Numerical examination of niche effect on sound transmission loss of glass panes

Tetsuya Sakuma¹*, Naohisa Inoue¹,∗ and Tsuyoshi Seike²,‡

¹Graduate School of Frontier Sciences, The University of Tokyo, 5–1–5 Kashiwanoha, Kashiwa, 277–8563 Japan
²Design Systems Engineering Center, Mitsubishi Electric Corporation, 8–1–1 Tsukaguchi-Honnachi, Amagasaki, 661–8661 Japan

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Abstract: In the laboratory measurement of the sound transmission loss of platelike building elements, a specimen mounted between coupled rooms causes the so-called niche effect. Normally a specimen is mounted inside an aperture in a thick wall, whereas in a special case where a specimen is mounted flush with the wall, a projecting box frame is additionally installed outside the opening. Firstly, the measurements of a glass pane with the two types of niche are numerically modeled by vibro-acoustic simulation, and the niche effect is examined while changing the niche depth and specimen position. As a result, it is revealed that the effect of the projecting niche is generally smaller than that of the recessing niche. Secondly, regarding the cross-sectional shape of the recessing niche, the smaller effect of the staggered niche specified in ISO 10140 is validated by comparison with that of a flat niche. Additionally, the incidence angle dependence of the niche effect is clarified.

Keywords: Sound insulation, Transmission loss, Niche effect, Vibro-acoustic analysis, Glass

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1. INTRODUCTION

In the laboratory measurement of the sound insulation performance of platelike building elements, such as walls, doors, windows, and glazing, a test specimen is normally mounted inside an aperture in a thick concrete wall between coupled reverberation rooms. This laboratory method of measuring sound transmission loss (STL) has been elaborately established over a long time and is currently standardized in the ISO 10140 series [1–4]. However, the reproducibility of the measurement among existing laboratories is not yet completely achieved owing to differences in room dimensions and other various factors in relation to the installation of specimens. It is well known that one of the most important factors is the so-called niche effect, which results from the configuration of a specimen inside the aperture.

Some decades ago, several experimental studies demonstrated the niche effect [5–9], which was later investigated in theoretical and numerical studies [10–13]. So far, the following general findings on the niche effect have been obtained: 1) the effect is significant below the critical coincidence frequency; 2) the effect depends on the position of the specimen in the niche; 3) the lowest STL is obtained when the sample is located in the middle of the niche; 4) the highest STL is obtained when the sample is mounted flush at one of the edges of the niche; 5) the effect depends on the sectional shape of the niche around the specimen. In view of these tendencies, ISO 10140-1 specifies that the niches on the two sides of a specimen should have different depths, preferably in a ratio of about 2:1 [1]. In addition, ISO 10140-5 specifies staggered niches with different widths and heights on the two sides [4].

Regarding the mechanism underlying the niche effect, three theoretical explanations are convincing at present. Firstly, Vinokur proposed an infinite three-layer model where a limp plate is sandwiched by two air layers with lumped mass and stiffness [11]. However, this model is only valid for a low-frequency range below \(c_0/S\), where \(c_0\) is the speed of sound and \(S\) is the aperture area. Secondly, Kim et al. suggested that the acoustic field inside the niche modifies the vibration field of a plate, which increases the radiation efficiency at resonances [10]. This modal cou-
pling effect can explain the decrease in STL in the intermediate frequency range below the critical frequency. Thirdly, Hopkins claimed that the shielding of the specimen surface from near-grazing incidence waves by the niche is the most significant factor for nonresonant transmission below the critical frequency [14]. In contrast to the above models, this shielding effect causes an increase in STL. Taken together, the niche effect must be considered as a complex effect based on the above three models depending on the frequency.

