Modeling and simulation of windows with noise mitigation and natural ventilation

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ABSTRACT

Noise is one of the most important factors which determine the livability in urban areas. It is common that buildings will be exposed to higher ambient noise level generated by various noise sources, as we intensify the land use. In a high density living countries like Singapore, the building envelop often constitutes to the primary path for external noise sources to travel into the living environment. Therefore it is desirable to develop windows which can address the issue of high noise levels while maintaining natural ventilation. It is often challenging and time consuming when one tries to design optimized windows by conducting extensive tests. Here we present a numerical approach to analyze the acoustic performance of ventilation windows. In particular, the sound reduction index of open single glazing and open double glazing will be evaluated using the proposed model. This gives us the numerical platform and basis for further developing real windows, which may also include the use of smart materials or active control elements.

Keywords: Ventilation window, Sound reduction index, ISO 10140
I-INCE Classification of Subjects Number(s): 32.4;32.6;51.3; 51.6

1. INTRODUCTION

The need for environmental sustainability calls for the development of natural ventilation technologies to ventilate buildings. But the fact that introducing unprotected openings suffering from poor sound insulation hampers their uses in dense and populous areas. Many researchers attempted to design windows in the shape of open glazing to achieve both natural ventilation and noise mitigation. For example, Ford and Kerry [1, 2] proposed the idea of using sliding windows consisting of partially open double glazing. Kang *et al.* [3, 4] tested the attenuation performance of ventilation windows with staggered inlet-outlet openings, and studied the effect of adding transparent micro-perforated absorbers between the double glazing. Yuya *et al*. [5] proposed a soundproofing casement window, where the acoustic and ventilation functions were achieved by making use of a cluster of expansion chamber units. Tong *et al*. [6, 7] proposed a plenum window design and conducted both scale-down laboratory measurement and in-situ field measurement to characterize its effectiveness.

Most of the studies found on the acoustic analyses of ventilation windows were experimental works [1-7]. However, due to the cost of porotypes, experimental reliability and repeatability issues, experimental method is generally more useful in terms of assessing the performance of an existing window rather than for seeking a better design. Here, we present a numerical approach which is capable of predicting the acoustic performance of ventilation windows. The numerical model attempts to simulate the test conditions complying with the ISO measurement standard. In this study, the sound reduction indices of open single and open double glazing are assessed and compared with experimental data. A brief parametric analysis is also presented to address the effect of varying opening size on the sound insulation characteristics.

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2. NUMERICAL MODEL

Theoretically, the sound reduction index (SRI) as the basic property of a window determines the proportion of incident sound energy that can transmit through it. To experimentally measure the SRI of a building element, ISO 10140 series [8] specify the necessary requirements and practical guidelines for conducting the experiment in laboratory. The test specimen is mounted on the separation wall between a source and a receiving room. In practice, the source room utilizes a large reverberant chamber to create a diffuse sound field, whereas the receiving room is designed either in an anechoic chamber or another reverberant chamber to measure the transmitted sound power, depending on the availability of the test-rig constructions. The sound power levels (SWLs) on the source and receiving side of the window are then subtracted to obtain the window SRI in one-third octave band.

The aim of this paper is to develop a numerical model that is capable of predicting the acoustic performance of ventilation windows, with an attempt to address the effect of changing window parameters. To evaluate the sound transmission, finite element method (FEM) model is implemented, which solves the acoustic wave propagation based on the discretized meshes. The frequency range of interest in this study covers from 125 Hz to 2000 Hz, which takes into account the typical spectra of traffic and activity noise, and at the same time tries to avoid the high computational cost using FEM at high frequencies (above 2000 Hz), as well as the low-frequency limit of the source room model due to lack of diffuseness (below 125 Hz).

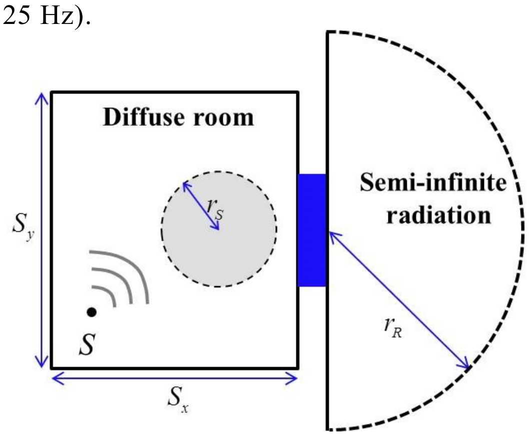

Figure 1 – Schematics of the numerical model for predicting the SRI of ventilation windows.

