Article title: Basic considerations on the practical method for predicting sound insulation performance of a single-leaf window

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Coverletter

Kurobe, 18 Mar. 2021

Dear Editors

We are pleased to submit a manuscript entitled as ‘Basic considerations on the practical method for predicting sound insulation performance of a single-leaf window,’ for a possible publication as an open commentary in UCL Open: Environment.

This work is an interim report of our project exploring the simple and practical method to predict the sound insulation characteristics of actual windows commonly used in various buildings. This report presents some cues for predicting reduction indices of actual windows. The quiet indoor acoustic environment is necessary in living places for the quality of human activities, and this depends on the sound insulation performance of exterior walls of buildings, especially windows. However, as there are fewer studies which show the data of actual windows, general characteristics of sound insulation performance of an actual window are less known. We consider that a practical predicting method of sound reduction index for actual window is necessary for the design of acoustic environment in buildings.

First, results calculated by an existing theory for a single plate for the sound reduction indices are compared with measured results of actual windows to assess the theory’s applicability for evaluating the sound insulation performance of windows. Next, a regression analysis is employed to measured results of a certain number of actual windows to explore a further development of a more practical prediction. Then, we obtained some findings for sound insulation performance of single glazing window below the critical frequency, which will become a basis of establishing a practical prediction method.

As the sound reduction indices above the coincidence frequency or those of multiple glazing windows are also important issues, this work is in the middle of our effort. In this sense, we consider that the present work is more suitable for an open commentary as a short communication providing a basic discussion on this topic.

We hope that this work can find a space in your journal.

Kindest regards
Yohei Tsukamoto, corresponding author

Basic considerations on the practical method for predicting sound insulation performance of a single-leaf window

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Abstract

As a basic study of a practical method for predicting sound insulation performance of windows, this report presents a study of the sound reduction index of windows with single glazing below a critical frequency. First, results calculated by an existing theory for a single plate for the sound reduction indices are compared with measured results of actual windows to assess the theory's applicability for evaluating the sound insulation performance of windows. Next, a regression analysis is employed to measured results of a certain number of actual windows to explore a further development of a more practical prediction. The following findings were obtained: (1) Sound reduction indices of actual fixed windows are predictable using Sewell's transmission theory for a single plate. However, sound reduction indices of openable windows, especially those of sliding windows, are affected strongly by window frame gaps. Therefore, predicting sound reduction indices of all windows accurately is difficult if using only one theory. (2) The frequency slope of the window reduction index is much lower than that of the mass law. Regression analyses indicate that the frequency slope of the reduction index of all examined windows is 3.0 dB per octave, on average.

Keywords: architectural acoustics, mass law, measurement, single glazing, sound insulation, window

1. Introduction

Indoor environmental quality (IEQ) is of paramount importance in houses, offices, and most types of buildings. Among various environmental factors, quiet indoor acoustic environment is necessary both in living and working places for the quality of human activities within those spaces, and this depends on the sound insulation performance of exterior walls of buildings, e.g., [1]. The indoor acoustic environment depends mainly on the window sound insulation performance because windows are the weakest components of exterior walls in many cases [2]. For acoustic environment design, predicting the sound insulation performance of windows is crucially important. Many points of consideration exist in window design include obtaining natural ventilation, day lighting, and the view from buildings. Actually, these functions often share a trade-off relation with sound insulation, which has eventually led to development of a wide variety of window types, with sound insulation performance depending on the window type. This leads to another approach of the performance of windows, especially natural-ventilating windows, to evaluate them by perceptual factors using indoor soundscape approach [3]. However, still it is important to develop a practical prediction method for sound reduction index that is applicable for windows of different types.

Although the mass law of a single plate gives a slope of 6 dB per octave [1], reduction indices of single glazing in an actual window frame usually indicate different values. It is therefore considered that the mass law is inapplicable to an actual window of usual size. Some other effects that are not observed in walls are unique to actual windows, such as air gaps between sashes and frames or degrees of fixation depending on the window type. Additionally, the window pane size should be a consideration when predicting the sound insulation of windows. Therefore, a simple mass-law based discussion cannot be sufficient for the present purpose: we must start with a theory that can accommodate the panel size effect.

