ACOUSTIC PROPERTIES OF VACUUM INSULATING GLAZING

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Abstract

Vacuum Insulating Glazing (VIG) is a technology that is capable of meeting increasingly stringent global standards for low thermal emittance (*U*-values) windows in the built environment; however, little acoustic data is available to describe the sound insulation performance of this approach to glazing. Rhetoric suggests that the vacuum element greatly improves sound insulation compared with conventional windows, which suggests the need for an investigation to test the hypothesis that VIG provides superior acoustic performance compared to monolithic glass of equal thickness. Sound reduction index (R) values were measured using the field sound intensity method (ISO 15186-2). Measurements correspond well with theory and reference data above 250 Hz, where the performance is determined by a combination of mass-law behaviour and a coincidence dip around the critical frequency. The results suggest that the mass-law behaviour is well predicted from the VIG's surface density (equivalent to a monolithic panel) and the coincidence dip is well predicted from the critical frequency of the individual layers of the VIG unit.

1. Introduction

This work was launched to answer the following question: Does an acoustic performance benefit exist in Vacuum Insulating Glazing (VIG) as compared to a monolithic glass pane of equal thickness? A body of research into VIG and its thermal transmittance, known as the *U*-value, suggests that it is a technology with the potential to meet future building standards and have a large impact on energy conservation in the built environment [1]. Although a large volume of data on the thermal benefits of this technology exists, little data is available that pertains to the acoustic performance of this glazing approach.

It is well understood that the main energy loss in sealed buildings is due to transmittance through the façade, which includes all components of the building envelope. Glass is typically the weakest insulation point: it is through the windows that up to 60% of total energy loss occurs [2]. VIG is a technology that has been in development since 1988 at the University of Sydney for the purpose of improving the efficacy of building envelopes by reducing thermal losses through glass elements. Their construction consists of two panes of glass with an evacuated gap that has been hermetically sealed around their perimeter. Similarly to traditional glazing, low-emittance coatings are applied to one or both panes of glass to significantly reduce surface-to-surface radiation between the paired glass panes. Since evacuating the gap between the glass panes produces a surface load of atmospheric pressure, an array of support spacers is required between the panes to prevent the glass from collapsing into contact. A typical VIG that is 1 m^2 uses an array of 2600 pillars with a 0.5 mm diameter, made of high strength steel (See Figure 1). While it might be tempting to think that the vacuum in VIG would deliver good acoustic insulation, these spacers must be considered for their potential to transmit vibration. Since the spacers directly couple the glass panes, it is important to characterise their impact on vibration within the construction.

The *U*-value of a building element describes its thermal conductance, and is the energy transfer through 1 m^2 for one degree of temperature difference, with the unit of measurement expressed as Watts per square metre per Kelvin. This thermal conductance is considered "air-to-air" and takes into consideration heat transfer from the glass to the surrounding environment. The long term target is to bring window construction to levels below 1 W m^{-2} K^{-1}, approaching that of a brick wall. The typical window *U*-value of a single glazed window is about 6 W m^{-2} K^{-1}, while an air-filled double glazed window with low-emittance (infrared reflecting) coatings and frame would typically have a *U*-value of about 1.2 W m^{-2} K^{-1}. Further improvements are possible using similar triple glazed constructions and heavier gases, with a *U*-value of about 0.4 W m^{-2} K^{-1}, roughly the practical lower limit. Double and triple glazing units typically have a minimum gap of 8 mm between panes, but can be manufactured with as much as 200 mm for optimised acoustic performance, often filled with a heavier gas such as Argon, or the more expensive Krypton and Xenon, for optimised performance. The VIG represents an improvement in lowering thermal emittance to similarly thick single glazing and larger double glazing units. *U*-values range between 0.8 to 1.2 W m^{-2} K^{-1} depending on double or single low-emittance coatings, respectively. As the glass panes are typically 3 mm or 5 mm thick per pane, with a 0.2 mm gap, overall constructions are comparable in thickness to single glazing and therefore extremely useful to the retrofit market.

