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# Prediction of the reverberation absorption coefficient of finite-size membrane absorbers

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*ABSTRACT*

This paper presents a method to predict the reverberation absorption coefficient of a finite-size membrane absorbers composed of a single- or double-leaf membrane structure of various configurations. In order to predict the sound absorptivity of such an absorber, it is needed to consider that sound is incident from both sides of the absorber, which has not been accounted for the previous studies on membrane absorbers. The edge effect also needs to be considered if the absorber is rather small. The present method is established based on the theory for absorbers hanged in a reverberation chamber developed by Fujiwara and Makita [J. Acoust. Soc. Jpn(E), **1**, 37-45, (1980)]. The same theory requires the fraction of energy dissipation in the absorber, which can be obtained by the difference of absorption and transmission coefficients, and the difference is calculated by the theories for various membrane structures presented in the authors' previous work. An experimental study was also conducted to validate the present method: the predicted values showed good agreement with the measured ones. The numerical examples calculated by the present method are also presented to discuss the effect of the various control parameters, and it is suggested how to improve the sound absorption performance of double-leaf membrane absorbers with a permeable and an impermeable leaves.

**KEYWORDS:** Sound absorption, Membrane absorber, Double-leaf membrane, Edge effect

# 1. INTRODUCTION

With the recent development in membrane-structure buildings, membrane material is now used not only for roofs/ceilings, but also for other purposes. Membranes are lightweight, durable, translucent, flexible and designable, thus they have a potential possibility for various applications including acoustical purposes: Sound absorbers with membranes are also known as alternative fibreless absorbers [1,2]. The acoustic properties of various membrane structures have been studied extensively [3-10].

The traditional use of a membrane for acoustical purpose is a conventional membrane-type absorber, composed of a single-leaf impervious membrane placed with a rigid back-wall and an air- or absorbent-cavity in-between [11,12]. However, the authors' work has focussed on the possibilities of an efficient sound absorber with membrane only. This is because the work is intended to develop a lightweight, translucent and movable sound absorber without other elements.

The authors have made a series of studies on the acoustic properties of membrane structures of various types [3-8]. In these studies the acoustic properties of a single-, double- and triple-leaf membrane were investigated: the theories to predict their acoustic properties have been established and experimentally validated. These theories are developed assuming membranes to be of infinite extent, however, they have been proved to show good agreement with experimental results for finite-size samples. These studies were originally intended for improving the acoustical condition in the interior spaces of membrane-structure buildings. However, a good possibility of membranes for acoustical purposes, especially as a sound absorber, has also been suggested. For example, a double-leaf membrane (DLM) shows resonant peak absorption, similar to the conventional membrane-type absorbers with rigid back wall, when the leaves are impermeable, and shows broad band absorption similar to porous materials, if one of the leaves has a reasonable permeability. This property can be useful for a sound absorber.

However, when a finite-size structure is considered, for example, in the case that these membrane structures are used as a sound absorber in rooms, e.g., 'space' absorber being hanged from the ceiling or standing on the floor, further consideration will be required. Because the theories in the previous work assume membranes of infinite extent to divide the space into two sound fields, and a sound is supposed to be incident from one side only. The experiments were performed to meet the above condition in the theory so that the sound transmission occurred only through the membrane structures, using specimens set into the aperture of a coupled reverberation chamber. Therefore, sound incidence from both sides of the structure must be taken into account in predicting theory. Moreover, finite-size absorbers can cause the edge effect (area effect) [13], and a correction needs to be included in prediction procedure if the size is rather small.

In this paper, in order to develop a prediction method for sound absorption characteristics of finite-size membrane absorbers, theoretical analysis on reverberation absorption coefficients of such an absorber is discussed, and it is experimentally validated. Some further consideration is made to improve the performance of such an absorber through the numerical examples calculated by the present theory.

# 2. THEORETICAL CONSIDERATIONS

### 2.1 Reverberation absorption coefficient of finite DLMs

In this section some theoretical considerations on prediction of reverberation absorption coefficient of a finite-size DLM absorber with diffuse sound incidence from the both sides are studied. The following theoretical consideration is based on the analysis developed by Fujiwara and Makita [14,15].

Fujiwara and Makita studied an absorber composed of a single material only, of which acoustic properties do not depend on which surface the sound is incident upon. Therefore, the material has the identical absorption characteristics on the both surfaces. However, considering a DLM structure, the acoustic properties can be different for each side, e.g., when a DLM is composed of a permeable leaf on one side and an impermeable leaf on the other side, it shows a low frequency moderate peak for impermeable side and high absorption at high frequencies for permeable side.
Let us consider the reverberation absorption coefficient of finite-size porous absorbers hanged in a diffuse sound field, as shown in Fig. 1. The room is divided into two spaces (Space 1 and 2) by the absorber and adjacent imaginary boundaries (dotted lines in Fig. 1): Space 2 is a prismatic space of volume $V_2$, of which the bases are the absorber and its orthogonal projection on the wall. Space 1 is the remaining portion of the room, and its volume is $V_1$. The absorber has absorption coefficient $a_1$ and transmission coefficient $t_1$ for the sound incident from Space 1 (volume: $V_1$, and energy density: $E_1$), $a_2$ and $t_2$ for the sound incident from Space 2 ($V_2$ and $E_2$), respectively. The surface area is $s_m$ for both surfaces, and the intensity of incident sound from Space 1 is $I_1$ and from Space 2 that is $I_2$.

Let the inflow energies (sound intensities) from Space $j$ ($j$=1,2) through unit area of its boundary in one second be $I_j$. The absorber is assumed to have a sound absorption and transmission coefficient, $a_j$ and $t_j$, to the sound incident upon it from Space $j$. These coefficients are values when the sound is incident on one side only and does not go round to the other side. It is also assumed that both spaces are diffuse sound fields of energy density $E_j$.