In a special case where a specimen is mounted flush with the wall, a projecting box frame is intentionally attached around the specimen to simulate the niche effect [6,15]. However, the difference in the effects between the two types of niche, recessing and projecting, has not been quantitatively clarified. Moreover, regarding the cross-sectional shape of the recessing niche, the superiority of the staggered niche specified in ISO10140-5 has not been fully verified. Focusing on the above two issues, in this study, we investigate the characteristics of the niche effect by numerical simulation. In Sect. 2, the recessing and projecting niches are numerically modeled for vibro-acoustic simulation, and in Sect. 3, the effects of the two types of niche on the STL of a glass pane are examined while changing the total niche depth and the position of the specimen. In Sect. 4, the effect of the standard staggered niche is numerically validated in comparison with a flat niche, and, the incidence angle dependence of the niche effect is examined.

2. NUMERICAL MODELING

For predicting the STL of platelike members, an ideal sound field condition is supposed, where a plane sound wave is incident upon a thin plate mounted in an infinite rigid baffle. However, two different numerical formulations are adopted to model the recessing niche and projecting niche.

2.1. Recessing Niche Model

In the recessing niche model, a thin plate is mounted inside an aperture in a thick rigid baffle, as illustrated in Fig. 1. The structural-acoustic finite element method (FEM) is applied to the air space (ΩA) and plate (Γp) inside the aperture, while the boundary element method (BEM) is applied to the two semi-infinite spaces of the incident and transmitted sides (Ωi and Ωt). Finally, the discrete systems determined by the FEM and BEM are coupled on the two imaginary boundaries along the wall surfaces (Γi and Γt) with the following boundary conditions:

\[ p_\text{i} - 2j\omega pGv_\text{i} = 2p_\text{st}, \]
\[ p_\text{i} + 2j\omega pGv_\text{i} = 0, \]

where \( p_\text{i} \) and \( v_\text{i} \) are the vectors of the sound pressure and particle velocity on \( \Gamma_\text{i} \) and \( \Gamma_\text{t} \), respectively, \( p_\text{st} \) is the vector of the incident sound pressure on \( \Gamma_\text{i} \), and \( G \) is the influence matrix given by

\[ p_\text{st} = \exp(-jk \cdot r_i), \]
\[ G_{ij} = \int_{\Gamma} G(r_i, r_j)N_j(r_q)dS_q, \]

where \( k \) is the wave number vector of the incident wave, \( G \) is the fundamental solution for the three-dimensional field, and \( N_j \) the interpolation function for the \( j \)th node. In the FEM, triquadratic hexahedron elements are used for the air space, and in the BEM, biquadratic quadrangle elements are used for the imaginary boundaries [16].

2.2. Projecting Niche Model

In the projecting niche model, a thin plate is mounted inside an aperture of the thin rigid baffle, and thin rigid frames are attached around the plate on the two sides, as illustrated in Fig. 2. In a different way from the recessing niche model, the structural FEM is applied to the plate (\( \Gamma_\text{p} \)), while the BEM is applied to the two semi-infinite spaces with the frames having no thickness (\( \Omega_\text{t} \) and \( \Omega_\text{i} \)).
Note that degenerate boundary elements are used for the frames, thus introducing a special formulation as follows [17]. This model is valid for a frame with a thickness sufficiently smaller than the wavelength.

If a source point is collocated on the plate \((\Gamma_p)\), the following discrete system is obtained:

\[
\ddot{\mathbf{p}}_p - 2H_{ij} \dot{\mathbf{p}}_j + 2H_i \dot{\mathbf{p}}_i + 4\omega^2 \rho G \mathbf{w} = 2p_d, \tag{5}
\]

where \(\mathbf{p}_{p,d}\) are the vectors of the sound pressure difference between the two sides of the plate and the frames in \(\Omega_i\) and \(\Omega_t\), \(\mathbf{w}\) is the plate displacement vector, and \(H_{ij}\) are the matrices of influence from the frames given by

\[
H_{ij} = \int_{\Gamma_i} \frac{\partial G(r_i, r_q)}{\partial n_q} N_j(r_q) dS_q. \tag{6}
\]