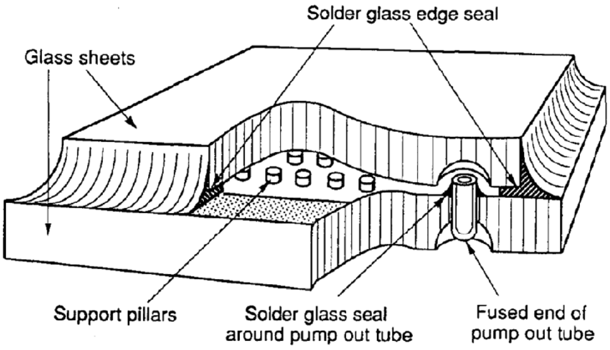

Figure 1 – Schematic diagram of Vacuum Insulating Glazing (Source: Collins and Simko, 1998 [1])

2. Acoustic Properties of Vacuum Insulating Glazing

Limited acoustic data is available for the VIG and the small amount of published material online does not provide the standards with which they were measured [3]. The fact that sound cannot exist in an absolute vacuum is the likely reason that VIG is cited for its excellent acoustic performance [4] over monolithic glass. Non-radiant thermal and acoustic energy require a medium to travel through, and an absolute vacuum inhibits the transfer of energy from pane to pane, provided there is no mechanical coupling. In a related study, Walters and Dance [5] discuss an impedance mismatch between the air and vacuum caused by vastly differing pressures that results in a reflected component. By evacuating a space, the reflected component can be increased, thereby reducing the transmission based on the law of conservation of energy. The VIG panels at the University of Sydney are evacuated to a pressure of about 1 milli-Torr or 0.13 Pa (ambient atmospheric pressure is in the vicinity of 101.3 kPa).

The acoustic properties of finite isotropic panels have long been investigated and the basic laws and theories pertaining to them are considered when investigating VIG. Calculations were performed to predict the acoustic performance of 3 mm, 6 mm and 10 mm monolithic samples, as well as 3 mm-Vacuum-3 mm (3V3) and 5 mm-Vacuum-5 mm (5V5) VIG samples. Finite isotropic panel acoustic performance is based on four material properties: mass, dimensions, longitudinal wavelength and damping. The frequency at which the speed of sound in a particular medium and that of its surrounding medium are equal is known as the 'critical frequency'. For airborne sound insulation, the speed of bending waves increases with frequency, whereas the speed of sound in air is independent of frequency. The critical frequency also represents the lowest coincidence frequency, whereby at grazing incidence (parallel), an acoustic trace wavelength is equal to the bending wavelength in the panel. Acoustic energy at this frequency drives a bending wave in the panel and propagates a corresponding acoustic wave on the other side. The critical frequency (f_c) is expressed by [6]:

$$f_c = \frac{c^2}{1.8 \times c_L \times h} \text{ Hz} \tag{1}$$

where c_L is the longitudinal wave speed in the panel and h is it's thickness. c_L is calculated as follows: [7]

$$c_L = \sqrt{E}[\rho_m(1 - v^2)] \ m/s \tag{2}$$

Here, E is Young's Modulus in N/m^2, ρ_m is the panel density in kg/m^3 and v is Poisson's ratio. Substituting the properties of the soda-lime glass used in all samples tested in the present study gives the longitudinal wave speed:

$$c_L = \sqrt{6 \times 10^{10}}\,[2500\,(1 - 0.21^2)] = 5100 \text{ m/s} \tag{3}$$

The region below $f_c/2$ is mostly controlled by the mass of a panel and resonances. The field-incidence mass law is suggested by Sharp [8] to be the best predictor of field measurements. It is based on a spatial integral limited to an 85° angle of incidence (rather than a half-space, or 90°, integral which is not a good representation of how practical diffuse fields in reverberant rooms impinge on the panel), expressed in equation (4):

$$R_{FIELD} = 20 \log \left[1 + \left(\frac{\omega \rho_s}{2\rho c}\right)\right] - 5 \text{ dB} \tag{4}$$

Here ρ_s is the surface density of the glazing in kg/m^2, while ρ and c are the density of air and the speed of sound in air, respectively (the product of which is the characteristic impedance of air). Sound reduction index, R, is the ratio of incident to transmitted acoustic energy, expressed in decibels. Resonances are caused by the bending stiffness of a panel and its dimensions that produce standing waves at certain frequencies due to edge reflections and can be calculated:

$$f_{m,n} = 0.45 \times c_L \times h \left[\left(\frac{m}{l_x}\right)^2 + \left(\frac{n}{l_y}\right)^2\right] \qquad m, n = 1,2, \ldots \text{ Hz} \tag{5}$$

