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THE INFLUENCE OF BASE PLATE PARAMETERS ON VIBROACOUSTIC METAMATERIAL EFFECTIVENESS

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ABSTRACT

Vibroacoustic metamaterials allow for mechanical impedance enhancement of the base structure to which they are attached. The effective frequency range of the metamaterial is called the "stop band", and it depends on individual element geometries and their arrangement. These parameters impact the vibration and sound transmission loss of the structure. Most of the solutions presented in the literature are developed for specific vibroacoustic problems with a pre-selected base structure and an ideal bonding method assumed. This limits the versatility of the developed solution and narrows the number of applications in which it could be used. It would be beneficial if one solution could be exploited in several different applications and suited for mass production.

This work studies the influence of the base structure, its mechanical parameters, and its dimensions on the effectiveness of the selected metamaterial prototype. Plates of various thicknesses combined with 3D-printed metamaterials are tested. Sound and vibration reduction parameters and changes in the solution's effective frequency range were investigated based on simulation and measurement results. The dispersion curves and sound insulation simulations were used to evaluate the potential effectiveness. The simulation results were compared with vibroacoustic measurements for selected metamaterial and base structure configurations.

Keywords: vibroacoustic metamaterials, sound transmission loss, locally resonant structures,

1. INTRODUCTION

Vibro-acoustic metamaterials are periodic structures based on simple mass-string-damper elements which exhibit improved acoustic properties in sound and vibration insulation for a specific frequency range. Metamaterials' lightweight structure and compact dimensions are essential, especially in improving acoustic properties in low-frequency regions [1].

The frequency range where metamaterial improves transmission loss parameters is determined by its resonance and antiresonance frequencies [2]. The resonance frequency is the resonance of the mass-spring-damper system, and antiresonance is the effect of the resonator and base plate movement in the antiphase. Therefore, the effectiveness of vibroacoustic metamaterial is dependent on the resonant element and base structure's physical properties [3]. Investigating the base material impact is particularly important when one metamaterial geometrical design is used in several applications, and using one design in many applications may partially solve the problems associated with the mass production of vibroacoustic metamaterials.

This work investigates the dependence between metamaterial effectiveness and base structure parameters. For this purpose, numerical simulations, as well as vibroacoustic measurements, were performed. The influence of base plate mechanical and physical parameters on the resonance and antiresonance amplitude is presented, as well as the base plate properties and distances between unit cells impact the stop band appearance in selected frequency range.

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2. VIBROACOUSTIC METAMATERIALS FOR SOUND AND VIBRATION MITIGATION

As indicated by Brillouin, the considered periodic structures can exhibit the so-called stop band behavior for a selected frequency range, where no free wave propagation is possible [4]. The stop band is limited by resonance and antiresonance frequencies. Metamaterial unit cell parameters and base structure properties influence the resonance and antiresonance frequency. Sound Transmission Loss (STL) amplitudes in these frequencies mainly depend on the damping factor and resonant element mass.

The stop band effect for bending waves propagating in the base structure is strictly bounded with the STL of the structure. In Fig. 1 dispersion curve of a single resonant metamaterial unit cell is presented. The stop band appears between 250 and 275 Hz for the selected metamaterial design, as marked in Fig. 1. In Fig. 2, the STL diagram is presented for the selected metamaterial design with different material damping factors μ. The highest STL can be observed for metamaterial resonance frequency and the lowest for the antiresonance frequency. The base curve for plain plate follows mass law which states that the STL of the structure increases as the mass of the structure increases. The resonance amplitude will change with the loss factor of the metamaterial; the higher the loss factor, the lower the amplitude for resonance frequency.

In literature, the base plate impact on metamaterial effectiveness is usually limited to the metamaterial to base mass ratio; the higher the ratio, the better the metamaterial's effectiveness [2]. However, besides this mass ratio, the loss factor, and the simulated stop band of the metamaterial, its effectiveness is dependent on the base structure's physical properties.

