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An experimental study on the absorption characteristics of a three-dimensional permeable membrane space sound absorber

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In this study, we propose a rectangular and cylindrical three-dimensional space sound absorber using a permeable membrane and the absorption characteristics which are examined experimentally by reverberation room method. As a pilot study, a two-dimensional boundary element (2-D BEM) analysis is also conducted to predict the absorption characteristics of the absorbers. The experimental study revealed that the absorption coefficient is low at low frequencies and gradually increases with frequency. The absorption coefficient converges to 0.5 at the maximum which is similar to a single-leaf permeable membrane. The flow resistance and the surface density of the permeable membrane mainly affect the absorption characteristics at middle to high frequencies. At low frequencies, the heavy membrane contributes to the higher absorption performance. In the experiment specimens with high flow resistance produce higher absorptivity. Also, the cylindrical absorber shows slightly higher absorption coefficient than the rectangular absorber mainly at low frequencies. The 2-D BEM results show similar frequency characteristics as the measured values when the membrane's flow resistance and surface density are low, but the numerical values overestimate overall the absorptivity of the absorbers. © 2015 Institute of Noise Control Engineering.

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1 INTRODUCTION

Sound absorption is one of the most important treatments for conditioning acoustic environment in buildings. For this purpose, porous absorbent materials, such as fibreglass or plastic foams, have been widely used for many years. These materials have a great advantage in that they offer high absorption performance at low cost. However, they have various problems in hygiene, durability and recyclability. Thus, substitutes, which are so-called next-generation sound absorbing materials, were developed in 1970 to 1980's.

Among various types of the next-generation sound absorbing materials, microperforated panels (MPPs)¹ and membranes are the most promising and attractive. Especially, MPPs can be made of various materials so that they can be lightweight, transparent, freely-shaped and designable. As for the space sound absorber using MPPs, three-dimensional MPP space sound absorbers (cylindrical and rectangular: CMSA and RMSA) have been proposed²⁻⁴. They have wide applicability and can be freely placed in various places. They have been studied both experimentally and theoretically and found to have reasonably effective absorption performance. They have a resonance peak at mid-high frequencies (the peak absorption coefficient is about 0.5 to 0.6) and an additional absorption at low frequencies of about 0.2 to 0.3. However, MPPs are still quite expensive so that they have not been widely used.

On the contrary, membranes are much less expensive than MPPs. Permeable membranes are a potential alternative. They are usually made of a core textile coated with resin. Because they have high flow resistance, they can absorb the sound energy via acoustic resistance. As

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for the space sound absorber, single- and double-leaf sound absorbers with permeable membranes^{5–8} have been proposed and examined theoretically and experimentally to prove that they have an efficient absorption performance. These single- and double-leaf structures are panel-like objects. Therefore, they can be used as a sound absorbing panel or a panel-like space absorber. However, in many cases there are limitations to their placement in rooms, i.e., they can possibly be hung from the ceiling or put on the floor as a sound absorbing partition. Considering their size and shape, it is difficult to put them in smaller rooms. Also, their designability is somewhat limited as it is hard to be made them in different shapes. In order to make membrane space absorbers more applicable and designable, it is necessary to develop a membrane space absorber of different shapes which can be placed and used more freely.

Considering the above points, in order to widen of the usage of membrane space absorbers, we propose three-dimensional space sound absorbers using less expensive permeable membrane materials. Such a three-dimensional space absorber can be either hung from the ceiling and put on the floor and also placed in small spaces. Also, it is possible to give the absorber added value such as a possibility to combine it with a lighting equipment. However, due to its three-dimensional (e.g., cylindrical or rectangular) shape, its acoustic characteristics will be different from those of a usual double-leaf structure. Therefore, in this study, first we propose cylindrical and rectangular three-dimensional membrane space sound absorbers and, as a pilot study to investigate feasibility, their absorption characteristics are experimentally examined using the reverberation chamber method. In the experiments, three types of permeable membranes with different flow resistances and surface densities are used in both cylindrical and rectangular shapes so that the effects of those parameters are determined through the measured results. Also, the effect of the shape, i.e. cylindrical and rectangular, is discussed. Furthermore, the effect of the cover on the open ends at the top of the specimens is considered. Finally, as a pilot study to help with the analysis of the measured results and to establish a prediction method, a two-dimensional boundary element method (2-D BEM) analysis is used for analysing the three-dimensional MPP space absorbers⁴. The numerical results are compared to the experimental results.

