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Prediction of Noise Transmission Loss and Acoustic Comfort Assessment of a Ventilated Window using Statistical Energy Analysis

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P A P E R I N F O

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A B S T R A C T

In this paper, a novel analytical method was developed based on statistical energy analysis framework to evaluate sound transmission loss through ventilated windows. The proposed method was compared to numerical and analytical models available in the literature. Results showed the success and advantage of the proposed model in predicting the acoustic performance of the ventilated window and the proposed method proved itself as a low-cost and high-accurate method. Considering the slit-like effect of the inlet and outlet of the ventilated window and channel attenuation is the distinct feature of the proposed method compared to the existing analytical models. This paper also discussed the effectiveness of the ventilated window in the provision of indoor acoustic comfort according to the different types of the outdoor traffic noise spectra and sound transmission loss. The results showed the acceptance of the indoor noise level made by the ventilated window. To recognize how the effective factors improve the acoustic performance of the ventilated window, the effect of window aspect ratio, channel thickness and opening size on Sound Transmission Class (STC) were studied. The results revealed that the ventilated window with higher aspect ratio and wider airflow channel has a higher STC while widening the opening size reduces the sound insulation.

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NOMENCLATURE

A_i	Subsystem surface area (m^2)
b	Channel thickness (m)
c_0	Sound speed (m/s)
c_L	Longitudinal wave speed
d	cavity thickness (m)
E_i	Energy of subsystem i
f	frequency (Hz)
H	window height (m)
h	Glass pane thickness (m)
L	perimeter length of the subsystem (m)
n_i	Modal density (s)
T	Reverberation time (s)

TL	Transmission loss (dB)
VF	View factor
V_i	Subsystem volume (m^3)
W_i	Acoustic power (W)
w_i	opening width (m)

Greek Symbols

α	Acoustic absorption coefficient
τ	sound transmission coefficient
η_i	Internal loss factor of subsystem i
η_{ij}	Coupling loss factor between subsystems i and j
ρ_0	air density(kg/m^3)
ρ_{si}	glass pane density (kg/m^2)

1. INTRODUCTION

Decreasing the heating and cooling loads of the building is one of the main concern of the building designers. According to Hossain et al. [1], the energy consumption for space heating and cooling is 17% of total primary consumption. Windows are the key elements of the building which contribute major proportion of heating and cooling loads. So, it needs proper design in order to minimize the heating and cooling loads while fulfilling its nature of providing natural lighting, external view and natural ventilation. The ventilated window is one of the best designs of windows, which utilizes the solar energy benefits to eliminate some disadvantages of

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conventional windows such as solar glare, energy loss due to infiltration, high glazing surface temperature and visual discomfort [2]. In addition, as the performance of the solar photovoltaic cells depends on its surface temperature [3], the ventilated window can be integrated with solar photovoltaic cells to improve their performance due to its lower glazing surface temperature. However, the most important challenge, which the ventilated window faced with, is the deterioration of the sound insulation. If one can make sure of the ventilated window ability to establish an acceptable insulation against outdoor noise, the ventilated window can be utilized as an efficient system for providing indoor air quality (IAQ). Therefore, analysis of sound transmission can be considered as the main and essential assessment of the ventilated window.

The study of sound transmission through the ventilated window returns to Kerry and Ford's work [4] where first proposed the use of partially open double-glazing with staggered inlet-outlet openings to improve the sound insulation. The experimental results showed an improved acoustic performance in comparison to the closed single glazed window. Since then, the acoustic study of ventilated windows has been developed. Kang and Brocklesby [5] studied the feasibility of using transparent micro-perforated absorbers (MPA) in a ventilated window to allow noise attenuation. Their numerical and experimental results revealed that applying MPA can reduce considerably the noise level. They also claimed that the acoustic response depends on window parameters and MPA material. Tong and Tang [6] studied the plenum window acoustic performance in the presence of line noise source. Yu et al. [7] proposed and developed a numerical simulation model for predicting the sound insulation performance of ventilated windows. They investigated different window configurations, consisting of partially open single glazing, double glazing with staggered openings and that with sound absorbers and proposed simple formulas to predict the SRI in the mid-to-high frequency range.