Evaluating equation (5) with panel dimensions ($l_x = 1.24$ m, $l_y = 0.72$ m), yields low order resonance frequencies for the panels in this experiment well below the range of interest for weighted sound reduction index, R_w. The calculations in this section are summarized in Table 1. Sharp extends the model by approximating a straight line between $f_c/2$ and f_c. At the point of the critical frequency and above, the following formula describes the behaviour of the coincidence dip:

$$R = 20 \log_{10} \pi f m/(\rho c) + 10 \log_{10} [2\eta f/(\pi f_c)] \text{ dB} \tag{6}$$

Here we see that the new parameter introduced is the frequency dependent loss factor (η) which controls the magnitude of sound reduction in the coincidence region (due to internal energy loss within the panel).

Five test samples were measured; two VIG samples and three monolithic samples (for comparison). The monolithic samples had thicknesses of 3, 6 and 10 mm, and the VIG samples were

3V3 (two 3 mm layers separated by a vacuum with support pillars) and 5V5 (two 5 mm layers separated by a vacuum with support pillars). Values shown in Table 1 have been derived from known sample properties, with loss factor refined by matching the experimental results presented in the next section.

Table 1 - Summary of glazing properties for mathematical modelling

VARIABLES	3 mm	6 mm	10 mm	3V3	5V5
Thickness (m)	0.003	0.006	0.01	0.006	0.01
Surface Density (kg/m^2)	7.5	15	25	15	25
Critical Frequency (Hz)	4463	2231	1339	4463	2678
Loss Factor	0.005	0.0075	0.0175	0.0028	0.003
Fundamental Resonance (Hz)	18	35	59	35	59

3. Measurement Limitations

The ISO 15186-2 field sound intensity [9] method was selected for its practical advantages in investigating the hypothesis, requiring only one reverberation room with a test opening in which the sample is mounted. The test opening is 1200 mm x 640 mm with a slight overlap (20 mm per edge) for the specimen to be mounted. This applies a hard frequency limit to the accuracy of the measurements at the equivalent longitudinal wavelengths of the panel – roughly 280 Hz and 50 Hz respectively. The latter is considered irrelevant as it is below the frequency of interest for the Weighted Apparent Sound Reduction Index (R'_w) and Sound Transmission Class (STC) single-number ratings. The size of the test specimen (as well as most windows) is not much larger than the acoustic and bending wavelengths within the audio spectrum. Within the panel, reflected longitudinal waves due to the panel edges interact with incident acoustic waves and radiate well. This will occur best at resonant modes, the fundamental of which, is of most concern ($m = 1$, $n = 1$) and calculated using equation (5) (see Table 1), which in all cases is well below the measurement frequency range.

The test panels probably have a higher bending stiffness due to their small dimensions, perhaps giving a false indication of how larger panels would behave. For this reason it was expected that results in this experiment would appear greater to those using the ISO recommended test specimen of 1250 mm x 1500 mm. The ISO 15186-2 annex provides an adjustment factor that positively weights the R' values measured as a function of frequency to better relate to pressure-pressure measurements performed as per ISO 140-3 [10]. This raises the question as to whether adjustment factors are suitable to be applied in this specific scenario given the additional effect of shorter panel dimensions. Nevertheless, in maintaining the approach of the intensity standard, apparent intensity sound reduction index are reported following the correction factor as per equation (7) which simplifies the standard for a single element under test.

$$R'_{IM} = L_p - 6 - \overline{L_I} + K_c \tag{7}$$

L_p is the logarithmically averaged source room sound pressure level, $\overline{L_I}$ is the time and space averaged sound intensity at normal incidence to the test element. The 6 dB adjustment in equation (7) comes from the spatial integration of a diffuse field impinging on a flat panel.

4. Measurement Method

The experiment was set up as per the schematic in Figure 2. Two Turbo Sound TA-500 horn-loaded cabinet loudspeakers were arranged asymmetrically in the reverberant room (source) at the University of Sydney Acoustics laboratory, and microphones were spatially distributed in the room, according to the spatial separation rules laid out in ISO 140-3. The reverberant room has a volume of 130 m^3, and static diffusing panels were suspended in the room. The test opening between reverberant room and general acoustic lab was fitted with the test specimen, rigidly mounted using rubber clamps fitted to a timber frame with bolts and wing-nuts. These were screwed in tightly to form a seal. Pink noise (twochannel incoherent), band limited between 80 Hz and 6300 Hz, was used as the test signal, and played into the room via the two loudspeakers.