2 EXPERIMENTS

2.1 Experimental Method

In this study, the random sound incidence absorption coefficients of the proposed space absorbers are

measured in a reverberation chamber in compliance with JIS A 1409 standard (ISO 354 compatible). The reverberation chamber has an irregular shape, with a 130 m³ volume and a 153 m² surface area. In the reverberation chamber, the sound source was fixed in one position and five microphone positions were taken. The reverberation time was measured five times at each microphone position and their average values were taken for obtaining the absorption coefficients. The interrupted noise method using a pink noise was employed in the measurements. For measuring the reverberation time, a real-time analyser (Ono-Sokki SR-5300) was used.

2.2 Specimens

In the experiments, three types of permeable membranes were used to fabricate the test specimens. Membrane A is the most lightweight and has the lowest flow resistance. Membrane B is heavier than A and has a flow resistance close to the characteristic impedance of the air. Membrane C is the heaviest among the three and its flow resistance is around twice that of air, which was, in the previous studies, found to be optimal for obtaining the best absorption performance for a single-leaf permeable membrane absorber⁸. Both membranes A and B are thin lightweight sheets made of a fibreglass fabric. Membrane C is fluororesin membrane with fibreglass textile core, which is designed for building purposes and mainly used as an inner leaf of a membrane structure building. Also, in order to confirm that the sound absorption of the proposed absorbers is caused by the membrane's permeability regardless of the absorber's shape, we measured the absorption of the proposed absorbers made of a polyethylene impermeable membrane. The parameters of the membranes used in the experiments are listed in Table 1.

The test specimens of cylindrical and rectangular three-dimensional space absorbers using the above membranes were made as follows. All specimens are made by using wooden frames on which the membranes are attached. As for the rectangular cases, frames of 0.25 m side and 0.5 m side, both of 1 m high, are

Table 1—Specifications of the experimental specimens.

Membrane	Surface density (g/m ²)	Flow resistance (Pa s/m)
Permeable membrane A	65.0	196
Permeable membrane B	120.0	462
Permeable membrane C	495.0	1087
Impermeable membrane	32.5	—

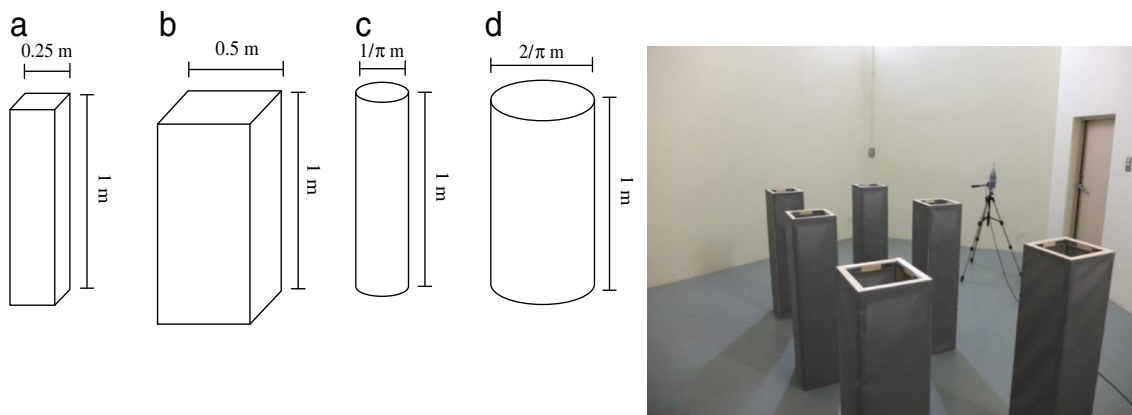


Fig. 1—Sketches and a photograph of the specimens used in the experiments. (a) Rectangular, 0.25 m, (b) Rectangular 0.5 m, (c) Cylindrical, $1/\pi$ m diameter, (d) Cylindrical, $2/\pi$ m diameter. Note that the bottom ends of the specimens are closed as they are placed on the floor (see Sec. 2.1). Regarding the top ends of the specimens, measurements are done in both open and closed cases (see Sec. 2.1). The photograph shown here is the specimen (a) with permeable membrane A.

used. On these frames, the membranes of 1 m^2 and 2 m^2 are attached. For the cylindrical shapes, the frames of $1/\pi$ m diameter (1 m perimeter) and $2/\pi$ m (2 m perimeter) are prepared, on which the membranes of 1 m^2 and 2 m^2 are attached, respectively. The sketches of these specimens are shown in Fig. 1.

