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Basic study of practical prediction of sound insulation performance of single-glazed window

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1. Introduction

The sound insulation performance of windows is one of the important factors in designing an indoor acoustic environment, because windows are usually considered to be a weak point for the sound insulation of a building structure, including external walls and roofs. Sound transmission through a plate is known to be described by a traditional mass law [1]. Therefore, the sound reduction index for a single glass plate follows this mass law, but it has been reported that even common fixed windows do not follow it [2]. Additionally, since there are many window types for different purposes, the sound insulation performance of windows is considered to differ in accordance with the various structures of window types. Although some groups have discussed the sound insulation performance of windows, there is no practical method of predicting the sound reduction index for different window types. As a hint to predicting the sound reduction index of a window, a reported trend is that the sound reduction index of windows below the coincidence effect has a certain slope of frequency characteristics [2]. In practical use, a simple method of predicting the sound reduction index of windows is needed.

The purpose of the present study is to develop a practical prediction method to obtain the sound reduction index of windows. First, the application of linear regression from the measured data of the sound reduction index of windows to a prediction method is studied. Next, to adapt it to different window types, a classification of frequency ranges depending on the window type is proposed. This study focuses on single-glazed windows, which are the simplest type of window.

2. Prediction with linear regression

The sound reduction index of windows usually does not follow the conventional mass law. However, the sound reduction indices of windows appear to increase linearly with a certain slope at frequencies below the coincidence effect. Our previous study showed that the average slope for different windows is 3 dB/Oct. in the range from 100 Hz to $f_c/2$, where f_c is the critical frequency [2]. A prediction method that includes the frequency above f_c is studied using this regression analysis and an existing theory.

2.1. Measured data for comparison with prediction method

The measurement data were taken from a database of actual products of a particular manufacturer. All measurements were conducted as specified by JIS A 1416 (compatible with ISO10140-2). To investigate the difference between the window types, data of three types of window were collected: a fixed window, a projected window, and a sliding window. They are illustrated in Fig. 1. The fixed window cannot be opened. The projected window opens with a horizontal swinging motion. The sliding window is composed of two movable sashes that open by sliding on a rail. The measured data of each window type are categorized into three glass thicknesses (5, 6, and 8 mm), which are commonly used for single glazing in Japan. Therefore, several data were collected for each of the nine categories—three types and three thicknesses for each type—and the averages and 95% confidence intervals were calculated. The sound reduction indices in the 1/3 octave bands were obtained from 100 to 5,000 Hz in accordance with the standard.

2.2. Theories of sound transmission through plate

Linear regression can be applied to the prediction method below f_c, and it can be supplemented with Cremer's theory above f_c. Cremer's equation [3] is well known for sound transmission through a plate above f_c. The sound transmission coefficient obtained using Cremer's theory, τ_c, is approximated as follows:

$$\tau_c \approx \left(\frac{2\rho c}{\omega m}\right)^2 \frac{\pi}{2\eta} \frac{\omega_c}{\omega} \tag{1}$$

$$\eta = 0.01 + \frac{m}{485\sqrt{f}} \tag{2}$$

where ω is the angular frequency, ω_c is the critical angular frequency, m (kg m^{-2}) is the plate surface density, ρ (kg m^{-3}) is the air density, c (m s^{-1}) is the sound velocity in air, and f (Hz) is the frequency. Referring to some approximations derived by Cremer, Eq. (1) is applied to the current prediction because it is the simplest expression in those approximations and it agrees well with the measured sound reduction index of windows. The first term in Eq. (2) represents the internal loss factor of the glazing. In this study, the value of 0.01 is adopted as the internal loss factor of glass. It is deemed a reasonable value for general architectural materials, as stated in ISO 12354-1 Annex C.

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Fig. 1 Illustration of measured window types: (a) fixed, (b) projected, and (c) sliding windows.

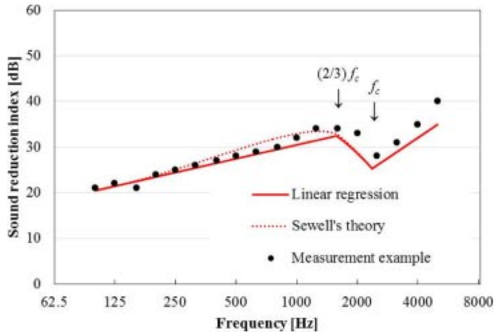

Fig. 2 Predicted sound reduction index with measured example data. The solid and dotted lines represent the prediction with linear regression and the prediction with Sewell's theory, respectively.

One of the main reasons for the discrepancy between the measured values of windows and the mass law is that the sound transmission theory of the mass law assumes an infinite plate. Sewell considered the radiation efficiency associated with the plate size, deriving the transmission coefficient for a finite plate below f_c [4]. The sound transmission coefficient obtained using Sewell's theory, τ_s, is given by

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

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

where $k = \omega/c$ is the wavenumber, F (m^2) is the sample area, and Λ is the ratio of the length of the shorter side to the length of the longer side of the sample. It is reported that the measured value of windows of different sizes converge to the value calculated with the area of 1 m^2 at a low frequency [2]. Therefore, in the present method, the sound reduction indices at the frequencies where Sewell's equation is applied are always calculated with the area of the window set to 1 m^2.

