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(Citation)

Applied Acoustics, 165:107317

(Issue Date)

2020-08

(Resource Type)

journal article

(Version)

Accepted Manuscript

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Experimental assessment of sound insulation performance of a double window with porous absorbent materials its cavity perimeter

Yohei Tsukamoto^a, Yoshihiro Tomikawa^a, Kimihiro Sakagami^b, Takeshi Okuzono^b, Hidetoshi Maikawa^c, and Yusuke Komoto^c

^a Central Research Laboratory, YKK AP Inc., 1 Ogyu, Kurobe, Toyama 938-8612, Japan

^b Environmental Acoustics Laboratory, Department of Architecture, Graduate School of Engineering, Kobe University, 1-1 Rokkodai, Nada, Kobe, 657-8501, Japan

^c Core Technology Research Center, Corporate Research and Development Div., Nitto Denko Corporation, 1-1-2, Shimohozumi, Ibaraki, Osaka, 567-8680, Japan

Abstract: As described herein, the sound insulation performance of a double window with absorbent materials on the perimeter of its cavity is studied experimentally. Two experiments are used to measure the sound reduction indices. The first experiment was performed with a double window composed of commercially available products. The second was conducted with a model constructed of two acrylic panels: a simplified model of a double window with a cavity between the panes. **As the result of the present experiment, the improvement in reduction index obtained by the attached absorbent was greater than 10 dB.** Consequently, the following findings were obtained: (1) Acoustic transmission characteristics of a double window are affected mainly by resonances of two types: mass-air-mass resonance of window panes and the air cavity, and the acoustic mode resonances of the air cavity in-between; (2) acoustic mode resonance is suppressed by attaching absorbent materials on the inside of the cavity of window. Consequently, the sound reduction index increases.

Keywords: Absorbent material, Double window, Experiment, Sound insulation

1. Introduction

Recently, acoustic environments in living spaces have attracted a paramount degree of interest by users, especially in collective houses. Moreover, the sound insulation performance of windows of buildings has become increasingly important. **Although simple single windows with lower sound insulation performance are weak points of building facades, windows are important devices for a view, ventilation and daylight lighting. Many researchers have investigated on effective noise control methods at windows. Tang summarizes the research and development of natural ventilation—enabling noise control device mainly at windows [1]. Field et al. suggested dual vented window system with absorbent material and study its sound insulation effect experimentally [2]. As another solution, Lam et al. reviewed the prior works in the active control of sound through apertures, and reported from the results of numerical and experimental study that distributed-layout ANC system shows better performance than boundary-layout ANC system for sound**

attenuation through apertures [3]. In the case of a single window, it is possible to use a transparent microperforated sheet as a window screen to add sound absorption and thereby improve the acoustic performance of the window [4]. As above, the trade-off between noise reduction and ventilation or daylight is a current challenge in study on windows. Therefore, recent trend in the study includes various approaches [5].

However, in many cases, particularly in highly urbanized area with higher noise levels or in collective houses, it is necessary for a window to obtain high sound insulation performance. In order to improve the window performance, another window is added inside the existing window. The system composed of two windows and a cavity in-between is designated as a “double window”. A double window is known to have higher sound insulation performance than a single one, especially in the high-frequency range when it is closed, and can ventilate the room when it is opened, although sound insulation performance is deteriorated. However, a double window is also known to have a remarkable drop of sound insulation performance at low frequency because of mass-air-mass resonance [6]. The mass-air-mass resonance frequency is a function of the surface density of panels and the air cavity depth. This difficulty has been well reported as a shortcoming of lightweight double walls. Many reports have specifically addressed it [7, 8]. Tadeu experimentally measured sound insulation of various single or multiple glazing with different depths of air cavities. The difficulty to predict sound insulation of multiple glazing with mathematical models was reported [9]. In the case of double walls, it is known that sound insulation is improved by filling the cavity with absorbent material. However, in the case of a double window system, such a method cannot be applied because the absorbent materials are usually not transparent, which prevents the functions of windows described previously. Therefore, in this case, the absorbent material is applicable only on the perimeter in its cavity, to improve the sound insulation performance. Actually, some studies have been conducted to improve the sound insulation performance of windows. For example, Shimizu reported that mass-air-mass resonance is lowered by an absorbent that has a high absorption coefficient of nearly 1.0. With a similar objective, double glazing with only 1 cm cavity and absorbent material on its perimeter was assessed using numerical and experimental methods. The paper focused on mass-air-mass resonance, and the dips of reduction index in higher frequency range were expressed to be caused by higher order resonance of mass-air-mass system [10, 11]. Iwase studied countermeasures against the mass-air-mass resonance of a double window with porous absorbent material or a Helmholtz resonator by using a double glazing model of acrylic plates. The result of measurement of excited vibration on plates of double glazing indicates that natural frequency of the plate affects strongly reduction index of double glazing [12]. Although they presented the possibility of suppression of resonance by absorbent systems, the sound pressure response inside the cavity of the double window and the effect of the arrangement of the absorbent had not been studied in detail. Detail of the mechanism of the effect of absorbent on the sound insulation performance due to the absorbent on its cavity perimeter needs to be studied.

As described in this paper, two experiments are performed to clarify the sound transmission characteristics of a double window with absorbent material on the perimeter in the cavity between the panes. The first experiment is performed with a double window composed of commercially available products. The second is performed with a model made of

two acrylic panels, which is a simplified model of a double window with a cavity between the panes. Based on results obtained from the two experiments, mechanisms for improving the sound insulation performance are discussed. In this paper, all experiments are conducted with window closed in order to investigate the relationship of sound pressure in the cavity and transmission through double window in detail with the simplest model.

2. Experiment with a commercial double window product

First, the effects on the sound reduction index are measured when using absorbent materials on the perimeter in the cavity of a double window. For this experiment, two sets of commercially available sliding windows are used.

