Rainbow labyrinthine metamaterials for sound absorption applications

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ABSTRACT

In this work, we demonstrate in a proof of concept experiment the efficient noise absorption of a 3-D printed panel designed with appropriately arranged space-coiling labyrinthine acoustic elementary cells. The labyrinthine units are numerically simulated to determine their dispersion and absorption characteristics and the designs are experimentally validated in an impedance tube test. Furthermore, the dependence of absorption characteristics on cell thickness and lateral size is studied and the resonance frequency is found to scale close to linearly enabling the tunability of the working frequency. Using these data, a flat panel is designed and fabricated by arranging cells of different dimensions in a quasi-periodic lattice, exploiting the acoustic "rainbow" effect, i.e., superimposing the frequency response of the different cells to generate a wider absorption spectrum, covering the targeted frequency range between 800 and 1200 Hz. The panel is thinner and more lightweight compared to other sound absorber solutions and designed in modular form. The performance of the panel is experimentally validated in a small-scale reverberation room, and an absorption close to 100% is demonstrated at the desired frequency of operation. Thus, this work suggests a design procedure for noise-mitigation panel solutions and provides experimental proof of the versatility and effectiveness of labyrinthine metamaterials for tunable medium- to low-frequency sound attenuation.

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1. INTRODUCTION

Acoustic Metamaterials (AMMs) have earned considerable attention in recent years due to their unique properties not found in naturally occurring materials. These materials have the potential to revolutionize the development of a new generation of absorbers and diffusers, which are customizable for a desired frequency spectrum, and can have deep-subwavelength thickness. AMMs offer the possibility of achieving high performance in noise reduction while reducing the size and weight of structures, going beyond the limitations of conventional technologies based on single-layer mass law, double-layer resonance frequency tuning, and porous absorber thickness optimization. One of the most promising types of AMMs is the "labyrinthine" or "coiled" structure, which exploits acoustic wave propagation in curved channels of subwavelength cross-section [1]. This structure provides a high effective refractive index and a decrease of the effective wave speed, enabling exotic effects like negative refraction and tunneling. Labyrinthine AMMs are promising for responding to the thickness and weight constraints in aircraft cabin design, where noise reduction is of outmost importance. These materials can also be combined with conventional solutions like porous materials, Helmholtz resonators, or tensioned membranes to optimize performance. Experimental demonstrations of the theoretically predicted broadband negative refractive index have been achieved through reflection or transmission measurements, and two-dimensional prism-based measurements on 3-D printed thermoplastic labyrinthine samples [2]. Labyrinthine structures with circular symmetry have been designed to generate Mie resonances with monopolar/multipolar characteristics, concentrating sound energy in the channels and radiating it equally in all directions, and giving rise to single or double negative acoustic parameters, for efficient ultra-sparse subwavelength metasurfaces with high reflectance. However, despite the potential of AMMs, several aspects hinder them from practical applications in the aircraft or other related industries. For this reason, the present study considers the case of labyrinthine AMMs in a process of optimization of their acoustic performance and characterization in realistic conditions. Further studies are required to investigate labyrinthine AMM performance on structures that are closer to potential operating conditions, i.e. in diffuse field conditions. In conclusion, the adaptability of labyrinthine AMMs could largely benefit noise absorption applications at small to medium scales, where restrictions on the structural size of the absorbers impose trade-offs between efficiency and encumbrance. This type of material provides a very convenient and efficient way to achieve sound control in large frequency ranges, especially in the subwavelength regime, by tuning geometrical design parameters. This work presents a proof-of-concept experiment to demonstrate efficient noise absorption of a 3-D printed panel designed with appropriately arranged space-coiled labyrinthine acoustic elementary cells.

2. UNIT CELL DESIGN AND CHARACTERIZATION

Three types of labyrinthine geometries are initially considered. The first, proposed in [3] is a circular spider web-inspired labyrinthine geometry embedded in a square cavity. The second and third correspond to first iteration and third iteration Wunderlich curves, respectively, whose attenuation properties have been numerically studied in [4]. These designs theoretically allow 100% wave reflection at resonance frequencies, and additional hierarchical levels, leading to increasing channel tortuosity, and therefore lower resonance frequencies. Here, we introduce a 3D extension of the mentioned designs, considering an additional thickness dependence of the labyrinthine cavities (Fig. 1). The UCs are designed for normal incidence, i.e., they feature rectangular apertures on the front and back rectangular surfaces of the cavities.

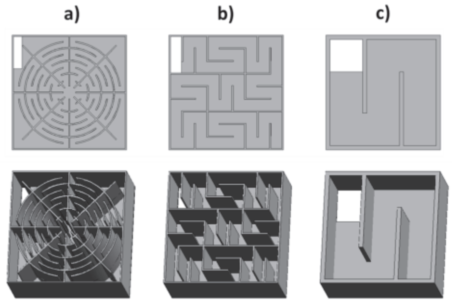

Figure 1. The three considered labyrinthine unit cells, shown in cross-section (above) and in "open" 3-D representation (below): a) spider-web inspired; b) Wunderlich curve third iteration; c) Wunderlich curve first iteration.

