Sound transmission via gas-filled insulating glass units

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ABSTRACT

Windows are points of the lowest resistance in the total sound and heat insulation of buildings. To enhance both thermal and acoustical qualities of windows with insulating glass units (IGU), the gaps between the panes can be filled with a heavier-than-air gas alone (for example, argon, krypton, xenon, and sulfur hexafluoride) or mixed with air. Here, the sound transmission loss (STL) may be increased in the low-frequency range dominated by acoustic resonances where the panes and gaps play the role of masses and springs. This frequency region (typically 100-500 Hz) is important for reducing traffic noise by windows. However, the expected acoustical improvement is often not measured using the standard two-reverberation room techniques. In this paper, such a discrepancy is theoretically and experimentally studied for physical interpretation and design optimization. Clear closed-form expressions have been derived and verified for the direct (via the panes and gaps) and flanking (via the panes and perimeter structural links) sound transmission through single-space and double-space insulating glass units, and improvement proposals have been developed. The results can be interesting for the scientists and engineers engaged in acoustics and construction.

KEYWORDS
Keywords: Sound insulation by windows. Gas-filled insulating glass units. Sound transmission analysis and testing. Design optimization.

1 Introduction

Both thermal and acoustic performance of windows can be improved by filling the gaps with gases that are heavier than air: typically non-toxic, clear, odorless, and relatively inexpensive inert gases such as argon and krypton. Single-space and double-space insulating glass units (IGUs), in which the edges of the panes are firmly joined by a metal or plastic spacer to form a sealed perimeter that traps air or another gas, are used for this purpose [1]. The gap thickness typically ranges from 6 mm to 20 mm. For structural reliability, the internal gas pressure is set equal to the average external air pressure.

A significantly higher sound insulation performance was first reported in the 1970s for experimental double windows filled with gases heavier or lighter than air [2–5]. However, heavier gases are more beneficial due to their superior thermal insulation properties. The enhanced sound transmission loss is usually observed in the frequency range associated with mass-spring-mass resonances (approximately 200 to 1000 Hz for typical windows) where the panes and gas layers act as masses and springs, respectively.

However, subsequent experimental studies, particularly those using the two-reverberation room method (where the test sample is installed in an aperture within a thick wall separating two rooms), found the acoustical effects of gas fills to be lower than those reported in earlier publications [2–5], or even negligible. It is important to identify the reasons for this discrepancy and propose practical recommendations for improvement. Numerous theoretical and experimental studies investigated sound transmission through single, double, and triple partitions (including various glazing systems) at low frequencies [6–19 etc]. There are two primary sound transmission paths in IGUs: direct transmission (through the panes and gas gaps) and flanking transmission (through the panes and perimeter connections). While gas fills can affect the direct transmission path, they have no influence on flanking transmission.

This paper introduces mathematical models for both direct and flanking sound transmission in gas-filled IGUs. Closed-form expressions are derived to highlight the physical trends, which are compared with experimental data measured using the two-reverberation room method. The results are analyzed to address: (1) why gas fills may appear acoustically ineffective in laboratory measurements but may prove beneficial in situ, and (2) how to further reduce both direct and flanking sound transmission in single- and double-space IGUs.

2 Theoretical Model for Direct Transmission via Single-Space IGU at Low Frequencies

2.1 Equation for Direct Sound Transmission at Normal or Oblique Incidence

In this paper, the calculation of direct sound transmission through a double glazing of infinite size is based on the classical impedance method [6–8], with two modifications including (1) cavity sound absorption and (2) revised angular distribution of incident sound energy. The panes are considered similar, thin and structurally uncoupled. The cavity is filled with air or heavier-than-air gas; the exterior medium is air, and the static pressures inside and outside the glazing are assumed equal. The direct sound transmission of a plane harmonic wave through a gas-filled double glazing is illustrated in Fig. 1. Here, θ is the incidence angle and Φ is the refraction angle, defined by Snell's law as:

$$\sin(\Phi)/\sin(\theta) = c_g/c_a = q \tag{1}$$

where c_g and c_a are the speeds of sound in gas and air, respectively.

The goal is to estimate the sound transmission loss in the low-frequency range:

$$f_i \ll f \le \min(0.5 f_{cr}, 0.2 c_g/d) \tag{2}$$

where f is the sound frequency, f_i is the fundamental natural frequency of bending vibration for each pane (commonly, $f_i < 100\ Hz$), d is the gap thickness (typically 9-15 mm for standard IGUs), f_{cr} is the critical coincidence frequency (e.g., 2000 Hz for a 6 mm thick pane).

Thus, the low-frequency region defined by Eq. (2) approximately spans from 200 to 1000 Hz. Within this range, the sound transmission coefficient for both normal and oblique incidence can be expressed, based on the previously obtained results [8,19], as follows:

$$\tau_\theta \approx \left\{1 + (Q\cos\theta)^2 \left[\eta_c^2 + \left(1 - (u\cos\Phi)^2\right)\right]\right\}^{-1} \tag{3}$$

where the dimensionless frequency

$$u = f/f_0 \ , \tag{4}$$

the fundamental frequency of mass-spring-mass resonances

$$f_0 = \sqrt{2\Upsilon P/(md)}/(2\pi), \tag{5}$$

the dimensionless impedance

$$Q = \pi M f/\,(\rho_a c_a) \gg 1, \tag{6}$$

and η_c is the cavity loss factor. Here, P is the static pressure in the gap (it is made close to the outer atmospheric pressure of 10^5 Pa), m is the surface density of each pane, $M = 2m$ is the total surface density of the double glazing, and Υ is specific heat ratio (for air or gas inside the gap) which equals 1.67 and 1.4 for monoatomic and diatomic gases, respectively. Inert gases like argon (Ar), krypton (Kr), and xenon (Xe) are monoatomic and air is mostly diatomic. For polyatomic gases, like carbon dioxide (CO_2) and sulfur hexafluoride (SF_6), the specific heat ration equals 1.28 and 1.09 (Table 1).

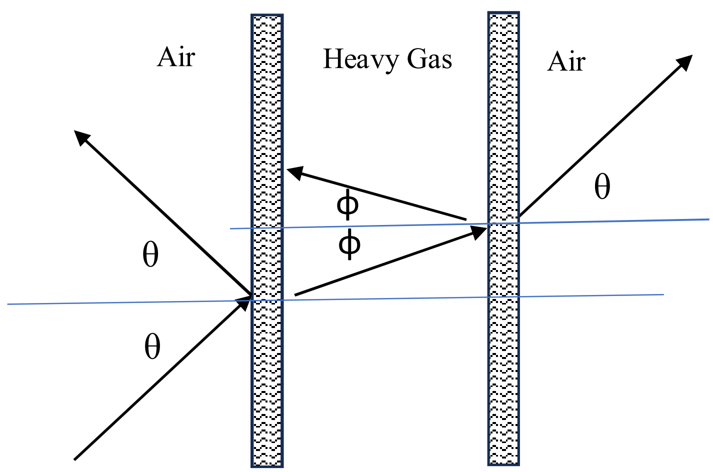

Figure 1: Direct sound transmission via gas-filled double glazing at oblique incidence.