On the other hand, if a source point is collocated on the frames \((\Gamma_f)\), the hypersingular formulation can be applied to \(\Omega_i\) and \(\Omega_t\). Considering the mirror field, the following systems are obtained:

\[
-\ddot{\mathbf{p}}_d + 2\omega^2 \rho G \mathbf{w} = 0, \tag{7}
\]

\[
-\ddot{\mathbf{p}}_d + 2\omega^2 \rho G \mathbf{w} = 0. \tag{8}
\]

where \(\ddot{\mathbf{p}}_d\) are the matrices of influence from the real and mirror frames, \(G_{ij}\) are the matrices of influence from the plate, \(\dot{\mathbf{p}}_d\) is the vector of the normal derivative of the sound pressure for the real and mirror incident waves on the frame in \(\Omega_t\). The above matrices are obtained from the hypersingular formulation as follows:

\[
H_{ij} = \int_{\Gamma_i} \frac{\partial^2 (G(r_i, r_q) + G(r, r_q))}{\partial n_i \partial n_q} N_j(r_q) dS_q, \tag{9}
\]

\[
G_{ij} = \int_{\Gamma_i} \frac{\partial G(r_i, r_q)}{\partial n_i} N_j(r_q) dS_q, \tag{10}
\]

where \(\hat{r}_i\) represents the mirror position of the \(i\)th node.

### 2.3. Plate Vibration Model

Regarding the plate vibration field, the classical thin plate theory is assumed with a lumped spring model for an edge support system [18]. As illustrated in Fig. 3, this model consists of two kinds of spring that are equivalent to the translational and rotational motion of the elastic sealing material around the plate. Assuming that the two springs react against the displacement and the slope of the plate at the edge, the mechanical impedance and moment impedance are given by

\[
Z_q = \frac{2(1 + j\eta_s)E_s d_s}{j\omega t_s}, \tag{11}
\]

\[
Z_m = \frac{(1 + j\eta_s)E_s d_t^2}{6j\omega t_s}, \tag{12}
\]

where \(E_s\) and \(\eta_s\) are the Young’s modulus and loss factor of the sealing material, and \(d_s\) and \(t_s\) are the depth and thickness of the one-sided seal, respectively. Finally, the above impedances are incorporated into the discrete system obtained by the structural FEM as follows:

\[
[(\mathbf{K} + \mathbf{K}_q + \mathbf{K}_m) - \omega^2 \mathbf{M}] \begin{bmatrix} \mathbf{w} \\ \theta_x \\ \theta_y \end{bmatrix} = \mathbf{Q}\ddot{\mathbf{p}}_p, \tag{13}
\]
where $\theta_{x,y}$ are the vectors of the $x,y$-directional slopes. $K$, $M$ and $Q$ are the elastance, inerterance, and conformation matrices for the plate, and $K_q$ and $K_m$ are the boundary stiffness matrices for the translational and rotational springs, respectively. In the structural FEM, ACM quadrangle elements are used for the plate, and the above vibration system is coupled with the acoustic systems on the two sides of the plate in the recessing or projecting niche model.

### 2.4. Calculation of STL

The STL of a specimen is calculated from the incidence power of a plane wave on the plate and the transmission power through the plate, where the former is theoretically given and the latter is calculated by integrating the sound intensity on the transmitted side of the plate. In the following study, the STL is calculated in each incident direction, with intervals of $3^\circ$ or less in the polar and azimuthal angles, at 1/24-octave-band center frequencies [19]. The random-incidence STL is obtained by statistical averaging over all incidence angles in 1/3-octave bands.

