Improving the airborne sound insulation properties of vacuum insulating glazing using dissimilar pane thickness and a laminated pane: experimental results

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Abstract. Vacuum insulating glazing (VIG) is a relatively new glazing technology that was first developed primarily for its thermal insulation properties. This research aims to continue a preceding study about the acoustic performance of VIG and to analyse the effects of dissimilar thickness and additional damping to the sound insulation performance of VIG. In this research, the airborne sound insulation performance of VIG is examined with theoretical and experimental approaches. Sound insulation performance was measured using the field sound intensity method for 5 configurations of VIG. Measurements were well-predicted by theory at low frequencies, where it is mostly governed by the mass-law with additional corrections. Sound insulation performance was heavily affected by the coincidence dip, and using dissimilar thickness in the VIG does not alleviate the problem. Additional damping affects the coincidence behaviour of the VIG, shifting the critical frequency and increases the sound insulation performance at and above the critical frequency with improvements up to 9 dB.

1. Introduction

As sustainability efforts in the built environment are rising, more novel ways are currently being developed to reduce energy consumption. Generally, windows are the weakest insulating element in a building’s façade due to its relatively high thermal transmittance (U-value) compared to other building elements (1). Even though windows contribute to 30%-60% of a building’s energy loss (2) (3), they also provide a huge potential to provide large amounts of energy savings by using glazing systems that have a high thermal insulation. This could be achieved by using state-of-the-art technology such as vacuum glazing, which can provide minimum heat loss in a slimmer construction.

Vacuum insulating glazing (VIG) is a relatively new glazing technology that is first developed primarily for its thermal insulation properties (4). It is made of two parallel pieces of glass separated by an array of support pillars (or spacers) with an evacuated space between which is hermetically sealed at the edges using solder glass.

The sparse literature available about the sound insulation performance of vacuum glazing means that this is still an ongoing field of research. A prior study by Cabrera, Ashmore and Kocer (5) investigated the acoustic performance of several commercial VIG products and comparing them to monolithic pieces of glass. Measurements showed that the VIG behaves like a single glazing construction in the low
frequencies, following the mass-law principle of an equivalent monolithic piece of glass with equal surface density to the VIG. Measurement results also correspond well with Asano et al.’s (2) findings about the VIG’s behaviour in the coincidence frequency, i.e., that the coincidence dip occurs at the same frequency as for a single constituent pane from the VIG assembly. It is also found that the coincidence dip can be greatly reduced by clamping another piece of glass into one of the glass panes, creating an asymmetric configuration with one side considerably thicker than the other. The additional glass pane introduces additional damping into the VIG, reducing the depth of the notch in the coincidence frequency which subsequently improves its single number ratings. It also shifts the coincidence frequency to that of the clamped pane pair, suggesting that behaviour near the coincidence frequency is influenced more by the thicker of the two layers of glass (as has been observed in double glazing).

This research aims to continue Cabrera, Ashmore, and Kocer’s work and to investigate their hypothesis by measuring several VIG configurations with different thicknesses and damping, and observing their sound insulation performance as well as their single number quantities. This study would also lead to a more general understanding of the acoustic properties of VIG, and to propose improvements in the design to provide better sound insulation.

2. Airborne Sound Insulation in Vacuum Insulating Glazing

The sound insulation properties of vacuum glazing may be approximated as that of a single isotropic panel as pointed out in previous studies (2) (5). Sound insulation is dependent on a panel’s mass, stiffness, damping, and dimensions – with each component affecting different regions across the whole frequency range (6). In the very low frequencies, sound reduction would be mainly determined by the stiffness as well as the physical dimension of the panel. Resonances can occur in a panel with finite size in the so called fundamental frequency $f_{1/1}$. In this frequency, the sound reduction will be at its lowest point, although usually this is outside the frequency range of interest.