The receiving room is not a special test room, but instead is a large general-purpose room in the acoustics laboratory. While sound intensity measurement has some immunity to steady state noise and reflections (reactive sound fields), it performs more accurately when these are minimised. To reduce acoustic reflections and background noise in the receiving room, an absorption 'tent' was set up in the general lab area, to cover the three sides and the top of the measurement position (Figure 3). Each of the four slabs of the tent were constructed from 2 layers of 100 mm thick CSR Martini Polymax absorptive polyester fibre.

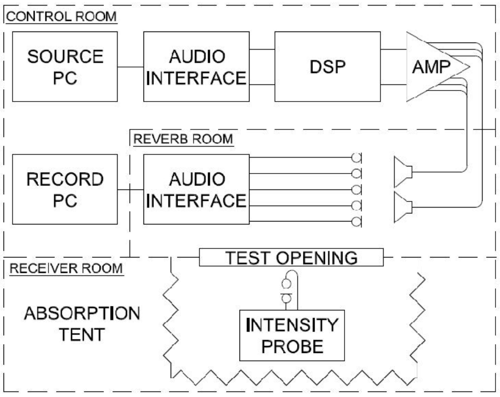

Figure 2 - System Schematic of Experiment

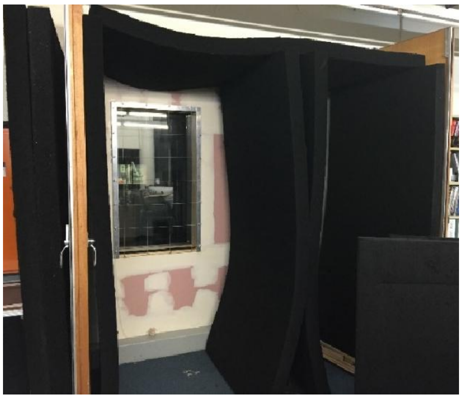

Figure 3 - 'Absorptive Tent' in receiver room, with the rear sheets of absorptive material (those closest to the camera) removed.

Measurements were taken using a continuous scanning method with the Brüel and Kjær 2260 Investigator (12 mm microphone spacer), 250 mm from the test specimen. This was done twice per measurement to ensure repeatability. Background measurements were taken at the start of each measurement to ensure a minimum of 15 dB signal-to-noise ratio in each 1/3-octave band (80 Hz – 6.3 kHz) was achieved. A fixed point laser Doppler vibrometer (LDV) was also used at the test opening, 238 mm from the surface to measure the normal velocity of the glass in response to test stimuli.

5. Experimental Results

The average of a series of measurements is presented in Figure 4. All samples tested showed excellent agreement with Sharp's modelling approach and monolithic samples tested also agree with existing reference data [11]. Figure 4 shows good agreement through the mass law region for all samples, particularly above 250 Hz and below $f_c/2$. In this low frequency region the VIG samples exhibit slightly higher sound reduction index values; this result could be attributed to their slightly larger (0.2 mm) thickness and the additional mass of the spacers. Actual measurements of test sample mass will be carried out to quantify this further. An early tapering off of the mass law can be observed in the 3 mm sample which was also observed in measurements of 3V3 glazing when the clamping conditions were relaxed. Reducing the rigidity of clamping of the 3 mm monolithic sample had little effect on its sound reduction index, reflecting the fact that the mounting system made it difficult to tightly clamp this thin sample.

All panel coincidence regions show a critical frequency that agrees well with theory based on equation (1) when the constituent thicknesses of each VIG layer are considered. The 3V3 sample dips at the 3 mm critical frequency however with much greater depth. Likewise, the 5V5 sample can be seen to reach its sound reduction minimum close to the calculated f_c of a 5 mm monolithic sample. This appears to be the first interesting, albeit simple, finding on the acoustic behaviour of VIG.