### 3. CASE STUDIES ON THE TWO NICHE MODELS

#### 3.1. Properties of Specimen and Niches

Table 1 shows the properties of a plate and a seal for the case studies in this section, supposing a glass pane supported with putty. The dimensions of the seal are in accordance with ISO 10140-5, but the plate is square and somewhat smaller with the intention of observing general tendencies of the niche effect under a simple and critical condition. The Young’s modulus and the loss factor of the seal are roughly given by referring to the measured values for the ISO-specified putty [20]. In theory, the critical coincidence frequency of a glass pane of 10 mm thickness is 1,135 Hz. In the first study, the niche depths of the two sides are equal, and the total depth is varied from 0 to 0.5 m (0 to 0.25 m for each side). In the second study, the total depth is fixed at 0.45 m, and the depths of the two sides are changed.

| Plate Seal |
|----------------|
| Dimensions [mm] | $W = 900$, $H = 900$ | $d_s = 15$ |
| Thickness [mm] | $t_p = 10$ | $t_s = 5$ |
| Density [kg/m$^3$] | $\rho_p = 2.500$ | N/A |
| Young’s modulus [N/m$^2$] | $E_p = 7.5 \times 10^{10}$ | $E_s = 1.0 \times 10^9$ |
| Poisson’s ratio | $\nu_p = 0.22$ | N/A |
| Loss factor | $\eta_p = 0.002$ | $\eta_s = 0.5$ |

The properties of the plate and seal.

#### 3.2. Effect of Niche Depth

Figure 5 shows the random-incidence STL differences calculated for the two types of niche, changing the total depth with the two sides having an equal depth, where the case without a niche is considered as the reference. Regardless of the niche type, it is seen that negative differences become greater below 800 Hz as the niche depth increases, whereas positive and negative differences appear above 1 kHz in relation to the wavelength. The tendency at low frequencies is consistent with the previous experimental results and the theoretical explanations by Vinokur [11] and Kim et al. [10]. Regarding the recessing niche, the variations of the STL difference reasonably well correspond with those for a larger glass pane in [12]. However, it is clearly seen that the projecting niche yields less effect than the recessing niche at lower frequencies.

**Use a diagram here if necessary**

#### 3.3. Effect of Specimen Position

Figure 6 shows the calculated results for the two types of niche, changing the plate position while maintaining a constant total depth. At a glance, symmetrical variations are confirmed with respect to the center of the niche. In the range from 200 to 800 Hz, the effects of both types of niche become smaller when the plate is mounted near one of the edges, and centering the plate yields the greatest decreases, which is also observed in [12]. However, below 125 Hz, negative differences do not disappear for the recessing niche even when the plate is located near the edge. Again, it is seen that the dependence of the position for the projecting niche is smaller than that for the recessing niche at lower frequencies. Therefore, it is concluded that the projecting niche cannot be an adequate substitute for the recessing niche in the STL measurement. Moreover, it is revealed that the specimen position of 2:1 specified in ISO 10140-1 reduces the niche effects a small amount in comparison with centering, but not in all frequency bands.
Fig. 5 Variations of random-incidence STL difference calculated for the two niche models, changing the total niche depth $D$ with the two sides having an equal depth ($D_i = D$). Upper: 80 to 315 Hz; lower: 400 to 1,600 Hz.

Fig. 6 Variations of random-incidence STL difference calculated for the two niche models, changing the specimen position ($D_i/D$) under the total niche depth $D = 0.45$ m. Upper: 80 to 315 Hz; lower: 400 to 1,600 Hz.
4. VALIDATION OF THE STANDARD STAGGERED NICHE

4.1. Properties of Specimens and Niches

Figure 7 illustrates the two types of cross section of niches, flat and staggered, tested in this section. The flat type is the one tested as the recessing niche in the above section, and the staggered type is the one in accordance with ISO 10140-5, having a larger niche on the incident side that is 60 mm wider at the sides and the top. Both types of niche have an equal total depth of 0.41 m, and a specimen is mounted at an equal ratio of about 2:1 in the total depth. The specimens are glass panes of 5 and 10 mm thickness, having the critical coincidence frequencies of 2,270 and 1,135 Hz, respectively, with the standard width of 1.25 m and height of 1.5 m, and supported with the seal whose properties are given in Table 1. In the following, the STL differences from the reference case without a niche are calculated for each type of niche.