2.1. Experimental setup

Measurement of the reduction index is conducted according to JIS A 1416 [13], which is compatible with ISO 10140-2 [14] at the YKK AP Central Test Center in Kurobe, Japan. The source reverberation room has 492.8 m^3 volume. The receiving reverberant room has 264.5 m^3 . The specimen, with total size of $1650 \text{ mm} \times 1300 \text{ mm}$, is portrayed in Figs. 1 and 2. The cavity depth is 187 mm . The glass pane thicknesses are all 3 mm . The cavity perimeter has channels between the panes. The channels are filled with equal-sized blocks of 24 kg/m^3 glass wool. The channel cross-section is $90 \text{ mm} \times 50 \text{ mm}$. In the measurements of the without-absorbent case, same-sized wood blocks are inserted into the channels instead of glass wool. As described in this paper, x , y , and z respectively represent the width, height, and depth directions.

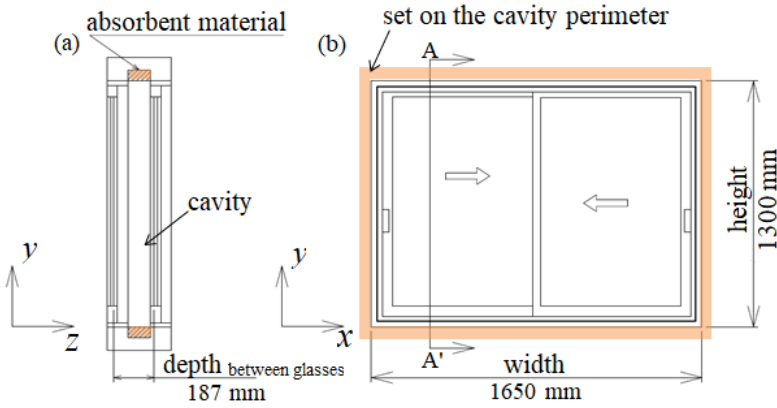


Fig. 1: Schematic representation of the experimental specimen of the double window: (a) cross-section at A-A' and (b) elevation of the specimen.



Fig. 2: Photograph of the double window specimen installed in the aperture of the coupled reverberation chambers.

2.2. Results of the measurement

Results of sound reduction indices R_s are depicted in Fig. 3. In this figure, the R_s in the cases with and without absorbent materials are presented. In addition, the difference between two results is shown. The R of the outer window only is presented also in Fig. 3 for reference. Both cases with and without absorbent materials show a trend by which,

as the frequency becomes higher, R becomes larger. Furthermore, they indicate a characteristic dip at about 4 kHz, which corresponds to the coincidence effect of 3 mm glass pane. The critical frequency f_c is given as shown below [6].

$$f_c = \frac{c^2}{2\pi h} \sqrt{\frac{12\rho_p}{E}} \quad (1)$$

Therein, $c=340$ m/s stands for the sound speed in the air, $h=0.003$ m expresses the glass pane thickness, $\rho_p=2500$ kg/m³ signifies the glass density, and $E=80.1 \times 10^9$ Pa denotes Young's modulus of glass. In the case of double window, there is higher R , especially at high frequencies than a single window. According to this equation, f_c is estimated as 3753 Hz. Double-leaf systems with an air cavity in-between are well known to have resonant frequencies. The lowest order resonance frequency f_{rmd} is given as shown below [15].

$$f_{rmd} = \frac{1}{2\pi} \sqrt{\frac{2\rho_0 c^2}{md}} \quad (2)$$

Therein, $\rho_0=1.2$ kg/m³ represents the air density, $m=7.5$ kg/m² signifies the surface density of the glass pane, and $d=0.187$ m denotes the air cavity depth. This is called the mass-air-mass resonance frequency. According to this equation, f_{rmd} is estimated as 71 Hz. It does not appear in the range of measured frequencies (100--5000 Hz).

In Fig. 3, there is a dip at 125 Hz in the graph of the result of the case without absorbent materials. Therefore, this dip is attributed to the acoustic mode resonance in the cavity. The acoustic mode frequency f_n of the air cavity is given as shown below [16].

$$f_n = \frac{c}{2} \sqrt{\left(\frac{n_x}{l_x}\right)^2 + \left(\frac{n_y}{l_y}\right)^2 + \left(\frac{n_z}{l_z}\right)^2} \quad (3)$$

Therein, $n_{x,y,z}$ stands for the number of modes, and $l_{x,y,z}$ represents the dimension of the cavity for x , y and z directions. According to this equation, the air cavity has the acoustic natural mode at lowest frequency, i.e., (1, 0, 0) mode at 103 Hz in the direction of x and (0, 1, 0) mode at 131 Hz in the direction of y . The results are represented in the values at each 1/3 octave-band. These acoustic modes are regarded as being involved at around the 125 Hz band. Therefore, this dip at 125 Hz is regarded as attributable to the acoustic modes. R with absorbent materials on the cavity perimeter is higher at 125 Hz than R without absorbent materials. Therefore, resonances by acoustic modes in the cavity can be reduced by attaching absorbent materials at the cavity perimeter.

The measured result of normal incidence sound absorption coefficient of the absorbent material used in this experiment is portrayed in Fig. 4. This was measured according to JIS A 1405-2 [17], which is compatible with ISO 10534-2 [18]. The normal incidence absorption coefficient is only 0.1 at 125 Hz. On the cavity perimeter of the double window system, absorbent materials can affect R , even if it has only a small normal incidence absorption coefficient.

The results shown above clarify that the absorbent materials on the cavity perimeter affect the sound field of the air cavity. The sound condition in the cavity is important for R of the double window. It is estimated that the acoustic modes in the cavity are reduced by the absorbent. However, that reduction cannot be ascertained from this experiment.