2.3 Measurement Conditions

As mentioned above (see Table 1), in the experiments, the absorption of 16 cases is measured in total: 2 shapes (rectangular and cylindrical), of 2 sizes (large and small), with 4 types of membranes (A, B, C and impermeable). In all the cases in which the permeable membranes are used, two patterns of top ends, i.e., open and close, are employed. In the measurement, for each case, six specimens are placed on the rigid floor of the reverberation chamber, with more than 1 m distance separation (see Fig. 1). Thus, the bottom ends of the specimens, both cylindrical and rectangular, are closed by the rigid floor of the chamber.

In the previous experimental studies on the three-dimensional MPP space sound absorbers^{2,3}, it was confirmed that, even if the number of the specimen is changed, the absorption power per one specimen does not change and absorption power per unit area is constant. Therefore, in the present paper, the total absorption power is normalised by the total surface of the membrane of specimens to obtain an equivalent value to the absorption coefficient (absorption power per unit area). In the following, this value is called absorption coefficient and regarded as an equivalent value of the conventional absorption coefficient.

3 RESULTS AND DISCUSSION

3.1 Cylindrical Absorber

Figure 2(a) shows the measured results for $1/\pi$ m cylindrical absorber with the membranes A, B and C, and Figure 2(b) shows those for $2/\pi$ m cylindrical absorber with the membranes A, B and C. In this section, the top-ends of the specimens are open throughout.

In both Figs. 2(a) and (b) the absorption coefficients increase with frequency in all the cases, which is a similar tendency to that of a porous absorbent. First, in order to determine the effect of the membrane type, i.e., membrane's mass and flow resistance, the difference among the membrane A, B and C are compared. Comparing the membrane A and B, B shows higher absorption coefficient at middle-high frequencies than A. This is because the flow resistance of B is higher than that of A. As for the surface density, although B is twice as heavy as A, both A and B are very lightweight so that little difference appears at low frequencies. In the previous study⁸, it is theoretically proven that the absorptivity of a permeable membrane is mainly governed by its flow resistance at middle to high frequencies and by its surface density at low frequencies. The above results reflect this tendency. Looking at the results for the membrane C, its absorption coefficient is close to that of B at high frequencies, but at low to middle frequencies, C shows on the whole higher absorptivity. This is because the surface density of C is much larger than A and B, as discussed above⁸.

Secondly, the effect of the size of the absorber is now explored by comparing Figs. 2(a) and (b). In this study, as the results are normalised by the area of the total

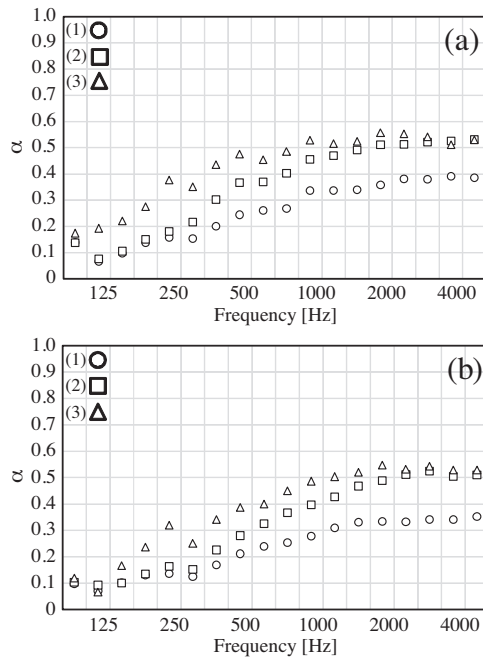


Fig. 2—Absorption characteristics of (a) $1/\pi$ m diameter cylindrical absorber and (b) $2/\pi$ m diameter cylindrical absorber: (1) Membrane A (round marks), (2) membrane B (square marks) and (3) membrane C (triangle marks).

surfaces of the specimens, the effect of the size is supposed to appear as that of the size of the cavity inside the absorber or the distance between the membranes. When the membrane A is used, in both $1/\pi$ m case and $2/\pi$ m case, the absorption coefficient at low frequencies is around 0.1 to 0.15 and at high frequencies converges to about 0.4. In the case of B, both $1/\pi$ m and $2/\pi$ m, the absorption coefficient is between 0.1 and 0.2 at low frequencies and converges to around 0.5. In the case of C, a similar tendency is observed, but for both sizes the absorption coefficient is higher at low frequencies than for A and B. Thus, it can be stated that the smaller absorbers give higher absorptivity, though the difference is rather small. The reason for this difference in absorption may be due to the change in strength of inner standing waves. However, this cannot be concluded from the present experimental results. However, on the whole, although the smaller absorber produces a slightly higher absorption coefficient, the size of the absorber can be said to have only a small effect.

