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Scalability of a metamaterial-based window

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ABSTRACT

Acoustic Metamaterials (AMMs) in building elements are an innovative solution that can be exploited to balance sound insulation and natural ventilation. Previously, an Acoustic Metawindow unit (AMW unit) was designed, prototyped and assessed in the laboratories of the University of Bologna. This study compares previous results with those of a full-scale Acoustic Metawindow (AMW) using a numerical analysis mimicking the experimental setup according to ISO 10140 standards. It evaluates the scalability of an AMM-based window system for simultaneous noise control and natural ventilation. A FEM analysis was used to replicate the experimental conditions outlined by ISO 10140-2 for sound insulation and ISO 9972 for air permeability. The findings demonstrate that the full-scale AMW provides similar sound attenuation performance compared to the AMW unit, achieving an average sound insulation of 25 dB in the 50-5000 Hz frequency range. Moreover, the full-scale AMW allows a higher airflow rate for natural and mixed ventilation (using a pressure difference varying from 10 Pa to 80 Pa). Therefore, this AMM-based window seems to have great scalability potential, confirming its feasibility for real-world applications in buildings requiring high indoor comfort standards. Future research will carry out experimental verifications and extend this work by evaluating the energy performance of the AMW across different climatic conditions and usage patterns. The results contribute to advancing metamaterial applications in architectural acoustics and sustainable building design.

1. INTRODUCTION

Strategies to manage sound insulation and façade ventilation have been developed separately in buildings [1]. Traditional windows provide natural ventilation and visual connection to the outside, but limit the user to choosing between sound insulation and ventilation, compromising a full Indoor Environmental Quality, IEQ [2]. So far, researchers have used different methodologies to overcome both problems, using, for example, mechanical ventilation and active or passive noise control systems [3]. The latter have the advantage that they consume little energy, if any, and can be implemented directly inside windows, improving their durability, as in the case of microperforated panels (MPPs) or acoustic metamaterials (AMMs) [2]. Metamaterials for noise and ventilation control are typically duct-like structures with built-in resonant systems (e.g., metasurfaces, metamaterial cages, and labyrinthine structures) and originated for mechanical applications (e.g., endo-thermal motor soundproofing) [4].

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Three of the current challenges on metamaterials for ventilated and soundproofed windows are: i) the availability of scalable metamaterials modules, ii) a numerically and experimentally coherent multi-physical analysis [4], and iii) the lack of consistent standards for evaluating the sound insulation of open windows [5].

2. MATERIALS AND METHOD

The experimental setup was numerically replicated using the Finite Element Method (FEM), assuming an air density of 1.215 kg/m³ and a sound speed of 343 m/s at 20°C.
First, a directive 1 Pa sound wave is emitted towards the test specimen from omnidirectional sound sources (S1 and S2), in the frequency range 100-5000 Hz (see Figure 1). The geometrical model replicates two coupled reverberation rooms (116 m³ total volume), with a partition housing the AMW test specimen. The setup includes several measuring points for sound transmission loss calculations (ten in the receiving room). The sound insulation achieved was evaluated as a Sound Level Difference (D)[6] using the formula:

$$D = L_1 - L_2 \ (dB) \tag{1}$$

Where L_1 and L_2 are respectively the average SPL measured in the source and in the receiving room.
Second, a numerical ventilation analysis was conducted on the modelled AMWs using FEM with the k-ε turbulence model to assess the pressure drop (ΔP) at varying airflow velocities (ranging from 0.5–1.132 m/s). Such a range of velocities allows for a set ΔP of 10, 20, 50, and 80 Pa. From a previous experimental setup [7], it is possible to derive a flow rate per person representing the available flow rate for a maximum of three people hosted in the room area (20 m^2). Flow velocities at the AMW's inlet and outlets can be assessed numerically through a point evaluation and converted to ventilation flow rates by multiplying area-averaged velocities by each cross-sectional area. The model assumed no-slip conditions in an air-filled 3D domain. The study focused on natural ventilation flows at low Mach number, minimising noise effects. The outlet pressure was set at 101.325 Pa, with mesh refinement in turbulence-prone areas. The stationary solver used CFD analysis based on pressure and velocity components.