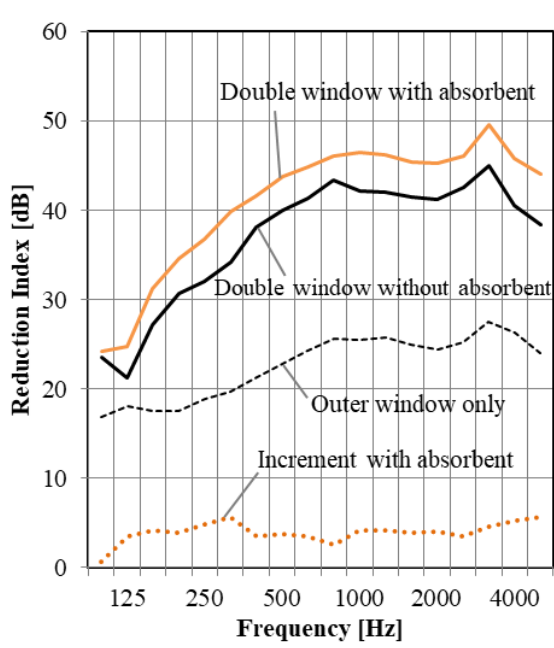


Fig. 3: Measured reduction indices of the double windows with and without absorbent, and the single window.

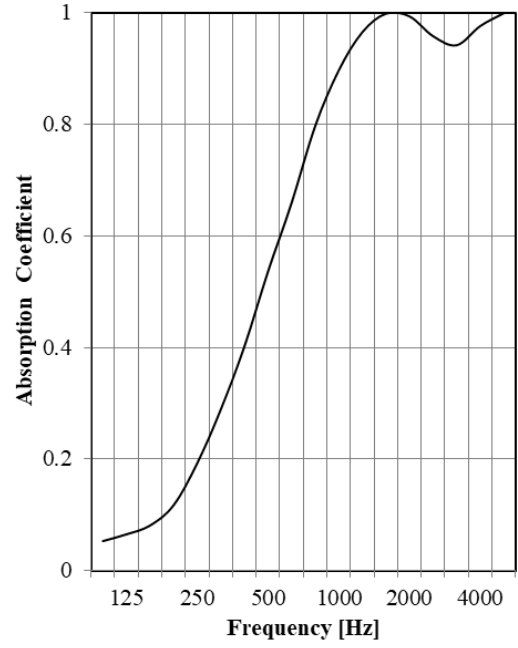


Fig. 4: Normal incident absorption coefficient of the glass wool used in the experiment.

3. Model experiment with acrylic panel model

3.1. Experimental procedure

From the first experiment, results showed that the absorbent materials on the cavity perimeter can improve the R of the double window. However, it is not clear how the absorbent materials on the cavity perimeter affect the sound reduction index at around the mass-air-mass resonance frequency. Therefore, it is necessary in the next experiment to examine the sound pressure response in the air cavity specifically including frequencies around the mass-air-mass resonance frequency. To investigate the sound insulation mechanism of the double window in detail, the second experiment is performed using a simple model. The experiment is conducted according to JIS A 1441-1 [19], which is comparable to ISO 15186-1:2000 [20]. The source reverberant room has 36.9 m³ volumes. The receiving room is a hemi-anechoic chamber. The model is presented in Fig. 5. It comprises two acrylic panels and wood frame. The acrylic panels are screwed to the wood frame. There is a 5-mm-thick rubber sheet between them for air tightness. The total size of this double window model is 1158 mm × 1159 mm. The cavity size in all cases is 800 mm × 800 mm × 90 mm. In the cases with absorbent materials on the cavity perimeter, the model can be installed glass wools up to 100 mm-depth at the maximum, and in the case without absorbent material, it has the wood blocks of the same size instead of glass wool. The glass wool density is 24 kg/m³. The two acrylic panels are 5 mm thick. The surface density is 6 kg/m². In the case of this model, according to Equations (1) and (2), the critical frequency f_c is 7991 Hz. The mass-air-mass resonance frequency f_{rmd} is 114 Hz. The f_{rmd} of this experiment is within the range of measurement frequency, 100–5000 Hz.

This experiment also measured the sound pressure level in the cavity to study the effect of the resonance in the cavity. The two measurement points, the center and the edge of the cavity, are presented in Fig. 5. To study the effects of parameters of absorbent materials, width, arrangement, and thickness, the measurements are conducted in various conditions as explained below.

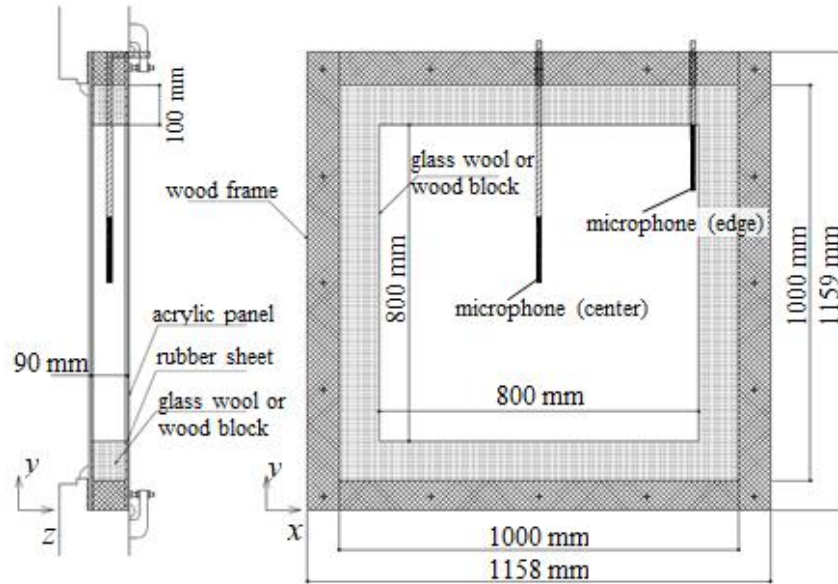


Fig. 5: Image of the double window. Cross-section and elevation.