In the steady state, the intensities of $I_1=c_0E_1/4$ from Space 1 and $I_2=c_0E_2/4$ from Space 2 for unit area are incident upon the absorber. In this absorber the energies designated by $(a_1-t_1)s_m$ (for sound from Space 1) and $(a_2-t_2)s_m$ (for sound from Space 2) are dissipated ($s_m$ is the surface area of one side of the absorber). Therefore, the energy dissipated in one second in this absorber is:

$$E_a = s_m\{I_1(a_1-t_1)+I_2(a_2-t_2)\} = \frac{c_0 s_m}{4}\{E_1(a_1-t_1)+E_2(a_2-t_2)\} \tag{1}$$

Then the following relation holds using the average energy density in the room $E_m$ and the reverberation total absorption coefficient of the absorber $a_r$*:

$$E_a = \frac{c_0 E_m}{4} a_r^* \cdot 2s_m = \frac{1}{2} c_0 s_m E_m a_r^* \tag{2}$$

Solving Equations (1) and (2) for $a_r$* gives:

$$a_r^* = \frac{1}{2E_m}\{E_1(a_1-t_1)+E_2(a_2-t_2)\} \tag{3}$$

where

$$E_m = \frac{E_1V_1+E_2V_2}{V_1+V_2} \tag{4}$$

In the experiment, the absorber will be placed far enough from walls so that the assumption $E_1=E_2$ is satisfied. Therefore, substituting these condition into Equations (3) and (4) leads to:

$$a_r^* = \frac{1}{2}\{(a_1 - t_1) + (a_2 - t_2)\} \tag{5}$$

From the above discussion the reverberation absorption coefficient of an absorber in a diffuse sound field is the average of the difference of absorption and transmission coefficients for each side of the absorber. Therefore, it can be predicted by the theoretical results calculated by the authors' theory for DLMs of infinite extent, e.g. [6,7]. One should note that $a_r$* here is for the cases in which the edge effect can be neglected.

## 2.2 Correction for the edge effect

In the discussion above the edge effect is neglected. Fujiwara and Makita [14,15] also first derived an expression of the reverberation absorption coefficient similar to Equation (5) with neglecting the edge effect. Then they proposed a correction. Here, based on the correction theory of Fujiwara and Makita, a correction for an absorber with different properties on each side is discussed.

Considering the predicted reverberation absorption coefficient with edge effect expressed in the following expression similar to Fujiwara and Makita's study:

$$a_{rp} = a_r^*(1 + Db\, lE) \tag{6}$$

where $D$ denotes the degree of discontinuity of the energy distribution in sound field with reference to that in the case of the absorber is placed on the floor, $b$ is the correction coefficient, $l$ is the acoustic wavelength in the air, $E$ is the perimeter length normalised to the area of the absorber. Regarding the value of $D$, when the absorber is placed on the wall it is defined as $D_F$, when it is placed well far from the wall it is defined as $D_s$. Fujiwara and Makita showed that its reverberation absorption coefficient is proportional to the degree of the discontinuity, therefore, denoting the theoretical value of the reverberation coefficient of the absorber on the wall is $a_{rF}$*, with the proportional constant $K_D$, these values of the degree of the discontinuity are:

$$D_F = K_D a_{rF}^* \tag{7}$$

$$D_S = K_D a_r^* \tag{8}$$

where $a_r$* is expressed by Equation (5) which is a value for the case in which the absorber is placed far enough from the wall.

Considering the above, when the absorber is placed on the wall

$$D = \frac{D_F}{D_F} = 1 \tag{9}$$

and when it is well far from the wall

$$D = \frac{D_S}{D_F} = \frac{a_r^*}{a_{rF}^*} \tag{10}$$

The correction coefficient $b$ is the value for the case in which the absorber is placed on the wall, and the reverberation absorption coefficient in this case can be obtained from the measured and the theoretical values, $a_{rF}$ and $a_{rF}$*, respectively. Using Equations (6) and (9),

$$a_{rF} = a_{rF}^*(1 + Db\, lE), \quad D = 1 \tag{11}$$

Solving this equation for $b$ gives

$$b = \frac{1}{lE}\left(\frac{a_{rF}}{a^*_{rF}} - 1\right) \tag{12}$$

Thus, substituting Equations (10) and (11) into Equation (6), the reverberation absorption coefficient with edge effect can be predicted when the absorber is placed apart from the wall by the following expression:

$$a_{rp} = a^*_r\left\{1 + \frac{a^*_r}{a^*_{rF}}\left(\frac{a_{rF}}{a^*_{rF}} - 1\right)\right\} \tag{13}$$

where $a_{rF}$ and $a_{rF}$* are given by the average values of those for each side, when the absorption characteristics are different for each side.

As is observed from Equation (13), if $a_{rF}$* is very small and discontinuity in the sound field is very low, $a_{rp}$ becomes infinite, and the correction above is not applicable.

## 3. EXPERIMENTAL VALIDATION

### 3.1 Outline of the experiment

An experiment was carried out to examine the validity of the present theory. Two samples of single-leaf membrane and four samples of DLM sound absorber were prepared with ordinary membrane materials for building purposes, and their reverberation absorption coefficients were measured in a reverberation chamber. The theoretical predictions for these samples were also calculated by the present theory, and compared with the measurement values.

