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Development of a metamaterial for acoustic and architectonical improvement of window design.

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ABSTRACT

The development of windows which can address the issue of high noise levels while maintaining natural ventilation has drawn significant attention recently. However, there are limitations to traditional double glazing together with duct designs. Previously, window systems have been developed based on the local resonant stopband of acoustic metamaterial (AMM) to achieve dual functions of noise reduction and natural ventilation. In this study, a new effort is made to develop a window system with foldable origami metamaterial, which conceptually proposes a novel approach for acoustic and ventilation design. The proposed device allows air exchange between the interior and exterior domains, and it forms an omni-directional acoustic metacage in the folded state. This paper elaborates the design concept of the proposed device and the important design parameters. The sound reduction performance is investigated using Finite Elements Method (FEM) simulations. The numerical method developed in this work can facilitate the optimisation of origami metamaterial for real window designs.

Keywords: Metamaterials, Ventilation, FEM.

1. INTRODUCTION

Conventional acoustic techniques allow controlling sound waves within a limited range of frequencies. Generally, noise control devices are bulky in order to operate in the typical airborne noise frequencies (1–5). Acoustic metamaterials are very versatile owing to its excellent properties related to its physical size (6,7). Particularly, origami metamaterial greatly extends the tuning ability and design range of existing metamaterial benefiting from its unique geometric flexibly. Recent studies have shown that origami folding can be combined with appropriate acoustic and mechanical design to improve the performance in many regards (8-10). Based on the interesting origami concept and the encouraging results so far, metamaterial window design with a specific aim to achieve both noise reduction and ventilation can be further improved.

This study presents the conceptual design of a novel origami acoustic metacage, whose performances are tunable during the reconfigurable process. The working principle for noise reduction is similar to the acoustic metacage structure proposed earlier (11), while the origami enables a unique mechanism to effectively vary the acoustic and ventilation characteristics in the folded and unfolded state. Starting from the metacage concept, a design to allow expansion and compression of circular boundary surrounding a sound source is developed as illustrated in Fig. 1. Unique structural design on the boundary forms a couple of metamaterial units in the folded state, which can control sound wave radiation to the exterior domain through the ventilation apertures. Two types of ventilation conditions are considered in this study, according to Fig. 1. Design 1 has distributed perforations along the perimeter, while Design 2 has ventilation apertures and thus much larger ventilation volume. In the first case, the open ratio (open surface/total perimeter) is 32% while for the apertures one is 52%. The folded and unfolded configurations of the two designs are compared in Fig. 1. As a preliminary study, only the two extreme configurations (completely folded and unfolded) are tested using 2D Finite

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Elements Method (FEM) simulations, hopefully, to demonstrate the dramatic change in the acoustic property resulted from the origami metamaterial.