(a) Conditions of the absorbent material width

To study the effects of the absorbent material width, three conditions are measured. The model is depicted in Fig. 6. The absorbent material width is changed to 100 mm, 50 mm, and 25 mm. The gap separating less absorbent material and the wood frame is filled by a wooden board.

(b) Conditions of the absorbent material arrangement

To study the effects of arrangement of absorbent material, two conditions are measured. The models are portrayed in Fig. 7. The absorbent material arrangement is changed only to the corner part (a) or only to the center part (b). The two conditions have the same area of absorbent material. The gaps are filled by wood blocks. The absorbent material width is kept constant at 100 mm.

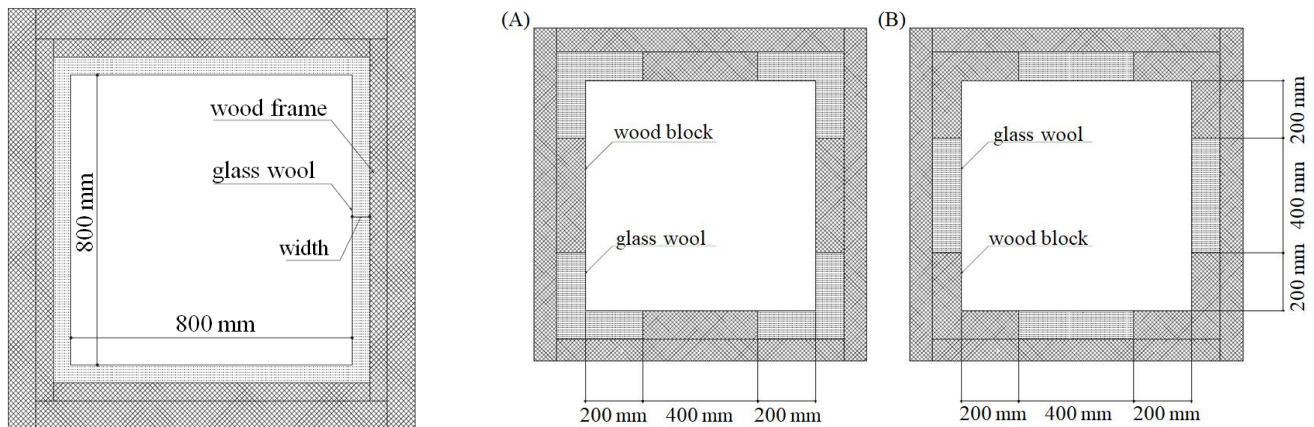


Fig. 6: Elevation of the double window model: the variation of the width of the absorbent material.

Fig. 7: Elevation of the double window model: the condition of the arrangement of the absorbent material. (A)absorbent material on only corner part. (B)absorbent material on only center part. Absorbent material on all of perimeter is shown in Fig. 5.

(c)Conditions of the absorbent material thickness

To study the effects of absorbent material thickness, three conditions are measured. Changing the thickness causes change to the area of the absorbent material. The model is presented in Fig. 8. The absorbent material thickness is changed to 80 mm, 40 mm, and 20 mm. Gaps between the absorbent material and acrylic panes are filled by wooden boards. The absorbent material width is kept constant at 100 mm.

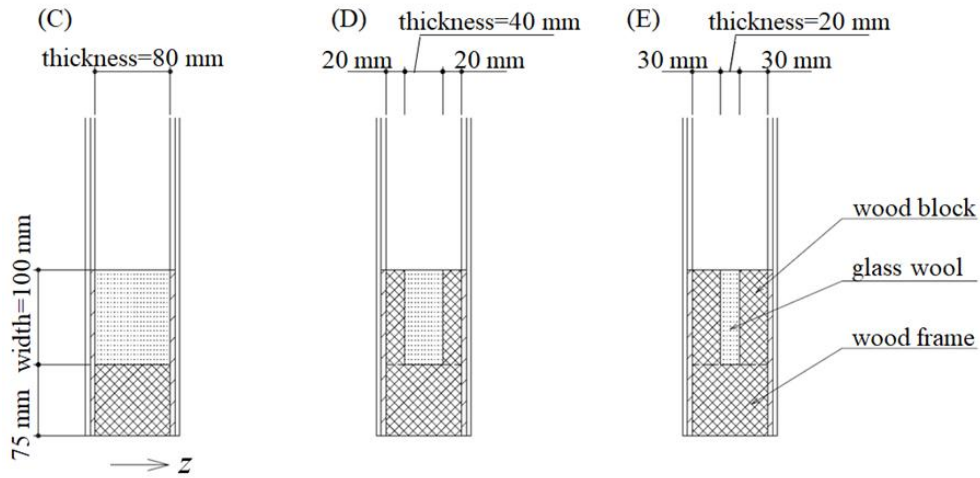


Fig. 8: Cross-section of the under part of the double window model: The variation of the thickness of the absorbent material.

3.2. Measurement results

First, measured values of R_s without absorbent material and with 100-mm-wide and 80-mm-thick absorbent material on the cavity perimeter are shown in Fig. 9. Furthermore, the measured values of sound pressure in the cavity are presented in Fig. 10. According to Fig. 9, R_s of the double window increase with increasing frequency. The value of R with absorbent material is much larger than that without absorbent material above 250 Hz. Especially above 400 Hz, the increment becomes greater than 10 dB. A dip occurs near 100 Hz because of mass-air-mass resonance. At this frequency, absorbent materials used in this experiment are ineffective, presumably because the absorption coefficient is low at low frequencies.