For this purpose, the theory developed by Sewell [4] is regarded as promising. Sewell developed an expression for reduction indices of finite single plates considering plate size effects, although the theory is limited to below coincidence frequency. Although Sewell's theory is not aimed at finite-sized sashed windows, it considers differences in radiation efficiencies depending on the plate size to include the plate size effect. Quirt studied sound transmission characteristics experimentally with modelled windows [5], and found good correlation with the experimental results. However his model was considerably simplified, it is still not very clear how well the theory can describe the sound insulation performance of actual windows. Regarding the gap, some cases exist in which effects are studied using numerical analysis [6]. However, no practical formula to predict or estimate window frame effects on the sound insulation performance of a window has been proposed. Iwase et al. [7–10] attempted to evaluate gap effects experimentally using modelled reverberation chamber. However, they did not present definite results that are applicable to practical cases. As there are fewer studies which show the data of a certain number of actual windows, general characteristics of sound insulation performance of an actual window are less known. Therefore, establishing a practical method to predict the sound insulation performance of an actual window with a simple expression is of paramount importance.

The goal of this project is establishment of a practical method of the sound insulation performance of a window. As a basic study, a sound reduction index of a single-leaf window below its critical frequency is discussed herein. First, we applied Sewell's theory for a single plate by comparing the calculated and measured results of reduction indices of actual windows. Results of the comparison showed the applicability of Sewell's theory. Secondly, as another alternative for obtaining a practical solution, we tried to apply regression analyses to our measured data of reduction indices of windows. For this purpose, we used 83 set of measured data of windows of three types; regression lines for windows of each type were obtained to confirm the slope of the frequency characteristics of the reduction index.

2. Prediction using Sewell's Theory

2.1. Fundamental principles of theoretical prediction of reduction index

According to the well-known mass law, field-incidence-averaged sound reduction index R_m is given by the following expression [11].

$$R_m = 10\log\left(\frac{\omega m}{2\rho c}\right)^2 - 5 \tag{1}$$

Therein, ω stands for angular frequency, m [kg m^{-2}] denotes the plate surface density, ρ [kg m^{-3}] expresses air density, and c [m s^{-1}] signifies the sound velocity in air. Because the mass law Eq. (1) is based on the assumption of an infinite plate in piston-like motion to a plane wave, it agrees with the measured result of a large homogeneous wall. Basically, the mass law in the original form is given for a normal incidence of a plane wave, but Eq. (1) is modified to adapt it for use in a diffuse sound field case by adding a correction factor of 5 [11].

However, for small plates, it cannot agree with the measured results. In most cases, R_m by Eq. (1) does not agree with measured results of window's reduction index. Sewell derived a formula for evaluating a reduction index for finite plate with sound-induced vibration that is applicable below the coincidence frequencies as follows.

$$R_s = 10\log\left(\frac{1}{\tau_s}\right) \tag{2}$$

$$\tau_s = \left\{\left(\frac{\omega m}{2\rho c}\right)\left[1-\frac{\omega^2}{{\omega_c}^2}\right]\right\}^{-2}\left[\ln\left(k\sqrt{F}\right) + 0.160 - U(\Lambda) + \frac{1}{4\pi k^2 F}\right] \tag{3}$$

$$U(\Lambda) = -0.804 - \left(\frac{1}{2}+\frac{\Lambda}{\pi}\right)\ln\Lambda + \frac{5\Lambda}{2\pi} + \sum_{n=1}^{\infty}\frac{(-1)^{n-1}\Lambda^{2n+1}}{2\pi n(n+1)(2n+1)^2} \tag{4}$$

In those equations, $k = \omega/c$ expresses the wavenumber, F denotes the sample area, and Λ represents the ratio of shorter side length to longer side length of the sample.

2.2. Measurement

Measurements were taken according to JIS A 1416 [12], which is compatible with ISO 10140-2 [13]. All measurements were taken in reverberation chambers at the YKK AP central test centre, which has coupled reverberant rooms: the source room has 492.8 m^3; the receiving room has 264.5 m^3 volume. Reduction indices in the 1/3 octave bands were calculated from 100 to 5,000 Hz.