A survey on researches studying the acoustic performance of the ventilated window showed that the approaches of most of the works are experimental and/or numerical. As the experimental method is time-consuming and costly and also the numerical method is required high computational efforts, analytical approach is beneficial to apply in the evaluation of the acoustic performance of the ventilated window at the stage of building design. There is a lack of an appropriate analytical method in the prediction of the acoustic performance of the ventilated window by which one can attain the accuracy and reliability of experimental and numerical approaches in parallel to reducing the time and cost. To this end, the present work developed an analytical method based on Statistical Energy Analysis (SEA) to address the sound performance of the ventilated window. This novel proposed method needs a low computational time and provides reliable and accurate results. There is no study using SEA for analysis of the ventilated window and this study is the first to develop SEA approach for evaluation of the acoustic performance of the ventilated window.

Although there are few acoustic analytical models studying the ventilated window such as one suggested by Bajraktari et al. [8], they are unable to consider some of the sound transmission processes such as the slit-like behaviour of the inlet and outlet of the ventilated window and channel attenuation. This issue makes an essential deterioration from the real condition and a remarkable error. However, the proposed SEA model is able to consider these effects on the acoustic performance of the ventilated window.

From an acoustic comfort point of view, in order to assess the indoor acoustic comfort due to exterior facades specifically ventilated windows, the outdoor traffic noise spectrum and sound insulation are required simultaneously whilst the majority of studies focused mainly on the acoustic behavior of the window and did not pay attention to the outdoor traffic noise spectrum. One of the aims of the present work is the integrated analysis including spectra of indoor and outdoor noise and transmission loss of the ventilated window using SEA to evaluate the success of the ventilated window for the provision of the indoor acoustic comfort.

The novelty of the present work is the introduction of a robust analytical model based on SEA framework to assess the acoustic performance of the ventilated window and evaluation of the effectiveness of the ventilated window in providing the indoor acoustic comfort according to outdoor traffic noise. To this end, how the proposed SEA model is first applied on the ventilated window and its distinction compared to the double-glazed window was described. Then, the efficiency of sound insulation of the ventilated window using the outdoor traffic noise spectra and indoor acoustic comfort criteria prescribed by acoustic standards was examined. Finally, a parametric study focusing on geometric factors was carried out and the variation of sound transmission loss was described. It is hoped that the present results can provide a more detailed picture on the benefit of using the ventilated windows in practice.

2. MODELING SOUND TRANSMISSION THROUGH THE VENTILATED WINDOW

In this study, Statistical Energy Analysis (SEA) has been used to predict transmission loss across the ventilated window. SEA is a powerful framework to analyze the acoustic performance of complex systems based on the concept of sound energy transfer between subsystems. This framework was developed in the early 1960's and has been successfully applied in many practical areas [12]. The approach of SEA is to split up the system of interest into subsystems. Subsystems are a division of several physical elements so that the vibro-acoustic characteristics are uniform over them like damping, excitation and coupling properties. According to SEA approach, the sound power balance should be satisfied in each subsystem. Thereby, a portion of the input sound power to each subsystem can be wasted and the rest will be transmitted to into another coupled subsystem.

The ventilated window is composed of two parallel glass panes separated by an air cavity through which air can flow between indoors and outdoors for ventilation. The schematic of the ventilated window and the subsystems are shown in Figure 1. The SEA block diagram for the ventilated window is also shown in Figure 2. As can be seen, there are sound powers entering and exiting each subsystem so that the energy conservation is established.

Writing the power-flow balance equation for subsystem 1 (outdoors) gives Equation (1):

$$W_1^{loss} + W_{12} + W_{13p} + W_{13s} + W_{15} - W_1^{in} = 0 \quad (1)$$

In this equation, W_1^{loss}`is the sound power lost in the subsystem 1; W_{12} is the net power transmitted between subsystem 1(outdoors) and subsystem 2 (outer glass pane); W_{13p} is the net power transmitted between subsystem 1(outdoors) and subsystem 3 (cavity) through the outer glass pane; W_{13s} is the net power transmitted between subsystem 1(outdoors) and subsystem 3 (cavity) through the inlet slit; W_{15} is the net power transmitted directly between subsystem 1(outdoors) and subsystem 5 (indoors) without incidence of acoustic behavior to the glass panes; W_1^{in} the input noise power.