Fig. 10(a) presents the sound pressure levels in the cavity without absorbent material. In the case of the cavity of 800 mm \times 800 mm \times 90 mm, the acoustic mode resonance frequencies are estimated by Eq. (3), and are shown in Table 1. According to Fig. 10(a), the sound pressure level shows marked peaks at these frequencies. Therefore, there are **standing waves in the direction along the glass surface** in the cavity of the double window system. Consequently, these peaks are attributed to the effect of the acoustic resonance in the cavity. **Below 500 Hz, in Fig. 9, the value of R without absorbent**

shows relatively low value at low-order peak frequencies of sound pressure level observed at the edge shown in Fig. 10 (a). The acoustic modes of cavity are considered to be the cause of the step-like behavior of R in the case without absorbent. The peak at around 100 Hz is the mass-air-mass resonance between the acrylic panel's mass and the air cavity. Fig. 10(b) also shows the sound pressure levels in the cavity with absorbent material. It shows that attaching absorbent material on the cavity perimeter can dampen the acoustic resonance in the surface direction and lower the significant peaks above 200 Hz. Tadeu described that natural excited frequencies of the receiving and emitting rooms influence greatly the sound insulation at low frequencies [9]. It is clarified that the acoustic mode resonances in the direction along the surface in the cavity also affect sound insulation by observing the behavior of the sound pressures in the cavity of double window. The largest peak at around 100 Hz, which results from the mass-air-mass resonance, is not damped by attaching absorbent material. It shows that, at mass-air-mass resonance frequencies, in this case, R cannot be increased by absorbent material on the cavity perimeter.

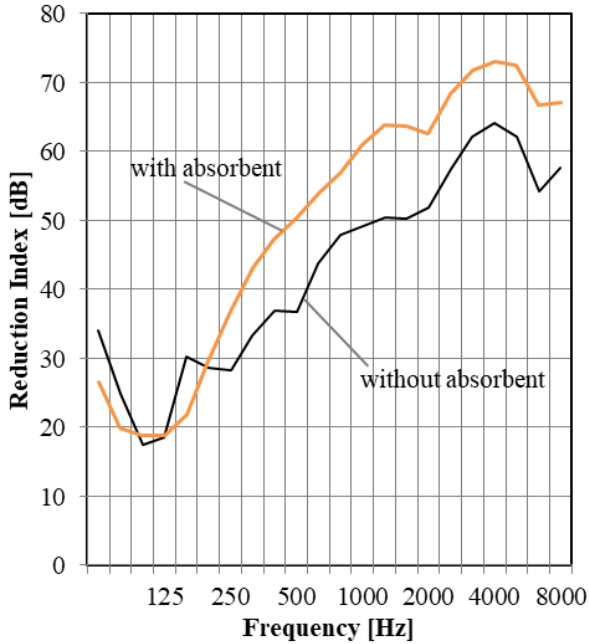


Fig. 9: Measured reduction indices of double window model with and without the absorbent material on its cavity perimeter.

Table 1: Acoustic mode frequencies of the air cavity of the double window model

mode number (x,y,z)	frequency [Hz] by Eq. (3)
(1,0,0)	213
(1,1,0)	300
(2,0,0)	425
(2,1,0)	475
(0,0,1)	1889

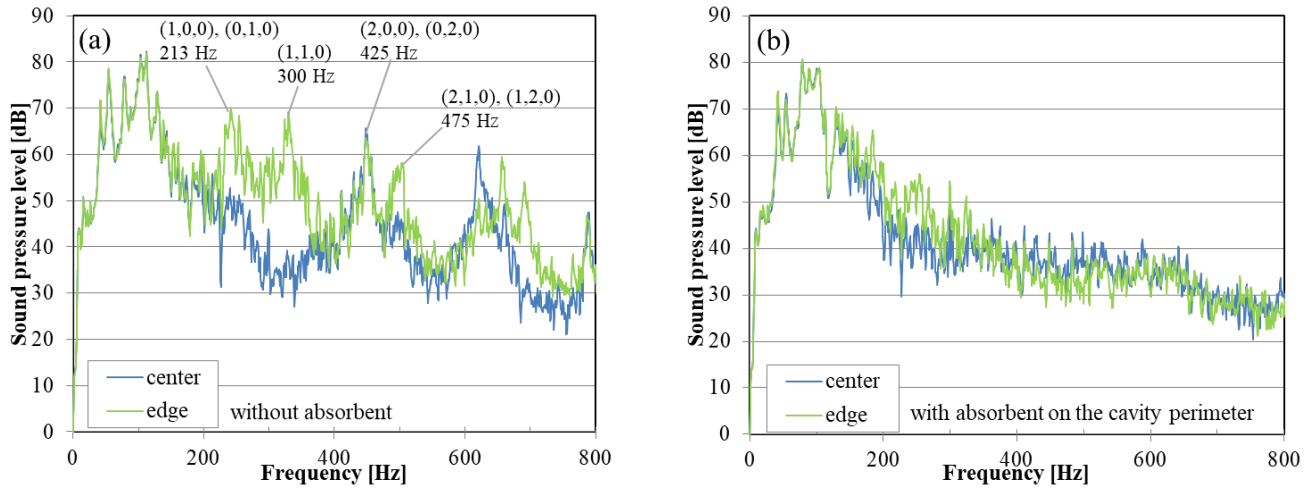


Fig. 10: Sound pressure level at the measurement point in the cavity. (a) without absorbent material in the cavity. (b) with absorbent material on the cavity perimeter. The blue line shows the result at the center. The green line shows the result at the cavity edge.

The decrement of the sound pressure level by the absorbent is represented in the values at each 1/3 octave-band, with the increment of the reduction index because of the attached absorbent at each 1/3 octave band, in Fig. 11. The graph of the sound pressure level shows the measurement at the edge point. The two results show similar frequency characteristics. It is observed that the decrease of the sound pressure in the double window cavity causes the increase of the R of double window. Furthermore, the decrease of the sound pressure is produced by the ease of the acoustic mode. This result shows correlation between the R value of a double window and the acoustic mode in the double window cavity.