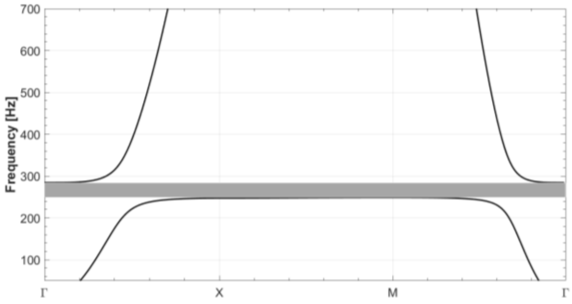

Fig. 1 Dispersion curve diagram for selected vibroacoustic metamaterial tuned to 250 Hz. The stop band is marked in grey color.

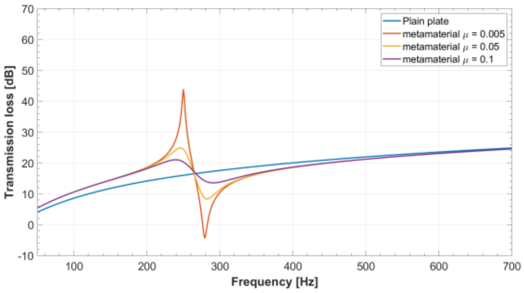

Fig. 2 Sound Transmission Loss of a plate with vibroacoustic metamaterial with different damping factors.

3. SIMULATION AND MEASUREMENT PROCEDURE

This section presents the procedure of simulations and measurements, which aimed to determine the influence of the base parameters on the vibroacoustic parameters obtained by adding a metamaterial. The experiment was divided into two stages: simulation and measurement verification. In this work, only the mechanical impedance is considered; as stated in [5], the Sound Transmission Loss parameter can be obtained based on mechanical impedance simulation and measurement. Simulations and measurements were performed for materials whose properties are listed in Tab. 1.

Tab. 1 Mechanical and physical material properties used in simulation and measurement procedure.

Material	Young Modulus [GPa]	Density [kg/m^3]	Poisson ratio [-]
Aluminium	69	2700	0.33
Steel	205	7500	0.28

3.1 Simulation procedure

In order to obtain simulation results for a specific 3D model, the numerical simulations were conducted using COMSOL 5.4 software with its Structural Mechanics Module. The numerical model in this work is presented in Fig. 5. The model consists of the unit cell: vibroacoustic metamaterial with a base plate. The point force is applied to one surface of the base plate, as presented in Fig. 3. marked with a red dot. Based on the simulation results, the mechanical impedance of the base plate is calculated by dividing the applied force over averaged vibration velocity. The STL value can be obtained through analytical calculations from the element's mechanical impedance, as stated in [6]. From the same numerical model, one can obtain the element's dispersion curves, which can also be used to determine the stop band characteristics of the structure.

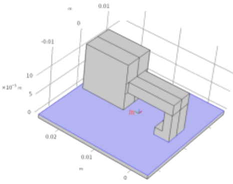

Fig. 3 Unit cell 3D model.

3.2 Measurement procedure

Typically the resonant frequencies of metamaterial unit cells are obtained from vibrometer measurement of a single element attached to a shaker. However, in this way, one would only obtain the characteristics of resonant elements without the base structure characteristics. In order to measure mechanical impedance of the unit cell, authors propose base impedance measurement of a single unit cell using an electrodynamic shaker Modal Shop 2004E with impedance head sensor ICP 288D01 attached to it. The measurement stand is presented in Fig. 4Fig. 5. the force and acceleration were acquired using the impedance head, while a white noise excitation signal was generated using the shaker. The resonant element was attached to the base plate glued to the impedance head. The base impedance was calculated based on the force and acceleration measurement results.

Fig. 4 Mechanical impedance measurement stand.

4. SIMULATION AND MEASUREMENT RESULTS COMPARISON

Simulations and measurements were performed according to the description in Sec. 3. The simulation and measurement results were compared for the selected configuration. The specimen used in simulations was a resonant element tuned to 250 Hz with a 25% mass addition of 1 mm aluminum plate mass. Prototypes were 3D printed using HP MJF 3D printer.

