DOI: 10.61782/fa.2025.0763

SCALABILITY OF VENTILATION AND NOISE INSULATION METHODS FOR ASSESSING A FULL-SCALE METAWINDOW

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ABSTRACT

Natural ventilation in homes often compromises indoor acoustic comfort by allowing outdoor noise to enter. Recent advancements in acoustic metamaterials (AMMs) have enabled the development of innovative solutions, such as integrating AMMs into windows, to provide effective natural ventilation while maintaining sound insulation. However, European standards for evaluating façade insulation properties primarily focus on closed systems, limiting their applicability to AMM-based windows (AMWs). This study addresses this gap by using the ISO 10140 measurement method to evaluate a full-scale acoustic metawindow (AMW) capable of simultaneous noise insulation and ventilation when open. The sound reduction index (R) was used to measure its noise insulation performance, showing an R in between 13 and 34 dB in the 100-3150 Hz frequency range combined with a more elevated flow rate than the AMW unit. Indeed, additionally, laboratory tests on airflow performance (adapted ISO 9972) across a pressure range of 10-80 Pa demonstrated that the metamaterial acoustic filter does not significantly affect airflow, making this solution versatile and practical. These findings underscore the potential of the AMW for multi-domain comfort with a more sustainable approach and scalable technology.

Keywords: *Acoustic metamaterials, Outdoor noise, Ventilation, Indoor Environmental Comfort, Environmental noise.*

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1. INTRODUCTION

Traditionally, sound insulation and façade ventilation in buildings have been managed separately [1]. Standard windows allow for natural ventilation and an outside view but force users to choose between noise control and airflow, affecting overall Indoor Environmental Quality (IEQ) [2]. Researchers have explored various solutions, such as mechanical ventilation and passive or active noise control systems [3–5]. Passive approaches, like microperforated panels (MPPs) and acoustic metamaterials (AMMs), are particularly advantageous because they require minimal energy and can be integrated into windows, enhancing durability [2].
Acoustic metamaterials used for noise and ventilation management are typically duct-like structures with embedded resonant elements, such as metasurfaces, metamaterial cages, and labyrinthine designs [2]. Originally developed for mechanical applications, such as soundproofing in engines, these structures are now being adapted for building use. However, there are three key challenges in developing metamaterial-based ventilated soundproof windows [2,6]: i) the need for scalable metamaterial modules, ii) a consistent multi-physical analysis approach that aligns both numerical and experimental results, and iii) the absence of standardised methods for assessing sound insulation in open windows.
More details can be found in the comprehensive paper [7]. For these reasons, a numerical and experimental study was run respectively for assessing the acoustic and the ventilation performance of an AMM-based window (AMW) at its full scale (0.8x1.2 m). Previously, an AMW unit was developed and assessed, but its dimensions were relatively small (0.4x0.4 m). This new prototype allows to prove the scalability of the AMM technology towards a more ergonomic and user-friendly design. FEM models were modelled to represent the experimental boundary conditions. ISO 10140 configuration was used to experimentally assess the acoustic performance in a diffuse sound field [6,8–10], while the ISO 9972 [31]) evaluates the ventilation capacity.

2. METHOD

The methodology follows the approach in [3], combining numerical and experimental techniques to assess the Acoustic Metawindow (AMW). First, the Finite Element Method (FEM) is used to simulate measurement configurations and validate the numerical model against laboratory boundary conditions, including source positioning, direction, and edge effects. Then, an experimental method is applied: the ISO 10140 test in a diffuse sound field [6,8–10] to measure the sound reduction index for the prototype (R_w). Additionally, the blower door test (ISO 9972 [31]) evaluates the ventilation capacity while maintaining acoustic insulation.
The AMW prototype measures 0.8 × 1.2 × 0.17 m and integrates an Acoustic Metamaterial (AMM) system within its frame. Key acoustic parameters—specific impedance ($Z_{1,2}$) and refractive index ($n_{1,2}$)—are considered for different regions of the AMW. Variations in the refractive index create an out-of-phase effect on sound waves passing through the AMM unit cell, independent of the angle of incidence. The prototype consists of 5-mm thick laser-cut plexiglass panels for the indoor and outdoor surfaces, with AMM unit cells 3D-printed in polylactic acid (PLA) using fused deposition modeling (FDM). The AMW slides within the wall, allowing two configurations: fully open (duct opening of 0.075 × 0.13 m) and half-open (0.075 × 0.06 m). Before experiments, FEM analysis is performed to optimize the test setup.