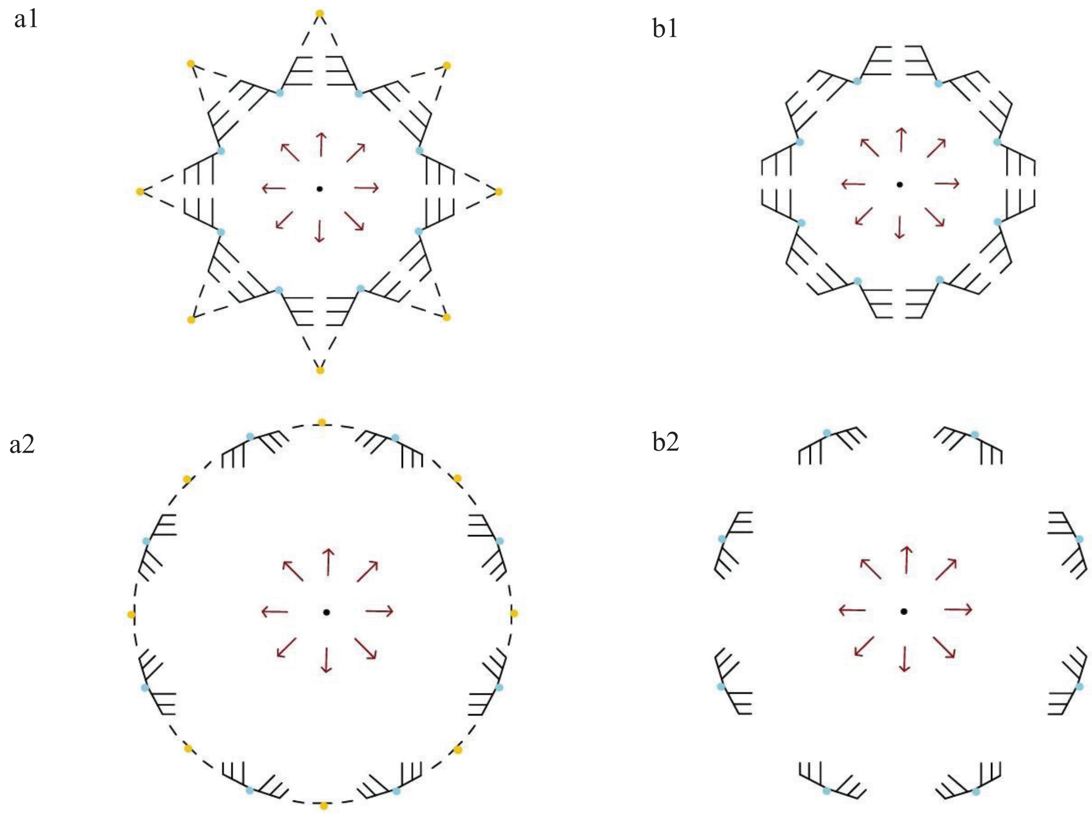

Figure 1– Schematic of Design 1 (Origami metacage with perforations) (a1) and Design 2 (Origami metacage with apertures) (b1) in the folded and unfolded (a2,b2) state. The yellow and light blue dots denote the movements of the folding points along the boundary: valley folds (light blue), and mountain folds (yellow).

This paper aims to demonstrate the effectiveness of this novel metamaterial for window applications. This model can be used at different frequency ranges (100-10000Hz), and several dimensions (0.2, 1, and 2 m in diameter) are tested to show the shift of working frequency with respect to system size. The device can be incorporated into a window without obstructing natural lighting from the outdoor environment. An inversely proportional correlation between the shifting of the most affected frequency range and the model dimensions is expected. This phenomenon should be accompanied by a Sound Pressure Level (SPL) dip, according to the resonator nature of this metamaterial.

2. METHODOLOGY

2.1 Geometrical Setting

In this research, the acoustic wave propagation is set to be originated from the interior of the origami metacage and radiates out through the distributed ventilation holes along the surface. The actual 3D system can be viewed as a protrusion from the 2D plane, where each cross-section has the same geometry. For this reason, 2D simulation is carried out for the sake of computation efficiency. The 2D FEM model represents the geometry of the origami metacage, and the folded and unfolded configurations are illustrated in Figure 2. The diameter of the metacage (refer to unfolded state) is 0.2 m and 0.4 m for the circular outer boundary. This diameter ratio 1:2 is kept the same for all the simulation cases with different scales which will be tested later, in order to understand the effect of system size on the frequency range.

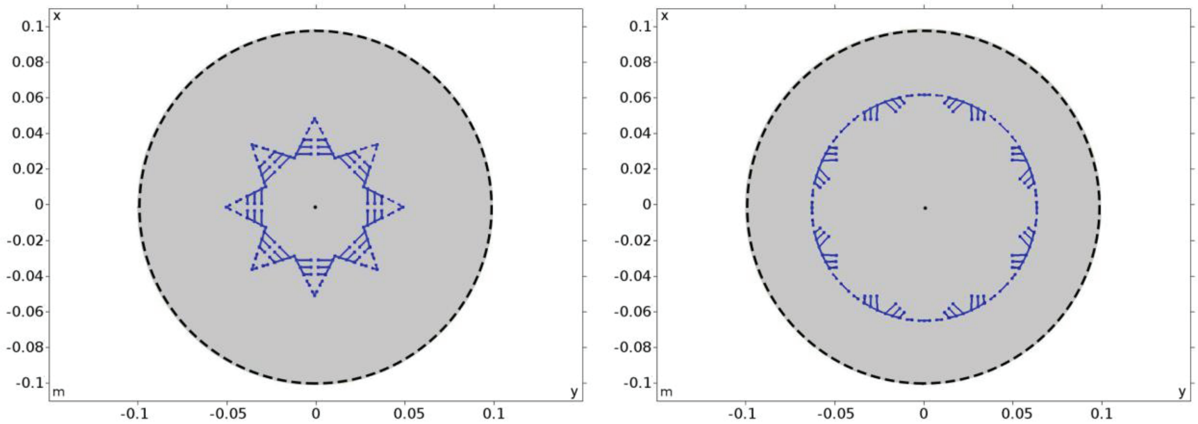

Figure 2 – Geometrical configurations of Design 1 (folded and unfolded) and boundary conditions: central point source, interior sound hard boundaries (blue), and cylindrical free wave radiation (dashed line).