From Eq. (1), for heavier-than-air gases

$$(\cos \varphi)^2 = 1 - (q \sin\theta)^2 \leq 1 \tag{7}$$

where the ratio q is defined in Eq. (1). For example, it equals 0.64 for krypton and 0.93 for argon (Table 1).

Gas Fill	Atomic or Molecular Weight	Specific Heat Ratio	q, defined by Eq. (1)
Air	29	1.40	1.00
Argon	40	1.67	0.93
Krypton	84	1.67	0.64
Xenon	131	1.67	0.51
CO_2	44	1.28	0.78
SF_6	146	1.09	0.39

Table 1. General physical and chemical parameters of some gases for insulating glass units.

2.2 Estimation of Cavity Loss Factors

For air-filled IGUs, the cavity loss factor $\eta_c = 0.2$ is estimated empirically, based on the analysis of laboratory measurements [19, etc]. This approximation appears reasonable, as the dips in the frequency characteristics calculated in Chapter 4 are of about the same magnitude as those observed experimentally. For gas-filled IGUs, the cavity loss factor is assumed to vary with the gas dynamic viscosity and thermal conductivity [21, 22]. The acoustic energy dissipation occurs due to viscous friction in the gas boundary layer and heat exchange between this layer and the glass pane. Since glass is not as thermally conductive as metal, the heat exchange effect can be neglected, and the cavity loss factor should be proportional to the dynamic viscosity of gas fill.

Gas Fill	μ_g, 10^{-5} Pa s (for 25^0C and 1 atm)	μ_g/μ_a	η_c
Air	18.5	1.00	0.20
Argon	22.6	1.22	0.24
Krypton	25.4	1.37	0.28
Xenon	23.1	1.25	0.25
CO_2	14.9	0.81	0.16
SF_6	15.6	0.84	0.17

Table 2. Dynamic viscosities μ_g and cavity loss factors η_c for various gas fills.

Hence, the cavity loss factor can be estimated as

$$\eta_c = 0.2\,\mu_g/\mu_a \tag{8}$$

where μ_g and μ_a are the gas and air dynamic viscosities. The dynamic viscosities and the calculated cavity loss factors for air and heavy gases are presented in Table 2.

2.3 Angle Distribution Pattern for Random Incidence

In the classical diffuse field model, the random incidence transmission coefficient is calculated by equation

$$\tau = \int_0^{\theta_m} \tau_\theta \, \Phi(\theta) d\theta \tag{9}$$

where τ_θ is the sound transmission coefficient for incidence angle θ, the maximum incidence angle $\theta_m = 90^0$, and the angle distribution

$\Phi(\theta) = 2 \sin\theta \cos\theta$.

In rectangular reverberation rooms, grazing incident waves strike the tested wall after one or more reflections from the side walls, and therefore attenuate more than the waves propagating normally to the tested wall. To account for this effect, the maximum incidence angle θ_m was reduced from 90° to 78–80° [6, etc.]. Under this correction, the random incidence sound transmission coefficient τ at low frequencies for a single glazing can be calculated by substituting

$$\tau_\theta = \{1 + (Q\cos\theta)^2\}^{-1} \approx (Q\cos\theta)^{-2} \tag{10}$$

into Eq. (9). Here, the dimensionless impedance Q is defined by Eq. (6), and the random incidence transmission loss for a single glazing is given by

$$R = 10\, log(1/\tau) = R_0 + \Delta R \tag{11}$$

where the normal incidence transmission loss

$$R_0 = 10\, log(1/Q) \tag{12}$$

and

$$\Delta R \approx -5\, dB. \tag{13}$$

In this paper, symbol log denotes just decimal logarithms.

The same result can be obtained using the maximum incidence angle $\theta_m = 90^0$ and angular distribution pattern

$\Phi(\theta) = 3 \sin\theta \cos^2\theta$.

This angular distribution pattern was calculated under the assumption that the reverberation room is cubic in shape and the sound absorption coefficient of the room walls is angle-independent and small [19]. However, real rooms are typically rectangular parallelepipeds, where grazing incident waves reach the tested wall after more reflections than in a cubic room. To account for this, the angle distribution function can be modified to

$$\Phi(\theta) = 4 \sin\theta \cos^3\theta. \tag{14}$$

Using Eq. (14), the random incidence transmission loss, calculated for a single glazing at low frequencies, is described by Eqs (11) and (12) but

$$\Delta R = -3\ dB. \tag{15}$$

Nevertheless, even this model does not account for waveguide effects in the aperture. The Gaussian distribution of incident energy, suggested in paper [17], is not clearly related to wave phenomena, which are important at low frequencies where (1) the cross-sectional dimensions of the sample and opening are small or comparable to the wavelength of the incident wave, (2) waveguide effects inside the aperture, both before and after the test specimen, are noticeable. This is actual for two-reverberation-room tests, where the dividing wall is thick (typically about 0.6 m).

The acoustic field in waveguide is a combination of modes with various pressure and velocity distributions [12, 21, 22]. Each mode can be propagating (if the operating frequency exceeds the mode cutoff frequency) or evanescent (if the operating frequency is below this cutoff frequency). For the zero mode which is a normally propagating plane wave, the cutoff frequency is zero. The next propagating mode appears only at frequencies $f \geq c/(2a)$, where a is the larger cross-sectional dimension of the waveguide (i.e., at $f \geq 170\ Hz$ if $a = 1\ m$). However, if the waveguide is short, evanescent modes may not decay significantly. In general, at low frequencies acoustic fields in a rectangular waveguide tend to resemble normal rather than diffuse propagation patterns. To simulate this effect, the angle distribution function is modified to the form

$$\Phi(\theta) = (4 \sin\theta \cos^3\theta)/[\sin^2\theta_m\,(1 + \cos^2\theta_m)] \tag{16}$$

where θ_m is the maximum angle for incident acoustic waves in the cavity. In this case, the random incidence transmission loss for a single glazing is described by Eqs (11) and (12) but

$$\Delta R = -3\ dB + 10 \log(1 + \cos^2\theta_m). \tag{17}$$

From Eq. (17), $\Delta R = -3\ dB$ if $\theta_m = 90^0$ and $\Delta R \to 0$ if $\theta_m \to 0^0$. Therefore, this value is relatively small for single glazings at both random and normal sound incidence. On the other hand, for double and triple glazings, including single- and double-space IGUs, it can be much more significant.