Table 1 shows the material used in the experiments, and Table 2 shows the detailed description of seven samples used in the experiment. Membrane absorbers are the samples Nos. 1…6: Nos. 1 and 2 are single-leaf permeable membranes. They are of the same material but in different size: No. 2 is smaller. Nos. 3 … 6 are DLMs composed of a permeable leaf on one side and an impermeable leaf on the other. Nos. 3, 4 and5 are of the same materials, but No.4 is smaller, and No. 5 is with larger cavity depth. No. 7 is a fibreglass board, which was used for reference. All specimens were set on a steel frame to stand vertically to the floor. They were placed in the centre of the floor. The reverberation chamber used is of 153m$^2$ surface area and 130m$^3$ volume. A photograph of the setting of a specimen is shown in Fig. 2. The chamber is irregularly shaped (pentagonal). The specimens were placed in the middle of the pentagonal shaped floor (15m$^2$), and was set on the stand perpendicularly to the floor (height: 1m from the floor to the bottom of the specimen.) The experimental set-up is shown in Fig. 3. The measurements were made according to JIS A1409 (compatible to ISO 354) except for the setting of the specimens. As required in JIS A 1409, five microphone positions (1.2m high from the floor) were used in the chamber during the measurements and the values were averaged so as to avoid the effect of incomplete diffuseness. Reverberation absorption coefficients $a_r$ are obtained from the measured reverberation time by using Eyring-Knudsen formula. The values of $a_r$ are compared with the theoretical values $a_r$*. To calculate $a_r$*, the theories for single-leaf permeable membranes [4] and DLMs (Regarding DLMs with a permeable leaf, for sound incidence on permeable side, see [7], and for that on impermeable side, see [16]) of infinite extent were used.

### 3.2 Comparison with theoretical prediction

Comparisons of the theoretical values without the edge effect, Equation (5), and measured results for the samples Nos. 1…6 are given in Fig. 4 (a)…(f). For reference the measured results for No. 7 (fibreglass board) are also indicated in all figures. In the theoretical calculations the tension in the membranes were all assumed to be 1.0 N/m: The effect of tension on the absorptivity has been demonstrated to be negligible in the previous studies [2,9]. The surface acoustic admittances of the impermeable membranes used in the experiments were measured and used in the calculation for the boundary conditions on the impermeable leaves surfaces. Note that in the measurement for the surface admittances the membranes were fixed on the rigid backing in the impedance tube so that the specimen could not vibrate by the incident sound.

For single-leaf permeable membranes, Nos. 1 and 2, the predicted values are in good agreement with the measured values (Figs 4 (a) and (b)). The difference between them is at maximum 0.06 but 0.01…0.03 at most frequencies. For DLM samples, Nos. 3…6, the theory and the experiment are in good agreement especially at high frequencies in all cases. Peak frequencies show some discrepancies (1/3 to 2/3 octave), however, peak values do not show significant differences. Thus, the present theory can give reasonably good prediction for reverberation absorption coefficients of finite-size single- and double-leaf membrane absorbers. As mentioned above, the prediction given by Equation (5) does not include the edge effect, yet it gives good prediction, which means that the edge effect was negligible in the present experiments. This is interpreted that, as the samples were placed in the middle of the reverberation chamber in the present experiments, the sound field on the either sides of the sample were similarly diffused. However, it does not mean that one does not need to consider the edge effect, as it can be more significant depending on the experimental condition. As it is difficult to know whether or not the correction is needed in prior to an experiment, it is important to include the correction in the theory as presented above. The judgement should be made upon each case.

From the results above, in the experimental condition in this study, the theoretical values of absorption and transmission coefficients calculated by the infinite-membrane theory [4,7] without the edge effect can be used for the prediction of the reverberation sound absorption coefficients of a finite-size membrane sound absorber. This indicates that the results and knowledge obtained from the authors' previous studies [3-7] can be useful for designing finite-size membrane sound absorbers as well.

### 3.3 Effect of the area of samples

The edge effect is known to change according to the perimeter and the area of the sample: it is said to increase when the relative perimeter becomes large or the area becomes small [13]. Therefore, the accuracy of the present theory can vary with the size of samples.

Figure 5 (a) compares the measured results for the samples Nos. 1 and 2, shown together with the theoretical results. The samples Nos. 1 and 2 are made of the same material but in different size. The theoretical prediction given by the present theory is the same for the both. The difference between Nos. 1 and 2 is at maximum 0.06 at 2000Hz but 0.01…0.03 at other frequencies. Except for 200, 400 and 500 Hz the smaller sample (No.2) shows greater value. The similar results are obtained for Nos. 3 and 4, which are also made of the same materials but in different size. Thus, in both cases the smaller sample shows greater values, which means the edge effect was present in the experiments. However, the difference due to the difference in size was very small and can be negligible.

### 3.4 Correction of the edge effect

The correction for the edge effect can be made by applying Equation (13) to Equation (5), and this can be useful to improve the prediction accuracy of the theory. However, if the edge effect is not present, the correction is of no use. Here the correction by Equation (13), is applied to the predicted values given by

Equation (5), and examine the results more in detail.

To use the correction by Equation (13) the measured absorption coefficient with the specimen laid down flat on the floor is required. For the samples Nos. 1 and 2, their absorptivity is extremely low when they are placed on the floor and the discontinuity of the energy distribution is almost zero. Therefore, the present correction cannot be applied to these samples. On the contrary, the DLM samples Nos. 3…6 show absorptivity to a certain degree even when they are laid down flat on the floor, and the correction therefore can be applied.

Figure 6 shows the corrected theoretical prediction with the measured results. The theoretical prediction without the edge effect is also presented in these figures. The corrected theory offers slightly more accurate prediction in the range of 250…1250 Hz in all cases. However, at the other frequencies, the corrected theory does not necessarily offer a better prediction: in many cases the corrected theory gives worse prediction. As in the present results, when the difference between theory and experiment is very small, the values hardly change even if the correction is applied. This correction theory uses a measured value, so that the correction unavoidably includes measurement errors. Considering the above circumstances, though the correction rather worsened the agreement of the theory and the experiment in the present study, the error was inferred to be caused by the measured value used in the correction and within the range of its accuracy. This suggests that the edge effect was negligible in the present experiments. Therefore, in the condition similar to the present experiment, the theory without the edge effect, Equation (5), can be used to predict the reverberation absorption coefficient of finite-size membrane absorbers, and the values obtained by the theory for infinite membrane structures [7] can be well used in Equation (5). However, one should note that, when the specimen is placed close to a wall in a reverberation chamber, the edge effect becomes stronger and the theory without the edge effect may be unable to give a good prediction.