The folded configurations represent in 2D an octagonal star (eight points) with 0.05 m length of each side. In each of these extremities two cavities are positioned towards the centre of the triangular point, delimited by layers which start from the sides and extend towards the middle of it for respectively 0.008 m, 0.012 m, and 0.016 m, and cavities width as 0.008 m (see Figure *2*). A parametric study, done to see an acoustic effectiveness difference while changing those components dimension, supports the setting of the dimension of both cavities and central duct (see Figure 3). The parametric study took in consideration three width configurations for the cavities (a= 0.007, 0.008, 0.009 m) and three for the central duct (b=0.007, 0.008, 0.009 m). From the results, it is clear that the cavities width change does not affect the metacage performance, so for the next parametric study, the a_2 configuration will be used. The next results show that the central duct width change does not affect the metacage performance in the considered terms of dimension changing. So the configuration a_2 and b_2 can be set as standard as explained before. The acoustic and airwave propagation from the inside to the outside of the metacage and vice versa is guaranteed by the resulted duct of width 0.008 m and by the four holes of 0.008 m length each on the point. When the geometric configuration passes from the folded to the unfolded one (see Figure 2), the sides of each extremity open and generate a circular perimeter shape. The holes rotate with the sides, and the layers that constitute the cavities rotate as well until getting oriented towards the centre with displacement from the direction perpendicular to it of 30° (see Figure 2).

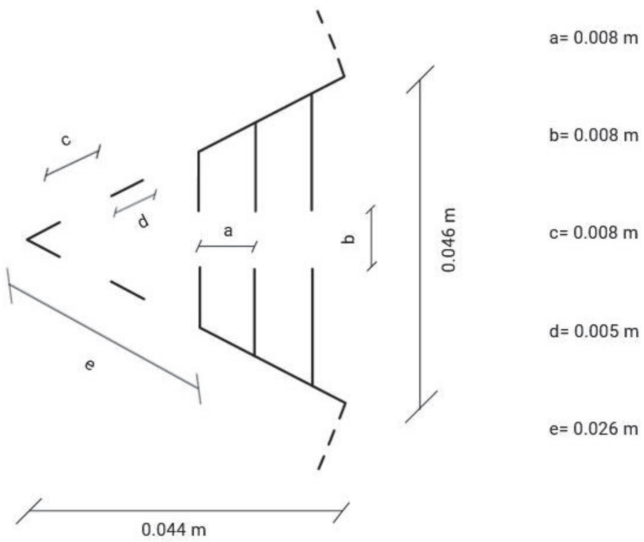

Figure 3 – Dimensions of the metamaterial unit formed in the folded state for Design 1.

2.2 Boundary Conditions and Study Settings

The numerical model is implemented using commercial FEM software Comsol Multiphysics under Acoustics module. A monopole point source is placed at the centre of the origami metacage with a volume flow rate of 0.01 m^2/s. At the outer boundary, cylindrical wave radiation is defined to simulate free outgoing waves without reflection. The simulation domain is filled with air, where air density and sound speed at room temperature are used. The walls of the metacage and material cells are set as interior sound hard boundaries, as depicted in Figure 2. Sound transmission through walls of the metacage and possible viscous-thermal effect in the narrow resonator channels are neglected in this study.

The SPL is averaged at the outlet boundary (dashed line in Fig. 2), to compare the acoustic response in the unfolded and folded state. A decrease in the SPL curve will thus indicate less efficient sound radiation because sound energy is more confined in the metacage. The mesh size is determined according to the FEM criterion, where at least six nodes are used to simulate a wavelength in air. To reach 10000 Hz, the maximum allowed element size is thus 343/6/10000=0.0057 m. The study is a frequency domain analysis from 100 Hz to 10000 Hz with a step size of 100 Hz. In the results, the SPL radiation is shown linearly in the simulation frequencies.

3. NUMERICAL RESULTS

3.1 Design 1

Figure 4 first shows the simulation results of Design 1 in the folded and unfolded state. The averaged SPL at the radiation boundary is between 40 dB and 120 dB, where some variations and peaks can be observed due to the resonance of the circular enclosure. From the SPL radiation graph (Figure 4a), both the folded and unfolded configuration effects are analysed. For the folded one the SPL radiations reduce significantly at low frequencies (average of 106.6 dB of SPL), while in medium frequency it loose efficacy, and from 2500 Hz to go on, an increasing sinusoidal behaviour starts, with a SPL average of 90 dB and a SPL dip of 48.7 dB at 8100 Hz. Figure 4b and 4c highlight the confinement effect of the SPL at the different dip frequencies for both unfolded (dip at 4700Hz) and folded (dip at 8100 Hz) configurations. In both graphs, it is evident how the folded state has a higher acoustic impact on the sound wave confinement.

