MADRID
inter.noise 2019
June 16 - 19
NOISE CONTROL FOR A BETTER ENVIRONMENT

Overcoming the Coincidence Effect of a Single Panel by Introducing and Tuning Locally Resonant Structures

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ABSTRACT

The acoustic performance of partition walls is usually based either in their mass or in a layered structure, including materials with different properties (external layers and internal absorbing materials, for example). In recent years, the consideration of additional dynamic effects in the behaviour of such systems has been used to improve their performance. Among these new proposals, metamaterials are a promising possibility.

In this paper, numerical and experimental analyses were carried out in order to investigate the sound transmission loss of a single particle board with periodically attached spring-mass resonators. The resonators were materialized by 3D printing and designed to achieve resonant frequency in the coincidence region of the panel. Both, numerical and experimental results showed that the resonance mode of the spring-mass resonators couples with the plate vibration in the way of breaking the mass law and overcoming the coincidence effect throughout the formation of a band

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gap in the desired frequency region. Therefore, this metamaterial design can serve as an effective solution for increasing the sound transmission loss of the panel.

Keywords: Metamaterials, Resonators, Coincidence effect
I-INCE Classification of Subject Number: 33

1. INTRODUCTION

In recent years, acoustic metamaterials have received great attention from the scientific community, which has rendered several concepts for their potential engineering use for noise abatement. The trigger for their origin was the analogy between the electromagnetic and elastic waves and the findings in the band theory of solids throughout the concept of photonic crystals, which was followed by the concept of phononic crystals. Phononic and sonic crystals (fluid medium) obey Bragg's law, which connects the lattice parameter of the periodic system with the acoustic wavelength and this link is unfavourable for low-frequency range application. With the introduction of locally resonant sonic materials in 2000, by Liu and co-workers [9], this limitation was overcome and acoustic metamaterials were established as artificial periodic structures with unique wave-manipulation performance that arise from the influence of their locally resonant units.

Acoustic metamaterials have given the researchers new possibilities and already can be found in a variety of designs for improving sound attenuation, like membrane type metamaterials, [6, 10, 11, 18, 19, 20], metamaterials with Helmholtz resonators, [14, 17], metamaterials with attached resonant structures, [2, 4, 7, 12, 13, 15, 16], metamaterials with embedded resonant structures, [1, 3, 5, 8].

In this paper, numerical and experimental analyses were carried out in order to investigate the sound transmission loss of a single particle board panel with periodically attached resonant structures. The resonators were materialized by 3D printing and designed to achieve a resonant frequency in the coincidence region of the panel so that the created stop band reduces the effect of the critical frequency (coincidence effect) on the sound insulation of such panels. The measurements were carried out in the laboratory facilities of the Department of Civil Engineering, University of Coimbra.

2. DESIGN OF THE RESONATORS

Single particle board panel with thickness of t=8 mm was used for the design. The coincidence dip for the considered panel starts from around 2300 Hz (according to referent measurements). In order to achieve efficient effect of the resonators (sufficient width of the band gap) the specific amount of mass is required, so to tune the resonator in the higher frequency range, the stiffer spring is needed.

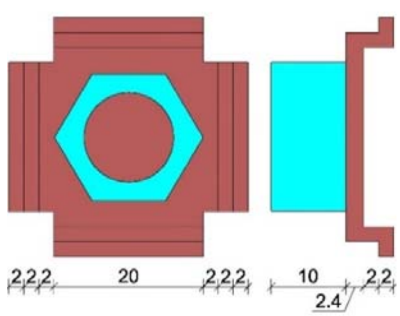


Figure 1 – Geometry of the resonator.

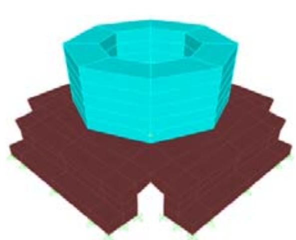


Figure 2 – 3D model of the resonator.

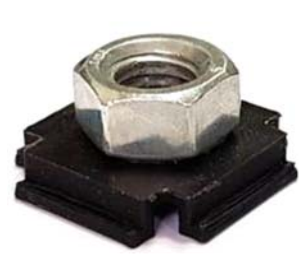


Figure 3 – Fabricated resonator.