The second interesting finding, relates to the depth of the coincidence region dip, which is typically controlled by damping. The 3V3 and 5V5 sample's mass law region acts as two panels glued directly together, resulting in higher sound reduction than a monolithic 3mm or 5mm sample, but we see this does not result in a downwards coincidence shift as would be expected from a panel of higher mass. Hence it appears that the critical frequency and coincidence region’s performance are determined by the individual sheets of glass. The greater depth of the dip (which implies less damping) in the VIG samples is consistent with the combination of individual layers’ transfer functions in this frequency region.

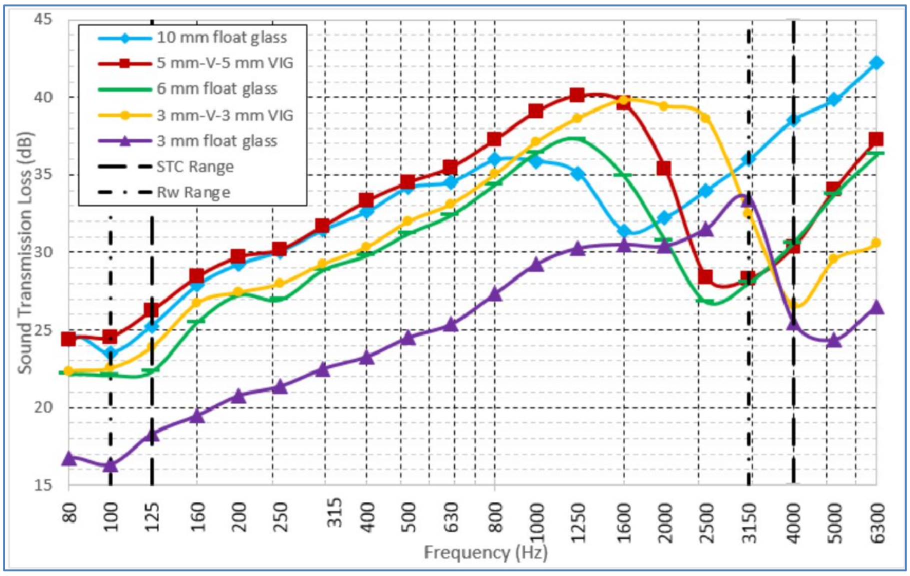

Figure 4 - Modified Apparent Intensity Sound Reduction Index of test samples

An unexpected curvature can be seen in the 3V3 and 3 mm samples in the 4000 Hz – 8000 Hz range. In the case of the 3 mm it appears the coincidence dip reaches its minimum point, whereas the 3V3 looks as if it should continue toward the 5000 Hz point before rising again. All signal to noise ratios were >15 dB in this region and up to 30 dB at lower frequencies; further testing will be required to pinpoint the reason for this result. Beyond the coincidence region an extension of the mass law slope can be observed in a 6 dB/octave increase in *R’*.

Single number ratings STC, $R'_{IM}w$ and octave band data are presented in Table 2. The VIG samples are significantly penalised for their steep (11-12 dB) coincidence dip in STC, due to the 8 dB rule. 5V5 maintains the same $R'_{IM}w$, however slightly lower STC than the 10 mm sample by comparison. The STC of both 3V3 and 6 mm are equivalent, however a 2 dB improvement in average results of $R'_{IM}w$ is apparent.

Results correspond well to mathematical models above 500 Hz, particularly with VIG and 6 mm samples (Figure 5). Discrepancies with 3 mm and 10 mm monolithic samples are suggested to be a result of edge clamping conditions. The frequency analysis of displacement measurements, obtained using the LDV, support the theoretical calculations of the fundamental resonance of each panel.

Table 2 – Measured values (R'_{IM}), and reference values [11], in octave bands and as Sound Transmission Class (STC) and Weighted Modified Intensity Sound Reduction Index ($R'_{IM}w$).