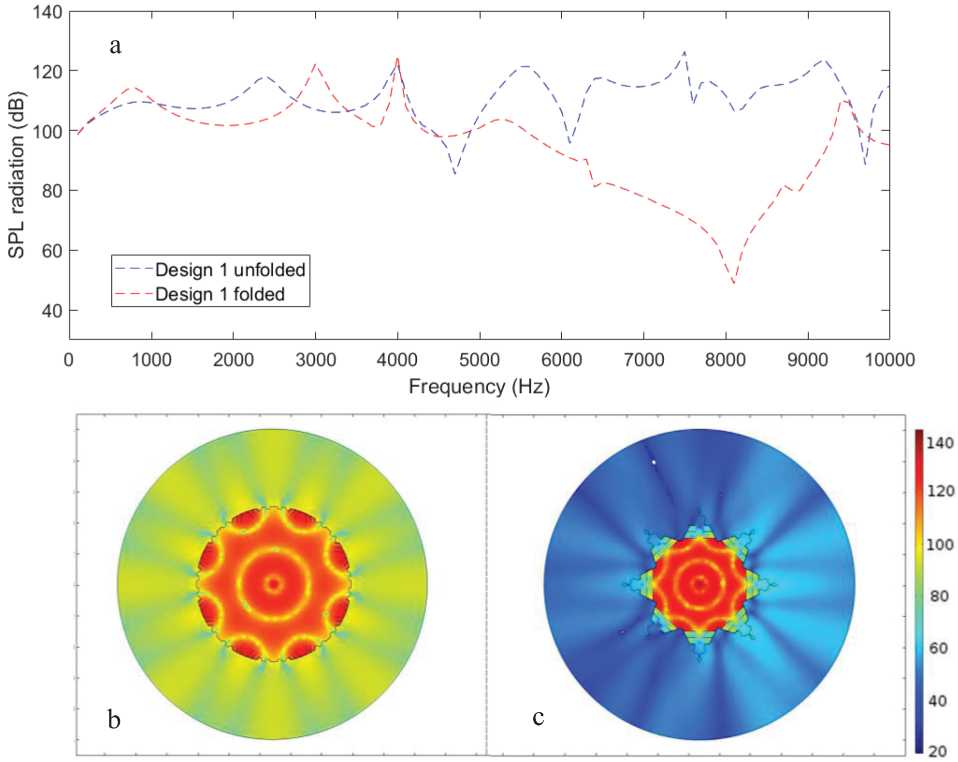

Figure 4 – SPL radiation (a) and SPL distribution graph for 0.2 m Design 1 at 4700 Hz of the unfolded (b) and 8100Hz of the folded configuration (c).

3.2 Design 2 and Comparison with Design 1

In the next subsection, the results of Design 2 are analysed and compared with Design 1. From the graph (Figure 5a and Figure 6) it is evident that the acoustic behaviours of the two samples are the same. This conclusion is visually supported also by the SPL distribution graph (Figure 5b and 5c), which shows how the distribution of the colour is similar. Moreover, also for Design 2, both graphs show clearly how the folded state confine the sound wave in the internal part with more effectiveness. This comparison result (between Design 1 and Design 2) is significant to understand how the design can allow a better ventilation condition without affecting the acoustic performance of the device. This improvement, as explained in the introduction about purposes, is needed to have proper ventilation of the contained mechanical or of the physical system.

