmission capacity, exceeding 20 dB at the tuned resonance frequency.

5. Conclusions

An acoustic metamaterial composed of a parallel arrangement of Helmholtz resonators, all tuned to the same resonance frequency, is presented, demonstrating its sound attenuation capacity under random incidence. As a result, significant sound attenuation is observed when exposed to realistic acoustic field conditions.

The theoretical results show strong agreement with the numerical values, validating the efficiency of the AMM and the accuracy of the theory developed here. Further testing of the AMM using a physical prototype is planned for future studies.

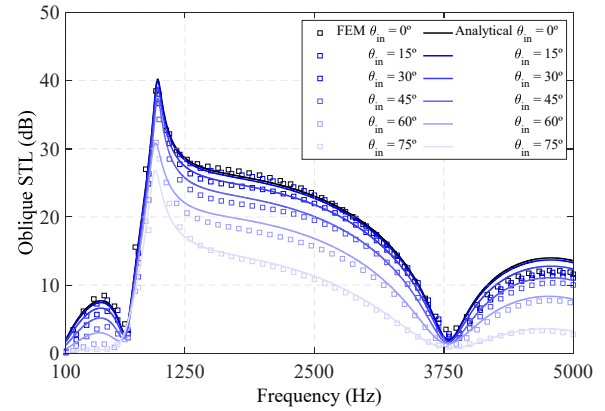


Figure 3 – Evolution of the oblique STL of the hexagonal metamaterial with changing incident angle θ_{in} . The azimuth angle is fixed at $\psi_i = 45^\circ$.

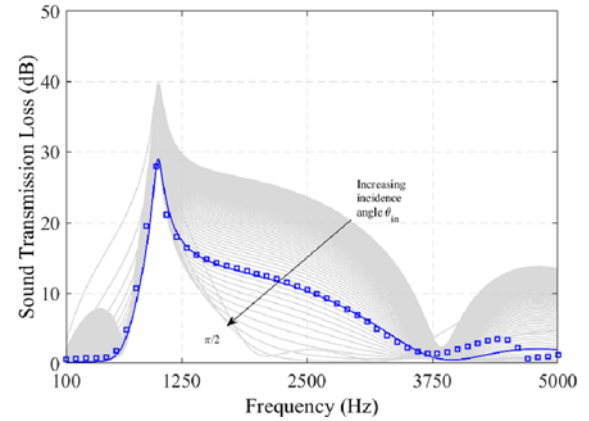


Figure 4 – Diffuse incidence STL of the hexagonal resonant metamaterial tuned at a single resonant frequency. The blue markers represent the finite element results, and the blue solid line represents the analytical result for the expressed STL for $1 < \theta_{in} < 78^\circ$. The grey lines represent the analytical oblique incidence for $1 < \theta_{in} < 90^\circ$.

6. References

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Acknowledgments

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