## 4. PARAMETRIC STUDY

In the preceding sections, a predicting theory for the reverberation absorption coefficient of a finite-size membrane absorber has been derived and experimentally validated. The present theory is now used for a parametric study in this section: the optimisation of the absorption characteristics is discussed through numerical examples calculated by the present theory.

The acoustic properties of a DLM including a permeable leaf on the sound incidence side are significantly affected by the flow resistance of the permeable leaf and the masses of the leaves. Therefore, these parameters are important in designing membrane absorbers of this type, and their effects on the acoustic properties need to be clarified. Here, the effects of these parameters on the sound absorption characteristics are discussed through theoretical results.

### 4.1 Effect of the flow resistance of the permeable leaf

The sound absorptivity of a DLM with a permeable leaf on the illuminated side is known to be maximised if the flow resistance of the permeable leaf $Rh$=1.5$r_0c_0$…1.8$r_0c_0$=612…734 Pa s m$^{-1}$ (for diffuse sound incidence)[16]. Therefore, it is expected that a finite-size DLM absorber of this type can also show the best performance when its $Rh$ is adjusted to the value above.

The permeable leaves used in the DLM samples in the experiment have rather low flow resistance: 454 Pa s/m in Nos. 3, 4 and 5, and 158 Pa s/m in No.6. Therefore, the main point here is how much the absorption performance is improved by changing *Rh* of the permeable leaf in DLMs: Among the experimental samples, No. 3 is taken as an example in the discussion below, and theoretically studied how much it is improved by optimising *Rh*.

In Fig. 7 the calculated result of $a_r$* for No. 3 (*Rh*=454 Pa s m$^{-1}$) and that for the same structure but with the optimised flow resistance (*Rh*= 700 Pa s m$^{-1}$) are compared. Even though the flow resistance is optimised, the reverberation absorption coefficient is 0.4…0.5 at high frequencies, which is still considerably smaller than No. 7 (fibreglass board). Therefore, it is difficult to obtain high absorptivity equivalent to fibreglass by the membrane structure of this type. This is because the reverberation absorption coefficient is the average of the absorption characteristics of each side, which are high at high frequencies for the permeable side but rather low for impermeable side. This indicates that, to obtain high absorptivity by finite-size DLM absorbers, it is important to have high absorptivity for both sides of the absorber.

## 4.2 Effect of the surface density of the leaves

The mass of the leaves is also important parameter to improve the absorptivity of DLMs. The effect of the mass of a single-leaf permeable membrane has been proven to be significant at low frequencies: the heavier the membrane is, the higher the absorptivity becomes, though the difference of absorption and transmission coefficients never exceeds 0.5 [5]. The effect of the mass of the impermeable posterior leaf is rather smaller, yet the sound absorption performance will deteriorate if it is very small [7].

Figure 8 shows the calculated reverberation absorption coefficient, $a_r$*, for various DLM absorbers of different combination of masses of the permeable and impermeable leaves. The curve (1) shows the result calculated for No. 3, (2) shows that for the same structure but the mass of permeable leaf $m_p$ is increased, (3) shows that for the same but the mass of the impermeable leaf $m_i$ is decreased, and (4) $m_p$ is increased and $m_i$ is decreased.

When the mass of permeable leaf $m_p$ is increased, the absorptivity improves at low frequencies and shows rather higher value than that of fibreglass (shown as crosses in the figure.) This tendency reflects the characteristics of a single-leaf permeable membrane mentioned above. This is because, at low frequencies, the lighter leaf causes larger vibration, which decreases the leaf's flow resistance [5].

On the other hand, when the mass of impermeable leaf $m_i$ is decreased, the structure shows as large absorptivity as the fibreglass. This is perhaps because the effect of the mass-spring resonance is reduced by the lighter impermeable leaf. Therefore, using heavier permeable leaf and lighter impermeable leaf can give higher absorptivity in wider range of frequency.

If the impermeable leaf in a DLM absorber is extremely lightweight, its effect on the acoustic characteristics of a DLM is almost negligible. Therefore, the acoustic characteristics of the permeable leaf become dominant over those of the DLM. In such a case, the acoustic properties of the DLM tend to those of a single-leaf permeable membrane. Therefore, when only sound absorption performance is concerned, there is no need to employ DLM system, but a reasonably heavy single-leaf permeable membrane can be better to obtain higher performance in wider frequency range. However, there is a different consideration, if sound insulation is also required: in such a case a DLM is much better than a single-leaf. One should choose suitable type according to its purpose.

## 5. CONCLUDING REMARKS

In this paper, a predicting theory for a finite-size membrane absorber has been presented. The theory was developed based on the theories previously developed for various types of single- and double-leaf membrane structures of infinite extent [3-8]. When a finite-size membrane absorber is placed in a sound field, sound is incident upon the both sides of the absorber, and the sound incident upon one side is transmitted through the structure to the other side. To predict the absorption characteristics of a finite-size membrane absorber, the theory needs to consider this situation. Referred to the Fujiwara and Makita's theory for predicting reverberation absorption coefficients of finite-size absorbers hanged in a reverberation chamber [14,15], the present theory has been developed, and the correction for the edge effect is also taken into account: The reverberation absorption coefficient is expressed by the average of the fraction of energy dissipation (expressed by the difference of the absorption and transmission coefficients) of each side of the absorber, when the edge effect is negligible. The correction for the edge effect is also presented following Fujiwara and Makita's correction method.

