Full-scale metamaterial window for building application

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ABSTRACT

The research on acoustic metamaterials (AMMs) has progressed rapidly over the last decades. One of the applications is for noise control and airflow in duct-like systems. These are useful features for natural ventilation window design; however, the visual impact between indoor and outdoor environment, as another key factor of windows, makes the existing AMMs not directly useable for this application due to their geometrical complexity and size limitations. In this research, an AMM previously developed by the authors is exploited for full-scale window design. The AMM is packed only in the window frame so that the window transparency is not compromised. A broadband attenuation performance is obtained by the resonant unit cells constituting the AMM. The effect of the geometric variation on the window performance in terms of both acoustics and the airflow is analysed numerically through Finite Element Method (FEM) models. The performances of different AMM windows are evaluated and compared with those of conventional window designs. The simulation results show that this new AMM-based window design can overcome the limitations of the conventional windows, with great potential in real applications.

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1. INTRODUCTION

Noise transmission is a significant factor when considering indoor comfort in building designs. [1] Nowadays, increasing noise issues are limiting building functions from different aspects. Active systems have been designed to improve the indoor comfort, leading for example, to mechanical ventilation and active noise control systems. [2] Windows, as an essential building element, play an essential role in addressing this issue, and relevant studies have been extensively investigated. [3], [4] Increasing window thickness could be a solution; however, it inevitably results in a bulky structure. Screening related systems (like rolling shutter boxes) have been proposed to overcome the thickness issue[5], and active noise control has been demonstrated to achieve effective low-frequency attenuation.[2] On the other hand, natural ventilation and air change rate (ACR) are highlighted as key factors to quantify passive energy requirements[6], [7] as contemporary architecture and engineering research are focusing primarily on energy-efficient approaches. With this aim, the latest development of AMMs managed to achieve tailored acoustic properties depending on the material geometrical structure more than the constituent material properties itself. [8], [9] The frequency ranges of application result in many cases limited by their large spatial footprint. For these reasons, it is necessary to further investigate an ideal design and application of AMM in order to address both noise control and natural ventilation, adaptable to different environmental situations.

Our previous study has investigated a promising acoustic metacage window with significant results in a frequency range of 300-5KHz (see Figure 1.a). [10] The tunability of the AMM unit cells constituting the metacage window, related to a few geometric parameters, has been demonstrated through parametric studies. Later, a preliminary realistic adaptation was speculated as acoustic metawindow (AMW) unit (see Figure 1.b). The acoustic metacage window geometry was better approximated to standard window design and tested both numerically and experimentally. The main conclusion is that significant noise reduction can be achieved while allowing 30% of opening ratio (OR).

This study aims to numerically investigate the applicability of previously used AMM on a full-scale window model (see Figure 1.c) and optimise the parameter settings according to different acoustic conditions (depending on the frequency range). Three specific targets are to be considered in the design, including visual impact, acoustics, and ventilation. The visual impact is addressed by using transparent glass as the central panel (dimensions 1.2x0.6 m). The acoustics and ventilation functions are fulfilled by integrating AMM unit cells in the window frame. The window performances are then characterised by different geometric parameters of the window and the AMM unit (described in the following section). The combined variables define different acoustic impact and ACR of the window system on the indoor environment. Finally, the parametric study results are compared to a standard sliding window to show the design benefits. Significant improvements from the standard window design performances could be found and a new AMM based windows set for building engineering or architecture applications.

