DOI: 10.61782/fa.2025.0764

FORUM ACUSTICUM EURONOISE 2025

SELF-SHIELDING WINDOWS : SCALE MODEL MEASUREMENTS AND NUMERICAL SIMULATIONS

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ABSTRACT

The concept of self-shielding windows is introduced as an innovative approach to mitigate sound exposure in urban environments at the most exposed façade. Unlike conventional windows aligned parallel to the building façade, this study examines the sound pressure level exposure at windows oriented obliquely toward the sky. This configuration forces sound from street-level sources to diffract around convex elements before reaching the windows, resulting in reduced sound exposure. Additionally, these façade geometries promote a diffuse sound field within the street canyon, diminishing the influence of specular reflections from opposing façades. However, reflections and scattering from nearby elements may offset these benefits by increasing exposure levels. To elucidate the significance of these physical phenomena, scale model experiments were conducted with simplified triangular façade elements at varying angles and story heights. Especially at the higher stories, significant noise reduction was measured. The experimental findings were further validated by 3D full-wave numerical simulations, reinforcing confidence in both the accuracy of the scale model measurements and the reliability of the numerical predictions for optimizing façade elements.

Keywords: *urban sound propagation, street acoustics, environmental noise, building envelope design, scale model.*

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1. INTRODUCTION

Street acoustics play a central role in urban sound propagation studies. Three main strategies can help limit noise exposure during propagation in streets: introducing absorption, implementing screening, or promoting diffusivity.
Since building materials are typically rigid or nearly so, achieving significant absorption with common materials is challenging. However, building envelope greening, such as non-ground-based green walls [1], is worth considering. The use of low-height screens has been shown effective [2][3], though they generally shield only a limited area. To maximize their noise-mitigating potential, incorporating some degree of absorption is recommended [3].
Promoting diffuse reflection is another effective approach. Studies have demonstrated its benefits for both longitudinal and cross-sectional sound propagation in streets [4][5]. Balconies along façades contribute to this effect [6][7]. With well-designed parapets, balconies can also provide direct shielding of the façade, though this differs from common practice, which often leaves gaps between the vertical and horizontal surfaces. Additionally, balconies enhance diffuse reflection. Due to their typical dimensions, they interact with lower-frequency sounds, which are more dominant in surface transport noise spectra.

2. SELF-SHIELDING WINDOWS

The concept of self-shielding windows is introduced here as an innovative approach to reduce noise exposure. Unlike conventional windows, which are aligned parallel to the building façade, these windows are oriented obliquely toward the sky. This configuration forces street-level sound to diffract around convex façade elements before reaching the windows, effectively reducing noise exposure. Additionally, these façade geometries enhance the diffusion

of sound within the street canyon, thereby minimizing the impact of specular reflections from opposing façades.
This concept was first introduced in Ref. [8] based on full-wave sound propagation simulations using a 2D approach, but validated with real-life sound measurements in street canyons [9]. It emerged from an exploration of both conventional and more inventive façade and street profiles to reduce road traffic noise exposure.
However, further studies on this specific building envelope geometry are needed to better understand the underlying physical mechanisms. Similar to the effects observed near balconies, reflections and scattering from higher-positioned elements could potentially offset the noise reduction benefits by increasing exposure levels. Therefore, further optimizations may be necessary to assess its feasibility for practical implementation

3. SCALE MODEL STUDY

3.1 Street geometry

A simple scale model of a street (length of 2450 mm) consisting of smooth plywood panels, with façade height of 910 mm and the distance between opposing façades of either 977 mm (no façade elements, perfectly rectangular cross-section) or 990 mm (with façade elements). Note that there is a slightly different street width in the reference situation for practical reasons. Foam blocks are used to terminate the street avoiding diffraction at its edges (see Fig. 1).

3.2 Sound source

The sound source (tweeter) is located in a strongly acoustically insulated box, hung below the bottom of the panel representing the street surface (see Fig. 1). The connection between the loudspeaker box and the street is by a cylindrical opening with diameter 10 mm. This setup should prevent all flanking transmissions. White noise sequences (of 30 seconds) were emitted by the tweeter with repetitions.

3.3 Microphones

Five type-1 ½ inch microphones were used for simultaneous measurements, one at the first floor at the left façade (only in the flat façade case, see Fig. 1), and 4 on top of each other along the right façade, all flush mounted. Given the execution of the measurements in a semi-anechoic room and having full control over the loudspeaker and its amplitude, high signal-to-noise ratios are obtained in this experiment.