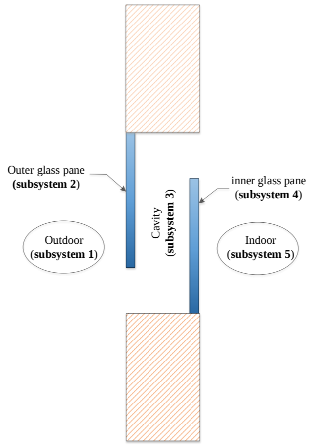


Figure 1. schematic of the ventilated window and sound transmission paths

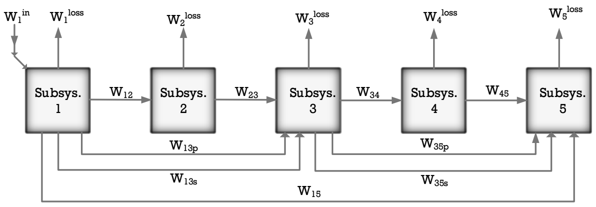


Figure 2. The SEA block diagram for the ventilated window with two glass panes for supply and exhaust modes

Accordingly, writing the power-flow balance equations for subsystems 2 to 5 gives Equation (2) to Equation (5):

$$W_2^{loss} + W_{23} + W_{24} - W_{12} = 0 \quad (2)$$

$$W_3^{loss} + W_{34} + W_{35p} + W_{35s} - W_{13p} - W_{13s} - W_{23} = 0 \quad (3)$$

$$W_4^{loss} + W_{45} - W_{33} - W_{24} = 0 \quad (4)$$

$$W_5^{loss} - W_{45} - W_{35p} - W_{35s} - W_{15} = 0 \quad (5)$$

Generally, the exchanged and lost powers of W_{ij} and W_i^{loss} are defined as Equations (6) and (7):

$$w_{ij} = \omega \eta_{ij} n_i \left(\frac{E_i}{n_i} - \frac{E_j}{n_j} \right) \quad (6)$$

$$W_i^{loss} = \omega \eta_i E_i \quad (7)$$

where η_{ij} and η_i are the coupling loss and internal loss factors of the *i*th subsystem; E_i is the total energy of the *i*th subsystem; n_i and n_j are modal densities of the subsystems i and j ; and ω is angular frequency.

Rewriting Equations (1) to (5) according to terms given by Equations (6) and (7), a system of equations with total energies as unknowns is obtained as follows:

$$\begin{bmatrix} \eta_{1t} & -\frac{n_1}{n_2}\eta_{12} & -\frac{n_1}{n_3}\eta_{13} & 0 & -\frac{n_1}{n_5}\eta_{15} \\ -\eta_{12} & \eta_{2t} & -\frac{n_2}{n_3}\eta_{23} & 0 & 0 \\ -\eta_{13} & -\eta_{23} & \eta_{3t} & -\frac{n_3}{n_4}\eta_{34} & -\frac{n_3}{n_5}\eta_{35} \\ 0 & 0 & -\eta_{34} & \eta_{4t} & -\frac{n_4}{n_5}\eta_{45} \\ -\eta_{15} & 0 & -\eta_{35} & -\eta_{45} & \eta_{5t} \end{bmatrix} \begin{bmatrix} E_1 \\ E_2 \\ E_3 \\ E_4 \\ E_5 \end{bmatrix} = \begin{bmatrix} \frac{W_1^{in}}{\omega} \\ 0 \\ 0 \\ 0 \\ 0 \end{bmatrix} \quad (8)$$

where η_{it} is total loss factor of the subsystem i calculated as Equation (9):

$$\eta_{it} = \eta_i + \sum_{j=1, j \neq i}^{N} \eta_{ij} \quad (9)$$

To solve the system of equations as matrix (8), it is necessary to calculate the terms of the coefficient matrix i.e. internal and coupling loss factors as well as modal densities.

Internal loss factors of outdoors and indoors (η_1 and η_5) are obtained as Equation (10) [13]:

$$\eta_i = \frac{2.2}{fT_i} \tag{10}$$

In this equation, T_i is reverberation time of outdoors and indoors calculated by the formula introduced by Beranek [14] as Equation (11):

$$T_i = a + 2.326 \times b \times \log(V_i) \tag{11}$$

a and b coefficients are frequency dependent and obtained from reference [14].