2.4 Direct Sound Transmission at Random Incidence

Substituting Eqs (3) and (16) into Eq. (7), obtain the random incidence sound transmission loss for a double glazing with infinite similar panes. The results is described by Eq. (11) but R_0 is the normal incidence transmission loss for a single glazing with surface density $M = 2\,m$ and

$$\Delta R = 10\log(H/W) \tag{18}$$

where

$$H = atan\{[1 + u^2(q^2\sin^2\theta_m - 1)]/\eta_c\} + atan[(u^2 - 1)/\eta_c], \tag{19}$$

$$W = \eta_c\, u^2 q^2 \sin^2\theta_m\ (1 + \cos^2\theta_m)\,. \tag{20}$$

Here, η_c is the cavity loss factor, q is defined by Eq. (3), and m is the surface density of each pane.

From Eqs (18)-(20), the frequency range of the mass-spring-mass resonances is

$$1 \le f/f_0 \le U = 1/(1 - q^2\sin^2\theta_m). \tag{21}$$

The approximate resonance zone width in 1/3-octave frequency bands, calculated as $N = 3\log_2(U)$, where U is defined by Eq. (21), and the ratio of the fundamental resonance frequencies for various gas fills are given in Table 3.

Gas Fill	Ratio of fundamental resonance frequencies for gas and air	Approximate resonance zone width in 1/3-octave bands, $\theta_m = 90^0$	Approximate resonance zone width in 1/3-octave bands, $\theta_m = 45^0$
Air	1.00	No upper limit	3.0
Argon	1.09	8.7	2.5
Krypton	1.09	2.3	1.0
Xenon	1.09	1.3	0.6
CO_2	0.96	4.1	1.6
SF_6	0.88	0.7	0.3

Table 3. Approximate resonance zone width for various gases and ratio of fundamental resonance frequencies.

In Table 3, the resonance zones are for air, argon and carbon dioxide fills are notably wide. Krypton, xenon, and sulfur hexafluoride create relatively narrow resonance zones which is favorable for the sound insulation at $f/f_0 > U$. However, in a narrow range around the fundamental resonance frequency, the sound insulation of gas-filled IGUs may be lower than that of air-filled ones if the dynamic viscosity of the gas is lower than that of air.

3 Theoretical Model for Flanking Transmission at Low Frequencies

The flanking sound transmission via single- and double-space IGUs was calculated using a simplified mathematical model where the unit is installed in an infinite air-filled waveguide of the same cross-section and with absolutely sound reflecting walls [19]. The panes were considered similar, their edges being structurally linked by linear, rigid, and massless ribs. The gap was a vacuum to prevent direct sound transmission through the IGU. Each end of the rib-to-pane link was either clamped (fixed) or simply supported (pinned).

For simplicity, it was assumed that only zero modes (with uniform amplitude across the waveguide, as in the case of normal incidence) can propagate in the waveguide. The frequency characteristics of sound transmission loss for harmonic waves were averaged in 1/3-octave bands, based on the assumption that at least five natural frequencies of bending vibrations fall within each band (in order to reduce the calculation error to below 1 dB). This approximation is practical at frequencies

$$f_i \ll f \tag{22}$$

where f_i is the fundamental natural frequency of bending vibration of each pane.

The calculated sound transmission loss at low frequencies is given by Eq. (11), where R_0 is the normal incidence transmission loss for a single glazing with the total surface density $M = 2\,m$, and

$$\Delta R = \Delta\, R_p = 10\, log\left\{1 + \left[(\pi/2)\sqrt{f/f_{ss}}\right]^3\right\}, \tag{23}$$

if the rib-to-pane links are pinned [19].

Here, f_{ss} is the fundamental natural frequency of bending vibration of each pane if all its sides are pinned. It is noteworthy that value f_i in Eq. (22) is closer to the fundamental natural frequency of the same pane but with all sides clamped (fixed), which is nearly twice the value f_{ss} [20].

If the rib-to-pane links are clamped (fixed), the sound transmission loss is calculated [19] as follows

$$\Delta R_f = \Delta R_p - 6\, dB. \tag{24}$$

This equation is more practical for IGUs than Eq. (23). It was also shown that Eqs (23) and (24) are valid for double-space IGUs with three similar panes and two equal gaps. In this case, R_0 represents the normal incidence transmission loss for a single glazing with the total surface density $M = 3\,m$ [19]. As a result, the flanking sound transmission via such a double-space IGU is lower than that via single-space IGU by $20\log(3/2) = 3.6$ dB if both units are made of similar panes.

Since $f_{ss} \sim h/a^2$ where h and a are respectively the pane thickness and average cross-section size, the flanking transmission can be reduced by: (1) replacing each pane with a pair of panes half as thick, separated by a very small air gap, (2) increasing the cross-sectional dimensions. In the first case, the flanking transmission should decrease at low frequencies by $15\log(2) = 4.5$ dB and even more, since the loss factor of thin panes used to be higher than for thick those [23]. However, this design may lack structural reliability if the individual panes are thinner than 4 mm. In the second case, the flanking transmission is expected to decrease by $30\log(2) = 9\,dB$ if both cross-sectional dimensions are doubled. In practice, however, this beneficial effect is less pronounced because the thickness of a larger pane must also be increased to maintain structural strength. Replacing ordinary panes with triplex panes of the same surface density does not appear to be efficient, as triplexes are relatively expensive, and the expected acoustical effect is typically limited to 2–3 dB at low frequencies.

Flanking sound transmission primarily occurs through the rigid lightweight links between the panes along the perimeter. The window frame typically plays a less significant role, as the connection between the panes and the frame is usually less rigid than that between the panes themselves. However, if the frame is sufficiently massive, it may contribute to reducing flanking sound transmission.

4 Comparison and Analysis of Calculated Results

Using Eqs (18)-(20), which describe the direct sound transmission, the frequency characteristics of the relative sound transmission loss $\Delta R = R - R_0$ are calculated for harmonic waves and averaged in one-third octave bands as functions of the dimensionless frequency f/f_0 for a single-space IGU with two similar panes and a gap filled with air or a heavier-than-air gas (argon, krypton, or xenon). Here, R is the sound transmission lossfor this single-space IGU and R_0 is the normal incidence "mass law" given by Eq. (12), where $M = 2m$ is the total surface density (m is the surface density of each pane). The calculated results are graphically displayed for analysis in Figs. 3–8. The acoustic and physical parameters used in the calculations are presented in Tables 1 and 2. Since the fundamental mass-spring-mass resonance frequencies are close to each other, the same value of parameter f_0 is used for all gas fills in the calculations.