Based on this analysis, the choice is made to adopt the first iteration Wunderlich curve design for further use in a larger structure, given its better performance in terms of absorption compared to the two other designs.

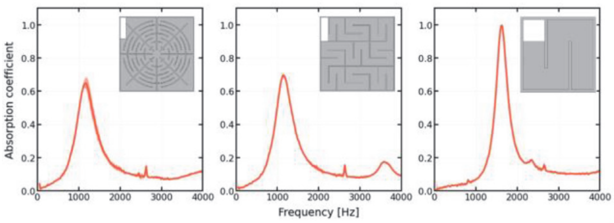

Figure 2. Representative absorption spectra for the three proposed structures. a) spider-web labyrinthine UC, b) third iteration Wunderlich curve cell and c) first iteration Wunderlich curve. Shaded areas correspond to standard deviations calculated over repeated measurements of each configuration.

Next, the resonance frequency dependence on the dimensions of the UC cavity was studied. In resonance-based metamaterials, the absorption frequency can be changed by modifying the UC edge size and scaling the channel width accordingly. Similarly, the resonance frequency depends on the UC thickness in the normal direction. To quantify the resonance frequency dependence on the geometrical size, we manufactured several UCs similar to the ones in Fig. 1 varying both their thicknesses t (within the 10-25 mm range, keeping their UC edge size a fixed to 21.2 mm) and their lateral edge size a (within the 15-23.0 mm range, keeping their thickness t fixed to 12.6 mm). Results are shown in Fig. 3.

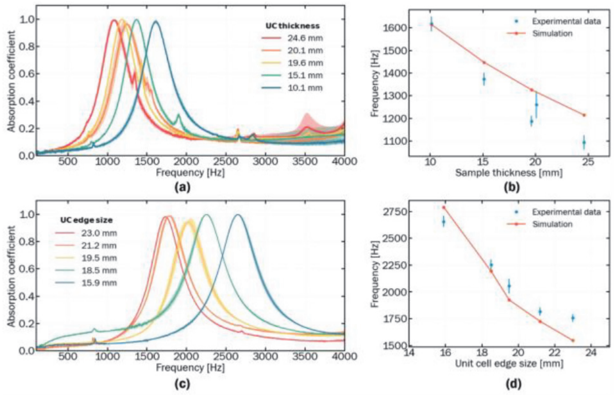

Figure 3. Averaged experimental absorption spectra of the selected UC structure (first iteration Wunderlich curve). a) Spectra for varying cell thickness and fixed edge size to 21.2 mm; b) Overall resonance frequency variation in comparison with corresponding numerical predictions; c) Spectra for varying cell edge size and fixed UC thickness to 12.6 mm; d) Comparison with corresponding numerical predictions.

3. RAINBOW-BASED AM LABYRINTHINE

Using impedance tube data relative to the characterization of the chosen UC, we establish the objective of sound absorption in a chosen low-frequency range of interest (e.g. for aeronautics applications), between 800 and 1200 Hz. This can be achieved by exploiting various UCs of sizes, so that the resulting resonance spectrum is given by their superposition, and the corresponding absorption range extends over the desired range. An AMM panel was thus designed, as illustrated in Fig.4. The panel consists of differently sized UCs, with varying thicknesses and areas. The internal wall thickness of each UC is proportional to the UC edge area. The resulting structure is modular, and we define these modules "macro-cells" (M and M' in Fig. 4a and 4b) because of its intermediate size between an UC and the complete sound absorbing panel. In fact, the complete panel consists of the combination of 20 macro-cells arranged in the plane (Fig. 4b), to cover a total surface of 628 x 784 mm^2, i.e., the area of the panel. Adjacent macro-cells are rotated by 90 degrees and reflected (Fig. 4), to ensure maximum spatial homogeneity in the sound absorbing properties.

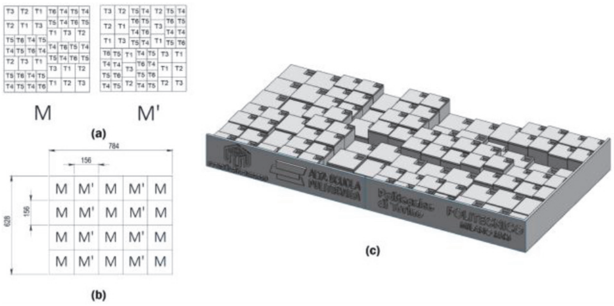

Figure 4. Modular elements of the complete sound absorption panel. (a) Two adjacent macro-cells. Each macro-cell consists of several UCs of edge size l1 and l2 mm with varying thicknesses (T1-T6); (b) Top view of the final panel, consisting of a regular arrangement of M and M' macrocells (geometrical sizes are indicated in mm); Adjacent macro-cells are reflected and rotated by 90° to guarantee a globally homogeneous spectral response. (c) 3D view of two adjacent macrocells.