Internal loss factors of panels (η_2 and η_4) are considered constant, which has value f 0.0013 for glass pane [15]. For cavity, η_3 is calculated as follows [11]:

$$\eta_3 = \begin{cases} \dfrac{A_{glass} c_0 \alpha_3}{4V_3 \omega}, \ \omega < \dfrac{\pi c_0}{d} \\ \dfrac{A_{glass} c_0 \alpha_3}{6V_3 \omega}, \ \omega \geq \dfrac{\pi c_0}{d} \end{cases} \tag{12}$$

α_3 is acoustic absorption coefficient of the cavity walls which is frequency-dependent as Equation (13) [15]:

$$\alpha_3 = 7.7 f^{-0.6} \tag{13}$$

Modal densities of the subsystems of outdoors, cavity and indoors, n_1, n_3 and n_5, as acoustic volumes are expressed as Equation (14) [9]:

$$n_{acoustic\ volume} = \frac{\omega^2 V}{2\pi^2 c_0^3} + \frac{\omega A}{2\pi c_0^2} + \frac{L}{16\pi c_0} \tag{14}$$

For glass panes, the modal densities (n_2 and n_4) are given by Equation (15) [16]:

$$n_{glass\ pane} = \frac{A}{3.6 c_L h} \tag{15}$$

Coupling loss factors between glass panes and acoustic volumes including outdoors, indoors and cavity are given by Equations (16) to (19) [9]:

$$\eta_{12} = \frac{\rho_0 c_0^2 A_2 f_{c2} \sigma_2}{8\pi V_1 \rho_{s2} f^3} \tag{16}$$

$$\eta_{23} = \frac{\rho_0 c_0 \sigma_2}{2\pi f \rho_{s2}} \tag{17}$$

$$\eta_{34} = \frac{\rho_0 c_0 f_{c4} \sigma_4}{4\pi \rho_{s4} f^2} \tag{18}$$

$$\eta_{45} = \frac{\rho_0 c_0 \sigma_4}{2\pi f \rho_{s4}} \tag{19}$$

In these equations, σ_2 and σ_4 are the radiation efficiency of the outer and inner glass panes which is calculated by formula derived by Maidanik [17]. f_{c2} and f_{c4} are coincidence frequencies of the glass panes which are expressed by Equation (20):

$$f_c = \frac{c_0^2}{1.8 c_L h} \tag{20}$$

η_{13}, coupling loss factor between outdoors and cavity, composed of two components as Equation (21):

$$\eta_{13} = \eta_{13p} + \eta_{13s} \tag{21}$$

η_{13p} is the non-resonant coupling loss factor due to the inner glass pane while η_{13s} is the resonant coupling loss factor due to the inlet. Similar trend is true for η_{35}. To calculate η_{13p} and η_{35p}, Equations (22) and (23) are used [9]:

$$\eta_{13p} = \frac{A_2 c_0 \tau_{13}}{8\pi f V_1} \tag{22}$$

$$\eta_{35p} = \frac{\tau_{35}}{4\pi} \tag{23}$$

τ_{13} and τ_{35} are the non-resonant transmission coefficients through the inner and outer glass panes and are calculated according to procedures described by Fahy [18].

η_{13p}, η_{35p} and η_{15} three coupling loss due to openings are added to the system, which make distinction between double-glazed and ventilated windows. Coupling loss factors from outdoors to cavitthe y through the inlet and from cavity to indoors through the outlet are written by Equations (24) and (25):

$$\eta_{13s} = \frac{A_{inlet} c_0 \tau_{slit}}{4V_1 \omega} \tag{24}$$

$$\eta_{35s} = \frac{A_{outlet} c_0 \tau_{slit}}{4V_3 \omega} \tag{25}$$

where A_{inlet} and A_{outlet} are the inlet and outlet areas. τ_{slit} is the transmission coefficient of the inlet and outlet and is calculated from Equation (26) [19]:

$$\tau_{slit} = \frac{mK\cos^2(Ke)}{(2n^2)} \left(\begin{matrix} \dfrac{\sin^2(KX + 2Ke)}{\cos^2(Ke)} \\ + \dfrac{K^2}{2n^2}\left(1 + \cos(KX)\cos(KX + 2Ke)\right) \end{matrix} \right)^{-1} \tag{26}$$