2.3. Comparing theoretical results and measurement results

The calculated results by Sewell's theory for the reduction index of a plate are compared with the measured results of windows of different types. Its applicability for predicting the sound insulation performance of windows is evaluated. The sketches of measured windows of three types (fixed, projected, sliding) are shown in Figure 1. All windows in this measurement consist of a glass and actual frames. The fixed window is not openable. The projected window and sliding window are defined in this report as follows. The projected window is an openable window that top and bottom of the frame are connected with the sash using friction stay, and the sliding window refers to a window composed of two sashes moving horizontally. The three windows are divided according to window glass thickness. The glazing considered here is commonly used float glass as a single glazing, with 5, 6, 8 mm thicknesses. Regarding the window size, the samples are organised to three categories according to the approximate sizes: window size *F* is within 15% of the represented value shown in figures. Up to three measured results are plotted in each graph. It is noteworthy that the data used for this comparison include particular trends of windows: thicker glazing tends to be used for higher-specification windows intended for use in high-rise buildings. Because these data are obtained from actual commercial windows, this tendency is reflected in this study.

Fig. 1 Sketches of the measured window types. (a), (b) and (c) are a fixed window, a projected window, and a sliding window, respectively.

2.3.1. Fixed window

Figure 2 portrays measured results of reduction indices of fixed windows with the corresponding results obtained using Sewell's formula (Eq. (2–4)). From the left side, the results obtained for 5, 6, 8 mm glass thicknesses are shown. The examined fixed windows with sizes of 0.5–2.0 m^2 are shown. The sizes are classified to three levels for each thickness in Fig. 2. Moreover, the field incidence mass law values for the same surface density are presented in the same figure for a reference. According to Fig. 2, the measured values have markedly lower slopes than the mass law: at 125 Hz, the measured values are greater than the mass law, but above 1000 Hz, they are consistently smaller than the mass law in all conditions. Sewell's calculated values show good agreement with the measured results of windows, especially at low frequencies. Therefore, Sewell's theory for a plate appears to be applicable for predicting the reduction index of fixed window. However, there is a following mismatching trend. The calculated results by Sewell's theory show greater values for smaller windows. However the experimentally obtained results, regardless of sizes, show similar reduction indices to each other. They are not regarded as depending on the window size.

2.3.2. Projected window

Measured results for projected windows with the corresponding calculated results are presented in Fig. 3, as described in the fixed window's section. The examined projected windows with sizes of

0.7–2.0 m^2 are classified into three levels according to respective thicknesses. The measurement results are expected to vary by the type of window, because openable windows have more complex construction than fixed window. But according to Fig. 3, a major trend of the results of projected windows is similar to the trend found for fixed windows. The measured values agree with Sewell's calculated values rather than the mass law. As described for fixed window, the measured results are not considered to depend on the window size. However, at around 500–1,000 Hz, some downward deviation from Sewell's curve is apparent. This downward deviation can be attributed to the effects of gaps and degrees of fixation of the window frame.

2.3.3. Sliding window

Measured results obtained for sliding windows with the corresponding calculated results are depicted in Fig. 4 as described in earlier sections. The examined sliding windows with sizes of 2.0–5.8 m^2 are shown, with sizes classified into three levels for each thickness in Fig. 4. According to Fig. 4, greater variation exists between samples under the same conditions than in fixed and projected windows. Especially at around 1,000 Hz, many samples show much lower values than Sewell's curve. This deterioration is regarded as attributable to the sash gaps because the sliding window tends to create gaps structurally to a greater degree than windows of other types. The values of windows with 8 mm thickness glazing do not seem to decrease at middle frequencies, probably because sashes and frames with such thick glass are designed for high airtightness. Regarding the size, the sample sizes of sliding windows are bigger than the other types because the sliding windows consist of two panes with two sashes. Sewell's curves of samples with large sizes are affected strongly by sizes showing lower values than the results measured at low frequencies. Consequently, Sewell's theory tends to present a low value for large windows. Then, Sewell's theory cannot apply for predicting the reduction indices of sliding windows.