3.4 Scale factor

Assuming a scale factor of 15, and taking into account the flat frequency range of a ½ inch microphone, the maximum sound frequency to be reached at full scale is 1330 Hz. Note that the scale model measurements are mainly intended for validation purposes, at least in this low frequency range. Nevertheless, the peak of road traffic rolling noise at moderate urban vehicle speeds is believed to be captured.

Figure 1. Scale model setup showing the surface sound source at street level, and the street canyon in absence of façade elements. In this work, focus is on the 4 flush mounted microphones along the right facade.

3.5 Façade elements

Isosceles triangular facade elements with external angles of 60°, 45° and 30° were used. In Fig. 2, the 60° outer angle configuration is shown, with triangles at both facades, and 4 microphones flush mounted at the elements' faces directed towards the sky, along the right façade.

Figure 2. Scale model showing a single configuration of 24 self-shielding façade elements (with 60° outer angles). Four microphones are visible along the right façade centrally positioned in the upwardly directed faces.

4. NUMERICAL SIMULATIONS

4.1 The 3D FDTD method

The explicit pressure-velocity finite-difference time-domain (FDTD) method is used, with staggered-in-place and staggered-in-time update schemes, modelling linear sound propagation in absence of air absorption. Acoustic pressures are located in the center of each computational cell, the particle velocities on the faces that border the cell. A lowest-order spatial and temporal discretization is used here. Perfectly matched layers (PML) are used to simulate an unbounded atmosphere where needed. All other surfaces are considered rigid. The interested reader is referred to Ref. [10] for a justification of these model choices.

For simplicity, the sound source is modelled as a point source in the centre of the first grid cell above the street surface. The receivers are similarly positioned in the centres of the first cells next to the flat façade or directly near the oblique face of the triangular elements. Although this involves reflections not present in the experimental scale model given the flush mounted microphones and the construction of a surface source, when comparing configurations in a relative way, as will be done here, such effects are expected to largely level out.

Grid spacing was equal to 5 mm, with a time step of 8.49 μs, leading to a Courant number equal to 1, ensuring numerical stability while minimizing computational cost and phase errors [10]. Optimized PMLs of 40 cells thick ensure near perfect reflection free boundaries. When imposing a limit of 10 computational cells per wavelength, the 1/3 octave band frequency of 6.3 kHz can be attained (scale model frequencies). Along the street length, a stretch of 2 m is modelled. Although there is a fine discretization in the model relative to the wave length, staircase effects cannot be excluded in case of oblique surfaces [11] which are prominent in this work.

4.2 Mirror source method

The FDTD simulations are accompanied with the mirror source method (see e.g. Ref. [4]), at least for the flat façade geometry. With this method, including higher frequencies comes naturally. Relevant parameters such as the number of mirror sources are increased until sound pressure level differences (see further) converged.

This technique is mainly used to assess the effect of small deviations from the exact positioning (but manually measured) of sources and receivers in the scale model.

5. RESULTS

5.1 Validation case 1 : Level differences between stories along flat façade

Figure 3 shows the differences in 1/3 octave band levels between the 4th floor and first floor microphone, in case of fully flat facades, along the right facade. The bunch of thin colored lines show mirror source simulations using a large number of combinations using small deviations on geometrical parameters such as street width and heights of the microphones.

The microphone capsule surface covers multiple FDTD grid cells, leading to significant variations in the actual exposure. To stabilize results, averaging over a receiver zones of 1.5 times the microphone diameter was performed. To some extent, this procedure also accounts for small deviations in exact positioning.

Starting from 400 Hz on, the scale model measurements, FDTD simulations and the mirror source approach are in good agreement. At high frequencies, small variations in exact positioning lead to strong level differences.

The peak at 315 Hz is almost perfectly predicted by the FDTD model. This peak is much more moderate with the mirror source model, potentially pointing at being related to diffraction of sound which is not modelled with the latter.

Note that the strong level difference peak at the 160 Hz 1/3 octave band only appears in the measurements, and might indicate a deficiency of the measurement setup (of unknown nature). When scaling up to real sound frequencies (so near 10 Hz at full scale), however, its relevance if very minor in environmental noise sources.