Where m represents the type of the sound field and is considered Equation 8 for diffuse field and Equation 4 for plane wave at normal incidence. n is the factor determining the position of the inlet and outlet. For the present work, as the inlet and outlet are located along the edge of glass panes, n=1 is considered. X is b/w, the ratio of glass thickness to the opening width. K and e are calculated from Equations (27) and (28):

$$K = \frac{\omega w}{c_0} \tag{27}$$

$$e = \frac{ln\left(\frac{8}{K}\right) - 0.57722}{\pi} \tag{28}$$

η_{15}, the coupling loss factor of W_{15}, is defined by Equation (29):

$$\eta_{15} = \frac{A_{inlet} c_0 \tau_{slit} VF}{4V_1 \omega} \tag{29}$$

In this definition, the analogy between radiation heat transfer and acoustic is used because of their wave nature. The shape factor concept is borrowed from radiation heat transfer for involving the effect of inlet and outlet position relative to each other. The specific formula of shape factor for the system of interest is given below [20]:

$$VF = \left[\begin{array}{l} \sqrt{d^2 + H^2} + \sqrt{d^2 + (H - w_1 - w_2)^2} \\ -\sqrt{d^2 + (H - w_1)^2} - \sqrt{d^2 + (H - w_2)^2} \end{array} \right] \Big/ 2w_1 \tag{30}$$

where d, H, w_1, and w_2 are the channel thickness, the height of the channel, the width of the inlet and outlet, respectively.

Substituting all terms of the coefficient matrix using the formula explained above and solving the equation system, the total energies of the subsystems are obtained. To solve this set of equations, a computer program based on FORTRAN 90 was written and implemented. The transmission loss of the ventilated window may be calculated from the energy difference between the indoors and outdoors as Equation (31) [11].

$$\mathrm{TL} = 10\log\left(\frac{E_1}{E_5}\right) + 10\log\left(\frac{ST_5}{0.16V_1}\right) \tag{31}$$

3. VALIDATION OF SEA MODEL

In the present study, the SEA modeling was validated against the experiment by Kang and Brocklesby [5]. The specification of the window compared is as follows: The window size is 850 mm width and 1270 mm height. The glasses are two 4-mm float glasses. The air channel thickness was considered 40 mm. The width of the inlet and outlet are 380 mm.

The variable compared for the validation was the transmission loss (TL). Figure 3 depicts the measured and calculated transmission loss of the ventilated window in the one-third octave band. The results show that SEA predicts the transmission loss well. The mean and maximum deviation of results were obtained 0.81 and 4.9 dB, respectvely.

4. RESULTS AND DISCUSSION

In order to evaluate the effectiveness of the proposed SEA in predicting the sound tranmission through the ventilated window, a comparison between results of the SEA and that of the analytical model of Bajraktari et.al [8] and Numerical simulation of Yu et.al [7] was made. The reference values for comparison is the experimental data reported by Sondergaard and Olesen [21]. As shown in Figure 4, the results of the present SEA model as well as Numerical model follow the trend of experimental data soundly. On the other hand, the analytical model predicts TL in low-frequency range well but TL reaches a constant value below the that of experimental data in mid-to-high frequency regions.

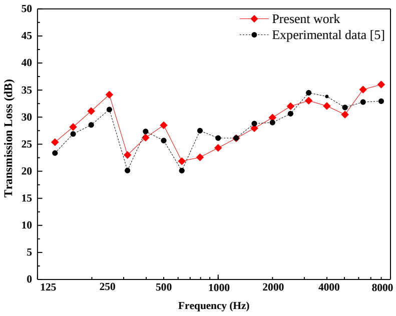


Figure 3. Comparison of the transmission loss of the SEA with Kang's experimental data [5]

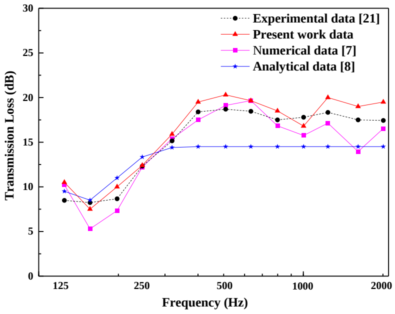


Figure 4. Comparison between tranmission loss of the present SEA model and numerical simulation of Yu et al. [7] and anlytical model of Bajraktari et al. [8]

The results show that the proposed SEA model inherites the simplcity from analytical models and accuracy from numerical methods. The mean deviation for SEA model is 1.37 dB. Also, the mean deviations for numerical and analytical models are 1.33 and 2.66 dB, respectively.

As previously stated, the air channel in the ventilated window deteriorates its acoustic performance. In order to better understand quantitatively, a comparison was made between the transmission loss of the ventilated window and conventional double-glazed window as shown in Figure 5. It can be seen that transmission loss difference in low frequency is small and the effect of the inlet an outlet is less relevant but is of increasing importance as increasing frequency. It means that the airflow channel in the ventilated window significantly decreases the sound insulation of the window in high frequencies. The boundary between these two regions is frequency-independent and relies on the relative magnitude of the transmission coefficient of the panels, and slits. Moreover, the ventilated window damps the fluctuations of the TL curve, especially in resonance frequencies. Also, considering slits wider leads to approach the TL curve to a plateau of 0 dB [7].