The first theoretical study considers the distance between periodically distributed metamaterial elements. The unit cell dimensions were changed from 0.03 to 0.09 m for selected resonant element and square base plate parameters. Simulation results are presented in Fig. 5. For small distances between the elements the stop band appears between 250 and 275 Hz. With the increase of the distance, the stop band shifts to lower frequencies than expected, and for a unit cell length equal to 0.08 m, the stop band effect disappears. It is related to Bragg Frequency which decreases as the distance between the elements increases.

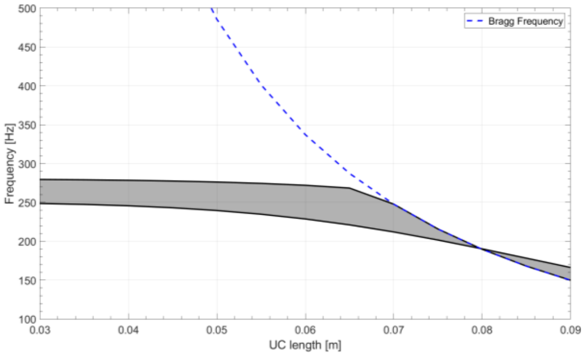

Fig. 5 The dependence of the stop band effect on base structure length.

The second element of this study was simulation and measurements comparison to determine the influence of base plate material on mechanical impedance characteristics. In Fig. 6. the comparison between simulation and measurement results for metamaterial element placed on a 1 mm steel plate is presented.

The simulation results match the measurement results for the mechanical impedance of the base plate. Fig. 7 presents the measurement results for different base structures with resonant elements attached. When the mass of the base structure increases, the overall mechanical impedance of the structure increases. What is worth noticing is that the amplitude od mechanical impedance for resonant frequency for all configurations is similar; only for the 3mm steel plate with the highest mass and thickness of all configurations is shifted, and the amplitude is lower than for other cases. Regarding antiresonance frequency and its amplitude, the difference between studied cases is more significant than for resonance frequency—the amplitude of antiresonance changes with the base plate parameters. The heavier the base plate gets, the difference between an empty base plate and a plate with metamaterial gets smaller. The differences between antiresonance frequencies reach 15 Hz for selected cases, while the difference is less than 2 Hz for resonance frequency.

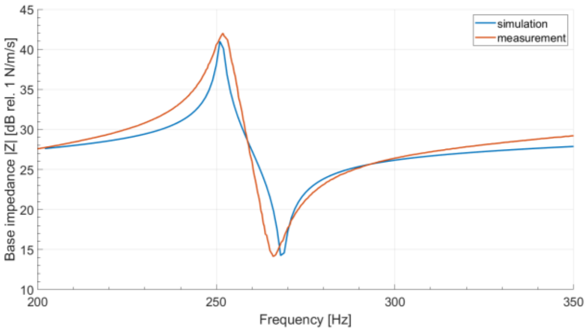

Fig. 6 Mechanical impedance of resonant element on the base plate: Simulation and measurement results comparison.

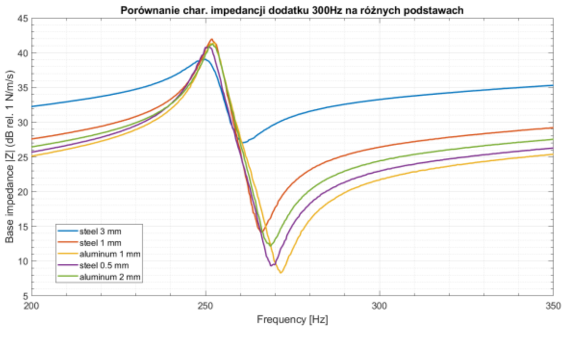

Fig. 7 Mechanical impedance measurement results for different types of base plates.

5. SUMMARY

This work presents results on base plate parameters' influence on vibroacoustic metamaterial effectiveness. The dependence between stop band appearance and the distance between metamaterial elements was analyzed, and the effect of base plate mechanical properties influenced the mechanical impedance characteristics. The results show that the distance between elements affects the stop band frequency range. The base plate material and its weight influence both resonance and antiresonance frequencies and their amplitudes and should be considered in simulations and resonance frequency measurements. The base's properties should be considered at every design stage. In the case of a universal solution, it is necessary to optimize the solution in terms of use in many different cases.

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