To illustrate the role of the maximum incidence angle θ_{max} and cavity loss factor η_c, the frequency characteristics are first displayed for air- and krypton- filled cavities (Figs 3–6). At normal sound incidence ($\theta_{max} \approx 0^0$) the direct sound transmission is nearly identical for air and krypton fills as shown in Fig. 3. However, the difference between the two fills increases with the maximum incidence angle (Figs 4 and 5), becoming especially significant at $\theta_{max} \approx 90^0$ (Fig. 6), particularly in the mass-spring-mass resonance frequency zones. These zones are identified using two levels of the cavity loss factor: 0.2 and 0.1 for air, and 0.28 and 0.14 for krypton. The zones extend from the lower bound $f/f_0 \approx 1$ to the upper bound, where the frequency characteristics for the two loss factors converge. At $\theta_{max} \approx 90^0$, the upper bound is infinite for the air fill (under the assumptions of the simplified mathematical model), while it remains finite for krypton and other heavy gases, as shown in Chapter 2.

However, at low frequencies, the effective maximum incidence angle may be significantly less than 90°, particularly in typical two-reverberation-room setups, where it appears to be close to 45°; this value is used now to calculate and compare the frequency characteristics illustrating direct sound transmission through IGUs filled with air, argon, krypton, and xenon (Fig. 6). The frequency characteristics related to the flanking sound transmission is also shown in the same graph. It was calculated using Eq. (24) for IGU with the glazing descriptive code 6+12+6 (two 6 mm panes with 12 mm gap between them)) and cross-area dimensions 1 m × 1 m. In this case, the fundamental natural frequency $f_{11} \approx 30\,Hz$ (calculated using the equation in book []21]) and $\eta_p = 0.03$ which looks consistent with the experimental data.

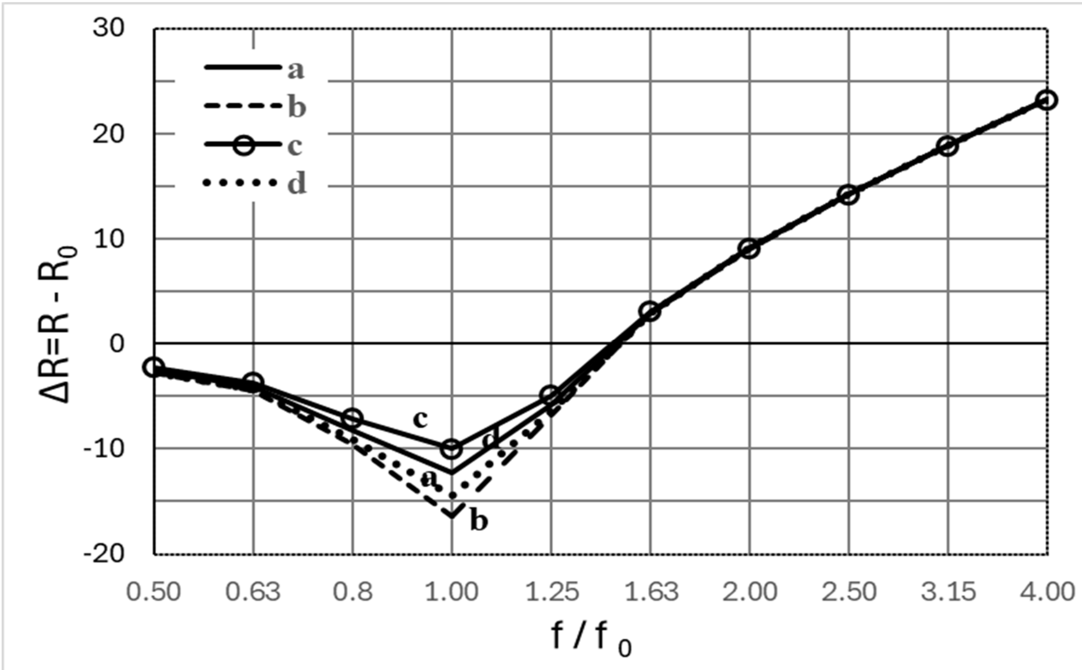

Figure 2: Relative frequency characteristics ΔR, calculated at $\theta_m \to 0^0$ for the single-space model with air and krypton fills: a – air, η_c=0.2; b – air, η_c=0,1; c – krypton, η_c= 0.28; d – krypton, η_c=0,14.

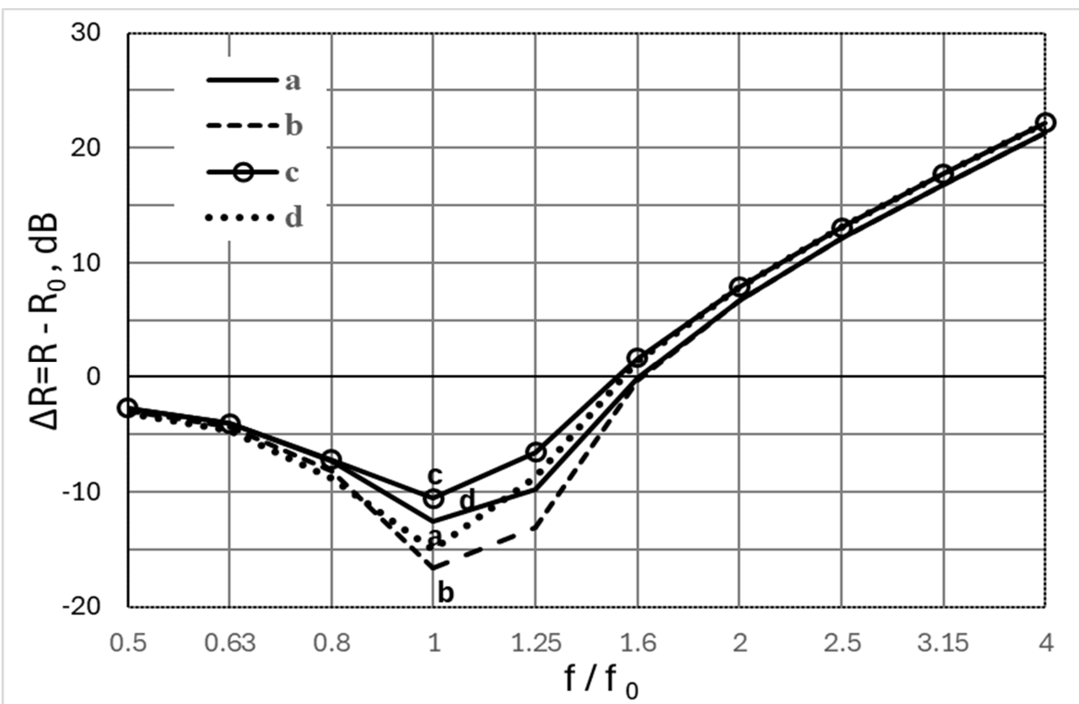

Figure 3: Relative frequency characteristics ΔR, calculated at $\theta_m = 30^0$ for the single-space model with air and krypton fills: a – air, η_c=0.2; b – air, η_c=0,1; c – krypton, η_c= 0.28; d – krypton, η_c=0,14.