In order to evaluate the adequacy of the ventilated window to insulate indoors from outdoors and provide the indoor acoustic comfort due to outdoor airborne noise, the traffic noise spectrum in the region where the window is installed should be available. The three primary sources of noise pollution in cities are road, railway, and airplane traffic noises.

Determination of traffic noise level is function of great deal of factors such as vehicle type (airplane, train, cars), traffic flow characteristics (acceleration, deceleration, cruise and …), noise propagation characteristics (density of buildings, diffraction and reflection, ground effect and …), road characteristics (road surface and tyre, road wetness, temperature and …) [22].

However, comparing the measured traffic noise in many studies shows that the noise spectral shapes are similar and the sound level concentrates around a peak at 800-1000 Hz [22].

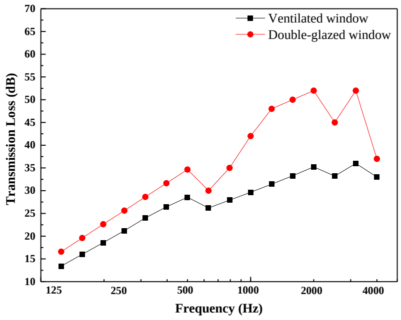


Figure 5. comparison of the transmission loss of the ventilated window with the conventional double-glazed window

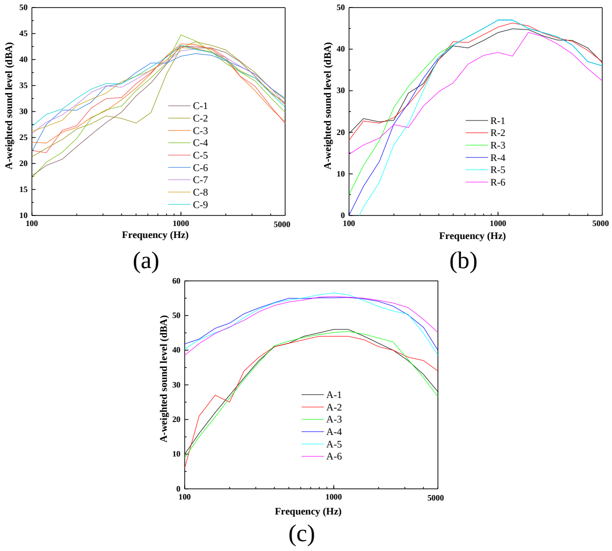
Figure 6 indicates three types of traffic noise spectra, road, railway and airplane, measured by different works [23–26]. Cars, railway and airplane traffic noise spectra are denoted by "C-X", "R-X" and "A-X", respectively where X is the sample number. Details of the sample spectra are available in the references given. In this work, these sample noise spectra were used to assess the acoustic performance of the ventilated window.

Subtracting the traffic noise spectrum from transmission loss of the ventilated window leads to the indoor sound level spectrum. Criteria evaluating acoustic comfort and presented by associated standards are based on single-number rating. For this study, two single-number ratings of Noise Rating (NR) and A-weighted sound level were calculated and compared to the maximum recommended values specified in ISO 1973 and ANSI 12.2 [27]. For office recommended NR is 35 and recommenced A-weighted sound level is 44. It is noteworthy the A-weighted is more suitable for office According to Ryhed [28].

NR and $L_{A\text{-weighted}}$ corresponding to three categories of traffic noise sources for the ventilated window configuration are obtained as Tables of 1 to 3. The results show the acceptance of indoor sound level and providing the acoustic comfort for the noise spectra. The airplane traffic noise makes the most dissatisfaction whilst the quietest indoor environment is provided by the road traffic noise.

4. 1. Parametric Study of the Ventilated Window

Geometry has an essential role in the acoustic performance of the ventilated window. The proper geometrical design of the ventilated window can efficiently improve its functionality.