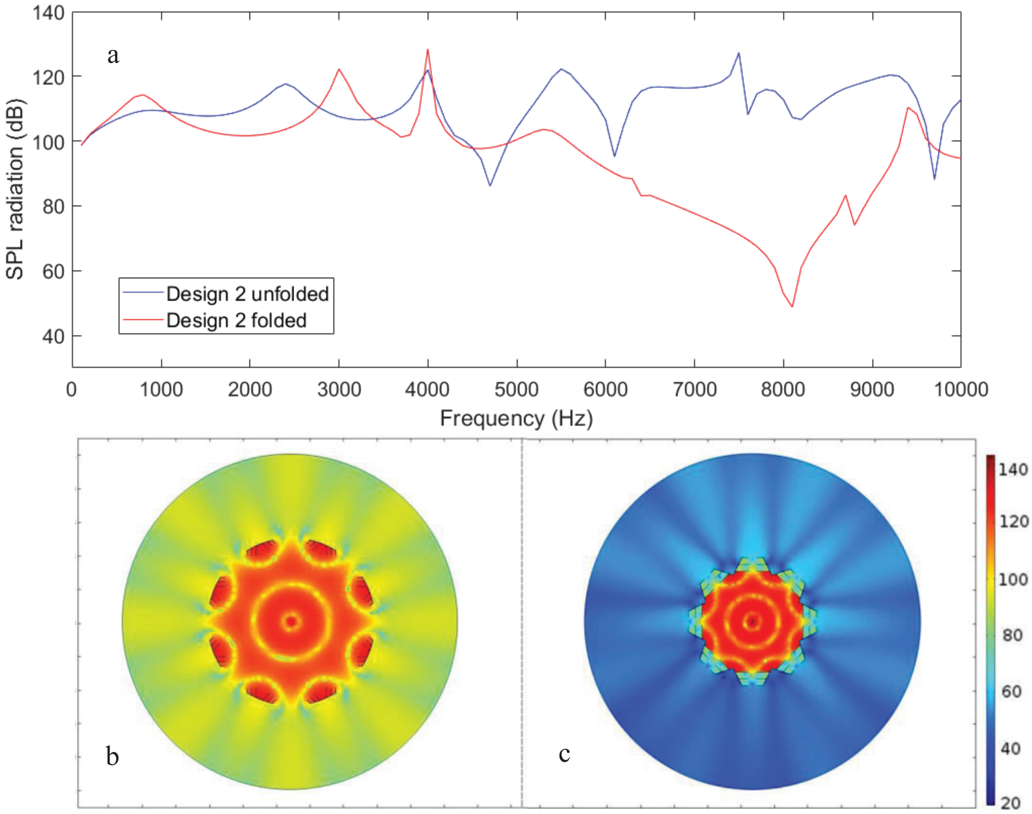

Figure 5 – SPL radiation (a) and SPL distribution graph for 0.2 m Design 2 at 4700 Hz of the unfolded (b) and 8100Hz of the folded configuration (c).

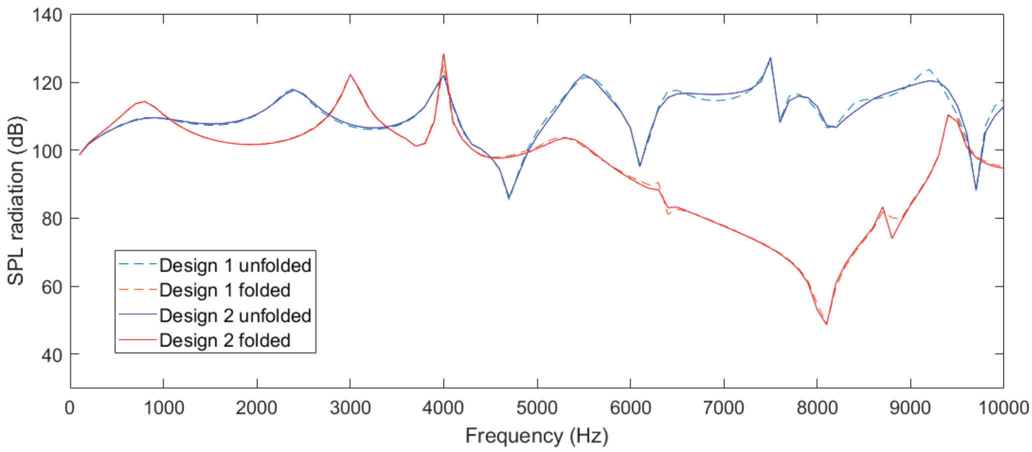

Figure 6 – Comparison between SPL radiation of Design 1 and Design 2.

3.3 Comparison of the Different Scaled Models

This section focuses on the correlation between the dimension of the device and the SPL reduction effect of it. For the sake of completeness, bigger samples of both Design 1 and Design 2, are built and analysed through the same acoustic simulation settings. Although, since the behaviour of Design 1 and Design 2 is mostly identical, it can be reasonable to consider using the second one to improve the ventilation for the same reason explained before. So for the sake of simplicity only results related to Design 2 will be presented, comparing the performance of the original model with those of diameter equal to 1 and 2 m.