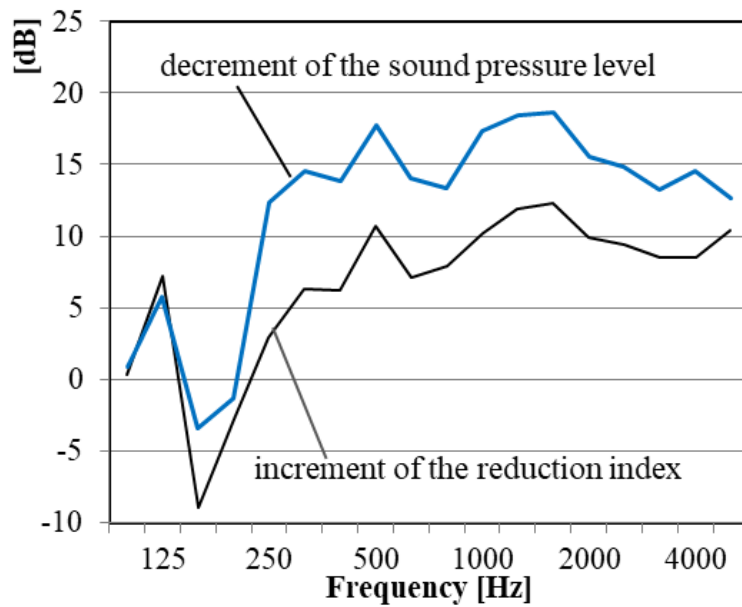


Fig. 11: Absorbent material effects on the perimeter of the cavity of the double window model. Blue line: decrement of the sound pressure in the cavity. Black line: increment of the reduction index of double window. The two results show similar frequency characteristics.

(a) Effects of the absorbent material width

The R values achieved with different widths of absorbent material are presented in Fig. 12. Normal absorption coefficients of glass wool in the conditions above are presented in Fig. 13. These were measured according to JIS A 1405-2 [17]. For comparison, the sound pressure level at the edge point in the cavity is shown in Fig. 14. According to Fig. 12, the increment of R becomes greater when wider glass wool is added. In Fig. 13, the increase of sound pressure level as a function of frequency is shown to have a tendency corresponding to that of the absorption coefficient of the absorbent used in the experiment. In this case, when the absorption coefficient is nearly 1.0, R increases about 10 dB. According to Fig. 14, the wider a layer of added glass wool becomes, the smaller the sound pressure level becomes. The results obtained using a 25-mm-wide absorbent, which has a low absorption coefficient at low frequencies, shows significant peaks such as a result without absorbent. However, it shows little peaks at high frequencies. When the absorbent material is narrow, the absorption coefficient is little in low frequencies and is sufficiently high in high frequencies. The degree of the effect depends on the tendency of absorption coefficient. In fact, the value of R is affected strongly by the absorbent material width.

According to Fig. 13, the absorption coefficients of the case with the 100-mm-wide absorbent at 125 Hz and that with 25-mm-wide absorbent at 500 Hz are both 0.2. However, according to Fig. 14, the effect of 100-mm-wide glass wool at 125 Hz is negligible, but the effect of 25-mm-wide glass wool at 500 Hz is great. This fact means that the two sound pressure peaks compared above should be attributed to different resonance mechanisms. The acoustic mode resonance in the cavity is especially affected by absorbent materials on the cavity perimeter. However, the mass-air-mass resonance in many cases is little affected by the absorbent condition, unless the absorption coefficient of the absorbent at the mass-air-mass frequency is sufficiently high. This discussion suggests that the increase of R in the present results achieved by attaching absorbent material results from damping of the acoustic mode resonance in the air cavity.

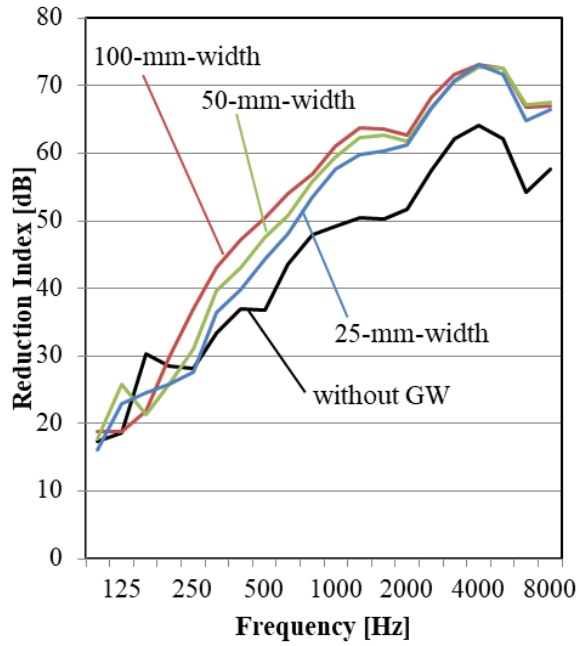


Fig. 12: Reduction indices of double window model: effects of the differences of the glass wool widths on the cavity perimeter.

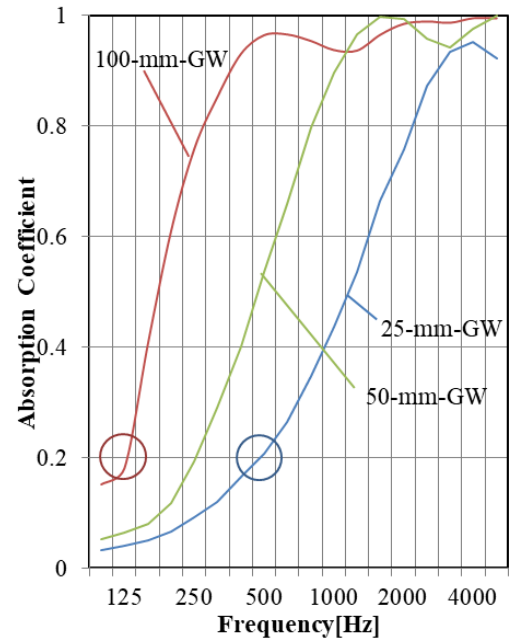


Fig. 13: Absorption coefficients with normal incidence of the glass wool: differences of the width of the glass wool. Circles show the two conditions have same coefficient 0.2 at different frequencies.