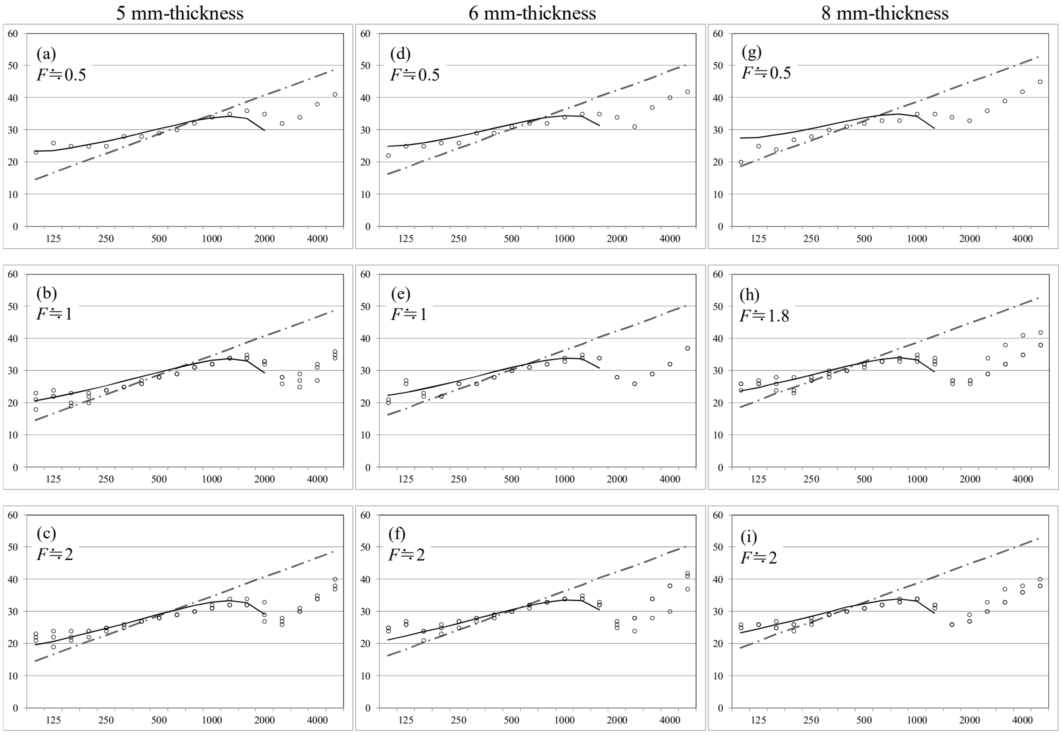

Fig. 2 Reduction indices of fixed windows with theories. Solid lines and dash-dotted lines respectively represent values by Sewell's theory and values by the mass law. *F* represents the window area.