4.2. Effect of Staggered Niche

Figure 8 shows the random-incidence STL of the two glass panes calculated with the flat and staggered niches and without a niche, and the STL differences for the two types of niche. In the upper graphs, the theoretical lines of STL obtained by Sewell, Cremer, and the mass law are additionally indicated. It is confirmed that the calculated STL of a 5-mm-thick pane without a niche corresponds reasonably well with Sewell’s line for the corresponding specimen area below the critical coincidence frequency, however a slight discrepancy is observed for the 10-mm-thick pane.

Regarding the STL differences, negative values appear below the critical frequency, whereas slightly positive values appear above the critical frequency, as mentioned in the previous section. In comparison with the flat niche, the staggered niche yields less negative effects by 2 to 3 dB, thus confirming its superiority. Nevertheless, it is noted that, even in the measurement using the standard staggered niche, negative and positive effects of about 2 dB can remain for a single-layer glass pane below and above the critical frequency, respectively. Furthermore, Dijckmans et al. demonstrated that a more negative effect occurs in the case with double-layer glass panes [12].
4.3. Incidence Angle Dependence of Niche Effect

For better understanding of the characteristics of the niche effect, the incidence angle dependence is examined. Figure 9 shows the oblique-incidence STL differences of the glass pane of 10 mm thickness calculated with the above two types of niche, where the values for each polar angle of incidence are given by averaging over all azimuthal angles.

In the lower frequency range below 630 Hz, regardless of the niche type, it is seen that the incidence angle dependence is relatively small, but the slopes are in the opposite direction below and above 160 Hz. Below this frequency, negative effects become greatest at the normal incidence, as suggested in the three-layer model of Vinokur [11]. Above this frequency, negative effects become greater with increasing incidence angle, which may be related to tangential modes in the niches.

In the higher frequency range above 800 Hz, the incidence angle dependence is considerably different between the two types of niche. In the case with the flat niche, the variations of the STL difference are relatively small below 40°, but are very large above this angle. In particular, a large peak appears around the coincidence angle above the critical frequency of 1,135 Hz, which is considered due to the shielding effect as Hopkins pointed out [14]. However, in the case with the staggered niche, the STL differences rapidly decline at smaller incidence angles around the critical frequency, although the peaks are broadened. One possible explanation is that at a small incidence angle, diffracted waves along the edges of the staggered niche more intensively impinge on the specimen at a grazing angle than those of the flat niche, but there is no evidence for this at present.

5. CONCLUSIONS

In order to clarify the characteristics of the niche effect in the STL measurement for glass panes, numerical examinations were conducted focusing on the difference between two models of recessing and projecting niches, and furthermore, on the validity of the standard staggered niche specified in ISO 10140-5.

Regarding the former issue, two case studies, in which the total niche depth and the position of the specimen were varied, were presented for the two niche models. Firstly, the following general tendencies were confirmed: 1) the negative effect on STL becomes greater with increasing the total niche depth below the critical coincidence frequency, whereas positive and negative effects appear around and above the critical frequency; 2) the negative effect becomes smaller when the specimen is mounted near one of the edges of the niche, and centering it yields the greatest decrease below the critical frequency. Note that the above tendencies are consistent with the previous studies. Finally, it was revealed that the effect of the projecting niche is generally less than that of the recessing niche. This suggests that the projecting niche cannot be an adequate substitute for the recessing niche in the STL measurement.

Regarding the latter issue, the effect of the standard staggered niche was compared with a flat niche by numerical simulation. As a result, it was observed that
the staggered niche yields less effect on random-incidence STL, thus confirming its superiority to the flat niche. Nevertheless, this result suggests that negative and positive effects of about 2 dB still remain for glass panes below and above the critical frequency, respectively. Moreover, regarding the incidence angle dependence of the niche effect, it was found that the staggered niche has strong dependence around the critical frequency.