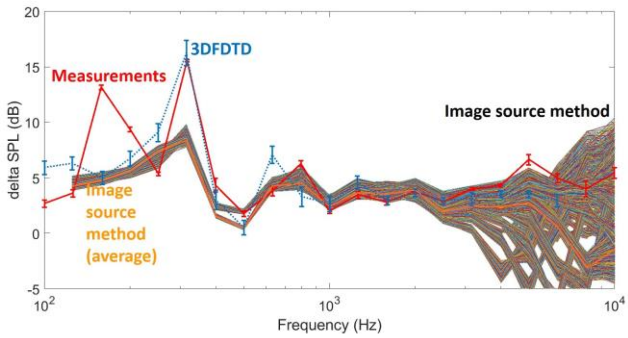

Figure 3. Measurements and simulations of the sound pressure level difference between the 4th and first floor microphone, for the flat façade case.

5.2 Validation case 2 : Self-shielding window insertion losses

In Fig. 4, measured and predicted insertion loss spectra are presented. The 3D full wave simulations are in adequate agreement with the measurements and give confidence on both the measurements performed and the numerical simulations.

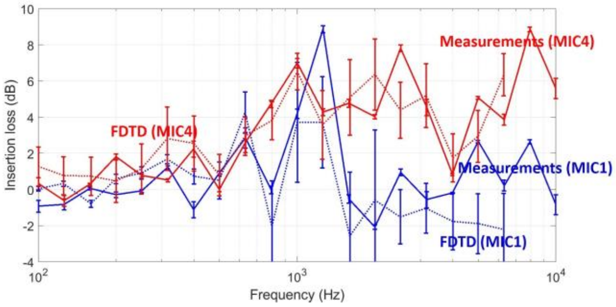

Figure 4. Measurements (full lines) and FDTD simulations (dashed lines) of the insertion losses at the 4th (MIC4) and first (MIC1) floor due to inclusion of 24 triangular elements (with 45° outer angles). The total length of the errorbars equals two times the standard deviation.

Note that simulating the insertion losses involves shifts in interference patterns, making it hard to correctly model the amplitude of these peaks. Further note that the microphones were placed in the middle of the oblique face pointing upwards, so microphone height relative to the street surface is not exactly the same as in the flat façade configuration. Another difference is that the street width in the flat façade situation is slightly lower than in the configuration including triangular façade elements. The large errorbars on the simulations further show that small shifts in receiver position can lead to large differences in insertion loss.

5.3 Element shape

In Fig. 5, insertion loss spectra with different outer angles are shown at the 4th floor, where effects are largest. A 60° outer angle involves smaller façade elements, and consequently, the position of the window pane stays closer to the flat façade configuration. At scale model sound frequencies between 10 kHz and 20 kHz (660 Hz and 1330 Hz at full scale), level reductions exceeding 8 dB (30°), between 6 dB and 8 dB (45°) and between 2 dB and 4 dB (60°) are measured.

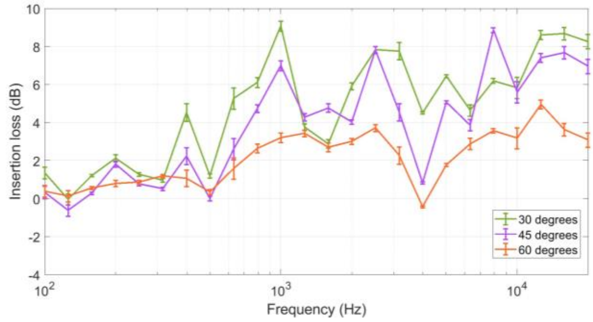

Figure 5. Measurements of the insertion losses at the 4th floor due to inclusion of 24 triangular elements with different outer angles.

5.4 Number of elements

Compared to the influence of the outer angles of the façade elements as discussed in Section 5.3, the effect of the number of elements is limited as becomes clear in Fig. 6. The neighboring columns of elements at the right façade (12 elements relative to 4 elements) hardly influence the insertion loss along the central column where the microphones were placed. This means that for the current setup scattering by these side elements do not influence the exposure levels.

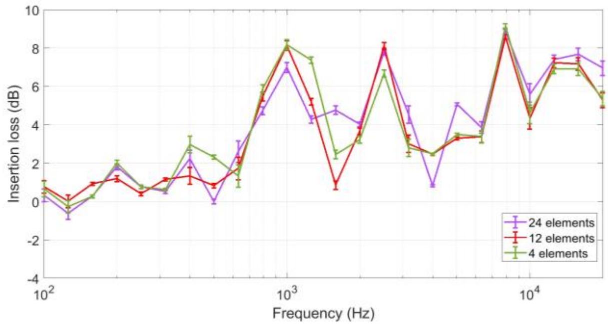

Figure 6. Measurements of the insertion losses at the 4th floor due to inclusion of an increasing number of triangular elements (45°). The case with 24 elements is the one shown in Fig. 2, "12 elements" only has elements along the right façade (with the left façade fully flat), and "4 elements" means a single column of elements on the right facade (with the left façade fully flat).