An experimental study was conducted to validate the present theory: the theoretical predictions by the present theory showed good agreement with the measured values of reverberation absorption coefficient for various finite-size single- and double-leaf absorbers.

In order to optimise the absorption performance of finite-size DLM absorber with a permeable and an impermeable leaf, a parametric study has been performed through the numerical results by the present theory. The discussion focussed upon the flow resistance of the permeable leaf and the masses of the leaves, as they are known to be main parameters dominating acoustic performance of a DLM absorber of this type. The results showed that, even though the flow resistance is optimised, the absorptivity of the absorber of this type is rather lower than that of a fibreglass board: Even if the flow resistance of the permeable leaf is optimised to gain high absorptivity for sound incidence upon the permeable side of the DLM, it is averaged with that for the impermeable side, which is low at mid-high frequencies, resulting in only moderate absorptivity. This indicates that, to obtain high absorptivity by finite-size DLM absorbers, it is important to have high absorptivity for both sides of the absorber. The mass of the permeable leaf has a significant effect at low frequencies, and should be as heavy as possible to improve low frequency performance.

## REFERENCES


[1] Koga S. Improvement of sound absorption of thin film – Studies of absorption characteristics by equivalent circuit. J. Acoust. Soc. Jpn(J), 1996, 52: 92-98. (in Japanese with English abstract)

[2] Fuchs HV. Alternative fibreglass absorbers – New tools and materials for noise control and acoustic comfort. Acustica/Acta Acustica, 2001, 87: 414-422.

[3] Sakagami K, Morimoto M, Takahashi D. A note on the acoustic reflection of an infinite membrane. Acustica 1994; 80(6): 569-572.

[4] Takahashi D, Sakagami K, Morimoto M. Acoustic properties of permeable membranes. J Acoust Soc Am 1996; 99: 3003-3009.

[5] Sakagami K, Kiyama M, Morimoto M, Takahashi D. Detailed analysis of the acoustic properties of a permeable membrane. Applied Acoustics 1998; 54(2): 93-111.

[6] Kiyama M, Sakagami K, Tanigawa M, Morimoto M. A basic study on acoustic properties of double-leaf membranes. Applied Acoustics 1998; 54(3): 239-254.

[7] Sakagami K, Kiyama M, Morimoto M. Acoustic properties of double-leaf membranes with a permeable leaf on sound incidence side. Applied Acoustics 2002; 63(8): 911-922.

[8] Sakagami K, Morimoto M, Kiyama M, Acoustic properties of a triple-leaf membrane, J Acoust Soc Am 2000; 108(5): 2513.

[9] Bosmans I, Lauriks W, Lombaert G, Mermans J, Vermeir G. Sound absorption of stretched ceilings with an impervious synthetic membrane. J Acoust Soc Am 1999; 106(1): 233-239.

[10] Song J, Bolton JS. Sound energy dissipation by finite, tensioned, fluid-loaded membranes. J Acoust Soc Am; (to be published).

[11] Brüel PV. Sound insulation and room acoustics. London: Chapman & Hall; 1951. Chapter 4.

[12] Sakagami K, Kiyama M, Morimoto M, Takahashi D. Sound absorption of a cavity-backed membrane: A step towards design method for membrane-type absorbers. Applied Acoustics 1996; 49: 237-247.

[13] Maekawa, Z. Environmental and Architectural Acoustics. London: E&FN Spon; 1993. pp 125-126.

[14] Fujiwara K, Makita Y. Reverberant sound absorption coefficient of a plane space absorber. Acustica 1978; 39: 340-344.

[15] Fujiwara K, Makita Y. Theoretical study on a method of estimation of the reverberant sound absorption coefficient of plane porous material under any mounting conditions. J Acoust Soc Jpn(J) 1978; 34(1): 21-28. (in Japanese).

[16] Kiyama M. Studies on acoustical properties of membrane materials for building purposes. PhD Thesis, Kobe University, 1998. Chapter 9. (in Japanese).

**Captions to tables**

**Table 1** Summary of material data.

**Table 2** Material samples used in the experiment.

**Captions to figures.**

**Figure 1** A membrane absorber hanged in diffused sound field.

**Figure 2** A photograph of the setting of a specimen in the reverberation chamber.

**Figure 3** The block diagram of the experimental set-up.

**Figure 4** The experimental results (dots) compared with the predicted values (solid lines) for each sample. The measured values for No. 7 (fibreglass board) are shown in all figures for comparison.

**Figure 5** The effect of the area of the sample. (a) compares Nos. 1 (closed circle) and 2 (open circle) which are of the same material but different area: No.2 is smaller than No.1. (b) compares Nos. 3 (closed circle) and 4 (open circle) which are of the same material but different area: No. 4 is smaller than No. 3. Solid lines are the predicted values by the present theory.

**Figure 6** The effect of the correction for the edge effect. Open circles show the predicted values with edge effect correction, closed circles show the measured values. Solid curves are the predicted value without the correction.

**Figure 7** Effect of the surface density of each membrane on reverberation absorption coefficient: (1) Theoretical prediction for No. 3 (original), (2) $m_p$=0.327 kg/m$^2$, $m_i$=0.01 kg/m$^2$ (3) $m_p$=4.0 kg/m$^2$, $m_i$=0.995 kg/m$^2$ (4) $m_p$=4.0 kg/m$^2$, $m_i$=0.01 kg/m$^2$ and (×) No 7 (fibreglass board).

**Figure 8** Effect of the flow resistance, *Rh*, of permeable membrane on sound absorption coefficient: (1) Theoretical prediction for No. 3 (original), (2) *Rh*=700 Pa s m$^{-1}$ and (×) No 7 (fibreglass board).