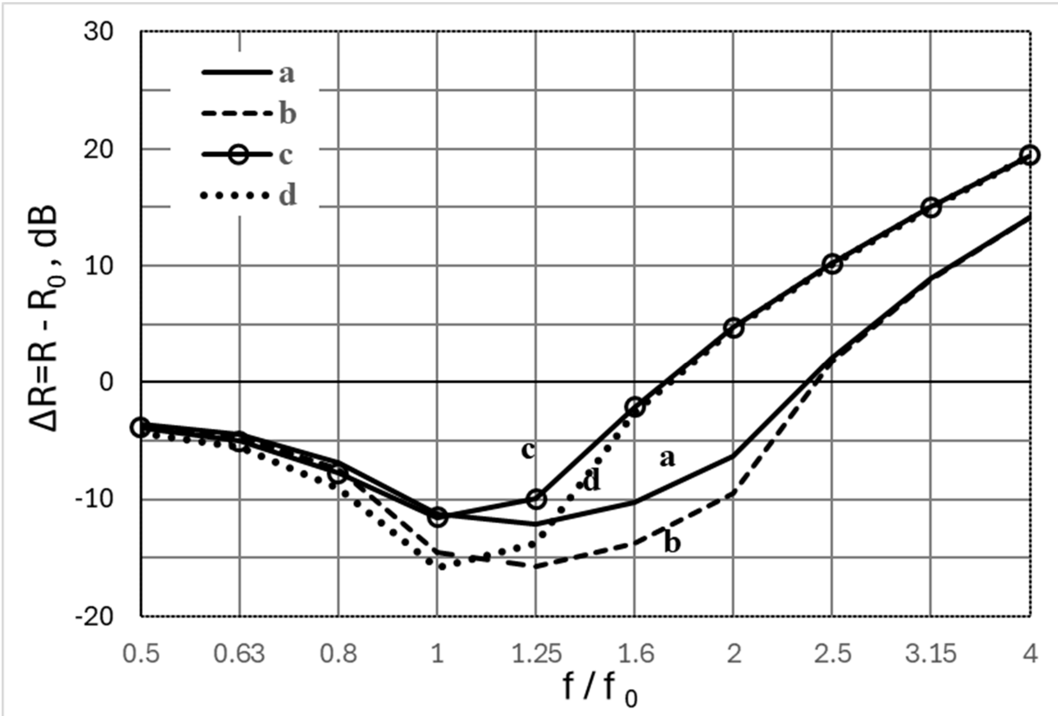

Figure 4: Relative frequency characteristics ΔR, calculated at $\theta_m = 60^0$ for the single-space model with air and krypton fills: a – air, η_c=0.2; b – air, η_c=0,1; c – krypton, η_c= 0.28; d – krypton, η_c=0,14.

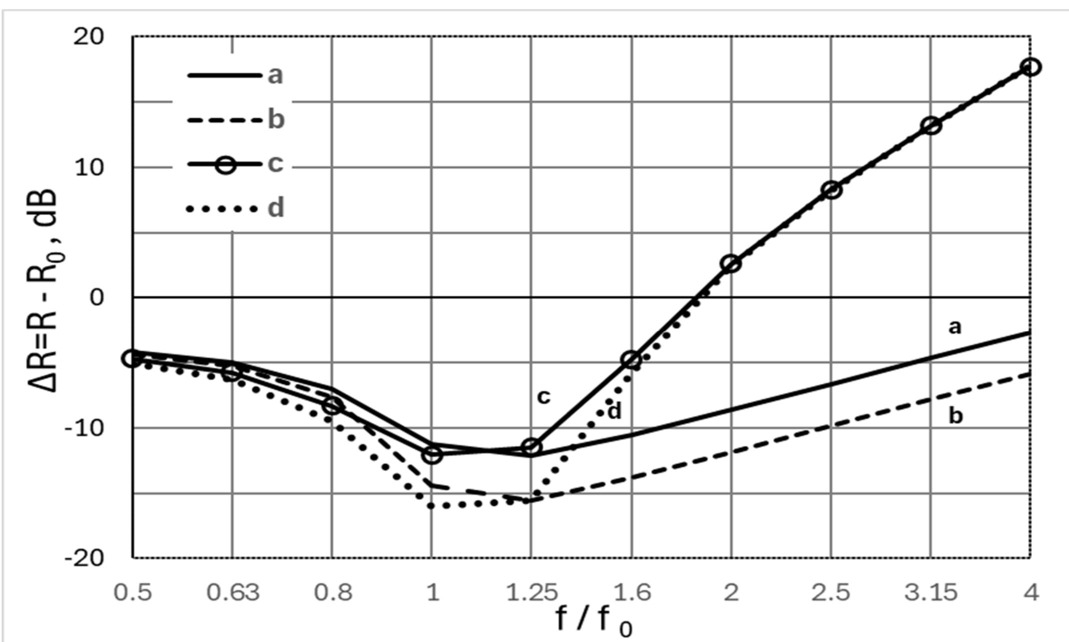

Figure 5: Relative frequency characteristics ΔR, calculated at $\theta_m = 90^0$ for the single-space model with air and krypton fills: a – air, η_c=0.2; b – air, η_c=0,1; c – krypton, η_c= 0.28; d – krypton, η_c= 0,14.