		125	**250**	**500**	**1K**	**2K**	**4K**	**STC**	$R'_{IM}w$
3 mm	Ref.	14	19	25	29	33	25		28
	Meas.	18	22	24	29	31	26	28	29
6 mm	Ref.	18	23	30	35	27	32		31
	Meas.	23	28	31	36	30	30	31	33
3 V 3	Meas.	24	28	32	37	39	29	31	35
10 mm	Ref.	23	26	32	31	32	39		33
	Meas.	25	30	34	36	33	38	35	35
5 V 5	Meas.	26	30	34	39	32	30	33	36

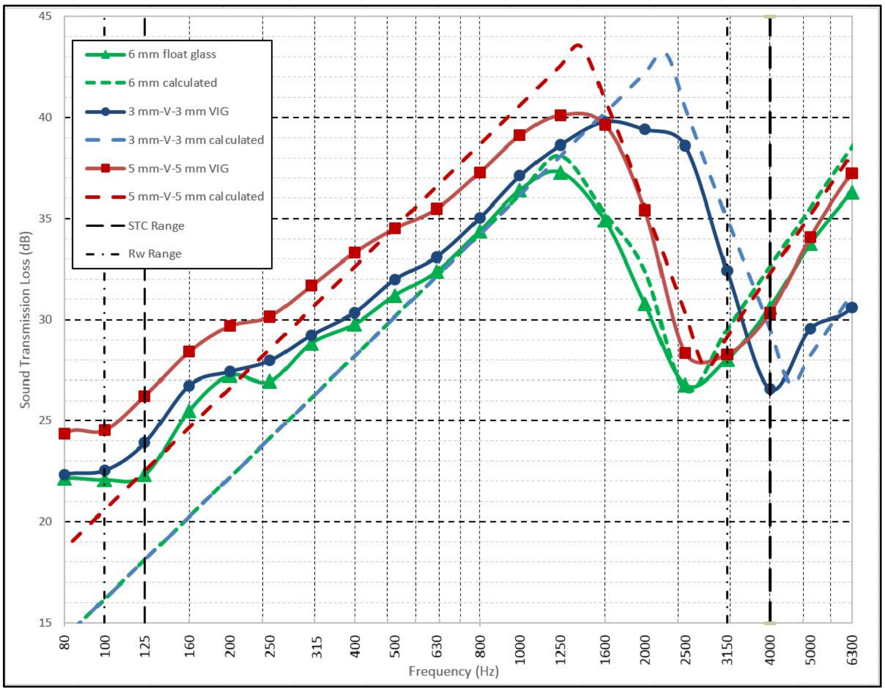

Figure 5 - Calculated vs. measured 1/3-octave band R'_{IM} for 6 mm monolithic, 3V3 and 5V5 samples.

6. Discussion

The application of adjustment factors (K_c) to this experiment appear to be of some concern as they result in a 1-2 dB discrepancy between the measured and reference data. This is likely due to the limitations placed on the lower frequency region where reference data and measurement differentiation was at its maximum. Use of standard openings will be better for further measurements using VIG and glazing in general (although it may be difficult or expensive to make much larger VIG samples for experimental testing). The cost-benefit ratio of VIG vs. monolithic samples appears null in acoustic terms due to the cost differential being an order of magnitude higher for evacuated configurations, however the thermal properties are the true driver of this technology.

Although results show marginal improvements at best, it appears that there is some scope for the VIG design to improve acoustic performance. Three areas for potential investigation are, 1. using different pane thicknesses, 2. lamination of one or both panes, and 3. optimised spacer layout.

6.1 Pane thickness

The concept of an improvement in sound insulation may be defined differently depending on the aim. One approach would be to consider an increase in a single number rating (such as R_w) to sufficiently represent an increase in sound insulation, which perhaps could be achieved by shifting the coincidence dip in R to just above the frequency range evaluated for the single number rating. It appears that this would be possible if at least one of the VIG layers were 2 mm (which may be impractically thin), or by using a glazing material characterised by greater bending wave speeds than soda-lime glass. In the case of R_w, the shift need only be one 1/3-octave band higher than the dip frequency measured for 3 mm glass; whereas for STC, the shift would need to be two 1/3-octave bands (which would have the additional benefit of avoiding the 8 dB rule determining the STC value).

A more comprehensive definition of an improvement in sound insulation would consider that a large dip just beyond the frequency limits of a single number rating is not a desirable outcome. Nevertheless, there is some prospect that pane thickness can contribute to improved acoustic design. The fact that the VIG results at the coincidence region correspond to expected results for the constituent panes considered individually suggests the hypothesis that the identical pane thicknesses reinforce transmission in this region, and that different pane thicknesses within a VIG sample could avoid this reinforcement. If this is the case, then different pane thicknesses are likely to yield improved sound insulation (compared to monolithic glazing of the same surface density) in the coincidence region by avoiding the matching of transfer functions of individual panes. For example, a 3V5 mm design may be acoustically superior to a 4V4 design.