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REFERENCES

[1] ISO 10140-1: Acoustics — Laboratory measurement of sound insulation of building elements — Part 1: Application rules for specific products (2016).
[2] ISO 10140-2: Acoustics — Laboratory measurement of sound insulation of building elements — Part 2: Measurement of airborne sound insulation (2010).
[3] ISO 10140-4: Acoustics — Laboratory measurement of sound insulation of building elements — Part 4: Measurement procedures and requirements (2010).
[4] ISO 10140-5: Acoustics — Laboratory measurement of sound insulation of building elements — Part 5: Requirements for test facilities and equipment (2010).
[5] T. Kihlman and A. C. Nilsson, “The effects of some laboratory designs and mounting conditions on reduction index measurements,” J. Sound Vib., 24, 349–364 (1972).
[6] R. Guy and P. Sauer, “The influence of sills and reveals on sound transmission loss,” Appl. Acoust., 17, 453–476 (1984).
[7] R. Guy, A. de Mey and P. Sauer, “The effect of some physical parameters upon the laboratory measurements of sound transmission loss,” Appl. Acoust., 18, 81–98 (1985).
[8] A. Cops, M. Minten and H. Myncke, “Influence of the design of transmission rooms on the sound transmission loss of glass: Intensity versus conventional method,” Noise Control Eng. J., 28, 121–129 (1987).
[9] A. Cops and D. Soubrier, “Sound transmission loss of glass and windows in laboratories with different room design,” Appl. Acoust., 25, 269–280 (1988).
[10] B.-K. Kim, H.-J. Kang, J.-S. Kim, H.-S. Kim and S.-R. Kim, “Tunneling effect in sound transmission loss determination: Theoretical approach,” J. Acoust. Soc. Am., 115, 2100–2109 (2004).
[11] R. Vinokur, “Mechanism and calculation of the niche effect in airborne sound transmission,” J. Acoust. Soc. Am., 119, 2211–2219 (2006).
[12] A. Diickmans and G. Vermeir, “A wave based model to predict the niche effect on sound transmission loss of single and double walls,” Acta Acust. united Ac., 98, 111–119 (2012).
[13] F. Sgard, N. Atalla and H. Nelisse, “Prediction of the niche effect for single flat panels with or without attached sound absorbing materials,” J. Acoust. Soc. Am., 137, 117–131 (2015).
[14] C. Hopkins, Sound Insulation, 1st ed. (Butterworth-Heinemann, Oxford, 2007), Chap. 3.
[15] J. Yoshimura, S. Sugie and E. Toyoda, “Effects of size and edge damping on measurement results for sound reduction index of glass pane,” Proc. Inter-Noise 2006, No. 641 (2006).
[16] N. Inoue and T. Sakuma, “Study on numerical prediction of the performance of arbitrary acoustic elements, part I: Proposal of analysis models,” Proc. Spring Meet. Acoust. Soc. Jpn., pp. 1221–1224 (2012).
[17] T. Sakuma, K. Adachi and Y. Yasuda, “Numerical investigation of the niche effect in sound insulation measurement,” Proc. Inter-Noise 2011, No. 432239 (2011).
[18] T. Sakuma, K. Egawa and Y. Yasuda, “Numerical analysis of sound transmission loss of glass pane: On the treatment of edge damping,” Proc. Inter-Noise 2008, No. 0486 (2008).
[19] T. Sakuma and T. Oshima, “Numerical vibro-acoustic analysis of sound insulation performance of wall members based on a 3-D transmission model with a membrane/plate,” Acoust. Sci. & Tech., 22, 367–369 (2001).
[20] K. Yamamoto, H. Ohyama and S. Sueyoshi, “Sound reduction performance of glass pane by the difference in the damping characteristics of the edge support system,” Proc. Tech. Meet. (Soc. Damping Tech.), pp. 51–58 (2009).