Polyamide (PLA) and steel are selected as constituent materials for the resonator. Using the finite element software SAP2000 for modal analysis, the resonators were designed (Figure 1 and Figure 2) so that their first mode fits in the coincidence dip range. Namely, the first and the second modes are predicted at around the frequency of 2900 Hz and the third mode at 3200 Hz. Also, the design of the resonators was chosen so that they can be easily applied in the embedded type metamaterial solution for a simpler engineering application. Using the 3D printer BLOCKS ONE and polyamide (PLA) as building material, the sprig structure was fabricated. The mass-spring resonator was created by attaching a steel nut M12 to the spring structure (Figure 3).

To confirm the dynamic behaviour of the resonator, before fabricating all of the resonators and gluing to the panel, a quick modal testing was performed using a force impact hammer and an accelerometer (Figure 4). From the obtained transfer function (relation between acceleration and force, Figure 5), the modal behaviour of the resonator was determined and the first resonant frequency of the fabricated resonator was registered at 2700 Hz, which fits in the coincidence dip region. One hundred resonators were then fabricated with the same design and dimensions.

Figure 4 – Modal testing set-up.

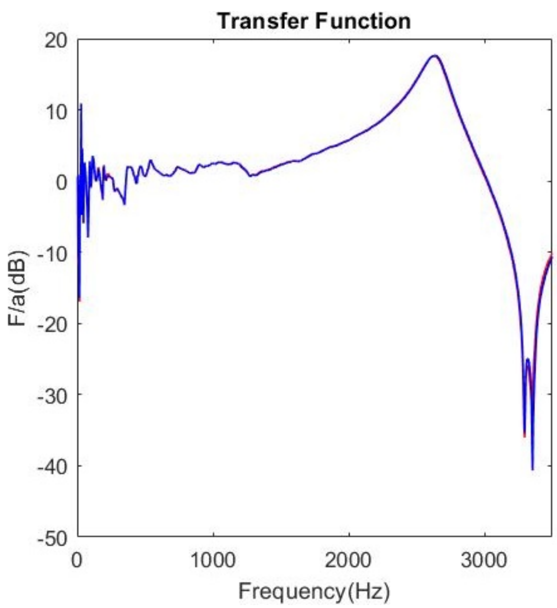


Figure 5 – Transfer function from modal (hammer) testing of the resonator.

3. METAMATERIAL PROTOTYPE

A metamaterial panel was created by gluing the resonators to the surface of the single particle board panel in periodical arrangement. The gluing of the resonators was carried out in several phases in order to investigate the periodicity effect on the transmission loss. Five different sets were measured: the bare panel and the metamaterial panels created with periodically attached 25, 50, 75 and 100 resonators (Figure 6), so the periodicity (lattice constant) was varying from a=12 cm to a=6 cm. The measurements of the transmission loss were performed in the laboratory facilities of the Department of Civil Engineering, at the University of Coimbra, with a simplified experimental procedure, using a concrete box with 55x55 cm^2 opening for the specimen implementation, as shown on Figure 6.

Figure 6 – Metamaterial panel prototype under test.

4. NUMERICAL MODEL

In order to perform conceptual numerical study, an adaptation was made to the existing FEM codes developed at the Department of Civil Engineering, at the University of Coimbra [1]. The sound transmission loss of the infinite meta-panel was predicted with a very efficient 1D uncoupled FEM model. The elastic panel was modelled with Timoshenko beam elements and the attached resonating structures were introduced to the panel as mass-spring resonators. The equation of motion was solved and the pressure of the radiated noise from the panel was calculated with the relation $|p|=\rho c|v|$. The periodic nature of the metamaterials was implemented through periodic boundary conditions based on Floquet-Bloch theory.

A bandgap is a band of frequencies where there are no mechanical (acoustic) free propagating waves. To identify the formation and the width of the bandgap and to compare the results with the predicted and measured sound insulation curves, the dispersion diagrams (band structure) were computed. This diagrams show the relation between frequency and wave number and give information about the wave propagation behaviour of the metamaterial. The band structure is obtained by solving the eigenvalue problem that is formed by FEM modelling of the parametric unit cell and by setting Floquet-Bloch periodic boundary conditions.