**TABLE 1** Summary of material data.

Membrane

| | Surface Density [kg/m²] | Flow Resistance [Pa s m⁻¹] | Note |
|---|---|---|---|
| A | 0.327 | 454 | Permeable membrane |
| B | 0.683 | 158 | Permeable membrane |
| C | 0.995 | ∞ | Impermeable membrane |

Fibreglass board

| | Density [kg/m³] |
|---|---|
| GW | 32 |

**TABLE 2** Material samples used in the experiment.

| No. | Material | Size* [mm] | Cavity Depth [m] | Note |
|---|---|---|---|---|
| 1 | A | 2050×1476 (2100×1500) | — | Single leaf |
| 2 | A | 1000×1476 (1050×1500) | — | Single leaf (Small) |
| 3 | A, C | 2050×1476 (2098×1500) | 0.05 | Double-leaf |
| 4 | A, C | 1000×1476 (1048×1500) | 0.05 | Double-leaf (Small) |
| 5 | A, C | 2050×1476 (2098×1500) | 0.15 | Double-leaf (Thick) |
| 6 | B, C | 2050×1476 (2098×1500) | 0.05 | Double-leaf |
| 7 | GW | 2050×1476 (2098×1500) | 0.05 (Thickness) | Fibreglass board |

*: Size of the membrane are of each sample. Full size of the samples, which includes wooden frame, is shown in parentheses.

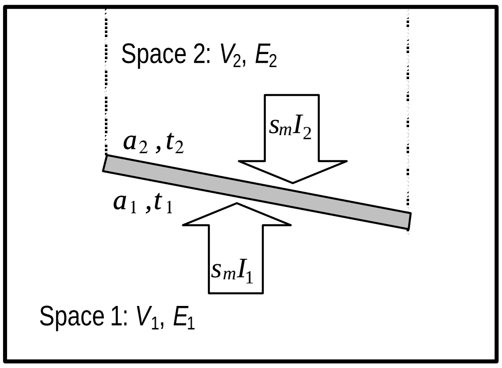


Figure 1 A membrane absorber hanged in diffused sound field.

**Figure 2** A photograph of the setting of a specimen in the reverberation chamber.

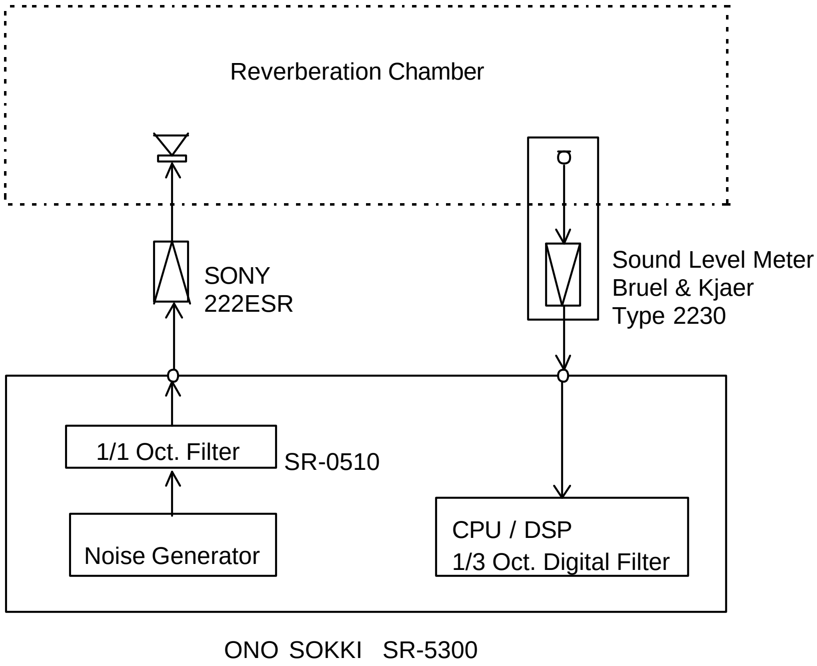


Figure 3 The block diagram of the experimental set-up.