In the higher sound frequency range (above 10 kHz, at scale), the presence of elements along the left façade leads to a small increase in insertion loss, likely by limiting specular sound paths reaching the upper microphone.

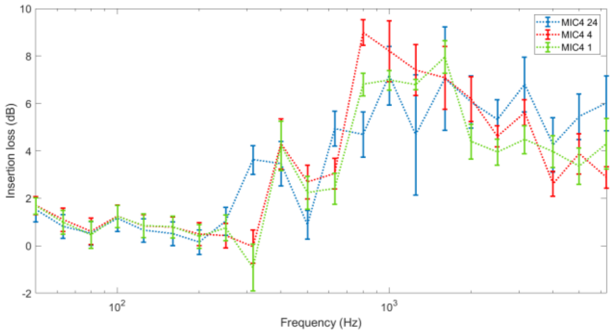

Figure 7. Simulated insertion losses with FDTD at the 4th floor due to inclusion of an increasing number of triangular elements (30°). The case with 24 elements is the one shown in Fig. 2, "4 elements" means a single column of elements at the right façade only (left façade fully flat), and "1 element" means a single element at the right façade (where the microphone is located) with the left façade fully flat.

Analysis of Figs. 7 and 8 indicate different behavior at the 4th floor (top floor) and second floor microphone with relation to the number of façade elements. At the top floor microphone, no elements are present above. Above 2 kHz (130 Hz at full scale) 24 elements lead to the highest insertion losses overall. Preventing specular reflections from the left façade leads to a significant reduction in exposure levels as can be concluded when comparing 24 elements to 4 elements.

Using 4 elements gives a slightly higher insertion loss than when only using a single element, although given the peaky behavior, this does not hold for any frequency. This might point at a second order effect where also specular reflections from the right façade are prevented. Overall, given that many reflections contribute to the sound pressure level at the higher stories, a large number of façade elements seems beneficial.

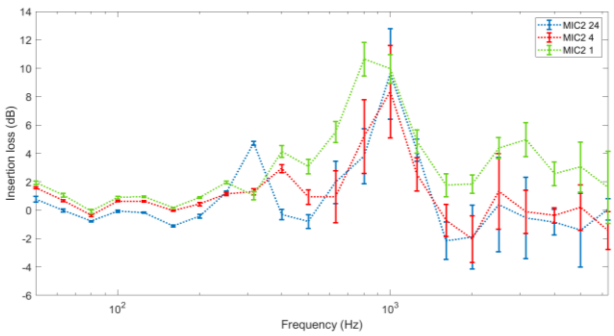

Figure 8. See caption of Fig. 7, but now for the microphone at the second floor.

At the lower stories (here second floor), a single element is clearly the optimum, only allowing for direct shielding. Note that the effect is quite pronounced since an outer angle of 30° leads to rather large façade elements. When having 2 elements on top and one below (so 4 elements in a single column along the right facade), multiple scattering and reflections tend to limit the insertion loss. Adding elements to the left façade (24 elements) does not impact the insertion losses relative to 4 elements.

6. CONCLUSIONS AND OUTLOOK

The concept of self-shielding windows presents a promising noise mitigation solution for the most exposed façades in urban streets. This approach is particularly effective at higher floors, where it can achieve substantial noise reduction compared to fully flat façades. Notably, the greatest improvements occur in key frequency ranges associated with common transport noise sources.

The design of individual elements plays a crucial role in achieving significant noise reduction, as demonstrated by studying triangular elements with varying angles in the current work. At higher stories, interactions with other elements help reduce the intensity of specular sound paths, enhancing overall effectiveness. At lower stories, these interactions mitigate insertion losses due to scattering and reflections from higher positioned elements

Scale model measurements, combined with full-wave 3D numerical simulations, confirm that the simulations accurately capture the underlying physics. Moreover, they validate the precision of the measurements, which is an equally challenging task. Predicting insertion losses in such environments is particularly complex, as pronounced interference shifts create a highly variable spectral response, making it very difficult to fully model their magnitudes.

The numerical model enables further optimizations without the need for labor-intensive scale model measurements. Continued research is required to enhance the architectural quality of the simplified triangular façade elements used in this study while considering cost-effectiveness and the potential integration of thermal performance.

7. ACKNOWLEDGMENTS

The authors are grateful to master thesis students Jules Bastiaensen and Joren Goeteyn for initiating the practical work on the scale model.

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