(a) (b)

(c)

Figure 6. The sample traffic noise spectra [20-23]. (a) cars traffic noise spectra; (b) Railway traffic noise spectra; (c) Airplane traffic noise spectra

TABLE 1. NR and $L_{A\text{-weighted}}$ for sample spectra of Cars Traffic Noise (CTN)

Sample	C-1	C-2	C-3	C-4	C-5	C-6	C-7	C-8	C-9
NR	11	11	12	13	11	9	10	11	11
$L_{A\text{-weighted}}$	18.9	18.8	20	19.9	20	20.6	20.8	20.6	21.5

TABLE 2. NR and $L_{A\text{-weighted}}$ for sample spectra of Railway Traffic Noise (RTN)

Sample	R-1	R-2	R-3	R-4	R-5	R-6
NR	12	14	15	15	15	9
$L_{A\text{-weighted}}$	21.8	22.9	23.9	23.8	23.7	18

TABLE 3. NR and $L_{A\text{-weighted}}$ for sample spectra of Airplane Traffic Noise (ATN)

Sample	A-1	A-2	A-3	A-4	A-5	A-6
NR	14	12	14	24	25	24
$L_{A\text{-weighted}}$	23.8	23	23.5	36.4	36.37	35.85

In the present study, the effect of the geometry characteristics (including the channel thickness, the thickness and aspect ratio of the glass, and the inlet and outlet width) on the sound insulation was investigated. The output considered for evaluation is Sound Transmission Class (STC) calculated in accordance with ASTM E413 and ISO 717 as representative of sound insulation of the ventilated window.

Figure 7 shows the effect of glass aspect ratio on STC. As can be seen, the sound insulation of the ventilated window has the direct dependence on aspect ratio. In this case, STC increases by 4 dB as aspect ratio changes from 0.5 to 2. The reason for this effect is that the inlet and outlet area reduces as aspect ratio increases and thus one of the sound transmission paths becomes tighter. In addition, as the window height increases, the view factor between the inlet and outlet decreases and consequently increases the sound insulation.

The effect of the channel thickness is described in Figure 8. As shown, the sound insulation of the ventilated window is enhanced by increasing the channel thickness, so that STC is improved by 18 dB when the channel thickness increases from 1 cm to 20 cm. As sound is transmitted through the glasses according to double panels and through the channel and openings, the channel thickness has the opposite effects on these two paths of sound transmission: In double panels, doubling channel thickness increases 6 dB transmission loss [18]. In other hand, an increase of channel thickness increases the view factor between the inlet and outlet of the channel and decreases the transmission loss of the window. As the effect of double panel mechanism is stronger, STC increases by increase of the channel thickness.

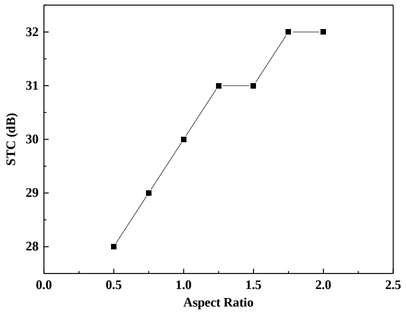


Figure 7. The effect of glass aspect ratio on STC

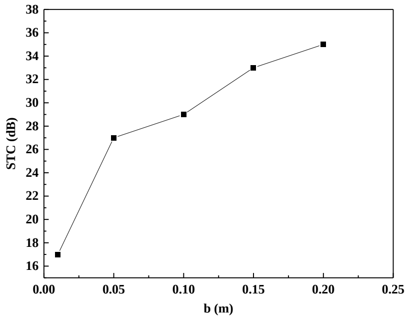


Figure 8. The effect of channel thickness on STC

Inlet and outlet width is another factor influencing the window performance. In the present study, both inlet and outlet widths are assumed the same. As depicted in Figure 9, STC declines as increasing the opening size. The predominance of the direct sound transmission through openings with increasing the opening size is the main reason for the descending trend. Widening the openings from 1 to 20 cm results in 9 dB decrease of STC.

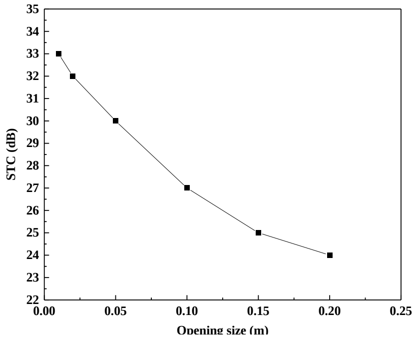


Figure 9. The effect of opening size on STC

5.CONCLUSION

In this paper, the acoustic performance of the ventilated window was investigated using a novel model based on Statistical Energy Analysis (SEA) considering the effects of attenuation in the channel and slit-like behavior in the inlet and outlet of the ventilated window. A comparison was first made between the proposed SEA model and the numerical and analytical models available in the literature to assess the effectiveness of the SEA. Then indoor acoustic comfort resulted from the sound transmission loss of the ventilated window and the outdoor traffic noise spectra, including car, railway and airplane spectra was evaluated using the proposed model. Finally, a parametric study was done to investigate the effect of the geometry characteristics (including the channel thickness, the thickness and aspect ratio of the glass, and the inlet and outlet size) on Sound Transmission Class (STC) as representative of the sound insulation. he results are as follows:

1. Comparing the results of the proposed SEA model and numerical and analytical models showed that the proposed model predicts transmission loss of the ventilated window as well as a numerical model. However, the analytical model underestimates TL in mid-to-high frequency range and reaches a constant for frequencies higher than 500 Hz. The main reason for the deterioration of the analytical model results is that the proposed SEA model considers the slit-like effect of the inlet and outlet of the ventilated window and the channel attenuation while the existing analytical model ignores these effects.
2. The proposed SEA model presents reliable and accurate results while reducing the time and computational costs of the numerical and experimental methods. These feature along to the simplicity makes the SEA model a robust alternative for the assessment of the acoustic performance of the ventilated window.
3. The comparison of TL for the ventilated window and double-glazed window revealed that the sound insulation of the ventilated window is deteriorated and is capable of increasing the indoor acoustic discomfort. This deterioration is enhanced in high frequency.
4. In order to check if the ventilated window can provide indoor acoustic comfort, the outdoor noise spectra were categorized as cars, railway and airplane traffic noise. The measured noise spectra reported in the literature were also collected. The observation showed the similarity of the spectra trends and sound level concentration around peak at 1000 Hz. Subtracting the outdoor noise spectra from sound transmission loss of the ventilated window results in the indoor noise spectra by which the acoustic comfort criteria of NR and $L_{Aweighted}$ were calculated. It was found that all selected noise spectra make NR and $L_{Aweighted}$ below the maximum values and do not disturb the acoustic comfort near the window.
5. Finally, a parametric study was done by which the effect of the geometry characteristics (including the channel thickness, the thickness and aspect ratio of the glass, and the inlet and outlet size) on Sound Transmission Class (STC) as representative of the sound insulation was investigated. It revealed that increasing the aspect ratio and channel thickness leads to STC increase while widening the opening size reduces the STC.

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Prediction of Noise Transmission Loss and Acoustic Comfort Assessment of a Ventilated Window using Statistical Energy Analysis

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چکیده

در مقاله حاضر یک روش تحلیلی نوین بر مبنای رویکرد تحلیل آماری انرژی برای ارزیابی عملکرد صوتی پنجره تهویه شونده توسعه داده شده است. روش پیشنهادی با مدل‌های عددی و تحلیلی موجود برای پیش‌بینی انتقال صوت پنجره تهویه‌شونده مقایسه شد که نتایج حاکی از برتری و موفقیت این روش در پیش‌بینی عملکر صوتی پنجره تهویه‌شونده با کاهش هزینه‌های محاسباتی و دقت قابل قبول است. لحاظ کردن اثر دهانه‌های ورودی و خروجی و میرایی کانال پنجره تهویه‌شونده از ویژگی‌های متمایز روش پیشنهادی نسبت به سایر مدل‌های تحلیلی موجود است. در این مقاله همچنین کارایی پنجره تهویه‌شونده در تأمین آسایش آکوستیکی فضای داخل با توجه به انواع مختلف طیف نوفه ترافیکی محیط بیرون و تلفات صوتی پنجره بحث گردید که نتایج حاکی از مقبولیت تراز صوتی محیط داخل ناشی از پنجره تهویه‌شونده است. همچنین برای تشخیص نحوه تأثیرگذاری فاکتورهای مؤثر بر عملکرد صوتی پنجره تهویه شونده، اثرتغییرات سه فاکتور نسبت منظر ، ضخامت کانال و اندازه دهانه‌های ورودی و خروجی پنجره بر شاخص کلاس انتقال صوت مطالعه شد. نتایج نشان داد که پنجره تهویه شونده با نسبت منظری و ضخامت کانال بیشتر مقادیر کلاس انتقال صوت بالاتری به همراه دارد در حالی‌که افزایش اندازه دهانه ورودی و خروجی منجر به کاهش کلاس انتقال صوت و تضعیف عملکرد صوتی پنجره می‌شود.

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