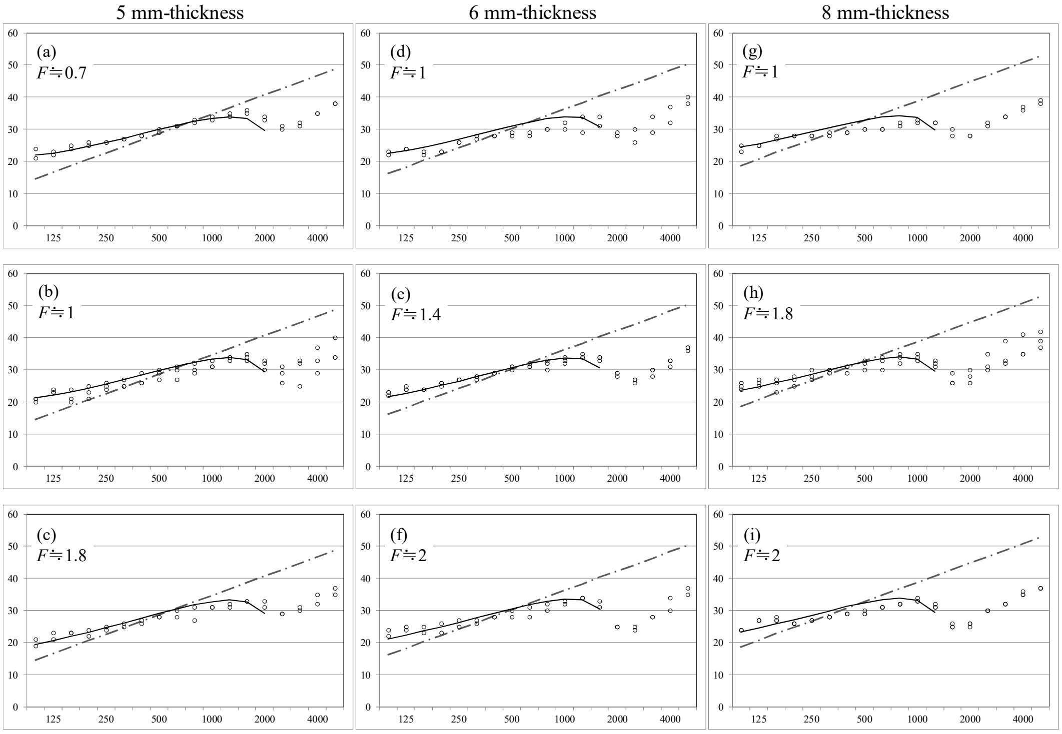

Fig. 3 Reduction indices of projected windows with theories. Solid lines and dash-dotted lines respectively represent values by Sewell's theory and values by the mass law. *F* represents the window area.

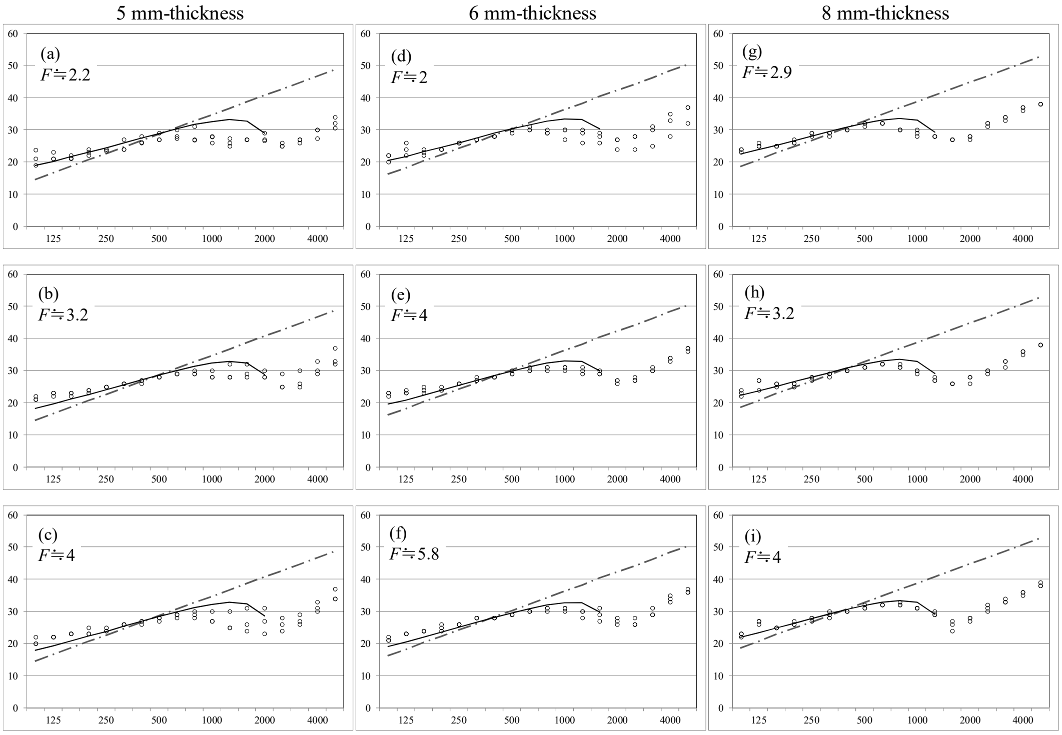

Fig. 4 Reduction indices of sliding window with theories. Solid lines and dash–dotted lines respectively represent values by Sewell's theory and values by the mass law. *F* represents the window area.