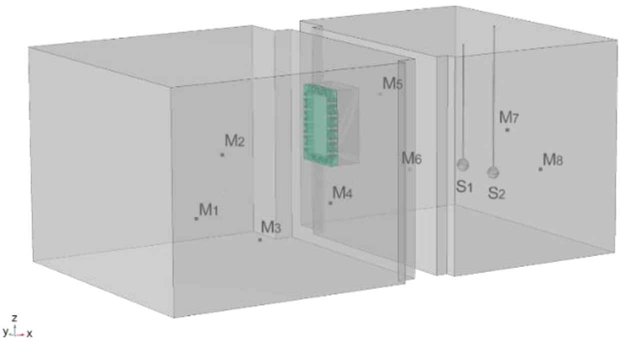

Figure 1. Numerical model of the coupled chambers test setup. S1 and S2 are the two omnidirectional sources, while M1- M8 represent one of the two microphones' positions.

Following ISO 10140, the specimen is installed in a partition between two coupled reverberation rooms to assess airborne sound insulation. ISO 10140-1 [8] defines the test element, while ISO 10140-2 [6] describes the façade opening. A sound source in one room generates noise, and sound pressure levels are recorded in both the source and receiving rooms. Sealant ensures airtightness around the structural window edges.
To address the challenges of having a coherent numerical model, a study was conducted using simulations with the Finite Element Method (FEM). The numerical model is characterised by an air density of 1.215 kg/m³ and a sound speed in air of 343 m/s at 20°C. A 1 Pa sound wave was directed at the test specimen using two omnidirectional sound sources (S1 and S2) across a frequency range of 100-5000 Hz. The simulation replicated two connected reverberation rooms (116 m³ total volume), separated by a 0.4 m partition containing the AMW test sample. The setup involved a coupled room geometrical configuration with a hole in the dividing wall of dimension 0.8x1.2 m. This hole represents the configuration without the AMW, while in the other configuration investigated in this study, the AMW would be placed instead. The receivers of the numerical analysis were placed at multiple points following the indications of to ISO 10140 [6] to calculate sound insertion loss. The sound insulation performance was determined using insertion loss (IL), calculated as:

$$IL_{AMW} = SPL_{noAMW} - SPL_{AMW}\ (dB) \qquad (1)$$

Where SPL_{noAMW} and SPL_{AMW} are respectively the average of SPL measured in the numerical model without and with the AMW unit.
Additionally, a numerical ventilation analysis was conducted using FEM with the k-ε turbulence model to evaluate pressure drop (ΔP) at different airflow velocities (0.5–1.132 m/s). The inlet surface, which represents the outdoor conditions, is used to define the flow, with the maximum wind velocity set according to Asfour and Gadi's criteria [11], based on a height of 20 m above the ground and a room height of 3 m. The model assumed no-slip conditions in a 3D air-filled domain, focusing on natural ventilation at low Mach numbers to reduce noise interference. The outlet pressure was set at 101.325 Pa, with refined meshing in turbulence-prone regions. A stationary solver performed CFD analysis based on pressure and velocity components. The geometric boundaries are the same as the acoustic FEM model, consistent with the 3 m room height assumption in the Asfour and Gadi criteria [11]. For the mesh size in this 3D study, the maximum element size is 0.115 m, and the minimum element size is 0.0144 m, with finer mesh in regions expected to experience turbulence, particularly near corners within the AMW structure. The study is performed using a stationary solver, with the CFD analysis depending on pressure (p) and velocity (u, and velocity components u,

v, and w). To analyse the flow velocity (*v*) the parameter was assessed as the average throughout the openings on the AMW. The pressure difference defining different flow rates per person was calculated considering the area of the receiving room (20 m²) able to host a maximum of three occupants. The flow rate per person was determined by the Blower Door Test method, which is pre-set by default to a *Δp* value for three people in the same room, with a gradual gradient from q10 to q80 (ISO 9972) [12].

3. RESULTS

3.1 Acoustic results

The comparison between experimental and numerical IL values in Figure 2 shows a reasonable agreement in the general trend, with both datasets capturing the main characteristics of the AMW's acoustic performance. However, some discrepancies are noticeable, particularly in the frequency range between 200 and 500 Hz. The numerical IL curve underestimates the experimental IL at certain frequencies and overestimates it at others, possibly due to model assumptions. One key factor could be the rigid wall assumption in the numerical model, which does not account for real-world material absorption and edge diffraction effects. Additionally, the sound field conditions in the experimental setup may differ slightly from the idealised conditions assumed in the FEM simulation, contributing to observed deviations. Improving the numerical model by incorporating realistic boundary conditions and absorption properties could enhance accuracy.

