STRUCTURED ASSEMBLY OF ACOUSTIC MATERIALS FOR MITIGATING LOW-FREQUENCY BROADBAND AIRCRAFT NOISE

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1 Introduction

The challenge of attenuating low-frequency noise in confined environments, particularly in industries like transportation and aeronautics, is crucial, especially for Unmanned Aerial Systems (UAS). Propulsion systems, especially propellers, emit both broadband and tonal noise, with total noise being predominant. Traditional methods for tonal noise reduction involve complex propeller blade and support structure design [4,6], while noise propagation reduction methods like acoustic liners add weight and space requirements, unsuitable for UAS platforms. Additionally, conventional materials for low-frequency noise attenuation are limited by volume constraints. Acoustic metamaterials, with structured designs comprising elements smaller than acoustic wavelengths, offer a promising solution.

Recent research [1-3] has focused on developing acoustic metamaterials with parallel periodic unit cell assemblies to attenuate multiple resonance frequencies. However, these designs often have narrow frequency bands. Inspired by previous work [1-3], the present study proposes acoustic metamaterial designs capable of widening resonance frequency bands and attenuating multiple frequencies. COMSOL Multiphysics finite element methods was employed to calculate the normal incidence sound absorption coefficient (SAC).

2 Materials

The metamaterial under investigation in this paper was meticulously designed as an intricate assembly, incorporating both structured materials (SMs) and Helmholtz Resonators (HRs). These elements were precisely arranged in parallel and embedded within a layer of fiberglass, conferring unique properties to the resulting configuration. The specific geometric arrangement involved three SMs and four HRs. The metamaterial, without the porous layer, had a cylindrical form with a diameter D_{HR} and a length L_{HR}. In a sectional view, the center of two consecutive structured materials formed an angle of 120 degrees relative to the axis of revolution of the metamaterial (see Fig. 1). Notably, each axis of revolution was located a distance d relative to the overall axis of revolution of the metamaterial. Each SM consisted of a series assembly of unit periodic cells (PUCs), where each PUC comprised a cylindrical neck with a diameter d_{SM_i} and height ℓ_{SM_i}This neck was followed by a cylindrical cavity of diameter D_{SM_i} and height h, referred to as a slit or small cavity, and concluded with another identical neck. This structural arrangement is illustrated in Fig. 1. The assembly also incorporated a classic HR, denoted as an outer HR, depicted in Fig. 1. The outer HR featured a neck with a diameter d_{HR_0} and a length ℓ_{HR_0}. The cylindrical cavity of the outer HR, with a diameter D_{HR_0} and length L_{HR_0}, was distinctively positioned outside its neck. The axis of revolution of the outer HR coincided with that of the metamaterial, as illustrated in Fig. 2c. In addition to the outer HR, the assembly included inner HR configurations, where the HR necks resided within the cavities. These inner HR necks were cylindrical, characterized by a diameter d_{HR_i} and length ℓ_{HR_i}. The cavities exhibited a complex shape, resulting from the difference between a cylinder with a diameter D_{HR_0} and length D_{HR_0}, and (i) three cylinders with the same axis of revolution as the three structured materials, each having a diameter $D_{SM_i} + 2e$ and length L_{HR_i} and (ii) a cylinder sharing the axis with the outer HR neck, featuring a diameter $d_{HR_0} + 2e$ and length ℓ_{HR_0}. The Ref. [5] gives more detail on the design parameters and their values.

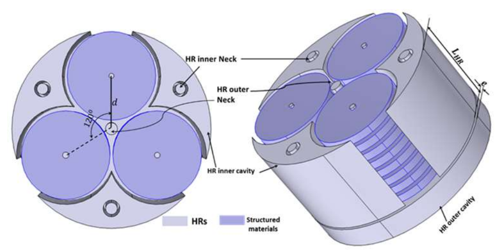

Figure 1: Metamaterial: Left section view end Right 3D view.

3 Modeling

COMSOL Multiphysics was utilized to predict the absorption coefficient of the metamaterial backed by a rigid wall at normal incidence, using frequency domain sound pressure modulus. 3D model configuration (Fig. 3) was employed. Model simulated an impedance tube with the same diameter as the metamaterial embedded in fiberglass wool, predicting the SAC for the hard-backed scenario. The model consisted of three regions: the metamaterial without porous material, the porous material, and the tube(s). Material properties were defined using the Johnson Champoux-Allard (JCA) [4] model for acoustic representations in different regions. Quadratic elements were employed with varied mesh densities across regions. A unit incident plane wave was imposed upstream, and rigid walls with no-slip boundary conditions were assumed throughout the simulation.

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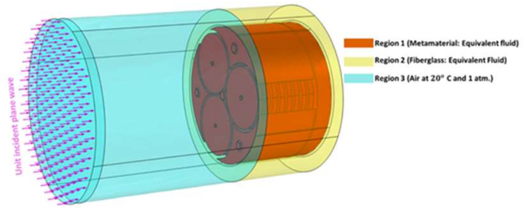

Figure 2: FEM model connected to simulated impedance tubes for the hard-backed.

4 Results

The SAC at normal incident of the metamaterial, with and without a layer of fiberglass, are shown in Fig. 3. The results reveal a widening of the absorption band for the first resonant frequency at lower frequencies, centered on 220 Hz and wide Δf =145 Hz with an absorption rate of approximately 35%. Specifically, Furthermore, a significant enhancement in acoustic performance, exceeding 50%, is observed above 600 Hz. This enhancement can primarily be attributed to the incorporation of a fiberglass layer, renowned for its exceptional absorption efficiency at higher frequencies. Additionally, the detailed analysis revealed the emergence of distinct resonance frequencies, which correspond to secondary resonances inherent in structured materials. These resonance peaks are notably observed at 600 Hz with 50% absorption, at 632 Hz with 66% absorption, and at 730 Hz with 61% absorption. However, despite these notable advantages, the metamaterial exhibits a performance dip within the frequency range of 313 Hz to 573 Hz, with the absorption coefficient dropping below to 30%.

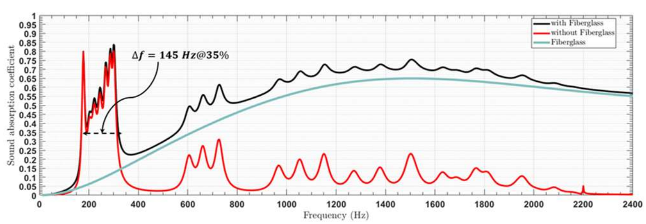

Figure 3: SAC predictions using the FEM calculations.

5 Conclusion

In conclusion, the present study provided valuable insights into the SAC of the metamaterial design, embedded in a fiberglass layer. The paper was successfully demonstrated that a widening of the absorption performance around the first resonant frequency at lower frequencies was possible. Furthermore, the emergence of distinct resonance frequencies, indicative of secondary resonances inherent in structured materials, has been observed. Despite these advancements, the present analysis also revealed a performance dip within a specific frequency range, emphasizing the need for further research to address this limitation. The present findings contribute to the understanding of metamaterials' sound absorption offering potential applications in noise control.

References

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