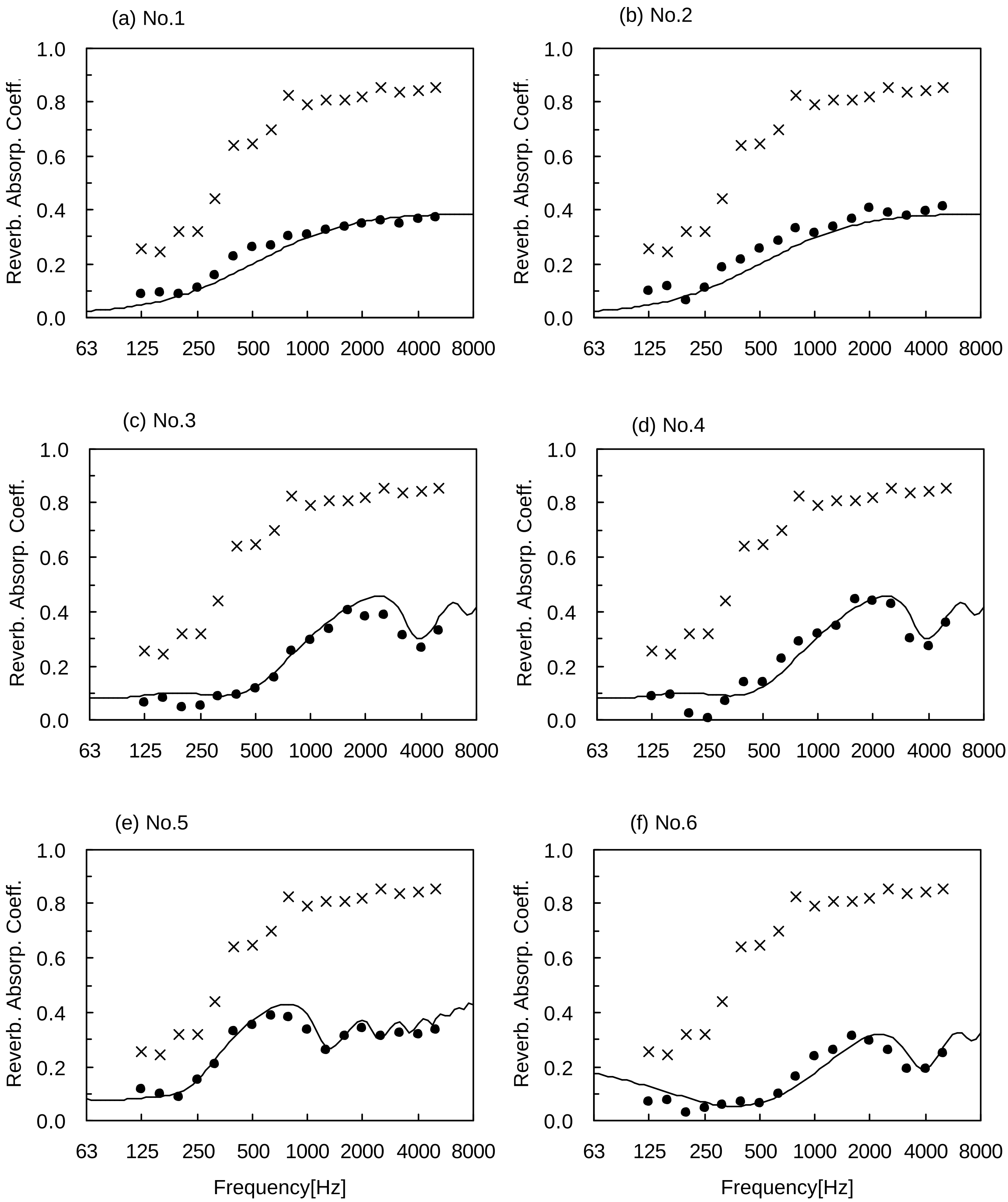


Figure 4 The experimental results (dots) compared with the predicted values (solid lines) for each sample. The measured values for No. 7 (fibreglass board) are shown in all figures for comparison.

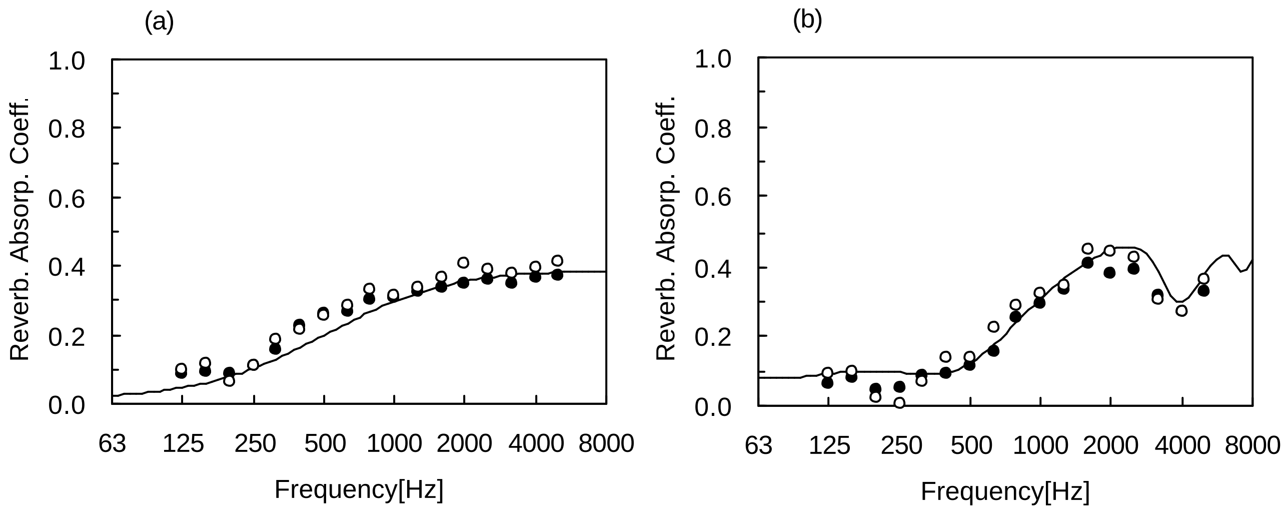


Figure 5 The effect of the area of the sample. (a) compares Nos. 1 (closed circle) and 2 (open circle) which are of the same material but different area: No.2 is smaller than No.1. (b) compares Nos. 3 (closed circle) and 4 (open circle) which are of the same material but different area: No. 4 is smaller than No. 3. Solid lines are the predicted values by the present theory.

