Acoustic Metamaterials for Low-Frequency Noise Reduction: a Review

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1 Introduction

Noise pollution from transportation vehicles is a growing problem in densely populated areas. Among various sources of noise pollution, helicopters are known for their disruptive and intrusive sounds, which can have harmful effects on the health and well-being of nearby residents. The continuous exposure to high levels of noise in urban environments can lead to annoyance, sleep disturbance, and even more severe long-term health problems, including hypertension, stroke, and heart attacks [1].

Conventional porous materials such as foams exhibit favorable sound absorption characteristics. However, very thick layers of such materials are required for absorbing low-frequency sounds, thus making them unpractical in most applications. Moreover, they have limited design tailorability, and they cannot be effectively employed in complex structures [2].

Acoustic metamaterials are innovative materials engineered to manipulate and control the propagation of sound waves in ways that are not possible with traditional materials. These structures typically consist of periodic arrangements of subwavelength unit cells, which interact with sound waves at specific frequencies to achieve desired acoustic effects [3].

The aim of this review is (i) to contribute valuable insights to the field of noise control and its practical implementation in the aviation industry and (ii) to propose a metamaterial design suitable for large-scale manufacturing and capable to address low-frequency noise reduction in helicopters.

2 Metamaterials

2.1 Folded Metaporous Materials

The "folding" technique is an innovative approach used in the design of acoustic metasurfaces to overcome the thickness requirements needed for effective low-frequency absorption with traditional porous materials. Instead of using thick materials, the folding technique involves creating intricate patterns or structures that allow sound waves to traverse through a compact and folded surface. This enables the metasurface to achieve efficient low-frequency sound absorption despite its reduced thickness, making it a promising solution for compact and effective acoustic absorption applications [4].

Boulvert *et al.* [4] proposed a folded metaporous surface for achieving sub-wavelength and broadband perfect sound absorption. As depicted in Fig. 1, the structure consists of four helicoidal cavities filled with porous media - in this case, micro-lattices. The effective thickness and intrinsic losses of each helicoidal cavity can be independently adjusted by varying their macro- and micro-structures. The results show almost perfect absorption over the frequency range 1000 – 2000 Hz that is not achievable with homogeneous porous materials or single helicoidal cavities.

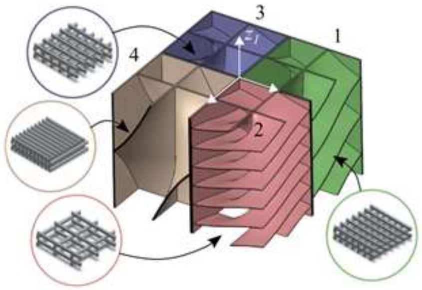

Figure 1. Schematic of parallel assembly of four folded metaporous materials [4].

2.2 Double Porosity Metamaterials

Double porosity metamaterial (DPM) refers to a type of porous material that has two levels of porosity: a meso-scale porosity and a micro-scale porosity.

Zhao *et al.* [5] designed a DPM, incorporating labyrinthine channels for meso-porosity and utilizing melamine foam to achieve microporosity. The DPM exhibits significantly lower frequency sound absorption compared to the homogenous porous materials with equal thickness. The distribution of sound pressure and velocity indicates that the improved sound absorption is brought about by two factors: the resonance of the labyrinthine channel and the hybrid resonance that occurs between the porous layer and the labyrinthine channel. These phenomena contribute to the overall enhancement in sound absorption. Moreover, the DPM offers greater design flexibility to customize the sound absorption spectrum in the desired frequency range.

2.3 Hybrid Acoustic Metamaterials

Costa-Baptista *et al.* [6] designed a multilayered microchannels structure which exhibited effective subwavelength and near-perfect broadband sound absorption. This metamaterial offered a good compromise between effective acoustic properties and useful mechanical properties, making them viable candidates for applications where both sound absorption and structural resistance are required. However, performance drops for frequencies lower than 1000 Hz. Therefore, for providing low-frequency absorption, helical tubes are combined with the multilayered microchannels, as depicted in Fig. 2. This hybrid metamaterial exhibits enhanced acoustic

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absorption capabilities, both in the low-frequency range and across a broader spectrum. The helical tubes would provide a smooth and continuous pathway for the sound waves to be trapped in and dissipated. Coiling is a highly effective method for compactly containing long tubes within limited volumes. In a subsequent work [7], the authors demonstrated that the helical conformation is the most efficient way to fold a tube to provide compact and structurally stable tubes. Furthermore, increasing the length of the tubes causes the resonance to shift towards lower frequencies, further optimizing the material's performance.

2.4 Acoustic Black Holes

An acoustic black hole (ABH) is a sound-absorbing structure designed to gradually slow down and weaken the sound waves as they travel towards the inner part of the structure. They are often comprised of a series of rings with different radii positioned along the inner wall of a rigid cylindrical tube, forming a conical shape. At the tip, there is an extremely small diameter, causing the sound waves to be reflected back and forth multiple times, resulting in a substantial reduction of sound energy and effective sound absorption [8].

Xiaoqi and Li [9] suggested combining an ABH sound absorber with microperforated panels (MPPs) as a liner covering the inner surface of the rings (Fig. 3). The designed structure demonstrates near perfect absorption performance in a rather low and broad frequency range from 200 Hz to 3000 Hz, with much fewer fluctuations of the absorption coefficient value compared to traditional structures.

MPPs offer high acoustic resistance and low acoustic reactance, which makes them a highly effective sound absorption material. The integration of the MPP with the cavity behind the panel creates a resonant system, facilitating the interaction of sound waves passing through the micro-perforations, thereby enhancing sound absorption within a specific frequency range. Furthermore, the MPP dissipates sound energy through viscous losses and frictional effects, contributing to the overall sound absorption performance of the ABH absorber. Therefore, incorporating the MPP into the ABH absorber significantly improves its sound absorption capabilities across both broadband and low-frequency ranges, making it a more versatile and efficient solution for noise control applications [9].

3 Conclusion

In conclusion, acoustic metamaterials offer innovative solutions for broadband and low-frequency sound absorption. Conventional porous materials, while effective in sound absorption, face limitations in dealing with low-frequency noise and complex structural applications. The studies on folded metaporous materials, double porosity metamaterials, hybrid acoustic metamaterials, and acoustic black holes have shown significant advancements in achieving efficient sound absorption across various frequency ranges. With their ability to overcome traditional material constraints and enhance sound absorption in both low and broadband frequencies, acoustic metamaterials hold great promise in creating quieter and more livable urban environments.

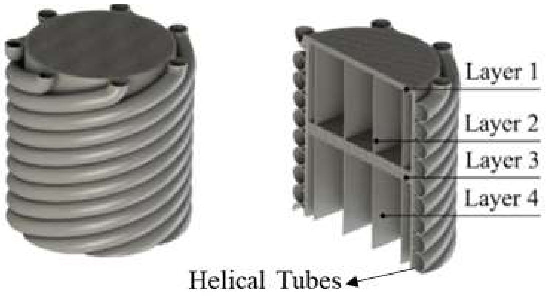

Figure 2. Schematics of hybrid metamaterials [7].

Figure 3. Schematic of acoustic black hole and microperforated panel as a liner [9].

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