From the results, it is clear that, as expected, the increasing of the dimensions (five and ten times bigger in this case), causes a shift of the SPL reduction peak towards lower frequencies. In particular, for the folded configuration, in the 1 m model, the dip is at 1600 Hz (Figure 7) with SPL of 38.25 dB. This phenomenon happens consistently and progressively with the increasing of the models, and it is demonstrated by the other study with dimensions ten times bigger than the original ones. For the 2 m models, the dip is at 800 Hz where SPL is 31.95 dB.

From Figure *7*, the effectiveness of the origami metacage it's demonstrated in this frequency range, and the contribution of the folded configuration in this process is proved.

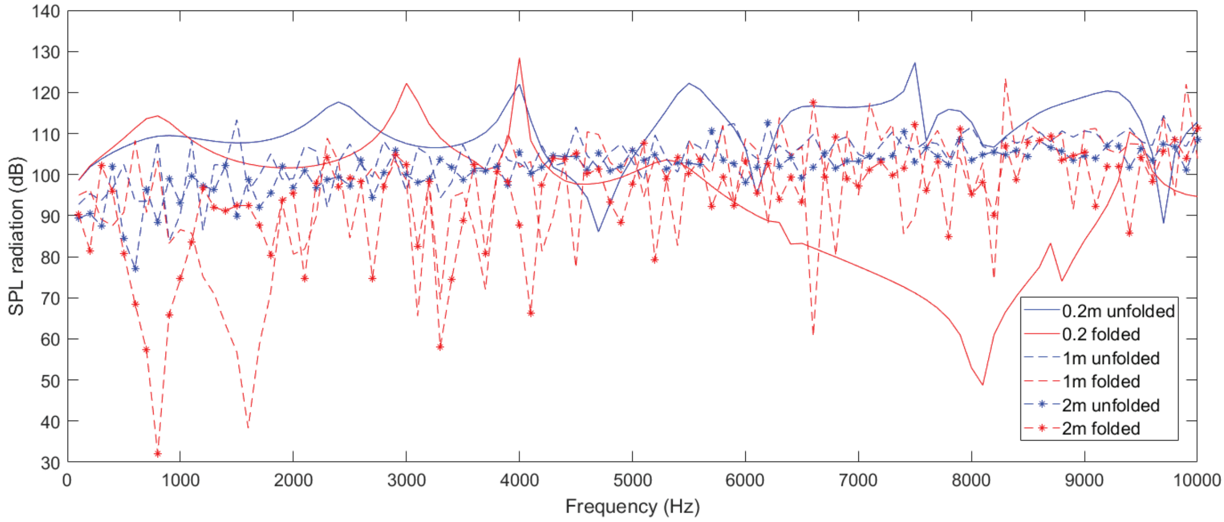

Figure 7 – SPL radiation of Design 2 with 0.2, 1, 2 m diameter.

4. DISCUSSION ON POSSIBLE DESIGN APPLICATIONS

The main aims of this research are achieved, and further experimental study will give more completeness to the research. So now new possibilities are open for devices' design which aim noise reduction together with natural ventilation. Applications can interest both private and public spaces, which are affected acoustically from the co-existence of different activities or infrastructures. For these reasons, windows systems might be taken into account. The proposed geometry may be embedded in a window design built on an external wall of a private or public building such as a house, a school or a hospital. The resulting SPL broad dips of 38.25 dB and 31.95 (1 and 2 m diameter model) might result of some impact in a situation where the area surrounding these buildings is very crowded, or when there are overlapping activities which might create high-level noise. An example could be to embed a system of origami metacage ducts in window frames or using the structure itself with increased width and a transparent back panel to allow also light exchange between two environments. A validation work will follow to test the actual building feasibility of a prototype and determine whether if the transparent back panel might affect its performance or allow a new generation of tunable window systems.

5. CONCLUSIONS

This study has investigated the acoustic characteristics of a proposed origami acoustic metacage with a unique reconfigurable mechanism. Two configurations with different ventilation designs (perforations/apertures) have been tested to assess the noise reduction and estimate the ventilation volume between the inside and the outside of the origami metacage (from 32% to 52% of opening ratio). The folded metacage shows a profound dip in the radiated SPL due to the excellent silencing effect provided by the metamaterial unit in front of the ventilation holes. The frequency and bandwidth of the effective region are related to the geometric parameters and scales of the system. Natural air ventilation is possible without any additional element, showing the potential of the proposed device to be used in ventilation window systems. The developed numerical model can be further employed to optimise the size and shape of the device to achieve better ventilation and noise reduction in the desired frequency range.

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