3.2 Rectangular Absorber

Figure 3(a) shows the measured results for 0.25 m rectangular absorber with the membranes A, B, and C,

and Fig. 3(b) shows those for 0.5 m rectangular absorber with the membranes A, B and C. In this section, the top ends of the specimens are open throughout.

In both Figs. 3(a) and (b), the absorption coefficients increase with frequency in all the cases, which is a similar tendency to that of a porous absorbent. First, in order to discuss the effect of the membrane type, i.e., membrane's mass and flow resistance, the difference among the membranes A, B and C is discussed. Comparing the membrane A and B, B shows higher absorption coefficient at middle to high frequencies than A, similar to that for the cylindrical specimens. This is because the flow resistance of B is higher than that of A. Regarding the membrane C, as in the cylindrical case, its absorption coefficient is almost the same as that of B at middle to high frequencies, but is higher than the others at low to middle frequencies, because of its larger mass.

In the case of the membrane C, a peak is observed around 500 Hz in Fig. 3(a). This infers that a kind of resonance occurs. It is interpreted as the result of the standing wave inside because of the large mass and flow resistance. The membrane in the opposite side works as a back wall. This behaviour is less significant in the case of the 0.5 m rectangular in Fig. 3(b). This infers that, as the opening at the top becomes larger,

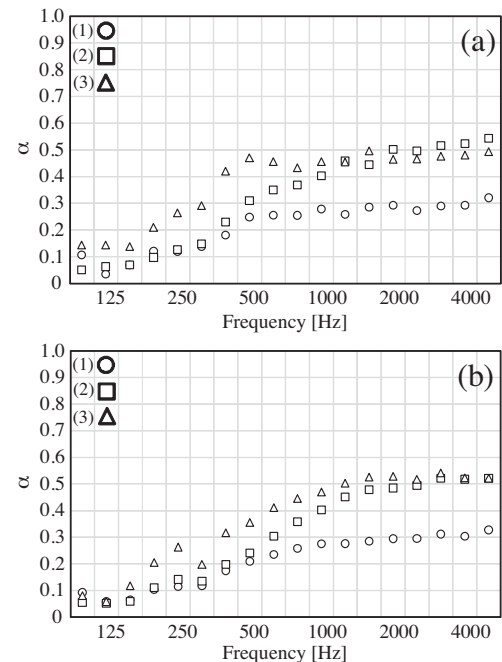


Fig. 3—Absorption characteristics of (a) 0.25 m rectangular absorber and (b) 0.5 m rectangular absorber: (1) membrane A (round marks), (2) membrane B (square marks) and (3) membrane C (triangle marks).

the sound incident into the absorber from the open top interferes more significantly with the sound field inside so that a standing wave may become less strong.

Comparing Fig. 3 with the results for the cylindrical cases Fig. 2, for example, the maximum value of the absorption coefficient for the membrane C is around 0.55 in both cylindrical and rectangular cases; however, at low to middle frequencies the values for cylindrical cases in Fig. 2 are slightly higher, especially in the cases of membrane C. In the diffuse sound field, although the plane sound wave is incident from various angles, all incident waves may be considered as to be incident normal to a certain point on the surface of a cylindrical object. In general, permeable sound absorbing materials show the highest absorptivity for normally incident sound wave²⁻⁴. Regarding the effect of the size of the absorbers, at low frequencies, the 0.25 m cases show slightly higher absorptivity. The difference in the size does not have a very significant effect. Regarding the difference due to the size, it may be interpreted as that given in Sec. 3.1 for cylindrical cases.

The results are omitted here, but in the case of impermeable membrane, the absorption coefficient is almost zero at all frequencies. This signifies that the abovementioned absorption effect cannot be obtained by an impermeable membrane and permeability is necessary to obtain the sound absorptivity.

3.3 Effect of the Covers on the Top-End

In the previous sections the measurement results for the cylindrical and rectangular three-dimensional permeable membrane space absorbers, with open top-ends, have been presented and discussed. As mentioned above, the sound is incident on the open top end and it may cause interference in the sound field inside the absorbers, which can affect their behaviour. Therefore, the same measurements for the same specimens with a cover on the top end were conducted. In these experiments, all of the specimens' top ends were closed with a 12 mm thick plywood panel. Regarding the effect of the cover on the top end on the absorption characteristics of the three-dimensional MPP space absorbers are reported to increase the absorptivity slightly^{2,3}. Therefore, a similar effect could be expected in the present cases. The purpose of this section is to discuss how much the cover affects the absorption characteristics of the three-dimensional permeable membrane space absorbers.