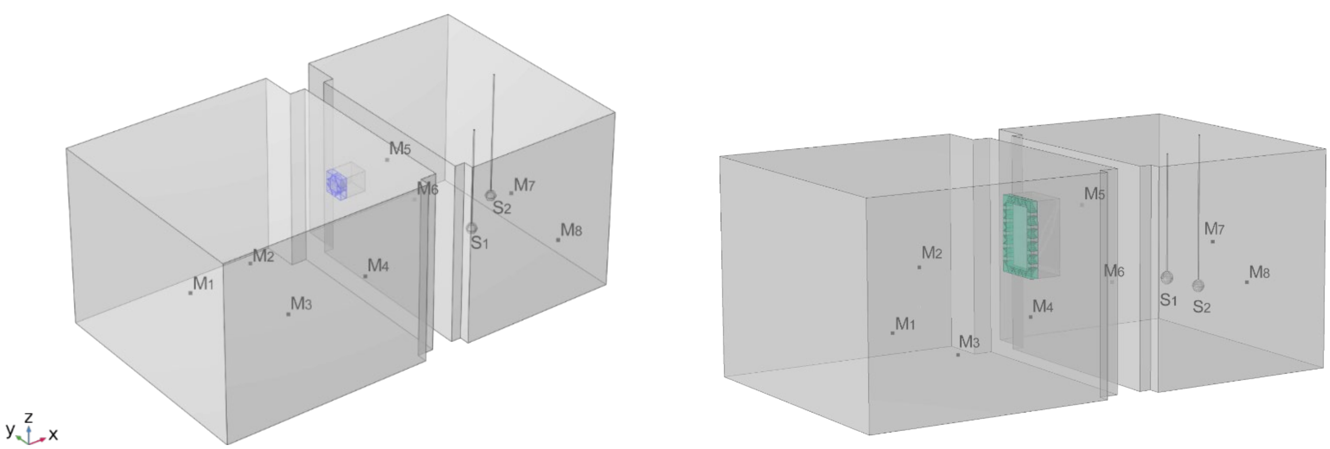

Figure 1 - Numerical model of the coupled chambers test setup. S1 and S2 are omnidirectional sources, while M1- M8 represent the microphones' positions. Left: AMW unit. Right: full-size AMW.

3. RESULTS

To assess the scalability of the metamaterial-based window system, FEM analyses of the acoustic and ventilation performances were run. Both analyses are fundamental for the sake of the method's growth and improvement. The acoustic FEM analysis method results are shown in Figure 2, illustrating that the Sound Level Difference curves of the reduced-size and full-size AMWs are different. Exploiting a smaller opening on the wall, the AMW unit shows higher D values than the full-size AMW. Despite being based on different prototypes, the two amplitude peaks exhibit similar characteristics and frequency peaks at 63 Hz and 315 Hz, showing a little shifting of the third peak that for the AMW unit is at 3200 Hz, while for the AMW full size is at 2000 Hz. The discrepancy observed in terms of amplitude may stem from the different diffraction effects of the two holes on the wall where the test specimens are inserted. The AMW unit hole has dimensions of 0.4 x 0.4 m while the one for the full-size AMW is 0.8 x 1.2 m. On the other hand, Figure 3 shows the comparison of airflow rate from a CFD FEM, which takes into account the experimental setup of the coupled chambers through the BDT (ISO 9972)[8]. The results from the full-size AMW analysis are increasing faster than those for the AMW unit ones, probably due to the bigger opening on the wall and the bigger open surface of the AMW system.