Above the fundamental resonance frequency, sound reduction would generally increase as a function of its surface density. The sound reduction performance in this region can be estimated using several approaches, and for this study the field incidence sound reduction is shown in Equation 1 (7), where $f$ is frequency (Hz) and $\rho_s$ is the surface density of the panel (kg/m$^2$).

$$ R = 20 \log_{10}(f \rho_s) - 48 \text{ dB} $$

(1)

The sound reduction continues to increase until it approaches the critical frequency $f_c$, where the wavelength of the incident sound on the panel is equal to the wavelength of the bending waves within the panel (7). Since the maximum and minimum peaks of the wavelengths are spatially matched, the resulting sound energy is easily transmitted through the panel (8), resulting in a significant decrease in sound reduction performance and can be estimated using Equation 2,

$$ f_c = \frac{c_0^2}{2\pi h} \sqrt{\frac{12(1-\sigma^2)\rho_p}{E}} \text{ Hz} $$

(2)

Here, $c_0$ is the speed of sound (m/s), $h$ is the panel thickness (m), $\sigma$ is Poisson’s ratio, $\rho_p$ is the panel density (kg/m$^3$), and $E$ is the Young’s modulus (Pa). Substituting the relevant constants of glass into Equation 3 results in a simple approximation (7):

$$ f_c \approx \frac{12}{h} \text{ Hz} $$

(3)

After determining the critical frequency, the sound reduction index at that point can be estimated using Equation 4 (8):

$$ R_{f=f_c} = 20 \log_{10} \left( \frac{\omega \rho_s}{2\rho_p c_0} \right) + 10 \log_{10} \left[ \frac{2}{\pi} \frac{\Delta f}{f_c} \right] \text{ dB} $$

(4)

Where $\eta$ is the panel’s damping coefficient / loss factor, and $\Delta f$ is the bandwidth (Hz). Just below the critical frequency, the sound reduction index is estimated by drawing a straight line between the mass-law curve at $f_c/2$ and the estimated sound reduction index calculated by Equation 5. At and above
the critical frequency, sound reduction is mostly governed by the damping properties of the panel as indicated by the $\eta$ variable. The sound reduction above the critical frequency is given by Equation 5 (9):

$$R = 20 \log_{10} \left( \frac{\omega \rho_s}{2 \rho_0 c_0} \right) + 10 \log_{10} \left( \frac{\eta f}{f_c} \right) + 10 \log_{10} \left( 1 - \frac{f_c}{f} \right) - 44.5 \text{ dB}$$ (5)

3. Measurement Method

3.1. Quantitative assessment of airborne sound insulation

Sound reduction index, or $R$, is defined as the ratio of sound power incident on the panel to the sound power that is transmitted through the specimen. This study uses the intensity method in accordance with ISO 15186-2 (10). The sound reduction index for the intensity method ($R_I$) is calculated according to Equation 6, where $L_p$ is the average sound pressure of the source room, $L_I$ is the measured sound intensity that is transmitted into the receiving room, $S_m$ is the measurement area and $S$ is the specimen area.

$$R_I = L_p - L_I - 6 + 10 \log \left( \frac{S_m}{S} \right)$$ (6)

In the ISO standard, the Waterhouse correction is applied to the calculation to avoid an underestimation of the low-frequency sound reduction performance. It is calculated by Equation 7, where $S_b$ is the area of the boundary surfaces in the receiving room ($m^2$), $V_2$ is the receiving room volume ($m^3$), and $\lambda$ is the wavelength of the frequency that is calculated (m).

$$K_c = 10 \log \left( 1 + \frac{S_b \lambda^2}{8V_2} \right) \text{ dB}$$ (7)

Thus, the complete modified intensity sound reduction index $R_{IM}$ would be:

$$R_{IM} = L_p - L_I - 6 + 10 \log \left( \frac{S_m}{S} \right) + K_c$$ (8)

3.2. Measurement Setup

3.2.1. Measured Samples

In total, 5 samples of VIG were prepared with various combinations for the thickness of the glass pane. Two samples had identical pane thickness, with 3 mm (3V3) and 5 mm (5V5) for each pane. One VIG sample was made from a combination of 3mm and 5mm panes (3V5) to test the hypothesis regarding the dissimilar thickness. The last two samples were 3V3 VIG samples combined with a single sheet of monolithic glass with a PVB interlayer in-between (3V3L3, 3V3L5) to investigate how damping affects the sound insulation performance of VIG. All VIG samples were provided by a Japanese manufacturer.