The simulation model considers a two-dimensional (2D) configuration in the first place for the sake of computationally achievable. Nevertheless, the 2D simulation provides as a good representation of the physics and general behavior of the 3D systems. To comply with ISO measurement, the source room is implemented as a large reverberant chamber with rigid boundary conditions. In Fig. 1, a rectangular acoustic cavity with dimension $S_x \times S_y = 5 \times 6$ m is used, where a point source is placed at 0.4 m and 0.6 m away from the left and bottom wall surfaces. For the receiving room condition, a semi-infinite radiation field is considered to measure the transmitted sound power, corresponding to an anechoic chamber condition in experiment. The SRI of the ventilation window can be evaluated by:

$$\mathrm{SRI} = 10\log_{10}(W_S / W_R) = L_S - L_R, \tag{1}$$

where W_S and W_R are the sound powers incident from and radiated into the source and receiving rooms, respectively. L_S and L_R are their corresponding sound power levels. The source SWL L_S can be calculated by spatially averaging the SPL in the circled area with a radius r_S in Fig. 1 [9]:

$$L_S(f) = 10\log_{10}\left[\frac{A}{2\rho_0 c_0}\left(\frac{1}{N_S}\sum_{1}^{N_S} 10^{L_p/10}\right)\right], \tag{2}$$

where A is the size of the test window specimen, N_S is the number of discretized measurement points within the circled area in the source room, L_p is the *root-mean square* sound pressure level (SPL) at the measurement points [8].

At the receiving side of the window, the receiving SWL L_R can be characterized by integrating the sound power radiated into the receiving room:

$$L_R = 10\log_{10}\left[\frac{1}{\rho_0 c_0}\int 10^{L_p/10} dR\right] . \tag{3}$$

where R denotes the arc length of the radiation boundary, namely the arc of the semi-circle with a radius r_R in Fig. 1.

In the calculation, the entire frequency range of interest is divided either linearly or logarithmically into a certain number of frequency points. For analysis to be conducted in the one-third octave band, the averaged band level $L(f_c)$ for each frequency band with a center frequency f_c is:

$$L(f_c) = 10\log_{10}\left[\sum_{f_l}^{f_u} 10^{L(f)/10}\delta f\right] , \tag{4}$$

where f_l is the lower-limit and f_u is upper-limit of a one-third octave band, δf is the spacing between the segmented frequencies. Assuming that a sufficient number of frequency points have been defined within each one-third octave band, the above equation can be approximated by:

$$L(f_c) = 10\log_{10}\left[L(\overline{f_c})\times\Delta f\right] , \tag{5}$$

where $L(\overline{f_c}) = \sum_{1}^{N_f} L(f)/N_f$ is the direct averaging of the SPL at N_f frequency points within a one-third octave band, Δf is the frequency bandwidth $\Delta f = f_u - f_l$.

Based on the proposed numerical model, the SRIs of two typical ventilation window configurations are to investigated in this paper, namely an open single glazing and an open double glazing with staggered openings as shown in Fig. 2(a) &2(b), respectively. The opening refers to the area which is physically left unblocked for air ventilation, which can operate either by sliding the window or pivoting the panel in practical implementations, e.g. as illustrated in Fig. 2(c). Note that no attempt is made to distinguish these two operating mechanisms, since the size and orientation of the opening is the predominating factor that determines the sound insulation. For open single and double glazing, attentions will be paid to compare the sound insulation for different dimensions of openings.

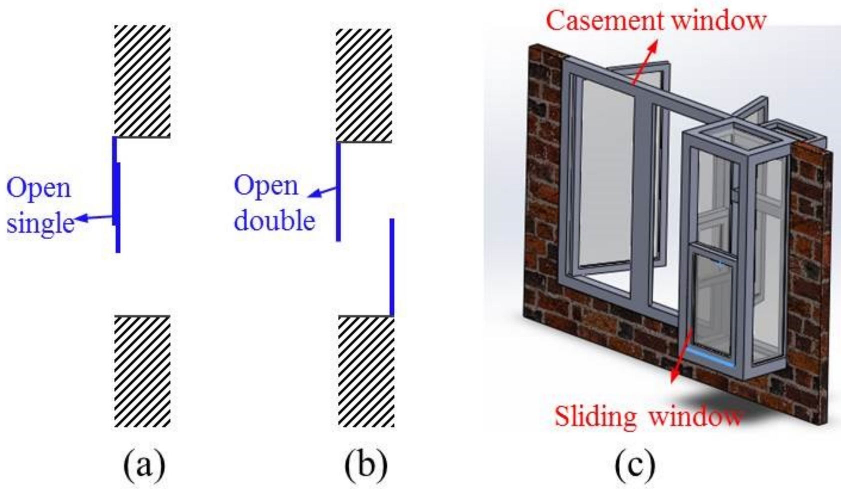

Figure 2 – Schematics of (a) an open single glazing; (b) an open double glazing with staggered openings; (c) a practical ventilation window design combining both open single and open double glazing.