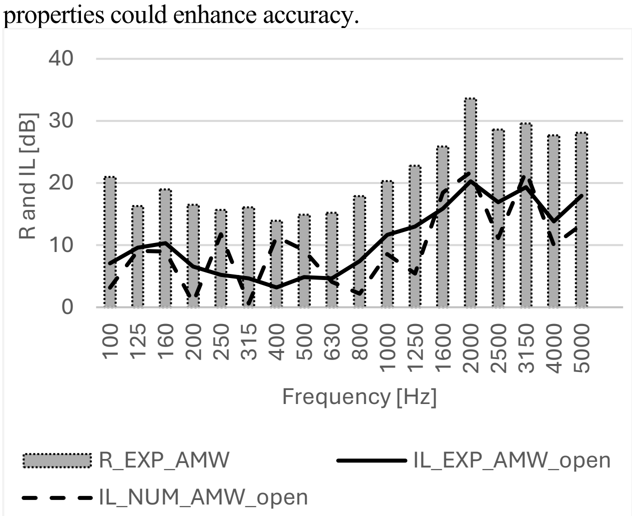

Figure 2. Comparison of the IL in a diffuse sound field calculated experimentally and numerically by subtracting a) the SPL with the fully open AMW from b) the SPL without the AMW in the wall opening.

R values on the other hand, result capturing the noise reduction index in a more realistic indoor acoustic setup.

3.2 CFD results

Building on a previous study [3], numerical analysis in the ventilation domain was carried out using computational fluid dynamics (CFD). The flow velocity and flow rate comparisons between experimental and numerical results in Figure 3 exhibit good agreement, with numerical results generally following the same trend as the experimental data. However, numerical results tend to slightly overpredict airflow velocity and flow rate, particularly at higher flow rates per person (q50 and q80). This discrepancy may be attributed to the k-ε turbulence model's limitations, particularly in capturing near-wall viscous effects and small-scale flow structures. Despite these minor differences, the overall similarity between the experimental and numerical results validates the CFD model's effectiveness in capturing airflow characteristics. Compared to the previous AMW unit model, the flow rate performance of the scaled AMW is higher (see Figure 3) while keeping a perceivable noise attenuation.

While both numerical and experimental analyses show similar trends, refinements in boundary conditions, material properties, and turbulence modeling could improve accuracy, particularly for the IL calculation in the low-frequency range and the airflow simulation at higher velocities. Future work should consider incorporating more complex wall absorption characteristics and refining turbulence models to better represent real-world airflow conditions.

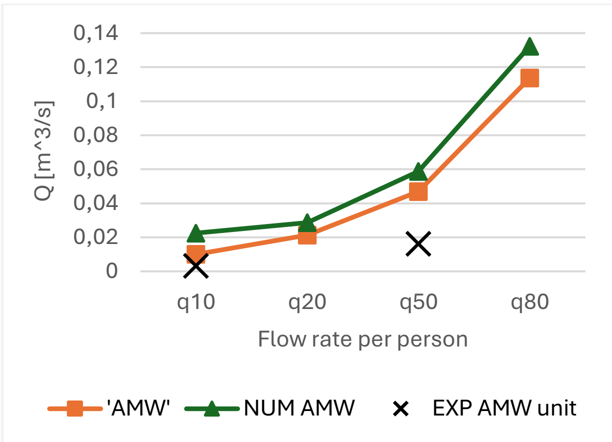

Figure 3. Comparison of different airflow rates of the AMW from Experimental and Numerical analysis.

4. CONCLUSIONS

This study demonstrates the potential of Acoustic Metawindows (AMWs) to provide both effective natural ventilation and significant noise insulation through a scalable technology and a sustainable design. Through a combination of experimental and numerical analyses, the AMW achieved an IL of 23 dB and R of 34 dB in the 100–3150 Hz range. Additionally, airflow testing confirmed that the integrated acoustic metamaterial does not significantly impede ventilation, ensuring a balance between acoustic and indoor environmental comfort. Moreover, the flowrate performance of the scaled-up AMW model is improved compared to unit one.

Numerical simulations using the Finite Element Method (FEM) and Computational Fluid Dynamics (CFD) largely aligned with experimental results, validating the modelling approach. However, minor discrepancies in low-frequency sound insulation and airflow predictions highlight the need for further refinement in boundary conditions, material properties, and turbulence modeling.

The findings underscore the viability of AMWs as a scalable, energy-efficient solution for sustainable building design. Future work should focus on optimizing material properties, refining numerical models, and exploring long-term durability in real-world applications. The integration of standardized testing methods for open-window configurations will be crucial in advancing the adoption of AMW technology in building acoustics and ventilation strategies.

5. ACKNOWLEDGMENTS

This research was funded by the Italian Ministry of University and Research, within the project PRIN 2022, Grant No. 2022RA785R: "METAWAVE - New METAmaterial Window for simultaneous Acoustic, Ventilation and Energy performance".

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