4. PANEL CHARACTERIZATION

The panel absorption properties were measured by comparing its absorption spectrum with and without admitting sound waves within the UC cavities. In Fig. 5, the comparison of the absorption spectrum in the two configurations is shown. Frequencies of interest are reported as third-octave bands in the range of interest (250-5000 Hz). The blue line shows the intrinsic absorption of the uneven surface, while the red line shows the effective sound absorption of the upper surface, which is close to the ideal value of 1 in the desired frequency range between 800 and 1300 Hz. Additionally, a theoretical broadband absorption curve (in yellow) is computed as the average absorption spectrum of various Lorentzian curves peaked around the resonance values inferred from the linear fits of Fig. 4. The plot demonstrates an excellent agreement between the predicted and measured overall spectra.

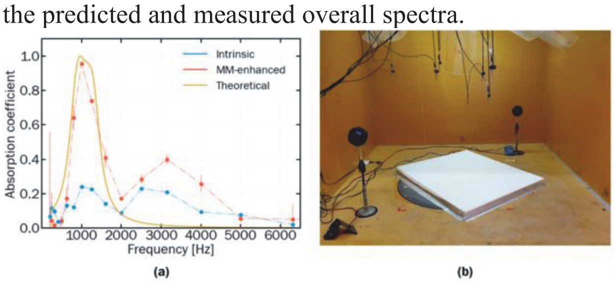

Figure 5. Absorption spectrum of the labyrinthine AMM panel in SSRR measurements. The comparison

between the MM-enhanced and the intrinsic polyamide absorption is plotted, together with the predicted spectrum by overlapping Lorentzian curves corresponding to the UC in the panel.

5. NUMERICAL EVALUATION OF DIFFERENT LABYRINTHINE SOUND ABSORPTION PANEL SOLUTIONS

Given the promising results for the design procedure outlined in the previous Sections, and the good agreement between numerical and experimental results, a further numerical study has been performed to evaluate possible developments of the AMM-based sound absorption panel. The objective is to assess its acoustic performance under different design configurations.

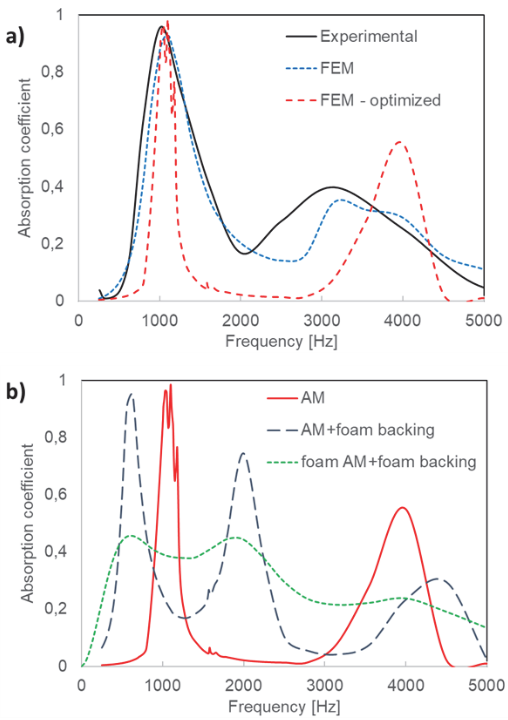

Figure 7. FEM simulation results for absorption coefficient vs. frequency for different sound attenuating panel solutions: a) Experimental (diffuse field) vs. FEM results (normal incidence) for the simple panel in Fig. 7; narrow region parameters can be optimized to obtain a closer fit ("FEM- optimized"); b) Effect of the addition of a 5-mm foam-filled backing on the panel (AMM+foam backing) and additionally filling the AMM cavities with foam (foam AMM+foam backing).

6. CONCLUSIONS

In this work, we have provided an experimental proof of concept for a novel approach to noise attenuation exploiting a rainbow-based design using labyrinthine metamaterials and combining UCs of varying thickness and lateral size in a quasi-periodic arrangement that ensured good homogeneity in the panel response. We have described the full design and validation procedure, from numerical modeling of the UC to its characterization in an impedance tube, to the design of the macrocells composing the panel, and its realization using selective laser sintering. The final structure has then been characterized experimentally in a reverberation chamber, demonstrating a close to ideal absorption over the targeted low frequency range, centred at 1 kHz, thus validating the approach. Finally, detailed FEM simulations have allowed to evaluate possible improvements/modifications to the panel by adding a foam filling and a foam backing cavity. The proposed prototype can be further developed, and thanks to its modular design, can be employed in diverse applications, e.g. in room acoustics, in automotive parts, or aeronautics in general.

7. ACKNOWLEDGMENTS

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