2.4. Discussion

For fixed windows with single glazing, Sewell's prediction theory shows good agreement with measured values of the reduction index. However, despite single glazing, in the case of openable windows, especially sliding window, Sewell's curve disagrees with the measured values at middle frequencies. That result is attributable to the effects of window frames including gaps and degrees of fixation. However, the decrement cannot be predicted. The theory is applicable for actual windows in limited cases. One is case in which the window is known to have very high airtightness. Other cases are those in which it is applied as an estimation method for the maximum expected value of the reduction index, assuming the window has no gaps. With respect to the effect of the size at low frequencies, Fig. 5 shows the average measurement reduction indices for windows of all types with 5-mm-thick glazing used in this chapter with the corresponding theory by sizes. Sewell's curves exhibit a trend by which larger plates show a lower reduction index. However, the measured results of all sizes of windows show that similar values constantly exceed 20 dB at low frequencies, unlike Sewell's theoretical values. This tendency is noteworthy because, in the case of the sound insulation of walls, the reduction index is well known to agree with Sewell predictions in many cases. Although the reason for this discrepancy remains an open problem, the presented results demonstrate that, for practical prediction of the sound reduction index of windows, it is not very important to include the window pane size effect.

Consequently, for prediction of the sound insulation performance of windows including sliding windows, Sewell's theory can be informative. However, it is impossible to accomplish by depending solely on Sewell's theory. It is necessary that the prediction method of reduction indices of windows be distinguished at least by the window type. Additionally, from the results in this section, shared trends are visible that reduction indices of windows have linear frequency characteristics with constant slopes in frequency range not affected by the coincidence effect. As a briefer method to express the characteristics of sound insulation of window, a regression analysis is performed in next section.

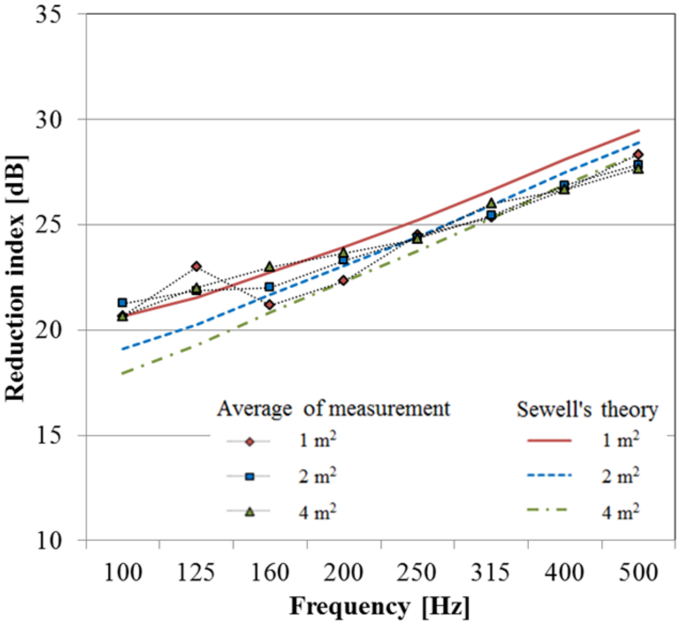

Fig. 5 Reduction indices of 5-mm-thick glazing. Comparison of experimental and theoretical size contributions.

3. Prediction by Regression Analysis

3.1. Analysis procedure

The statistical prediction method of the sound reduction index for single-glazed window is studied. A number of measured samples are divided based on the window type and glass thickness. Because the window size effect is regarded as unimportant based on earlier discussion, this analysis is not divided by size. Windows are categorised into three types (fixed, projected, sliding), with glass of three thicknesses (5, 6, and 8 mm); up to 10 measured results of reduction indices falling into the categories are shown, respectively. The samples used for analyses are measured results of product windows. Linear regression is applied to the average of 10 samples in the range below half of critical frequency to observe the frequency characteristics without coincidence effect. This is because the coincidence effect appears above the half of the critical frequency. Some conditions did not get 10 samples, showing the number of samples in the graph. In addition, measured data of reduction indices of single glazing without window frames [14] and the field incidence mass law are shown in the same figure for reference. From the regression results, the slopes of reduction indices of windows of different types are calculated.