2.3. Prediction procedure

The present prediction method involves calculations using different equations depending on the frequency range. The prediction method comprises a linear regression derived in our previous study [2] and Cremer's theory (Eq. (1)). The sound reduction index of a plate decreases at the frequency somewhat lower than f_c owing to the coincidence effect. In many cases, the measured value of the sound reduction index of windows also indicate a decrease due to the coincidence effect, and it is found that this tendency appears above $2f_c/3$ from closer study of the measured data. The linear regression agrees well with the measured value of windows in the range unaffected by the coincidence effect [2]. Therefore, it is considered that the tendency of 3 dB/Oct. can be applied below $2f_c/3$, because the slope below $2f_c/3$ is independent of the coincidence effect. In the present paper, the prediction method is selected with reference to the frequency range: linear regression is applied below $2f_c/3$, Cremer's theory is applied above f_c, and linear interpolation is applied from the value calculated by linear regression at $2f_c/3$ to the value calculated using Cremer's theory at f_c. As an example, the values calculated using these methods and the measured value of a fixed window with 5-mm-thick glazing are shown in Fig. 2. The value for the lower limit at 100 Hz for each type of window was calculated from the regression results [2]. For example, in the case of 5-mm-thick glazing, the calculated values for the fixed, projected, and sliding windows were 20.3 dB, 20.1 dB, and 21.1 dB, respectively. In Fig. 2, the value of 20.5 dB was obtained by averaging the values for all measured windows with 5-mm-thick glazing [2]. For reference, the result of calculation using Sewell's theory instead of linear regression is also shown in the same figure. In this example, both prediction models appear to give good prediction, although there are discrepancies between the two models. In this study, the linear regression method is suggested for the practical prediction, because linear regression is much simpler than Sewell's theory, and its errors are mostly on the safe side, as shown in Fig. 2. Additionally, both calculated values at 100 Hz are very close for each condition. To apply this regression without any data, the calculated value using Sewell's theory is adopted for only the lower limit of 100 Hz in the following calculation. The validity of this prediction method is assessed in the next section.

2.4. Comparison between predicted and measured values

Figure 3 shows the predicted and measured values of the sound reduction index. The measured values are averaged, and 95% confidence intervals are shown. From the left, the results for the 5-, 6-, and 8-mm-thick fixed windows, projected windows, and sliding windows are shown. The number of test samples, n, is indicated in each graph. The critical frequency of each glass thickness was calculated using a well-known formula [1] to be 2,368 Hz for 5-mm-thick glass, 1,973 Hz for 6-mm-thick glass, and 1,480 Hz for 8-mm-thick glass.

According to Figs. 3(a)–3(c), the predicted values agree well with the averages of the measured values of the fixed windows in the range of 100–5,000 Hz, and the errors are mostly within the 95% confidence interval. The sound reduction index of an actual window decreases owing to the coincidence effect. The frequency range affected by this effect is approximately above $2f_c/3$, as observed in the measured values, and the present prediction method describes this trend well.