The results are presented in Fig. 4 for the cylindrical absorber (diameter $2/\pi$ m) with the membrane A and Fig. 5 for membrane C. Figure 4 is the example of the case in which the effect of the cover is the smallest and Fig. 5 is the example of the case in which the effect

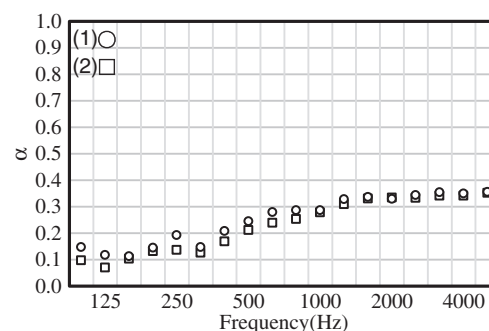


Fig. 4—The effect of the cover on the open top-end at the top of a cylindrical absorber with the membrane A. Diameter $2/\pi$ m. (1) Without cover (open top-end: round marks) and (2) With cover (closed top-end: square marks).

of the cover is the largest. Note that the somewhat larger differences at 100 and 125 Hz in Fig. 5 are considered to be attributed to a variance in the measurement due to the low diffusivity in the small reverberation chamber. As observed in these figures, it can be said that the cover has only a small effect on the absorptivity of this type of sound absorbing structure. The effect of the cover can be less than 0.05 at mid-high frequencies. Since similar results are observed in all other cases, whether the top end is open or closed does not affect the absorptivity of the three-dimensional permeable membrane space absorbers. In the case of the three-dimensional MPP space absorbers, covering the open top end at the top of specimen makes the resonance slightly higher, but in the present cases it does not produce a significant effect. This difference might be the cause of the difference in the absorption mechanism between the MPP space absorber and the permeable membrane absorber.

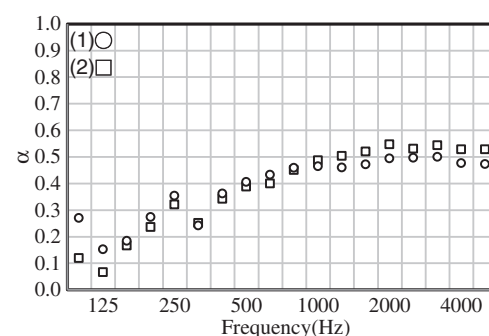


Fig. 5—The effect of the cover on the open top-end at the top of a cylindrical absorber with the membrane C. Diameter $2/\pi$ m. (1) Without cover (open top-end: round marks) and (2) With cover (closed top-end: square marks).

4 A PILOT STUDY FOR NUMERICAL ANALYSES

So far in the previous sections, the fundamental acoustic behaviour of the three-dimensional permeable membrane space sound absorbers is explored by experimental results. However, in order to obtain more detailed results, as well as to establish a prediction method for the absorption characteristics of the three-dimensional permeable membrane space absorbers, a theoretical analysis of the absorbers should be beneficial. Since these absorbers have a finite size, it is very difficult to employ analytical methods, so we need to employ a numerical method. Here, as a pilot study, we tried to analyse their sound absorption characteristics by using 2-D BEM developed for analysing three-dimensional MPP absorbers (CMSA and RMSA)⁴. The detailed explanation and formalism, omitted here for the sake of conciseness, are found in Ref. 4. However, it is emphasised that this 2-D BEM model used for CMSA and RMSA has been validated with measured results⁴. Therefore, the 2-D BEM analyses can be expected to be applicable.