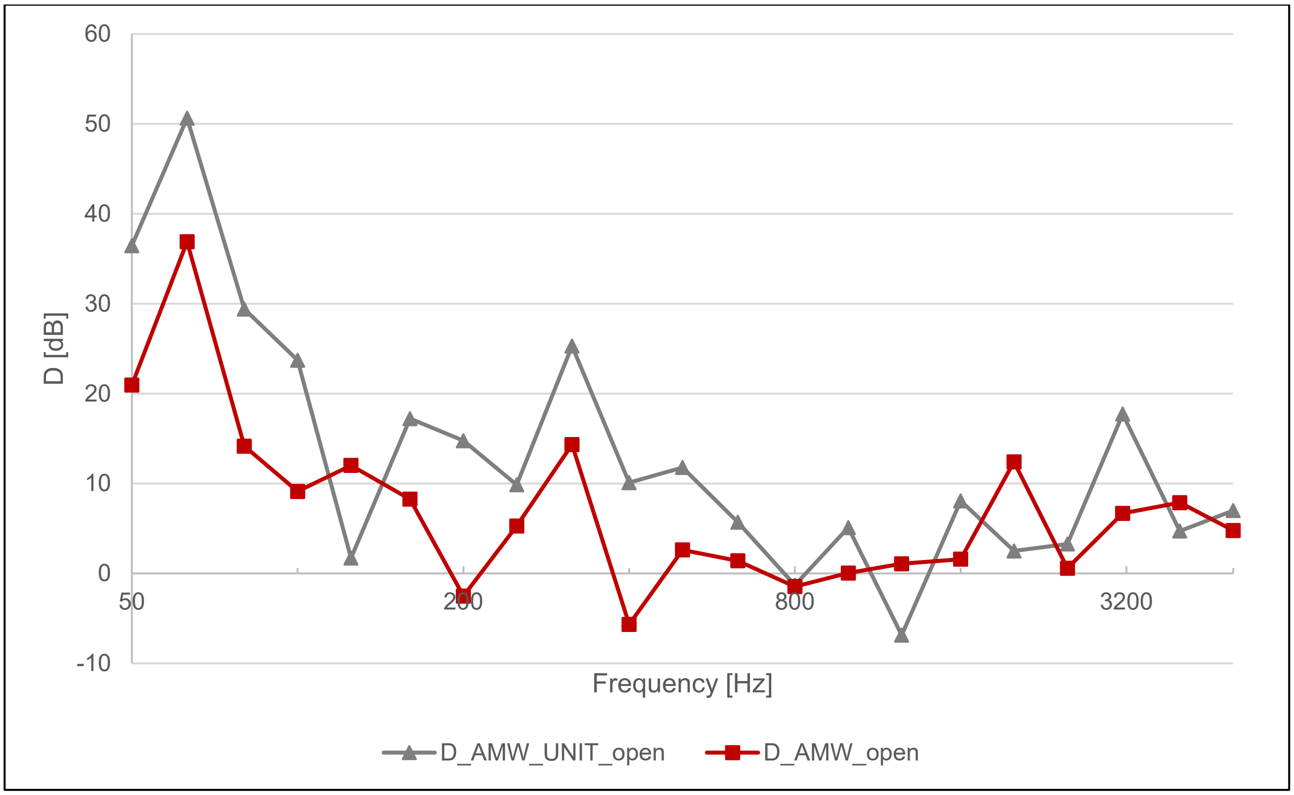

Figure 1 - Comparison of the Sound Level Difference *D* from a FEM analysis that takes into account the boundary conditions and setup of ISO 10140-2 of a AMW unit and a full-size AMW.

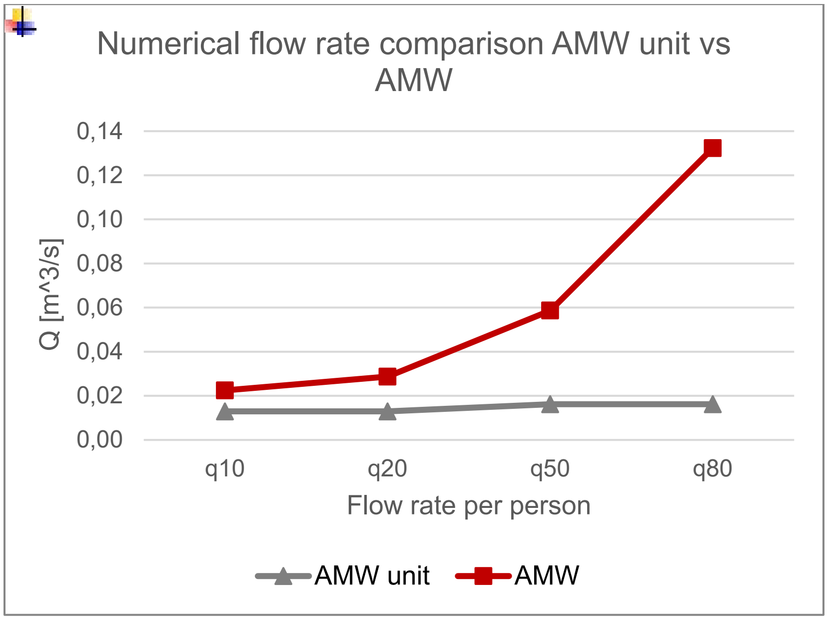

Figure 2 - Comparison of the airflow rate Q from a FEM analysis that takes into account the boundary conditions and setup of ISO 9972 of a AMW unit and a full-size AMW.

3. CONCLUSIONS

This study investigates the scalability of an Acoustic Metawindow (AMW) system through numerical analysis, demonstrating its effectiveness in balancing sound insulation and natural ventilation. The FEM-based simulations align with experimental conditions, confirming that the full-scale AMW achieves similar sound attenuation to the prototype, with a D ranging from -6 dB to 51 dB across the frequency range 50–5000 Hz. Additionally, the larger AMW facilitates increased airflow, making it a promising solution for real-world architectural applications requiring high indoor comfort. These results need to be compared with experimental measurements to confirm the scalability of AMM effects on building elements, using the standard parameters considered by ISO 10140-2 (R and Dn,e).

The numerical results highlight the feasibility of integrating scalable AMM-based windows into building designs, addressing the challenge of maintaining both acoustic insulation and ventilation. While minor discrepancies in frequency response were observed due to structural differences, the overall trend is encouraging and supports the AMW's practical implementation. Future research will focus on evaluating its energy performance across various climates and operational conditions, further advancing metamaterial applications in sustainable building design.

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