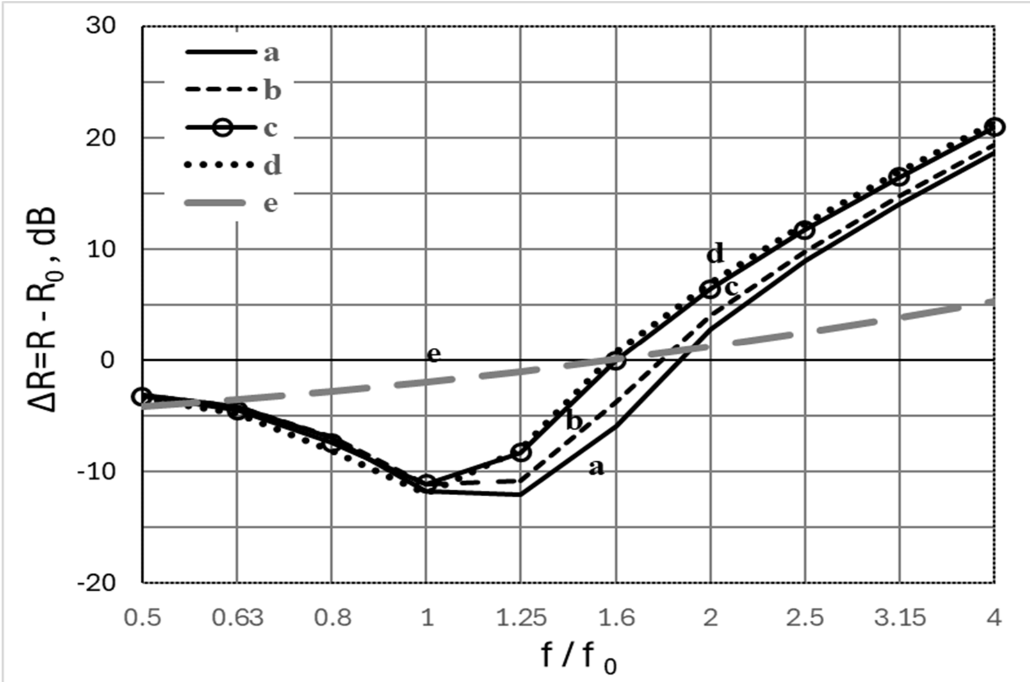

Figure 6: Relative frequency characteristics ΔR, calculated for flanking sound transmission (e) and direct transmission at $\theta_m = 45^0$ via the single-space model with air (a), argon (b), krypton (c), and xenon (d) fills.

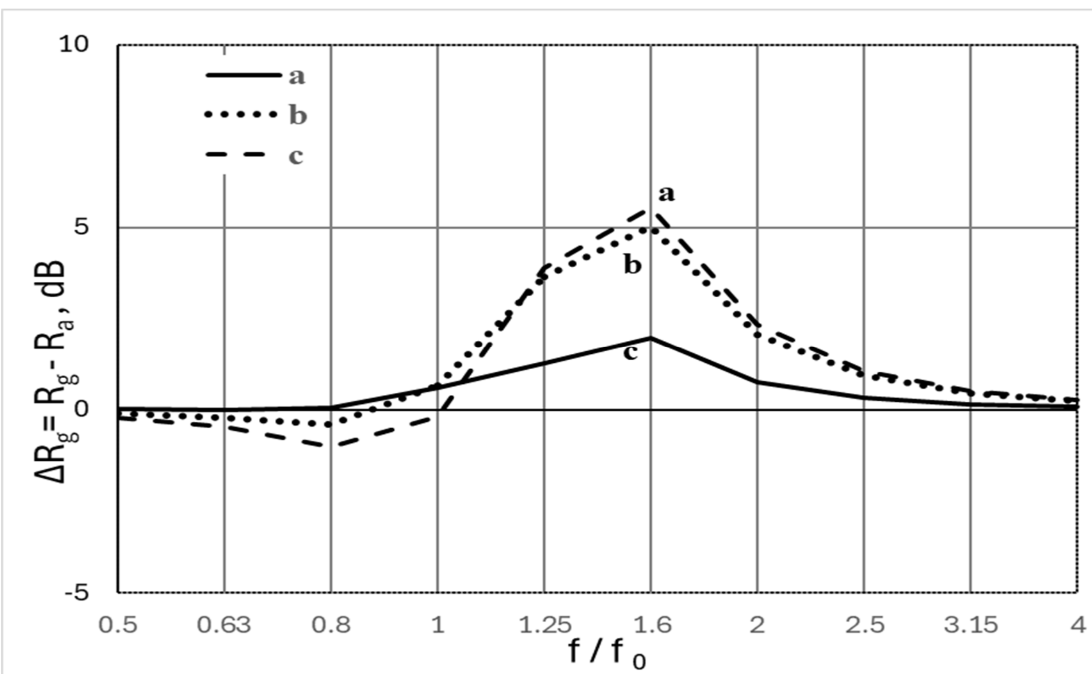

Figure 7: Calculated increase in sound transmission loss for single-space IGU filled with (a) xenon, (b) krypton, and (c) argon compared to that for the same IGU filled with air. Here, $\theta_m = 45^0$.

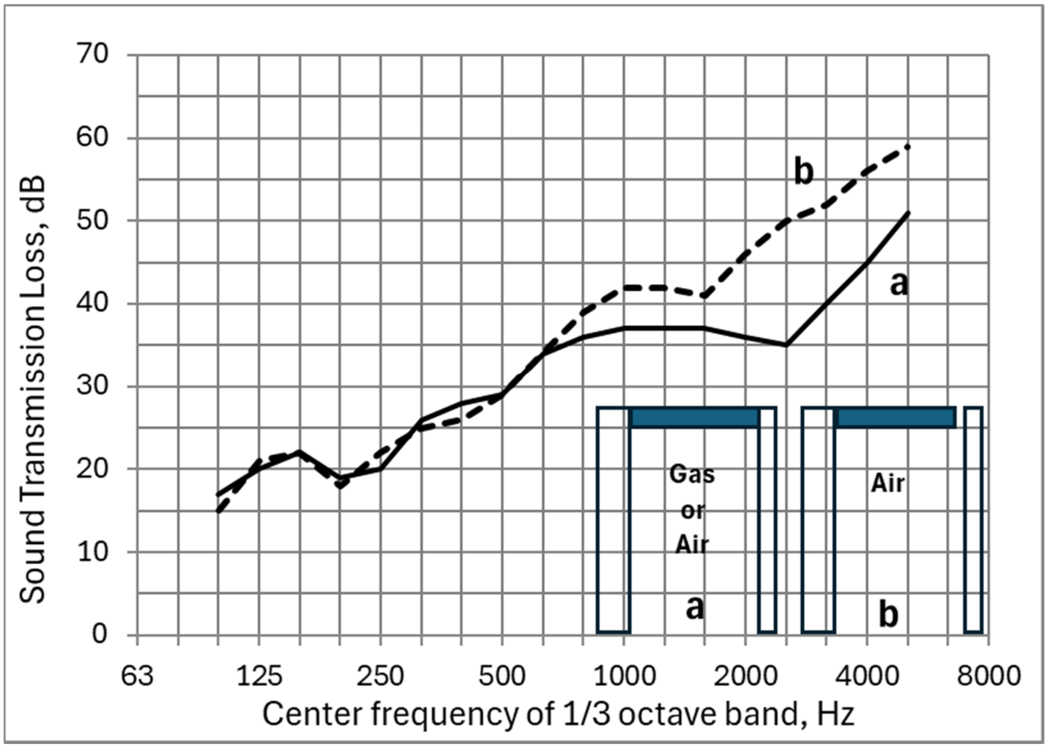

Figure 8: Frequency characteristics of sound transmission loss measured for single-space IGU (8+12+5): a -original specimen, b –the structural links between the panes are weakened.