3.2.2. Laboratory Arrangement

The VIG samples were mounted in the wall between the reverberation room and the general laboratory area (Figure 1). The samples were mounted in the test aperture measuring 1200 mm x 640 mm. The samples were sealed around the edges with closed-cell foam tape, and were tightly clamped into the aperture using metal strips with additional closed-cell foam tape. Each sample was clamped at the source room side, creating a constant shallow niche with a depth of 150 mm from the receiving room.

The six microphones were used to measure the sound pressure level in the source room and were distributed in the room adhering to ISO 15186-2. Since the rooms were in reality not perfectly diffuse, the sound pressure level at the source must be measured at a number of locations and then averaged (11), to obtain a spatially averaged sound pressure level used to determine the sound reduction index of the VIG samples. The microphones were also set in different heights to obtain a better spatial averaging of the room.
Figure 1. General arrangement of the measurement setup.

The two Turbosound TA-500 loudspeakers were used as the primary sound source. The loudspeakers were placed in the corners of the source room as shown in Figure 2, and each of the sound sources produced steady state mutually incoherent pink noise. Since the two channels are not correlated with each other, destructive interference between the two sources could be ignored, rendering the sound field to be homogenous and isotropic and the average squared pressures within the rooms to be additive (12). The spatially averaged sound pressure level in the source room was kept around 112 dB for all measurements. The 6 microphones and two sources that were used are equivalent of 12 source-receiver combinations for each measurement. Acrylic diffusers measuring at 1.22 m x 0.92 m were distributed pseudo-randomly within the room to improve the diffusivity of the sound field by redirecting the incident sound energy, which increases the sound field isotropy.

3.2.3. Measurement Procedure
The transmitted sound intensity was measured in the receiving room using a pair of ½-inch B&K 4197 microphones that are connected to a handheld B&K 2260 Investigator. A 12-mm spacer was chosen for its suitable range from 100 Hz – 5 kHz, which is of particular interest for this research.

The average sound intensity level, $L_I$, was measured on the receiving side of the VIG sample by scanning the intensity probe continuously over the measurement surface at a fixed distance. Measurements were made with the intensity probe’s orientation normal to the measurement surface. Absorptive panels were also placed around the opening on the receiving room side (Figure 2). This is mainly to optimise the condition of the sound field from background noise as well as to avoid the intensity probe registering negative intensity from sound that is reflecting back into the probe.

Background noise measurements were made before each measurement, and a signal-to-noise ratio of at least 15 dB was always maintained at every frequency band. In total, each VIG sample was measured a minimum of 4 times with different source-receiver combinations. This was done to reduce the uncertainty that can be caused by measurement errors from various factors. Results were then averaged to obtain 1/3-octave band sound insulation performance and to determine the single number quantities.

4. Measurement Results

4.1. Single VIG
Measurement results showed that the VIG is in good agreement with the mass-law theoretical predictions following the combined panel surface density as per equation 2. A significant dip in the critical frequency is still present in all samples. For the 3V3 and 5V5 sample, the critical frequency closely follows the theoretical prediction for 3 mm glass and 5 mm glass respectively.

The 3V5 sample produces an interesting result; the measured critical frequency does not match the predicted critical frequency of the thicker glass (5 mm), as per the initial hypothesis. By observing Figure 3, it is clearly seen that the measured coincidence dip frequency lies between the predicted values for 3 mm & 5 mm glass, which means that the 3V5 sample has a similar effective critical frequency as 4 mm glass. In addition, using a dissimilar glass thickness does not significantly reduce the depth of the dip.
4.2. Laminated VIG
Likewise, with the measurement results for the single pane VIG, the laminated composite VIG samples are also in close agreement with the mass-law prediction calculated from equation (4) as observed from Figure 4. It is also noted that since the laminated VIG are thicker than the single VIG, higher sound reduction indexes are expected because of the increased surface density.