5. RESULTS AND DISCUSSION

The results from the numerical analysis show that by tailoring the dynamic behaviour of the resonators, metamaterial panels can be designed to achieve stop band in the coincidence region of the panel and, hence, forbid elastic wave propagation within the bandgap frequency range. After locating the coincidence region of the bare panel, the spring-mass behaviour of the resonating structures gives a simple tool for tailoring the bandgap of the metamaterial simply by tuning the properties of the mass and/or the elastic material (softer/stiffer spring, larger/smaller mass etc.), as shown in Figure 7.

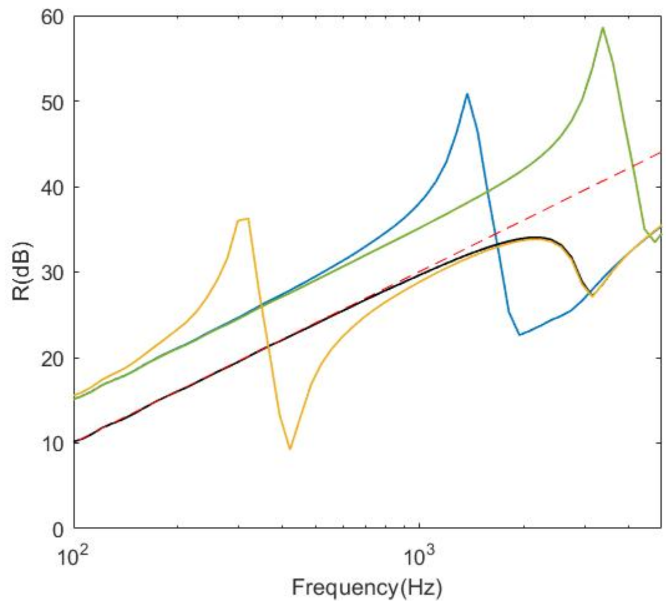


Figure 7 – Tuning the resonator.

The measurements were performed for metamaterial panels with four different periodicities and the results are displayed in Figure 8. By decreasing the periodicity, extra mass is added to the panel, which can be seen through the shifting of the mass-law controlled region of the sound insulation curves. The mass law is overthrown around the resonance of the attached structures. This is a very positive effect that reduces the coincidence effect because of the creation of a bandgap. The width of the bandgap is strongly correlated to the periodicity. Smaller lattice constant leads to wider bandgap.

By attaching 25 resonators, the total mass is increased by 20% and for this set-up, the effect of the resonators is not effectively registered in the measured results. By attaching 50 resonators, the mass is increased by 40% and for the frequency of f=2400 Hz the sound transmission loss is increased for almost 10 dB in comparison to the bare plate. By applying 75 resonators to the plate, the total mass is increased by 60% and for the frequency of f=2400 Hz, the sound transmission loss is increased for almost 12 dB. For 100 resonators, the mass is increased by 80% and for the frequency of f=2600 Hz the sound transmission loss is higher than the bare plate for more than 20 dB. This effect cannot be achieved with the standard mass-law treatments like choosing a material with 80% higher density or by increasing the panel thickness for 80%.

Transmission loss curves for the bare panel and metamaterial panels with four different periodicity were calculated with a FEM code developed in Matlab. The results are shown in the Figure 8 and a good agreement can be seen between the experimentally and numerically obtained curves.

