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FINITE ELEMENT MODELLING OF THE SOUND TRANSMISSION PROPERTIES OF A SYMMETRIC META-ABSORBER COMPOSED BY SIDED BRANCH HELMHOLTZ RESONATORS

Denilson Ramos (1), Francesco Pompoli (2), Cristina Marescotti (2), Luís Godinho (1), Paulo Amado-Mendes (1), Paulo Mareze (3)

1) ISISE, ARISE, Department of Civil Engineering, University of Coimbra, Coimbra, dtramos@student.dec.uc.pt
2) Department of Engineering, University of Ferrara, Ferrara, francesco.pompoli@unife.it
2) Department of Engineering, University of Ferrara, Ferrara, cristina.marescotti@unife.it
1) ISISE, ARISE, Department of Civil Engineering, University of Coimbra, Coimbra, lgodinho@dec.uc.pt
1) ISISE, ARISE, Department of Civil Engineering, University of Coimbra, Coimbra, pamendes@dec.uc.pt
3) Acoustical Engineering, Federal University of Santa Maria, Santa Maria, paulo.mareze@eac.ufsm.br

ABSTRACT

In the present study, the authors develop a subwavelength open acoustic metamaterial, composed by the axial coupling of sided branches Helmholtz resonators. A finite element model was developed and the results demonstrate the proposed absorber system works on a subwavelength regime, allowing low-frequency broadband absorption (approx. 500 Hz to 800 Hz). Finally, an experimental campaign was realized at the Department of Engineering of the University of Ferrara, and the simulated results showed good agreement when compared with two standardized methodologies, the ISO 10534-2 and the ASTM E2611-09.

1. Introduction

In acoustics, the interest in sound wave manipulation on subwavelength regimes has been an object of recent and intense research. The continuous advances in the science of materials have led to the development of a new class of acoustic materials, namely acoustic metamaterials (AMM), allowing optimized responses in controlled low-frequency sound wave fronts while ensuring low density in sub-wavelength dimensions.

Recently, the investigation of acoustic metamaterials with negative bulk modulus achieving broadband perfect sound absorption [1] enabled by the axial coupling of six Helmholtz resonators critically coupled, hinted to the possibility of developing new acoustic systems with a significant optimized acoustic response in the specific frequency range.

As a continuation of the mentioned work, this study has the objective to model and evaluate the acoustic behaviour of the proposed acoustic metamaterial under two different boundary propagation conditions under normal incidence.

2. Proposed Design

Due to the limitations posed by resonant systems and their resonant capacity occurring in a narrow band, the concept of the basic unit of the proposed acoustic metamaterial consists of the axial coupling of six Helmholtz resonators and its distinct local resonances, as presented in figure 1.

In figure 1(a), six generic resonators are considered, where, $l_{\mathrm{n}}^{[n]}$ corresponds to the length of the resonator's neck, $w_{\mathrm{n}}^{[n]}$ corresponds to the width of the neck opening with a rectangular section, $l_{\mathrm{c}}^{[n]}$ corresponds to the length of the resonator cavity, $w_{\mathrm{c},1}^{[n]}$ and $w_{\mathrm{c},2}^{[n]}$ correspond, respectively, to the length and width; by mathematical simplification, the resonant cavities will be considered as a parallelepiped. All the tested samples have been fabricated by using a Blocks One 3D printer with Polylactic Acid (PLA), considering the nozzle extruder with 0.4 mm; one of the produced samples is illustrated in figure 1 (b).

Assuming the investigation of the two boundary termination conditions, figure 1 (c) represents the schematic illustration for the theoretically rigid condition; and figure 1 (d) illustrates the schematic theoretically infinite condition.

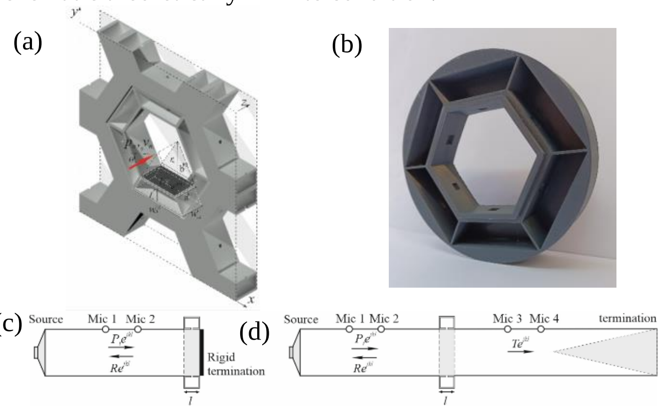

Figure 1 - (a) Schematic description of the unit cell. (b) The produced (3D print) sample for experimental analysis. (c) Schematic representation of the impedance tube backed by a rigid termination; (d) backed by an anechoic termination;

3. FEM Modelling

To predict the acoustic behaviour of the proposed AMM, two models were implemented through the commercial software COMSOL multiphysics, numerically simulating the ISO 10534-2 [3] and ASTM E2611-09[4] tests. The tridimensional finite element model in linear regime is considered, and the investigation is conducted assuming the time-harmonic dependence ($e^{\mathrm{j}\omega t}$). A plane wave of unitary amplitude (1 Pa) excites the system, impinging and propagating under normal incidence conditions through a domain defined as air, with mass density (ρ_0 = 1.23 kg/m^{-3}), air dynamic viscosity (η = 1.82 $\times 10^{-5}$ Pa·s), under ambient pressure P_0= 101325 Pa; all surfaces are assumed to be perfectly rigid and reflective.