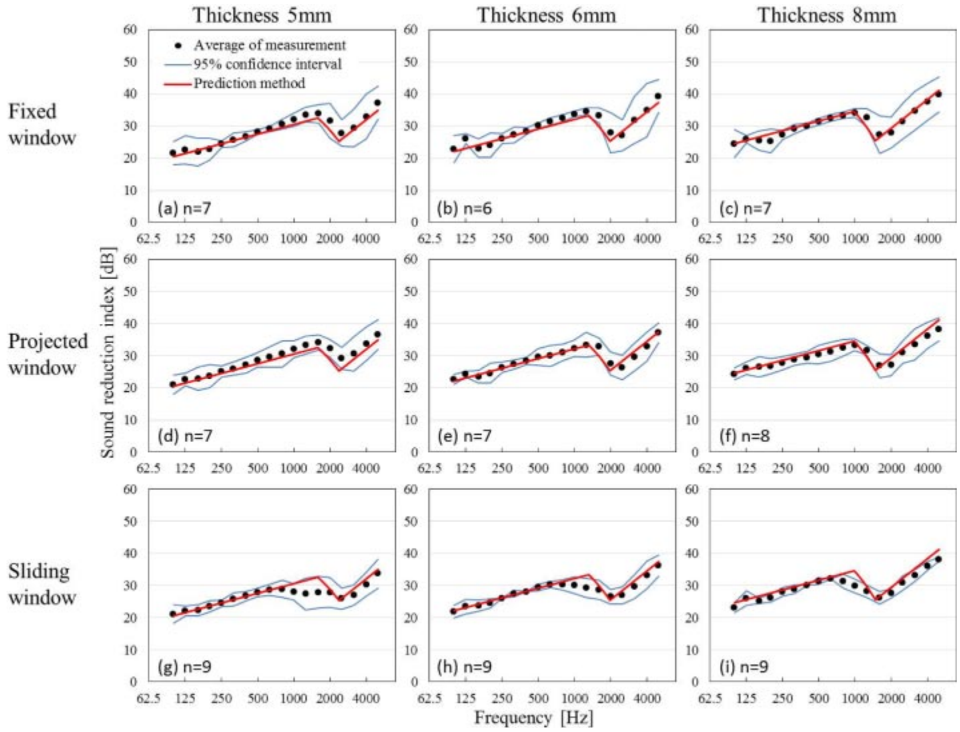

Fig. 3 Sound reduction indices from measured data of three window types and prediction method using regression analysis.

Figures 3(d)–3(f) show that the predicted value also agrees with the averages of measured values of the projected windows. The tendency of the projected window is similar to that of the fixed window in spite of the opening function. This is considered to be because the swing-type openable window can gain a high degree of airtightness by strongly compressing the gasket. However, as shown by the relatively larger 95% confidence interval, the projected window has a relatively high variation at moderate frequencies, which suggests that there is a high degree of individual difference.

In Figs. 3(g)–3(i), the prediction also agrees with the averages of measured values of the sliding window at low frequencies. However, the measured values are lower than the predicted values at 800 Hz–f_c. One of the main reasons for this is the effect of the gaps between sashes and frames, which is likely to exist in sliding windows. The prediction method does not consider the effects of the characteristics of windows, such as these gaps. Therefore, this model based on linear regression is unsuitable for sliding windows, as it is difficult to make predictions for these different window types using only one formula: the model requires a modification. Thus, a prediction method is required for at least two separate cases: the fixed window type and the sliding window type. The prediction of the sound reduction index for the sliding window type needs a revised equation to consider the lower sound insulation at moderate frequencies.

2.5. Correction for sliding window

A correction to improve the prediction method for the sliding window is discussed. In Fig. 3, the measured values tend to be lower than the predictions above 800 Hz. Therefore, the frequency range for the linear regression is changed only in the case of the sliding window. The regression is applied to 100–630 Hz, and then the linear interpolation is applied from the value calculated by the regression at 630 Hz to the value calculated using Cremer's theory at f_c. Above f_c, it is calculated using Cremer's equation.

Figure 4 shows the corrected predicted values of the sound reduction indices, the averages of the measured values, and 95% confidence intervals in the case of sliding windows with 5-, 6- and 8-mm-thick glass. According to Fig. 4, the predicted results show good agreement with the average measurements for all glass thicknesses. The frequency at which the decrease in sound reduction index occurs is independent of glass thickness. Hence, this corrected prediction method is useful for the sliding windows.

3. Concluding remarks

The application of a linear regression to the prediction of the sound insulation performance of a window was studied. The prediction method using a combination of linear regression and Cremer's theory was found to be useful. Furthermore, the prediction method could be applied to various windows by classifying the frequency ranges depending on the type of window. The 3 dB/Oct. slope from the regression was applied to 100 Hz–$2f_c/3$ for the fixed and projected windows and 100–630 Hz for the sliding window.

The method proposed in this paper is based on the analysis of a database of the products of one particular manufacturer, as mentioned above. Therefore, there are some limitations to the proposed method, such as the frequency of classification, which may need to be changed for the products of other manufacturers. However, we believe that the idea

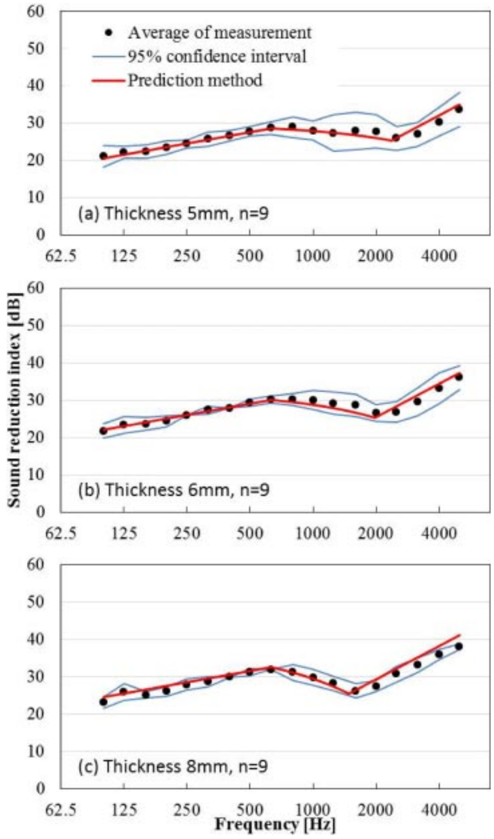

Fig. 4 Sound reduction indices of sliding window from measured data and prediction method using regression analysis with correction for sliding window.

behind the prediction method proposed in this paper can be applied in general settings.

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