6.2 Laminate

Laminating panels together (with a resilient interstitial layer) is one of the most effective ways to increase the sound reduction index of single glazing units, and this is likely to translate to VIG. Typically, lamination of single glazing yields improvements of 1-4 dB [12] between 2 kHz and 5 kHz. The resilient layer increases the internal damping (and hence reduces the depth of the coincidence dip). Lamination is not appropriate where design requirements include high light transmission because the laminate layer can have the effect of reducing transparency. Based on the results of this experiment VIG samples with a laminate layer would improve, however likely still be comparable to monolithic samples that were also treated with an absorptive lamination. The potential for sound insulation would be maximised using two absorptive laminate layers; however, this may not be possible considering the high temperature processes involved in the manufacture of the VIG.

6.3 Aperiodic placement of spacers

Acoustic waves cannot travel in a vacuum, however from the results we can deduce that all sound is transmitted via the mechanically coupled support spacers and edge seals of the VIG. The uniform distance between the spacers equating to ¼, ½ and full wavelengths may result in additional resonances caused by longitudinal bending waves. The calculation of such an effect is beyond the scope of this paper. Hypothetically, by placing the spacers in an aperiodic pattern over the internal surface of the glass panes, coupling might be reduced, and hence, an improvement on sound reduction index would be observed. This possible avenue for acoustic design improvement may be both marginal and impractical, due to the mechanical design requirements for long-term structural stability of VIG units.

7. Conclusions

Two VIG samples with pairs of identical pane thicknesses were tested and showed little improvement in sound insulation compared to monolithic glazing of the same surface density. The results suggest that the mass law behaviour is well predicted from the VIG's surface density (equivalent to a monolithic panel), and the coincidence dip appears to be well predicted from the critical frequency of the individual layers of the VIG unit. Accuracy of results in the coincidence region were inconsistent due to mounting conditions, and the test opening size compromised the mass-law region. The major limitation in improvement was the depth of the coincidence dip, and there is some prospect for ameliorating this (e.g., by using dissimilar pane thicknesses). Alternative designs incorporating lamination to improve acoustic performance should be explored.

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References

[1] Collins, R. E., and Simko, T. M. "Current status of the science and technology of vacuum glazing", *Solar Energy*, **62(3)**, 189-213, (1998).

[2] Winsmart Report Summary, *European Commission* (2015) Retrieved from: http://cordis.europa.eu/result/rcn/155685_en.html

[3] Sound Reduction, *Nippon Sheet Glass* (2003) Retrieved from: http://www.nsg-spacia.co.jp/tech/sound.html

[4] Properties and Performance of Vacuum Insulated Glazing, *McGraw Hill* (2015) Retrieved from: http://continuingeducation.construction.com/crs.php?L=133andC=1280

[5] Walters, S., and Dance, S. “Noise Control Potential of Vacuum Isolation Panels”, *INTER-NOISE and NOISE-CON Congress and Conference Proceedings,* **249(8)**, 1-10. Institute of Noise Control Engineering (2014, October)

[6] Beranek, L. L., and Ver, I. L., Noise and vibration control engineering-principles and applications. *Noise and vibration control engineering - Principles and applications* John Wiley and Sons, Inc. *275,* 1992

[7] Bies, D. A., and Hansen, C. H., *Engineering noise control: theory and practice*. CRC press. 257, 2009

[8] Sharp, B. H. “A study of techniques to increase the sound insulation of building elements” *US Department of Commerce*, National Technical Information Service (NTIS) 1973

[9] ISO 15186-2 – Acoustics – Measurement of sound insulation in buildings and of building elements using sound intensity – Part 2: Field measurements. *International Organization for Standardization,* Geneva, Switzerland, 2003.

[10] ISO 10140-2:2010 – Acoustics – Laboratory measurement of sound insulation of building elements – Part 2: Measurement of airborne sound insulation. *International Organization for Standardization,* Geneva, Switzerland, 2010.

[11] ISO 22897 Glass in building - Glazing and airborne sound insulation, *International Organization for Standardization,* Geneva, Switzerland, 2003.

[12] Lu, J. "Passenger vehicle interior noise reduction by laminated side glass." *International Noise Control Conference* (2002)