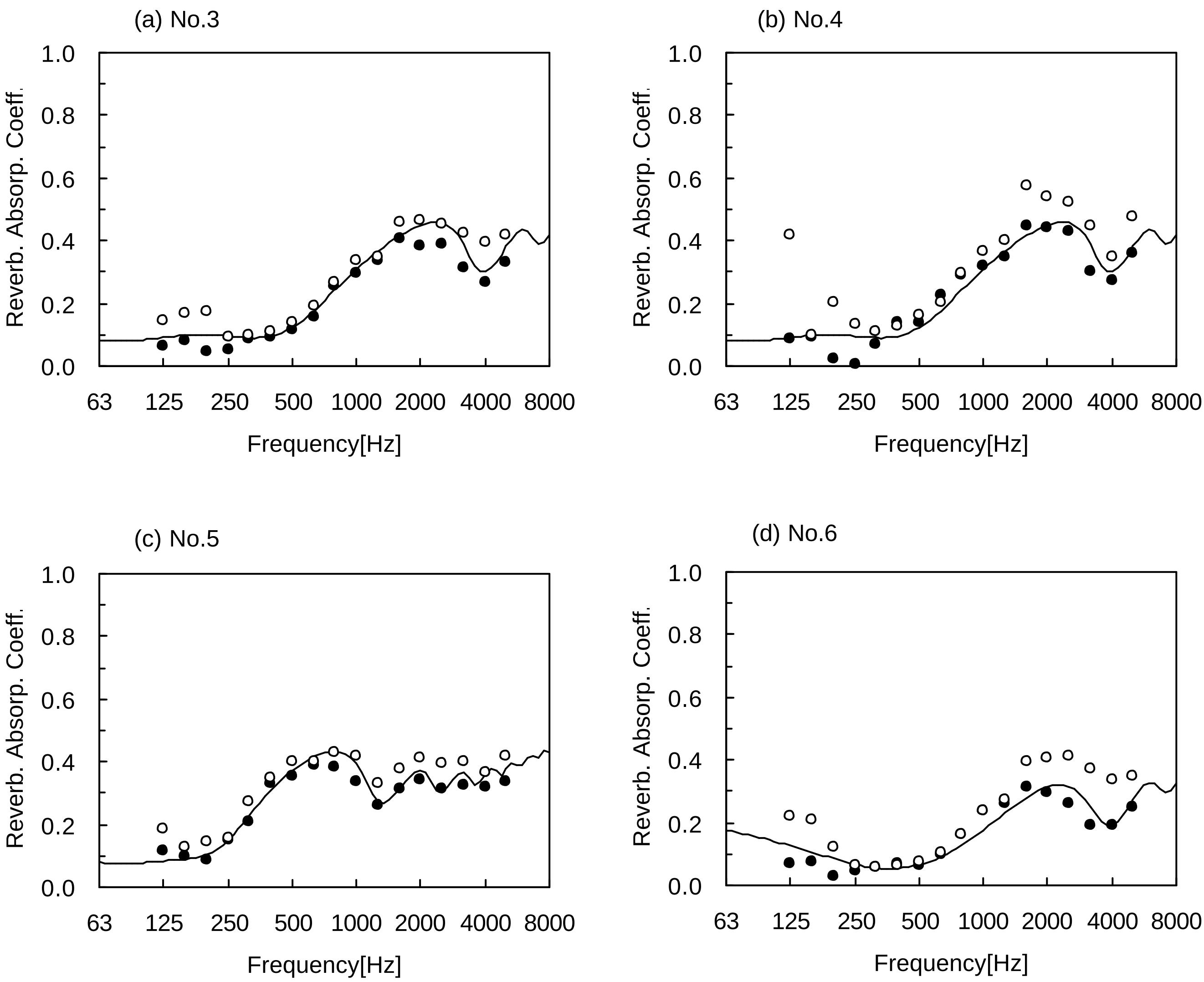


Figure 6 The effect of the correction for the edge effect. Open circles show the predicted values with edge effect correction, closed circles show the measured values. Solid curves are the predicted value without the correction.

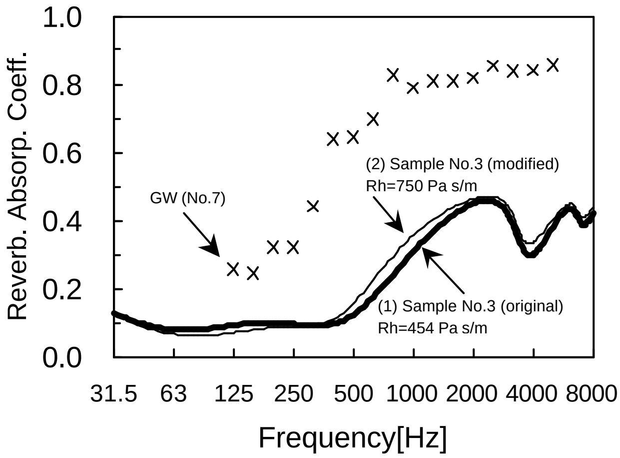


Figure 7 Effect of the surface density of each membrane on reverberation absorption coefficient: (1) Theoretical prediction for No. 3 (original), (2) $m_p$=0.327 kg/m$^2$, $m_i$=0.01 kg/m$^2$ (3) $m_p$=4.0 kg/m$^2$, $m_i$=0.995 kg/m$^2$ (4) $m_p$=4.0 kg/m$^2$, $m_i$=0.01 kg/m$^2$ and (×) No 7 (fibreglass board).

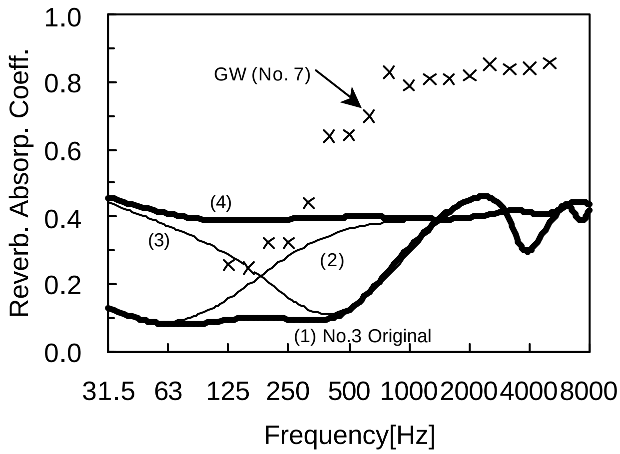


Figure 8 Effect of the flow resistance, *Rh*, of permeable membrane on sound absorption coefficient: (1) Theoretical prediction for No. 3 (original), (2) *Rh*=700 Pa s $m^{-1}$ and (×) No 7 (fibreglass board).