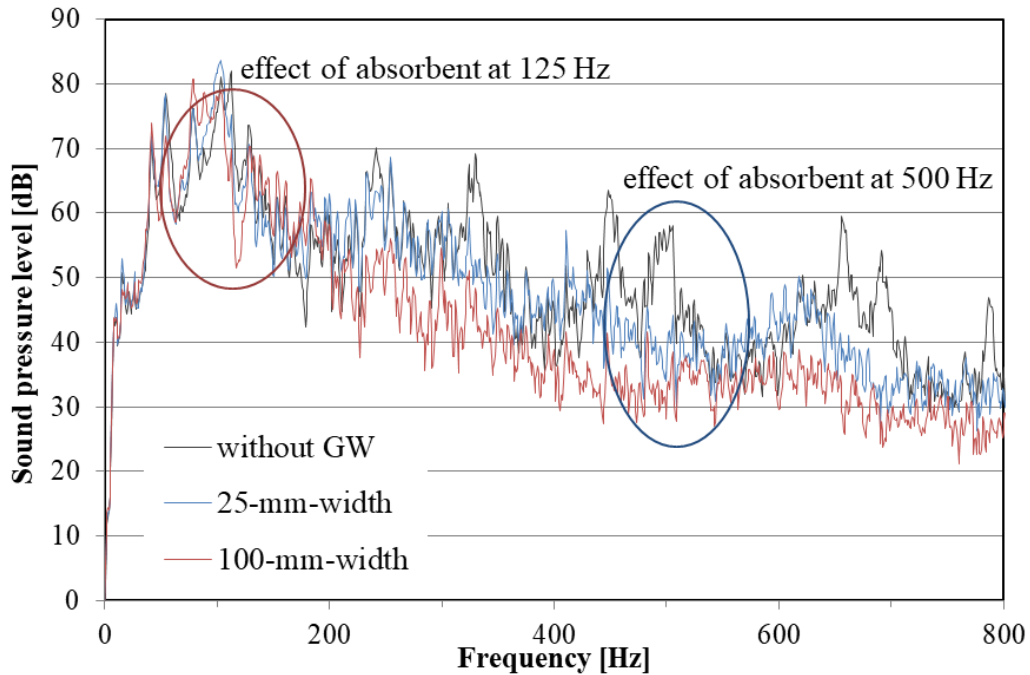


Fig. 14: Sound pressure level at the edge point in the cavity: the different widths of glass wool.

(b) Effects of the absorbent material arrangement

The R values with different arrangements of absorbent material are presented in Fig. 15. The R with absorbent material on all parts of the cavity perimeter is of the largest absorption area among these conditions. The two values of R s with

absorbent material on part of the cavity perimeter, i.e., corner, such as Fig. 7(A) and center, such as Fig. 7(b), also show improvement. Their effects are almost comparable under 1 kHz and above 3 kHz. However, at 1–3 kHz, R with absorbent only on corner is about 5 dB less than that with absorbent only on the center. They have the same absorption area. Therefore, absorbent material on only the center part is demonstrably more effective than that only on corner part in particular frequency. From the discussion above, it seems that a close relation exists between the position of absorbent and acoustic mode in the cavity. Further study of the mechanism is necessary to clarify that relation.

(c) Effect of the absorbent material thickness

The R values with different thicknesses of absorbent material are presented in Fig. 16. The R in the case of 80-mm-thick absorbent material on the cavity perimeter is the largest in these conditions. However, especially within the 500 Hz -- 2 kHz frequency range, the R s with any thicknesses of absorbent material are comparable. Above 2 kHz, the differences by the thicknesses are apparent. At the coincidence frequency, R for 80-mm-thick absorbent material is about 7 dB larger than that for 40-mm-thick absorbent material. It is necessary to consider that the conditions for 80-mm-thick absorbent material only on the corner part as shown in Fig. 7(A) or only on the center part as shown in Fig. 7(B), and for 40-mm-thick absorbent material on all parts of the cavity perimeter as shown in Fig. 8(D) have the same areas of absorbent, i.e., the same absorption power. However, they show different R s, especially under 2 kHz. That fact suggests that the increment of R by attaching absorbent material cannot be ascertained solely by the absorption power in the cavity.

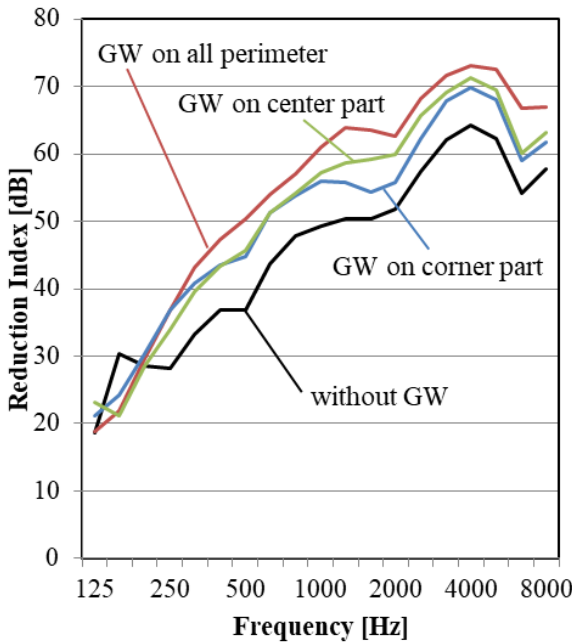


Fig. 15: Reduction indices of double window model: effects of the different arrangements of the glass wool.