3.2. Analysis result

Analysis results are displayed in Fig. 6 for nine categories: from left to right, the results of 5, 6, 8 mm glass thicknesses are shown; from top to bottom the results obtained for fixed, projected, and sliding window types are shown. The plots show data of 10 sample reduction indices. The solid line shows the linear regression result. It is noted that the line above half of the critical frequency is the extrapolation. Although the 10 samples in one figure have the same glazing and same type of frame, all conditions show variation. Therefore, despite using the same glass, the sound insulation performance of a window varies because of structural differences or other window features.

Single-pane glass without a frame shows a slope of about 6 dB/ oct below the critical frequency as the general theory of mass law shows. However, no case exists in which the reduction index of a window agrees with the slope of the mass law. These behaviours below their critical frequencies tend to show linear increases with characteristic slope that differs from the mass law. Figure 6 presents slope values for each condition. The slope values for fixed windows show a 3–3.3 dB/ oct increase; those for sliding windows show a 2.7–2.9 dB/ oct increase. The cause of lower slopes of sliding windows is the marked deterioration of the reduction index of sliding windows around 1000 Hz. This finding is attributed to the effects of gaps. The slope for projected window shows wide variation: 2.6–3.4 dB/ oct. Because the projected window has an openable sash, individual differences exist. Presumably, there are variable states from almost fixed windows to windows with a wide gap such as a sliding window. The average slope of all windows used in the present exam is 3.0 dB/ oct. Furthermore, for regression, R_{100} is presented as a cue for the height value. R_{100} in Fig. 6 shows a value of the regression at 100 Hz that is readable from the graph. The thicker the glass which is used, the higher a value of R_{100} is shown.

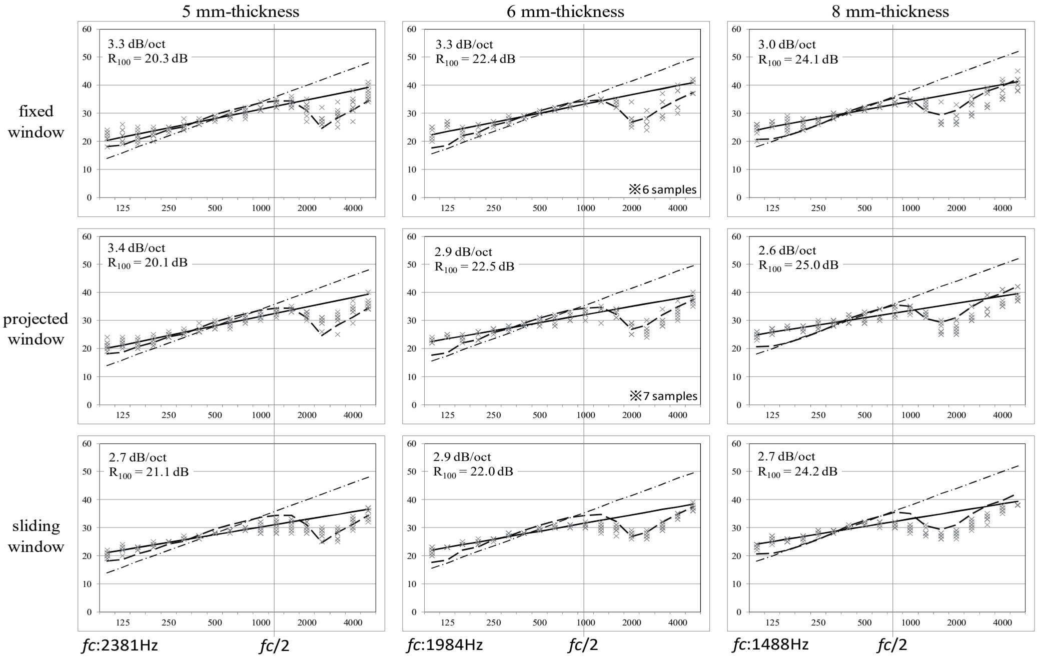

Fig. 6 Reduction indices of 10 samples for each condition. Solid lines show results of linear regression for an average of 10 samples in the range 100 Hz to *fc*/2. Broken lines and dash-dotted lines respectively represent values of single glass only and values by mass law.