Prediction of the critical frequency for the laminated composite VIG is much more difficult compared to the individual VIG samples. For the 3V3L3 sample, the predicted critical frequency is off by two 1/3 octave bands as shown in Figure 4. The same pattern is also observed in the 3V3L5 sample, with the measured critical frequency corresponds to that of a 5 mm glass.

The additional effects of laminated glass can also be observed by comparing it with Cabrera, Ashmore, and Kocer’s results (5). From Figure 4, we can observe that the 3V3+3 has two dips that are visible, one at 2000 Hz and another one at 4000 Hz. Those frequencies correspond to the critical frequencies of 6 mm and 3 mm glass respectively. Also, there is a small dip present in 1250 Hz for the 3V3+6 sample, which correspond to the theoretical critical frequency of a 9 mm glass. It appears that combining the glasses together creates an additional coincidence dip that corresponds to the thickness of the clamped pane. By comparing it to the sound reduction indexes of the laminated composite VIG from this research, it can be said that adding an intermediate layer would improve the sound reduction performance as well as shifting the coincidence dip to higher frequencies.
The added intermediate layer affects the depth of the coincidence dip considerably. Improvements of 8-9 dB are achieved when the laminated VIG is compared with the 5V5 sample, which has a similar thickness (9 mm for the 3V3L3 and 11 mm for 3V3L5, compared to the combined 5V5 thickness of 10 mm). These findings agree with the reported 8-11 dB improvement in laminated glass by Marsh (13).

4.3. Single Number Quantities

Table 1 shows the single number quantities (SNQ) that are obtained from the measured sound reduction indexes. Interestingly, the single VIGs more or less produce the same numbers even though the samples are different in thickness. The thicker sample should have a better sound insulation performance, but this added value is offset by the large dip at the critical frequency that lowers the performance significantly. This is also proven by the STC ratings that are 3-4 dB lower than their respective $R_w$ counterparts for these samples, as the 8 dB maximum deviation rule for STC plays a prominent part in lowering the STC values. Even so, the SNQ of these samples are comparable to that of an insulating glass unit that consists of 10 mm & 6 mm float glass with an air gap between 6 mm - 16 mm (14).

| VIG Sample | $R_w (C, C_n)$ | $R_w + C_n$ | STC |
|------------|----------------|-------------|-----|
| 3v3        | 35 (-1, -3)    | 32          | 31  |
| 3v5        | 35 (-3, -3)    | 32          | 31  |
| 5v5        | 35 (-3, -2)    | 33          | 32  |
| 3v3L3      | 38 (-1, -4)    | 34          | 38  |
| 3v3L5      | 38 (-1, -3)    | 35          | 38  |

The laminated VIG produces respectably high single number values considering its thickness. Values are close to those for 19 mm monolithic glazing (15) which is almost double the thickness. Values are also comparable to an insulating glazing configuration of 6 mm and 8 mm laminated glass with a 16 mm air gap filled with argon gas (14). For laminated VIG, the STC values match the $R_w$ values due to the absence of a large coincidence dip as opposed to the single VIG.

5. Discussion

The general sound insulation performance of VIG has been reasonably predicted using an approximation from an isotropic thin panel. Experimental results have shown that the VIG will follow the mass-law depending on its surface density in the low frequencies, and exhibiting a reduced performance in the higher frequencies which is affected by bending waves.

Cabrera, Ashmore, and Kocer’s hypothesis of improving the sound insulation performance of VIG by using a dissimilar thickness was tested with the 3V5 VIG sample, and improvements in the $f_c$ are not as expected by the hypothesis. The original thought of using a dissimilar thickness is based on reducing mutually-reinforced bending waves due to the matched thickness of the individual panes. Since one of the panes is only 2 mm thicker, the difference in bending wave speed in this configuration might be insufficient to remove the constructive interference. Assessing the SNQ also showed that there was no improvement, with the 3V5 VIG showing a lower $C$ correction factor than the 3V3 sample.