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To ensure better accuracy of the results, visco-thermal losses in narrow domains, such as the necks of the resonators, were considered, through the approach based on Johnson-Champoux-Allard (JCA) using rigid framed porous model [2], dealing with the dissipation loss of the acoustic energy of the structure.

The discretization of the model was performed with tetrahedral elements, with the maximum element size of 1/10th of the smallest simulated target wavelength, corresponding to a maximum frequency of 1 kHz. To accurately calculate the inherent dissipations of the narrow channels through the JCA rigid frame model, the maximum mesh size at the neck of HRs is $w_n^{[n]}/4$ and the minimum size is $d_v/2$, where $d_v = \sqrt{2\mu/\rho_0\omega}$ is the thickness of the viscous boundary layer.

4. Experimental Evaluation

To validate the FEM simulations an experimental campaign was performed at the Acoustic Lab of the Department of Engineering of the University of Ferrara.

The absorptive characteristics of the proposed AMM were investigated considering the sound absorption measurement under normal incidence in an impedance tube with 45 mm of diameter backed by a rigid termination (finite condition), as illustrated in figure 1(c), making use of the two-microphone technique based on the transfer function method (following ISO 10534-2 [3]).

To describe the acoustic wave propagation in a theoretically infinite acoustic system, the sound transmission properties under normal incidence were performed in an impedance tube with four microphones backed by an anechoic termination, as illustrated in figure 1(d), reproducing the standardized method ASTM E2611-09 [4].

5. Results

Initially, the first configuration of interest, the single model, consists of a symmetric system composed of six identical Helmholtz resonators axially coupled and tuned at f_1 = 550 Hz. Then, the coupling between multiple resonant frequencies will be considered; in a second case, the dual model, the coupling of the set of three identical resonators tuned to two resonance frequencies, at f_1 = 560 Hz and f_2 = 625 Hz; and, in a third case, the triple model, it is composed by three different resonance frequencies, at f_1 = 540 Hz, f_2 = 590 Hz and f_3 = 740 Hz.

The results presented in figure 2 correspond to the investigation of the respective sound absorption characteristic for a finite system [3]. The acoustic behaviour of the proposed AMM is given by the combined contribution of each local resonance; however, it is important to account for the critical coupling condition [1] between the resonators, previously optimized by a nonlinear optimization algorithm [1], to guarantee a significant absorptive characteristic leading to the perfect absorption phenomena at the specified frequencies, allowing wideband absorption in subwavelength.

The results presented in figure 3, correspond to the sound transmission properties, namely the transmission (|T|), reflection (|R|), and absorption (α) coefficient for theoretically infinite systems [4], disregarding the direction of sound propagation, satisfying the symmetric condition imposed. The investigation of the STL of the proposed solutions is presented in figure 4, and the results evidence the widening of the curve of transmission loss being conditioned by a significant reduction of the attenuation capacity of the system.

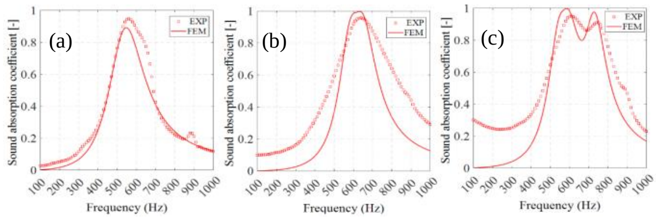

Figure 2 - The sound absorption coefficient spectra for proposed models under finite system condition (rigid backed-end). (a) Single model; (b) the dual model and (c) the triple model, respectively.

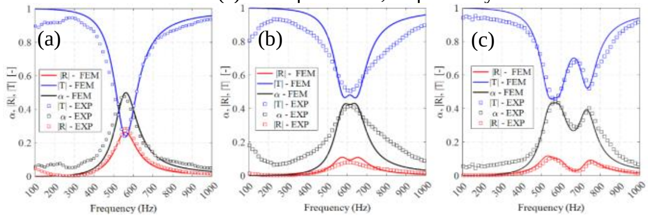

Figure 3 - Comparison of the transmission properties spectra for the proposed model under infinite system (anechoic termination). (a) Single model; (b) the dual model and (c) the triple model, respectively.

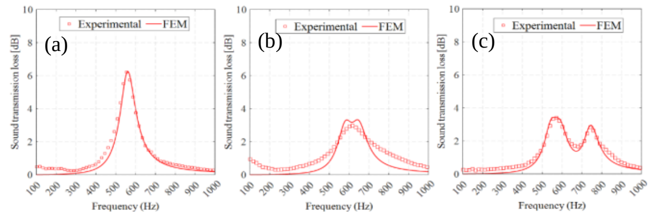

Figure 4 - Comparison of the sound transmission loss in dB. (a) Single model; (b) the dual model and (c) the triple model, respectively.

6. Conclusions

In this work, a subwavelength acoustic metamaterial for low-frequency based on the axial coupling of six Helmholtz Resonators has been designed and fabricated through additive manufacturing techniques, e.g. 3D printing, corresponding to a symmetric acoustic metastructure tuned at one, two and three resonance frequencies, guaranteeing a low structural thickness. Based on the models presented here, the authors intend to extend the research to employ the concept of tunable critically coupled resonators, being able to guarantee perfect absorption, as well as a high transmission loss, only through geometric changes.

7. References

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