3. MODEL VALIDATION

In Ref. [10], the SRI of an open single glazing (standard top hung window) and a double glazing (supply air window) were measured according to the laboratory standard. As a validation, the proposed numerical model is used to study the same window configuration as considered in the experimental work [10]. Figure 3 shows the cross-sections of the two window configurations, where the heights of the window and sizes of the opening are specified. The 3D vertical window construction tested in the experiment has the horizontal opening width equal to the whole window width, such that the horizontal dimension is not considered in the present 2D model. During the simulation, sound transmission, absorption through the window glass and room wall, as well as the air damping effect was neglected for the sake of simplicity.

In Fig. 3, the predicted and experimental SRI curves are compared, where general good agreements were observed for both single and double glazing cases, especially below 1000 Hz. This shows that the present 2D model is able to capture the SRI behavior of the 3D system. The good agreement in the low frequency range indicates that the edge effect due to sound diffraction is not significant, whereas the noticeable discrepancies at high frequencies could mainly attribute to the neglected damping effect in the model. It is well-known that damping effect (from panel &wall roughness, air absorption, etc.) plays an important role in lifting-up the SRI at high frequencies. This makes the numerical prediction lower than the experimental curve by around 3~5 dB above 1000 Hz.

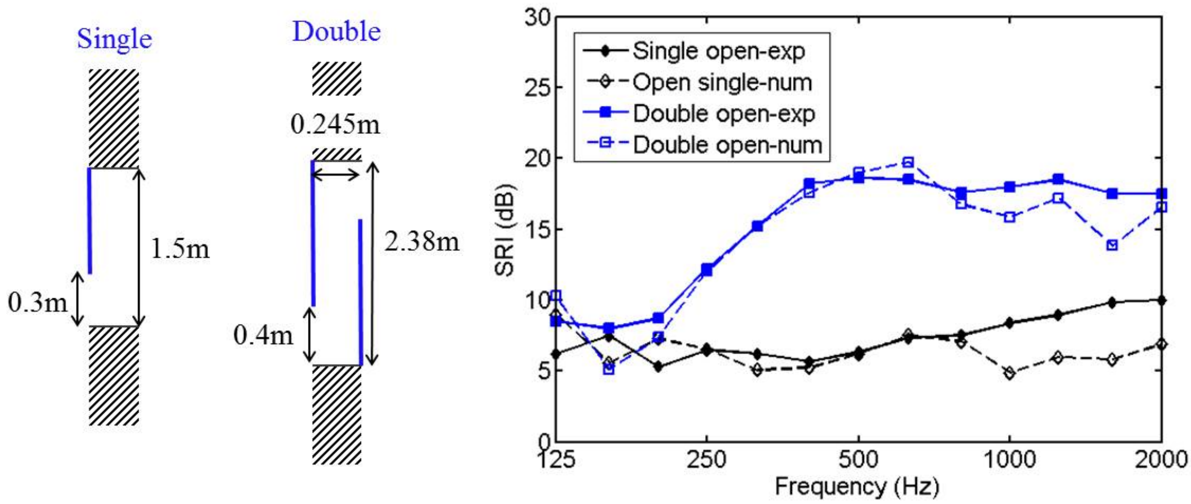

Figure 3 –Comparisons of the predicted SRIs from the proposed model and experimental data from Ref. [10], on an open single glazing and an open double glazing.

4. PRELIMINARY SIMULATION RESULTS

The effect of varying the opening size which is the dominating factor that controls the sound insulation and ventilation is studied. As shown in Fig. 4, an open single glazing is inserted onto an aperture with a fixed height of H=1.5 m, leaving an adjustable opening size O. The degree of opening varying from full open to 1/2, 1/3 and 1/5 partially open were simulated. Assuming that the ratio of the transmitted sound energy to the incident one depends only on the opening size, the ideal SRI can be estimated by SRI=$10\log_{10}(\mathrm{H/O})$.