Results shown that adding an intermediate resilient layer into a VIG construction is beneficial in increasing the sound reduction index at high frequencies. The coincidence dip is still present, but it has been greatly reduced due to the added damping by the intermediate layer. Direct improvements to the sound insulation performance are evident, especially above the critical frequency.

An interesting observation from the measurement results is that the $f_c$ for the laminated VIG samples does not follow the prediction of the $f_c$ of a combined pane thickness. The measured $f_c$ is two 1/3-octave bands higher than the predicted values, which may be affected by the additional damping that is introduced into the glazing. Further investigation is required to predict the coincidence behaviour in laminated VIG.
VIG offers a reasonable sound insulation performance even though it was developed primarily for its excellent thermal properties. Although the sound insulation performance in the lower frequencies and at the critical frequency is still a concern, incorporating the VIG into a double glazing or even triple glazing construction should improve both of its acoustic and thermal performance significantly, which would make VIG an excellent choice for a high-performing façade in a sustainable environment.

6. Conclusion
Methods for improving the airborne sound insulation performance of VIG has been explored to a certain degree of success. Five VIG samples with different configurations have been analysed with theoretical and experimental approaches. The hypothesis that using a dissimilar pane thickness would improve the sound insulation performance of VIG has not been thoroughly proven, and further testing is required to fully understand its potential benefits. The addition of an intermediate resilient layer in the VIG construction significantly improves the sound insulation performance in the higher frequencies. The coincidence behaviour of laminated VIG is affected by the additional damping, reducing the coincidence dip and shifting its critical frequency. The overall conclusion is that further studies must be made to obtain a more thorough understanding of the sound insulation performance of VIG, especially concerning the damping properties.

7. References
[1] Cuce E and Cuce P M 2015 Vacuum glazing for highly insulating windows: Recent developments and future prospects. Renewable and Sustainable Energy Reviews 54 pp 1345–1357
[2] Asano O, Misonou M, Kato H and Nagasaka S 1999 Advanced window incorporating vacuum glazing In SPIE Conference on Solar Optical Materials XVI (Denver: Colorado)
[3] Jelle BP, Hynd A, Gustavsen A, Arasteh D, Goudey H and Hart R 2012 Fenestration of today and tomorrow: A state-of-the-art review and future research opportunities Solar Energy Materials & Solar Cells 96 pp 1-28
[4] Collins RE, Turner GM, Fischer-Cripps AC, Tang JZ, Simko TM, Dey CJ, et al 1995 Vacuum Glazing - A New Component for Insulating Windows Building and Environment Vol 30 No 4
[5] Cabrera D, Ashmore N and Kocer C. 2016 Airborne sound insulation of vacuum insulating glazing: General observations from measurements. Building Acoustics Vol 23 (3-4) pp 193-206
[6] BSI. BS EN ISO 15186-2:2010 Acoustics — Measurement of sound insulation in buildings and of building elements using sound intensity Part 2: Field measurements. 2010.
[7] Dijckmans A and Vermeir G 2013 Numerical Investigation of the Repeatability and Reproducibility of Laboratory Sound Insulation Measurements Acta Acustica United with Acustica Vol 99
[8] Jacobsen F 2011 The sound field in a reverberation room Lyngby (Denmark: Technical University of Denmark)
[9] Marsh J 1971 The airborne sound insulation of glass: Part 2 Applied Acoustics 4
[10] Pilkington UK Ltd. Pilkington Optiphon™ Laminated Glass for noise control. 2014.
[11] Viridian Glass. Viridian Glass. [Online]. 2017. Available from: http://www.viridianglass.com/~media/viridian-glass/files/downloads/tech-direct/sound-and-noise.pdf.

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