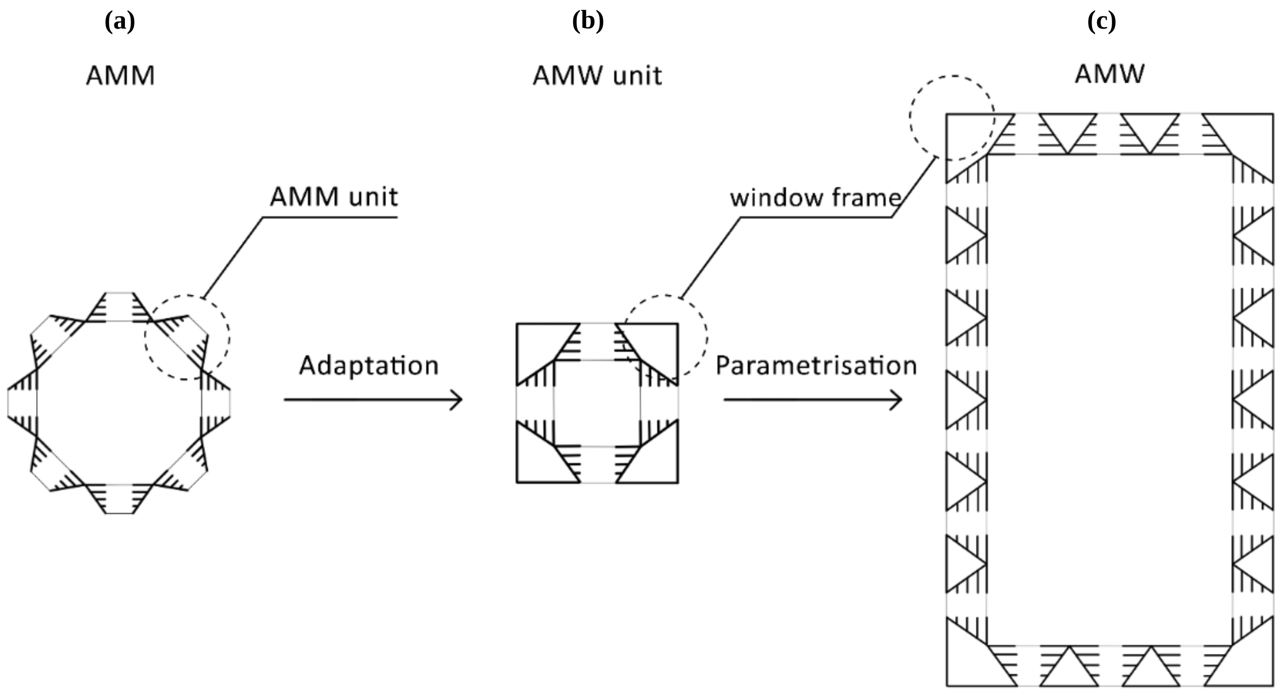

Figure 1 Geometrics and physics concept-flow from the acoustic metacage window, to the AMW unit and finally AMW as per its full-scale application (cross-sections).

2. METHOD

2.1. Geometric setting for acoustic and ACR analysis

Numerical simulations are used to evaluate the performance of the proposed full-scale AMM window. Both acoustic and ACR simulations are performed based on the same 3D geometric settings; however, the physics models have different governing equations and boundary conditions (specified in the following section). For each analysis, Finite Element Method (FEM) is used to perform the parametric study. The geometric elements considered in this study are: a spherical boundary of 0.9 m radius, a 0.13m division in the middle (representing the building's wall), and the AMW attached to one side of the division (see Figure 2.a). The sphere's partitions are considered as the indoor and outdoor environments. The "inner wall" is where the AMW geometry is placed. The dimension of the central transparent panel of the AMW is 1.2 x0.6 m and is constant for all the parametric studies. The input wave (modelled as background pressure field or air velocity) passes through the AMW and radiates in through the distributed ventilation holes along the AMM units surface. As depicted in Figure 2.a, few parameters are considered for this study.

The first parameter T represents the AMW frame thickness starting from the inner side of the division (see Figure 2.a). The 3D window system can be viewed, indeed, as a protrusion from a 2D plane placed on the inner wall. The previous studies highlighted that T influences the frequency range of acoustic application. However, beforehand, there has never been such a parametric study to understand which T dimension can activate the noise reduction on specific frequency bands. In this research T varies within these values: A, T= 0.13 m; B, T= 0.11 m; C, T= 0.09 m; D, T= 0.07 m; E, T= 0.05 m; F, T= 0.03 m. A variation of T determines a variation of the total opening areas of the AMM units in the AMW frame (see Figure 2.a). They vary as 0.14 m^2 (T=A), 0.12 m^2 (T=B), 0.10 m^2 (T=C), 0.08 m^2 (T=D), 0.05 m^2 (T=E), 0.03 m^2 (T=F).

The second parameter, depicted in Figure 2.b, is the frame height (H), which varies in a range of 0.04 m (H=4), 0.05 m (H=5), 0.06 m (H=6), 0.075 m (H=7.5), 0.10 m (H=10), 0.15 m (H=15). A variation of H results in a variation of the frontal area of each window (see Figure 2.b) without varying the central transparent panel dimensions. The frontal area changes within this range: 0.88 m^2 (H=4), 0.91 m^2 (H=5), 0.95 m^2 (H=6), 1.01 m^2 (H=7.5), 1.12 m^2 (H=10), 1.35 m^2 (H=15). A third parameter to evaluate our study is the OR. This unit represents the percentage ratio between the total opening areas of all the AMM units in the AMW frame and the frontal area of each window (see Figure 2); so, the combination of different T and H generates a variation of the OR. These variations are: 30% (T=A=0.13 m), 25% (T=B=0.11 m), 20% (T=C=0.09 m), 16% (T=D=0.07 m), 11% (T=E=0.05 m), 7% (T=F=0.03 m). This specific definition of the OR will allow comparing on a later stage the AMW's performance with common window design' ones (see Section 2.2 and 3.1).