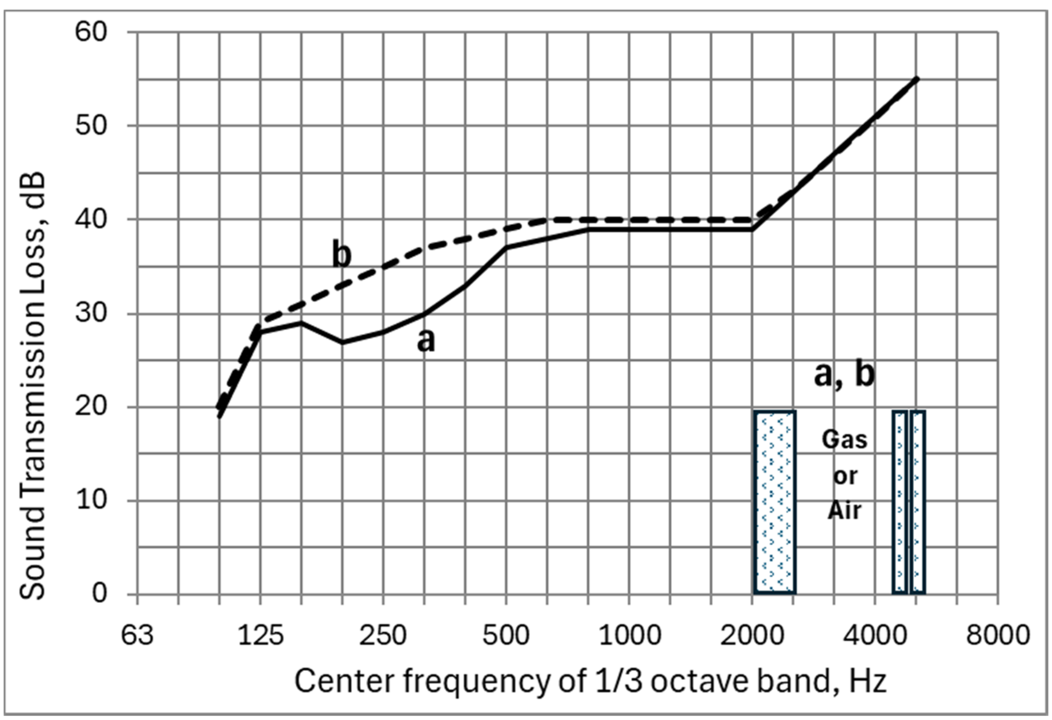

Figure 9: Frequency characteristics of sound transmission loss measured for double-space IGU (10+20+5+0.5+6): a – filled with air, b – filled with gas mixture, 73% Freon-12, 27% air.

To reconcile the displayed results for both direct and flanking sound transmission, the fundamental frequency of the mass-spring-mass resonance was assumed to be 200 Hz, as in the case of the 6+12+6 glazing.

Now, the frequency characteristics, accounting for both direct and flanking sound transmission, are calculated using the results presented in Fig. 7 and the following approximate equation

$$R \approx -10\log(10^{-0.1R_d} + 10^{-0.1R_f})$$

where R_d and R_f represent the sound transmission loss for direct and flanking transmission, respectively. The difference $\Delta R_g = R_g - R_a$ where R_g and R_a are the calculated frequency characteristics for the heavy gas and air fills, respectively, is graphically shown in Fig. 7. As illustrated, the expected increase in sound transmission loss occurs within a relatively narrow frequency range (three-four 1/3 octave bands) and does not exceed 5-6 dB for krypton and xenon. For argon, the effect is minimal: just 1-2 dB in the same frequency range. This frequency range can be wider, and the sound transmission loss may be greater in situ because, in actual buildings, the effective maximum incidence angle is typically higher than 45^0, while the normal incidence is smaller (particularly for the windows at high floors).

5 Direct and Flanking Sound Transmission via Double-Space IGUs

A typical double-space IGU consists of three identical panes and two gaps of equal thickness. According to the theory of triple partitions [7], the direct sound transmission through such a symmetric configuration can be high in the frequency range of mass–spring–mass–spring–mass resonances, as was confirmed both theoretically and experimentally [7–9, 14, 15]. As a result, the sound transmission loss of symmetrical triple glazing is identical to that of double glazing made with the same setup but without the middle pane. Furthermore, the sound insulation of a symmetrical triple glazing with a thick middle pane proved paradoxically low.

However, the sound transmission can be reduced by using an asymmetrical design in which one of the gaps is considerably wider or narrower than the other [7, 9]. In a double-space IGU, a beneficial effect can also be achieved for two equal gaps, if one gap is filled with a heavy gas while the other remains air-filled. As mentioned in Chapter 3, the flanking transmission through a double-space IGU is generally 3–4 dB lower than that through a single-space IGU with similar panes.

6 Experimental Results

To clarify the role of gas filling, experimental studies were conducted in the laboratory using the standard two-room techniques. It should be noted, however, that for the reasons mentioned above, these experimental results may underestimate the role of gas filling in improving sound insulation.

The sound transmission loss measurements were conducted in one-third octave bands with center frequencies ranging from 100 to 5000 Hz, using the two-reverberant-room technique. The widths of the source and receiving reverberation rooms were 3.3 m and 4.5 m, respectively; the length and height of both rooms were 6.0 m and 3.0 m. Thus, the volumes of the source and receiving rooms were approximately 60 m^3 and 80 m^3.. The average sound absorption coefficient in each room varied from 0.07 at 63 Hz to 0.15 at 5000 Hz. The Schroeder cutoff frequency, which marks the approximate transition from room resonances to a diffuse sound field [24], was around 200 Hz for both rooms. A loudspeaker was placed in one of the corners of the source room, away from the test aperture. Seven fixed microphone positions were used in each room. The microphones were installed at a height of 1.5 m, and the distance from each microphone to the nearest wall was at least 1.2 m.

Two experimental IGUs are schematically illustrated in Figs 8 and 9. Their glazing descriptive codes were 8+12+5 for the single-space design and 10+20+5+0.5+6 for the double-space design. The pane edges were connected along the entire perimeter by either a thin aluminum profile or a 0.5 mm layer of mastic (functioning as a firm frame) and were sealed with thiokol (a rubber-like material). Each specimen (1.30 m × 0.95 m) was mounted in a rectangular wooden frame, which was centered in a 1.40 m × 1.05 m test aperture made in a 0.6 m thick brick wall separating the source and receiving rooms. Since all specimens were mounted in the same (central) section of the test aperture, the niche effect influenced all sound transmission loss measurements similarly [23], without altering the key differences between the measured frequency characteristics. The gap in the single-space IGU was filled in turn with air, argon, krypton, carbon dioxide, and a mixture of Freon-12 (73%) with air (27%). The thicker gap in the double-space unit was filled only with the mentioned Freon-12 and air mixture (its average molecular weight is 96). The chemical composition of each gas fill was analyzed twice using a gas chromatograph (the day before and the day after the acoustic measurements) and was found to be consistent in both cases. The fundamental resonance frequency were 200 Hz and 115 Hz for the single-space and double-space specimen, respectively.