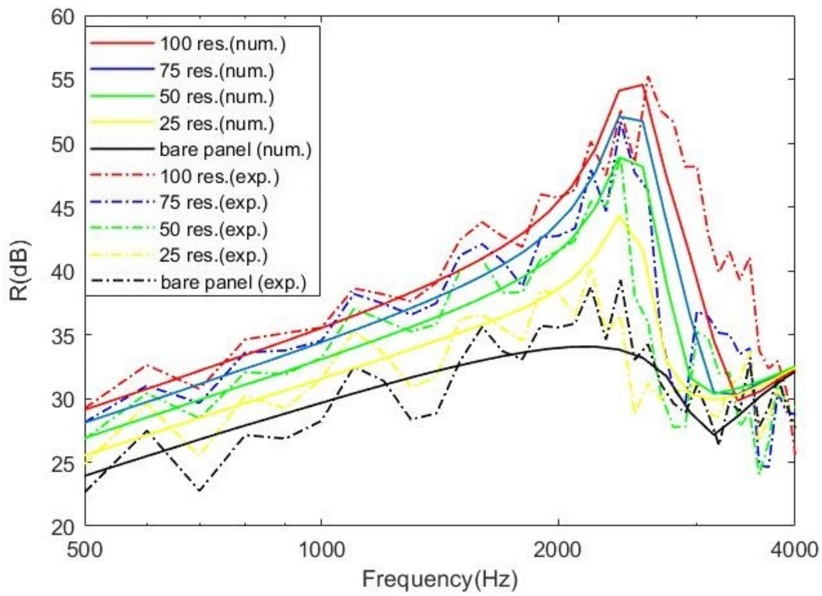
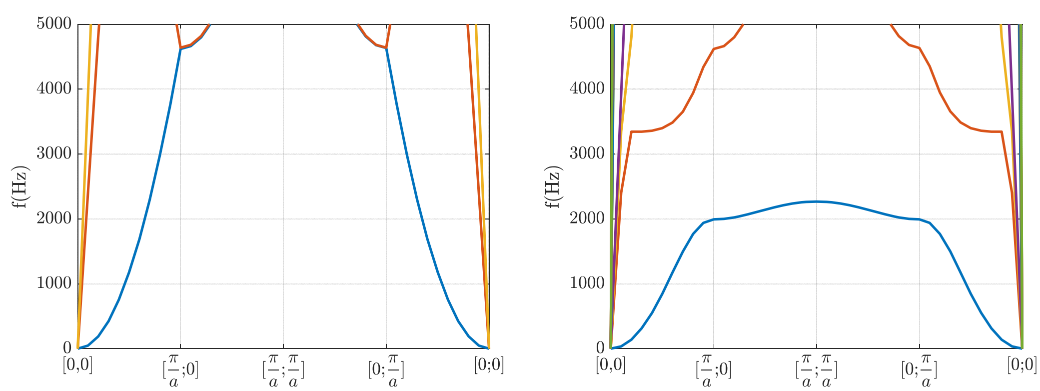


Figure 8 – Sound transmission loss for bare panel and meta-panel with different periodicity.

The effect of the attached locally resonant structures on the transmission loss has also been studied through the analysis of the dispersion diagrams. A 3D FEM model of the unit cell, developed in Matlab, was used to compute the dispersion curves for bare and metamaterial panel with 100 resonators, and are shown in Figure 9.

For the bare panel it is evident that no bandgap exists (Figure 9a). For the metamaterial with 100 attached resonators the width of the bandgap is 1250 Hz, from 2133 Hz to 3383 Hz (Figure 9b). This result correlates well with the measured and calculated transmission loss curves (Figure 8).



a) *Bare panel (a=0.06m).* b) *Panel with 100 resonators (a=0.06m).*

Figure 9 – Dispersion curves.

6. CONCLUSIONS

Both numerical and experimental results have shown that the resonance mode of the spring-mass resonators couples with the elastic wave in the plate in the way of breaking the mass law and reducing the coincidence effect through the formation of a band gap in the desired frequency region. Therefore, it can be underlined that such metamaterial design of panels can serve as an effective solution for increasing the sound transmission loss beyond the possibility of classical treatment.

7. ACKNOWLEDGEMENTS

This article is based upon work from COST Action DENORMS CA15125, supported by COST (European Cooperation in Science and Technology). This work has also been framed within the POCI-01-0247-FEDER-017759 (SmartCore) Project, funded by the COMPETE 2020, Portugal 2020 and FEDER funds. This work was partly financed by FEDER funds through the Competitivity Factors Operational Programme – COMPETE, by national funds through FCT – Foundation for Science and Technology within the scope of the project POCI-01-0145-FEDER-007633 (ISISE) and through the Regional Operational Programme CENTRO2020 within the scope of the project CENTRO-01-0145-FEDER-000006 (SUSpENsE).

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