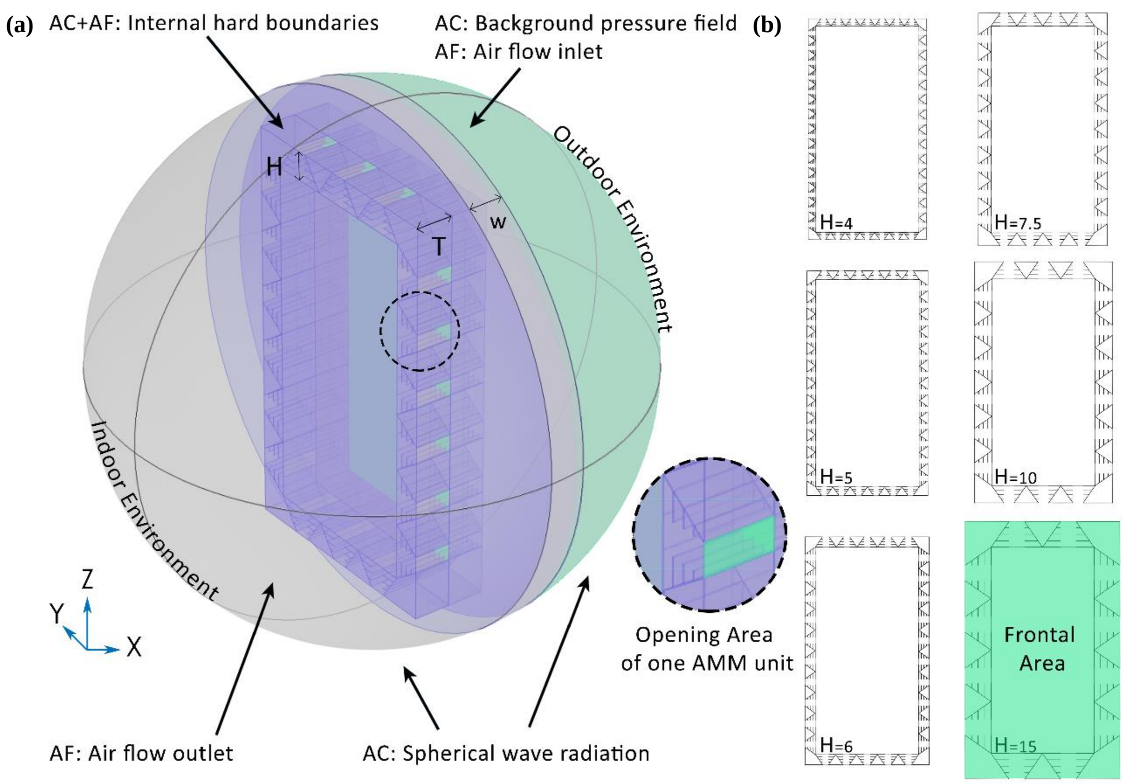

Figure 2 a) 3D representation of boundary conditions and parameters used in both acoustics (AC) and airflow (AF) studies. b) 2D AMW section to show the variation of the H parameter.

2.2. Boundary Conditions and Study Settings

The numerical model is implemented using commercial FEM software Comsol Multiphysics under Acoustics and Fluid Dynamics modules. For the first parametric investigation, semi-infinite acoustic conditions are applied to the two boundary sides of the sphere (see Fig. 2.a). Free spherical wave radiation conditions are applied to all the spherical geometry. The separation walls and the AMW geometry are considered as interior sound hard boundaries. Sound transmission through walls of the AMW and possible viscous-thermal effect in the narrow resonator channels are neglected in this study. The 3D domain is filled with air, where air density and sound speed at room temperature are used. The outdoor boundary is characterised by a background pressure field directed towards the indoor with a pressure amplitude of 1 Pa and an airspeed of the sound of 343 m/s. TL is calculated by the reduction of sound power through the metamaterial interface (in dB). The extra sound attenuation (called ΔTL) of the AMW compared to the standard window's one is defined to show our design benefits, and it is calculated as:

$$\boldsymbol{extra\ attenuation} = \boldsymbol{\Delta TL} = \boldsymbol{TL_{AMW}} - \boldsymbol{TL_{SW}} \quad \text{(dB)} \tag{1}$$

where:

- TL_{AMW}= AMW's transmission loss (dB)
- TL_{SW} = Standard window's transmission loss (dB)

Regarding the mesh size for the 3D study, this model results very complex, and, since the convergence of results is proven, simplification is needed, so the maximum allowed element size is 343/6/2000=0.0286 m. The study is a frequency domain analysis from 0 to 5000 Hz with a step size of 100 Hz. In the results, the TL is shown linearly within the simulation frequencies.