Curve ‘a’ in Fig. 8 represents the air-filled IGU only, as the frequency characteristics of the gas-filled IGU (not shown in the graph) match it within the experimental error margin (±1 dB). To enable physical interpretation, the effect of flanking transmission was examined by removing the cement layer connecting the 5 mm pane to the aluminum frame and replacing it with paper tape, while resealing the specimen edges with thiokol. The curves ‘a’ and ‘b’ in Fig. 8 represent the frequency characteristics of sound transmission loss, measured before and after this modification, mostly coincide in the 100–630 Hz range. However, at higher frequencies, the specimen with the weakened structural links exhibited significantly greater sound transmission loss. This comparison experimentally confirms that flanking sound transmission can notably limit the potential benefits of heavier-than-air gas fills. As expected, using panes of different thicknesses did not significantly reduce flanking transmission in the low-frequency range. However, flanking transmission was significantly reduced in the double-space IGU, where a relatively thick pane (10 mm) is firmly connected to a pair of thin panes (5 mm and 6 mm), separated by a small air gap (0.5 mm). In this case, as shown in Fig. 9, a notable improvement (up to 7 dB in the 160–500 Hz range) was observed if the larger gap was filled with a mixture of Freon-12 (73%) and air (27%).

7 Conclusions and Recommendations

1. To enhance both thermal and acoustical performance of windows with insulating glass units (IGUs), the gaps between the panes are filled with a heavier-than-air gas (such as argon, krypton, xenon, or sulfur hexafluoride), either alone or mixed with air. Sound insulation may be improved in the low-frequency range dominated by acoustic resonances, where the panes and gaps act as masses and springs. This frequency range (typically 100–500 Hz) is important for reducing traffic noise through windows. However, significant acoustical improvements are often not observed experimentally, particularly when using the standard two-reverberation room method. In this paper, theoretical and experimental studies are conducted to clarify this situation for both direct and flanking sound transmission via IGUs.

2. All theoretical results presented here were derived using idealized models, and the experimental data were obtained in a laboratory setting using the two-reverberation room method. However, those results can be reasonably extrapolated to in-situ conditions for comparative assessments and design improvements.

3. Flanking transmission (via the panes and perimeter structural connections) is one of the primary limiting factors. However, these connections are essential for the structural integrity and gas tightness of the unit and should not be removed or weakened. Under this constraint, flanking transmission can be reduced by: (1) replacing each pane with a pair of panes half as thick, separated by a small air gap (approximately 1mm), or (2) using laminated (triplex) panes with about the same surface density. In the first case, flanking transmission can be reduced by 4–5 dB, or potentially even more, at low frequencies, but the design may lack structural reliability, if the individual panes are thinner than 4 mm. The second option is more costly, and its acoustic benefit is typically limited to 2–3 dB at low frequencies.

4. On the other hand, flanking sound transmission tends to decrease as the unit area increases – by 9 dB if the cross-section linear sizes are doubled. In practice, however, this beneficial effect is less pronounced (about 7.5 dB) because the thickness of a larger pane must also be increased to maintain structural strength.

5. The direct sound transmission (via the panes and gaps) can be lower if the gap is filled with a heavier-than-air gas instead of air. This occurs because the angle of refraction (between the wave in the gas-filled gap and the normal to the panes) can be significantly smaller than the angle between the incident wave and the normal. In this case, the frequency range of the mass-spring-mass resonances can be much narrower than for an equivalent air-filled unit (for very heavy gases, it falls within a 1/3-octave band). The direct sound transmission at frequencies above this zone is not affected by the mass-spring-mass resonances. Therefore, the sound insulation surplus can be achieved mainly in the frequency range above this zone for the heavier gas fill, but still within the mass-spring-mass resonance zone for air fill. The dynamic viscosity of either the gas or air must be high enough to mitigate the mass-spring-mass resonances.

6. The fundamental mass-spring-mass resonance frequency is approximately the same for both air- and gas-filled units, as the internal gap pressure must remain close to atmospheric pressure to ensure structural reliability. Consequently, at normal incidence (where sound refraction does not occur) the direct sound transmission through a given unit should be similar for both air and gas fills, assuming their dynamic

viscosities are equal. At low frequencies, where the window's cross-sectional dimensions are smaller than the sound wavelength, the incident acoustic pressure is distributed almost uniformly across the window surface, resembling the condition of normal incidence. Additionally, the outer and inner regions of the aperture, where the window is installed, can behave like acoustic waveguides, particularly in laboratory test setups where the separating wall is typically thick (around 0.6 m). In such low-frequency conditions, the associated wave phenomena can be approximated by introducing a maximum incidence angle, which may be significantly less than 90 degrees. As a result, the acoustic performance difference between air and gas fills in small-area units may not be as pronounced as in larger units. Moreover, since actual building walls are usually thinner (often 0.3 m or less) than those used in laboratory reverberation tests, the beneficial effects of gas fills may be present in real-world settings but not clearly reflected in lab measurements.

7. Based on the results obtained, IGUs filled with heavier-than-air gases can provide better sound insulation than those filled with air. Krypton, with an atomic weight of 80, or more cost-effective gas mixtures with similar molecular weight and dynamic viscosity, appear to offer optimal performance (for reference, air has a molecular weight of 29). Argon is less effective due to its relatively low atomic weight of 39. The same applies to carbon dioxide (molecular weight 44), which also has a lower dynamic viscosity than air.

8. Flanking sound transmission through typical double-space units is lower than that through single-space units. To reduce the direct sound transmission in a typical double-space unit (with three similar panes and two equal gaps), it is advisable to fill only the gap closer to the building's interior with a heavier-than-air gas, as it is less exposed to external weather conditions. The other gap should remain air-filled.

9. In general, the sound insulation performance of gas-filled IGUs may exceed that of air-filled ones. This improvement is most apparent in the low-frequency range (primarily 200–500 Hz), tends to increase with the IGU's surface area, and typically does not exceed 5 dB. Nonetheless, even this level of enhancement is important for protection against traffic noise. It is worth noting that the improvement measured using standard two-reverberation room testing may be smaller than the in-situ performance.

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