Figure 4 shows the behavior of the four opening sizes, where the trends of the curves are similar and the smaller opening gives the better sound insulation. The predicted SRIs follow the estimation formula well. The O=1.5 m curve (full open, H/O=1) has a SRI fluctuating around zero dB. With the window left half-open (O=0.75 m), the SRI curve has a higher mean value of around 3 dB [$10\log(1/2)$]. The one-third open (O=0.5 m) and one-fifth open (O=0.3 m) curves then have mean values of $10\log(1/3)=4.8$ dB and $10\log(1/5)=7$ dB, respectively. It is noted that in order to achieve a SRI of 10 dB, the opening size shall fall below 1/10 of the total window size, indicating that a good sound insulation with adequate ventilation is difficult to achieve by using open single glazing.

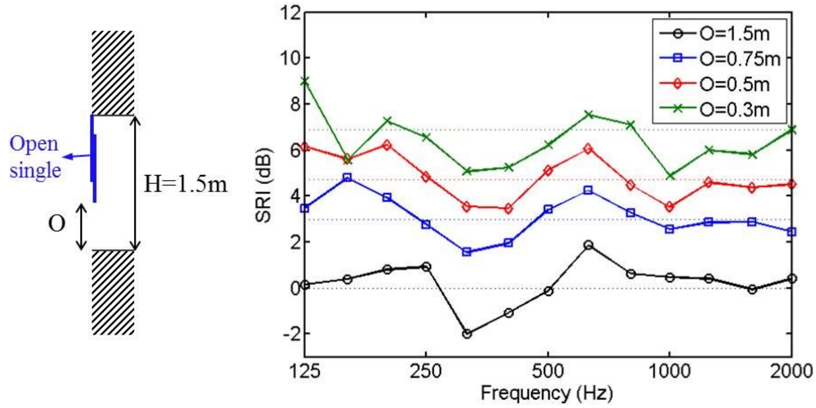

Figure 4 –SRI of open single glazing with adjustable opening size O in one-third octave band.

To enhance the sound insulation, open double glazing separated by a distance of W is considered. The two openings on the dual glazing have identical size O and are always staggered. Such window design acts like a duct silencer, where the impedance mismatch at the staggered openings triggers the sound reflection back to the source, thus to suppress the sound transmission. In Fig. 5, the SRIs of open double glazing with varying opening size are presented, where the spacing W is fixed at 0.245 m. It is seen that smaller opening size generally gives better insulation in the mid-to-high frequency range, which is just the opposite at low-frequencies below 250 Hz. The detailed reason still needs to be explored. The improvement by using double glazing to replace single glazing is also obvious. For the same opening size O=0.3 m, the SRI of the double glazing is at least 7 dB higher than the single glazing above 315 Hz, even without considering the damping.

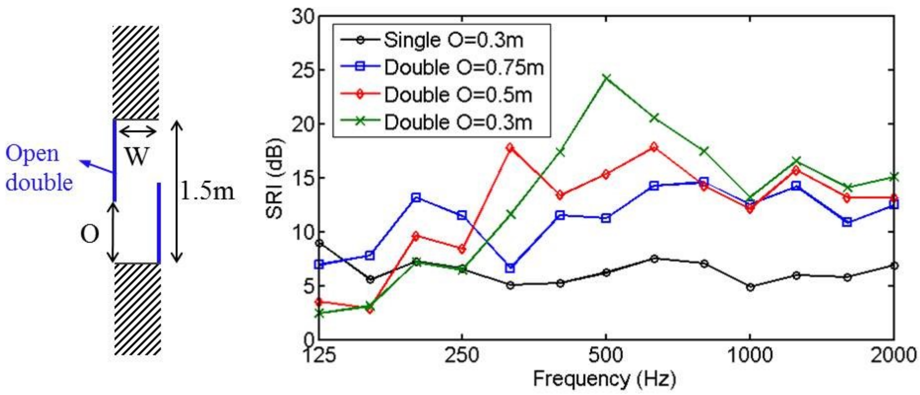

Figure 5 –SRI of open double glazing with adjustable opening size O.

5. CONCLUSIONS

A numerical model for predicting the sound reduction index of ventilation windows in building has been developed. The model consists of a reverberant source room to excite the sound field incident on the window, and utilizes a semi-infinite receiving room to measure the radiated sound power. The prediction has been validated against data collected from an experimental study.

For open single and open double glazing, the effect of varying opening size on the SRI behavior has been studied. A single glazing requires very small opening size for good sound insulation, which in turn deteriorates the ventilation performance. The improvement by using double glazing is significant, generally leading to an extra sound insulation of 7 dB in the mid-to-high frequency range. Besides, the double glazing allows additional sound control devices such as absorbing materials or active control techniques to be applied inside. The built model provides a general numerical platform for further exploring the feasibility of these techniques.

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