In the parametric airflow study, the same geometric boundaries are used for a laminar flow study in order to calculate the air changes per hour (ACPH). An air change is the number of times the air enters and exits a room from the heating, ventilating and air conditioning (HVAC) system in one hour. ACPH is a measurement of air volume that is added to (or removed from) a room divided by the total volume of the room; so, it measures how many times the air in the room is replaced. Higher ACPH values result in adequate ventilation. The formula is as follows:

$$\boldsymbol{ACPH = \frac{Q}{V}} \quad (h^{-1}) \tag{2}$$

where:

- Q = Volumetric flow rate of air in cubic metres per hour (m^3/h) = $3600 \cdot A \cdot v$
- V = Space volume L × W × H in cubic metres (m^3)
- A = Cross-sectional area of the duct (m^2)
- v = airflow velocity (m/s)

This unit allows comparing the AMW performances to the standardised value for public buildings[11]. Moreover, with an easy time unit adaptation, air change per minute (ACPM) can be calculated in order to describe more precisely the extra opening time that AMW requires when compared to the standardised value for offices. In this case, for example, ACPH= 6 h^{-1} [11] while ACPM=0.1 min^{-1}. From this unit, another time-based indicator, air change requirement in minute (ACRM), can be defined as:

$$\boldsymbol{ACRM = \frac{1}{ACPM}} \quad (min) \tag{3}$$

So for ACPH=6 h^{-1}, ACPM=0.1 min^{-1}, and ACRM=10 min. ACRM is then calculated for all the different AMW model, according to each T and H combination. Finally, the extra time needed for the AMW to reach the standard window (SW) ACR performance is calculated as:

$$\boldsymbol{extra\ time = \Delta ACRM = ACRM_{AMW} - ACRM_{SW}} \quad (min) \tag{2}$$

where:

- $ACRM_{\boldsymbol{AMW}}$ = AMW's ACRM (min)
- $ACRM_{\boldsymbol{SW}}$= Standard window's ACRM (min)

For boundary conditions definition, the 3D geometry is filled with air where air density at room temperature is used. Inlet conditions are applied in the outdoor boundary surface. Normal wind velocity flow at the inlet is 1.132 m/s according to Asfour and Gadi criteria[12] depending on the height above the ground (20m) and the room height (3m). The indoor boundary is characterised with outlet conditions with 0 Pa pressure. In this analysis as well, the walls of the AMW and material cells are set as interior hard boundaries. The mesh size for this 3D study is defined by a maximum element size of 0.18 m and a minimum element size of 0.03m. Indoor average air velocity is analysed in this parametric study to define ACPH for each configuration.

3. NUMERICAL RESULTS

3.1. Thickness variation and frequency range parametric study

Table 1.a shows the ΔTL mean value according to different H and T. ΔTL goes from a minimum of 19.37 dB to a maximum of 39.75 dB showing increasing values in relation with high H; so this parameter might be significant in the determination of the ΔTL amplitude and a more specific frequency related analysis is needed. In Table 1.b, individual bands (low= 0-500 Hz, middle= 500-2000 Hz, high= 2000-5000 Hz) are analysed. From a first look at this table, mostly higher frequencies result significantly affected by the AMW performance in terms of ΔTL; however, focusing on the frame height, the results show that when H increases together with the dimensions of the AMM units, they affect more significantly the low frequencies component of the soundwave.

Models with H=7.5, 10, 15 generates a cut off frequency in the low band, up to a significant mean ΔTL of 10.94, 16.10, and 12.3 dB, respectively. At the same time, bigger AMM units, also determine a significant ΔTL at the higher bands (500-2000 and 2000-5000 Hz) making their application effective on the broad frequency range. In conclusion, within the same audible spectrum, the noise reduction performance of full-scale AMW is better than a comparable sliding window, regardless of the different thickness (or OR). Moreover, H=10 results to be the overall best performing model.