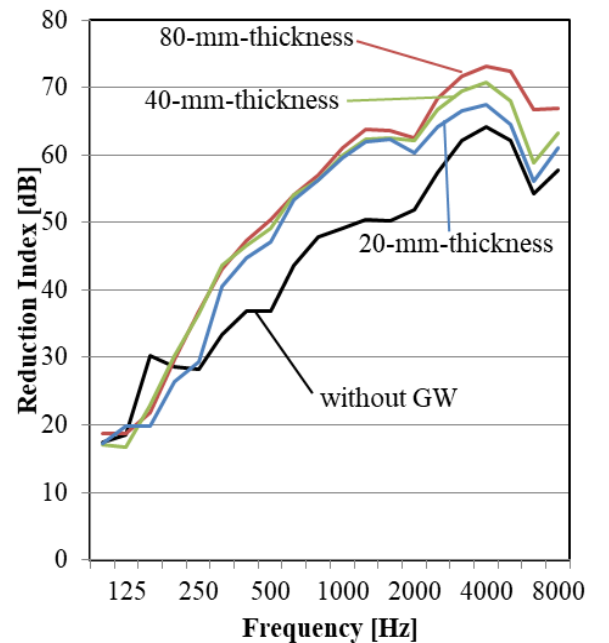


Fig. 16: Reduction indices of double window model: effects of the glass wool thickness differences on the cavity perimeter.

4. Discussion through two experiments

It is noteworthy that a difference exists between the two experiments in the effects of the absorbent. The increments of R_s because of the same 24 kg/m^3 glass wool of 50 mm width from the two experiments are presented in Fig. 17. Regarding the first experiment, with the commercially available products, above 125 Hz, the R improves about 4 dB by attaching the absorbent. In the second experiment with the model, above 250 Hz, the R improves about 10 dB by attaching the absorbent, although it varies widely. The acoustic mode frequencies can be estimated using Eq. (3). It varies with the cavity size. The first acoustic mode of the x or y direction occurs at 103 Hz in the first experiment, and at 213 Hz in the second experiment, and the effect of the absorbent appears above these first mode frequencies. Consequently, it can be inferred that the absorbent on the cavity perimeter can strongly affect the acoustic mode especially. Attaching thin absorbent material between double walls is well known to be able to improve its sound insulation performance because of damping of the sound propagation parallel to the walls [15]. These results show that the absorbent only on the cavity perimeter can be regarded as damping the acoustic mode resonance of x, y directions in the cavity, although it has only a small absorption coefficient.

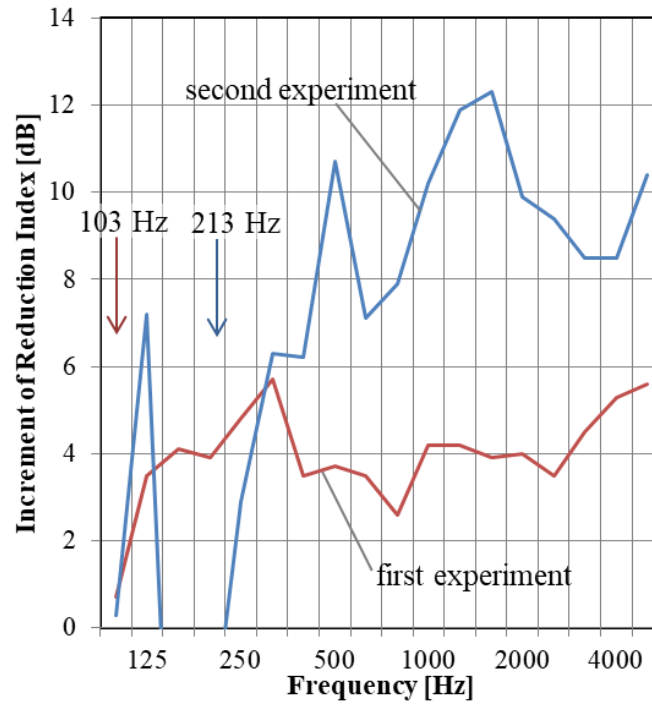


Fig. 17: Increment of R by 24 K, 50-mm-thick glass wool on the cavity perimeter from the two experiments. Arrows and frequencies show the lowest acoustic mode frequencies of the two specimens.

5. Conclusions

As described in this paper, the sound insulation mechanisms of double window with absorbent materials on the cavity perimeter are found through the two types of experiment. As a result, the following conclusions have been derived: (i) The sound transmission through a double window is increased by resonance of two type, either the acoustic mode resonance in the cavity or the mass-air-mass resonance. By attaching absorbent material on the cavity perimeter of a double window, the acoustic mode resonance is damped, thereby the sound reduction index is increased. (ii) By attaching

absorbent material on the cavity perimeter of a double window, the mass-air-mass resonance cannot be affected by conventional fibrous materials such as glass wool. As described in this paper, we were able to observe the mass-air-mass resonance only in the second experiment with a modelled double window. The results showed that attached glass wools have no significant effect. (iii) The increment of sound reduction index by attaching absorbent material on the cavity perimeter depends not only on the cavity absorption power. This topic is the subject of the further studies in the next step.

In practical design of an actual building, ventilation and daylight are as important as sound insulation performance. However, windows, which are basic ventilation device, are often weak points of sound insulation in buildings. Therefore double window with absorbent material on the cavity perimeter can be advantageous in sound insulation performance. In this paper, the possibility of the improvement of sound insulation by adjusting the arrangement of absorbent in the cavity of double window is suggested.

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