3.3. Application of regression

As ideas of the practical prediction method of the reduction index of a window, regression equations from the preceding section are explained. This regression application is also useful to confirm the slope of the frequency characteristics of the reduction index of windows. As an example, the case of a sliding window with 5-mm-thick glass is depicted in Fig. 7. The plots demonstrate other measured data of the window in the same category: The solid line shows the regression equation: The broken line shows the field incidence mass law for reference. The regression equation is a straight line that increases by 0.9 dB every 1/3 octave. Expressed as an equation, it becomes $R = 9 \log f + 3.1$ [dB]. In this case, the regression line shows good agreement with measured data: the maximum error is -1.8 dB at 800 Hz. The measured value exceeds the regression line at middle frequencies, probably because this window has good airtightness. The value would be slightly lower than the regression line in these frequencies if a window with weak airtightness were measured. In any case, the measured values of the reduction indices of sliding windows would not deviate from the regression line. Consequently, this can be inferred as the simplest method of practical prediction of sound insulation performance for a window. This regression line is regarded as an important cue for practical prediction. However, the utility of the method is limited below the critical frequency. Some study must be conducted of the prediction of the reduction indices of windows above the critical frequency.

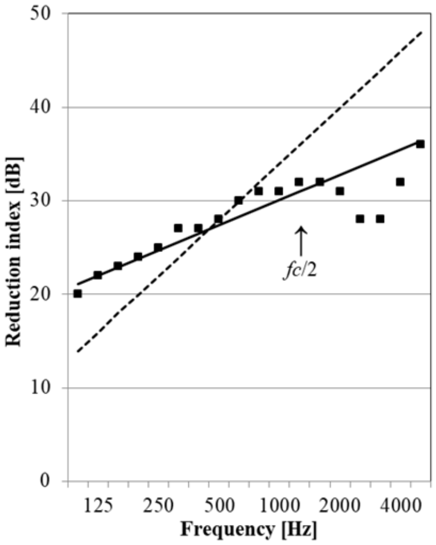

Fig. 7 Reduction index of a sliding window. The solid line represents the result of the regression analysis. The broken line represents values by mass law.

4. Conclusions

A basic study was conducted to explore methods for practical prediction of the sound insulation performance of windows. First, Sewell's theory for walls, which incorporates panel size effects, was applied to windows. The results were compared with the measured results of window reduction indices. Next, a regression analysis was performed from the measured results of 10 samples for each window type and each glass thickness. Consequently, the following findings were obtained:

1. Sewell’s theory showed good agreement with measured results obtained for fixed windows with single glazing. Sewell’s theory for a plate appears to be applicable for predicting the reduction index of a fixed window. However, sound reduction indices of openable type windows, especially of sliding windows, were affected remarkably by window frame gaps. Consequently, predicting sound reduction indices of all windows accurately is difficult when using Sewell’s formula alone. Results also clarified that Sewell’s formula overestimates the window pane size effect.
2. The frequency slope of windows is much lower than the general theory of mass law. There are characteristics of slopes below the critical frequencies for windows of different types. The frequency slope values for fixed windows are 3–3.3 dB/ oct. Those for sliding windows show 2.7–2.9 dB/ oct. Regression analysis shows that the reduction index slope with the frequency of all windows used is an average 3.0 dB/ oct.

As described in this report, important cues were obtained for practical prediction of the sound insulation performance of a window. However, the range of the problem remains limited to single glazing below the critical frequency. Sound reduction indices of multiple glazing or above the coincidence frequency are also important matters that will be the subject of future work.

Conflict of interest

There is no conflict of interest.

Funding

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Data availability

The data used in this study can be provided with reasonable request.

Author contribution

Y. Tsukamoto: conceptualisation, data curation, data analysis and draft writing; K. Sakagami: project supervision and draft editing; T. Okuzono: theoretical consideration; Y. Tomikawa: project management

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