3.2. ACRH and time gap for optimal ventilation conditions

Table 1.c illustrates the difference in terms of AMW ACRM. These values represent the extra opening time that AMW requires when compared to the standardise value for offices (ACRM= 10 min)[11]. The standard value in this analysis is initially defined by DIN 1946 part 2, which is set by the German Institute for Standardisation and accepted worldwide[11], and where it is expressed in ACPH. The specific function was taken into account as an example of a public indoor environment where the acoustic and ventilation comfort is crucial for the occupants. In Table 1.c, negative values mean that the performance of the studied model is even better than a standard window and that shorter opening time is required to achieve the standard ACRM. Overall the shorter time required to satisfy the ACRM standards is between -6.52 min (= -6’31’’) and -9.18 min (= -9’11’’). There is an improvement for bigger T values (A, B, C) as the ΔACRM probably due to their OR. The ventilation performances for these thickness values are the best among the AMW models. In future studies, the AMW ACRM can be compared to standardised values of other indoor functions to have a broader idea of its application in public buildings.

Table 1: a) ΔTL mean of the total value of the acoustic parametric study according to different AMW T or OR; b) ΔTL mean by different frequency bands: low= 0-500 Hz, middle= 500-2000 Hz, high= 2000-5000 Hz; c) ΔACRM between standardised value for offices expressed in additional opening window time (min).

(a)

	ΔTL mean total (dB)						
	4	5	6	7.50	10	15	Mean
A	19.37	21.23	24.63	30.04	39.75	34.11	28.19
B	21.73	22.53	26.93	29.63	30.47	35.30	27.77
C	18.24	22.53	27.16	28.94	32.36	34.97	27.37
D	23.81	27.15	28.90	31.47	32.84	35.88	30.01
E	19.67	23.59	30.86	34.15	34.65	34.95	29.65
F	31.43	33.26	35.31	35.87	36.28	34.17	34.39
Mean	22.37	25.05	28.96	31.68	34.39	34.90	

(b)

	ΔTL mean freq. bands (dB)							
	Freq. Bands	4	5	6	7.5	10	15	Mean
A	LOW	2.44	3.04	3.95	5.00	16.10	4.94	21.58
	MID	18.19	17.85	18.57	19.66	31.75	38.99	
	HIGH	23.34	26.56	31.79	40.24	48.48	37.51	
B	LOW	1.49	2.16	3.08	4.24	4.99	4.12	20.37
	MID	19.77	18.83	18.33	17.97	19.24	40.60	
	HIGH	26.76	28.46	36.00	40.54	41.18	38.89	
C	LOW	2.15	2.95	4.01	5.26	6.46	5.01	20.80
	MID	18.69	18.70	19.38	20.81	28.46	43.21	
	HIGH	21.23	28.36	35.67	37.74	39.49	36.85	
D	LOW	3.06	4.14	5.28	6.66	8.15	6.26	22.39
	MID	14.17	14.13	14.77	21.52	31.26	44.18	
	HIGH	32.78	38.27	40.69	41.41	38.58	37.65	
E	LOW	4.02	5.15	6.58	8.25	10.08	8.65	21.58
	MID	7.67	7.53	8.67	17.85	25.55	36.44	
	HIGH	28.79	35.32	46.81	47.48	44.12	39.46	
F	LOW	7.54	7.10	8.82	10.94	13.20	12.30	24.58
	MID	5.28	3.89	5.06	14.21	25.91	33.09	
	HIGH	49.29	53.18	55.73	51.68	46.07	39.09	
	Mean	15.93	17.53	20.18	22.86	26.61	28.18	

(c)

	ΔACRM (min)					
	4	5	6	7.5	10	15
A	-9.16	-9.18	-9.15	-9.12	-8.92	-9.00
B	-9.02	-9.05	-9.01	-8.98	-8.94	-8.86
C	-8.89	-8.85	-8.84	-8.82	-8.76	-8.68
D	-8.63	-8.61	-8.59	-8.57	-8.49	-8.36
E	-8.27	-8.22	-8.20	-8.11	-7.97	-7.81
F	-7.56	-7.46	-7.18	-6.99	-6.78	-6.52

4. CONCLUSIONS

This study has attempted to explore the applicability of a specific AMM for noise reduction and natural ventilation in window systems. A total of 72 parametric analyses have been presented in order to assess the effectiveness concerning two design parameters: frame's thickness and height (T and H). It has been shown that with a tailored AMM structure, noise attenuation can be achieved and opening time can be increased or reduced mostly without depending on the outdoor acoustic stimuli. Models with T=7.5, 10, 15 can achieve interesting TL value with optimal ACRM, making this design suitable for most of the indoor public functions.

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