To apply this model for CMSA and RMSA to the three-dimensional permeable membrane space sound absorbers, the boundary conditions are changed. The boundary condition is given by the following specific impedance of the permeable membranes⁹:

$$Z = (1/R - 1/i\omega m)^{-1} / \rho_0 c_0, \quad (1)$$

where R is the flow resistance, m the surface density of the membrane, ω the angular frequency and $\rho_0 c_0$ the characteristic impedance of the air. The model for 2-D BEM analyses is sketched in Fig. 6. In this model, the ratio of the energies dissipated by the sound absorbing

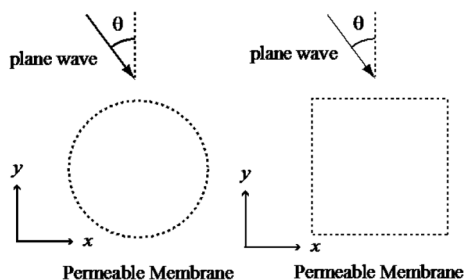


Fig. 6—Two-dimensional model for BEM analyses of the sound absorber. Left: cylindrical cases, right: rectangular cases. As the model is two-dimensional, only a cross section is considered. The boundary is given the impedance Eqn. (1) for the boundary condition.

system with the incident plane wave at angle θ is computed. To estimate the random incidence sound absorption coefficient, the ratio is averaged over the angle of incidence from 0 to 45 degrees for the rectangular cases. However, in the cylindrical cases it is not necessary to average over angle because of the symmetrical geometry.

Substituting the boundary condition in Eqn. (1) to the boundary of the model, 2-D BEM analyses were carried out and the numerical results are compared with the measured results.

The results are shown in Figs. 7 (cylindrical cases) and 8 (rectangular cases). In both figures, (a) is for the cases with low flow resistance and surface density. In these cases, the calculated and measured results show a similar tendency, which is low at low frequencies and gradually increases with frequency; however the values are substantially different. BEM results are higher than measured results. The discrepancies become

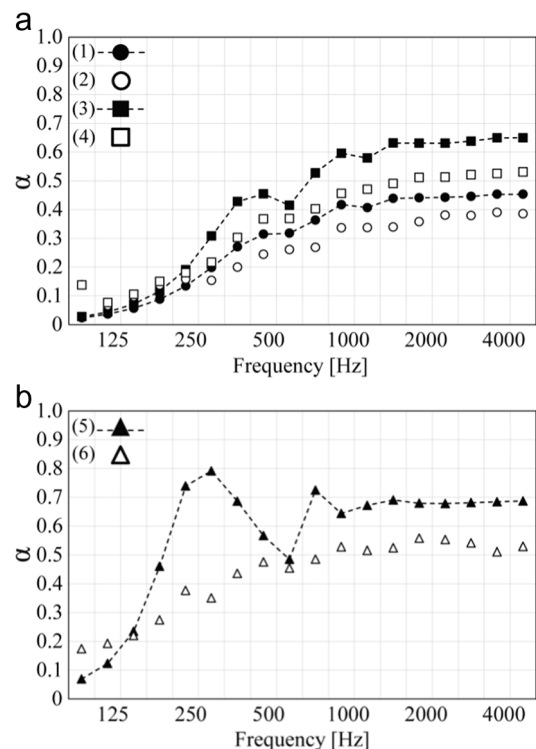


Fig. 7—An example of the comparison of the calculated results by 2-D BEM and the measured results. The cylindrical absorber of diameter is $1/\pi$ m. (a) (1) 2-D BEM and (2) Measurement for the absorber using the membrane A. (3) 2-D BEM and (4) Measurement for the absorber using the membrane B. (b) (5) 2-D BEM and (6) Measurement for the absorber using the membrane C.

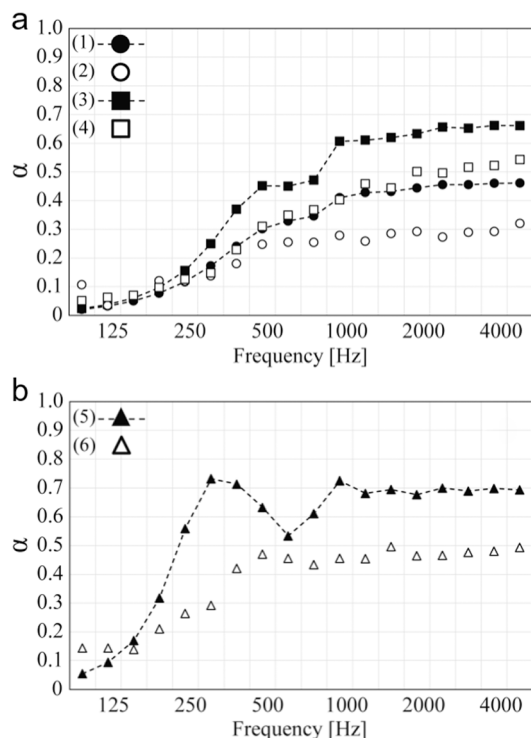


Fig. 8—An example of the comparison of the calculated results by 2-D BEM and the measured results. The rectangular absorber of 0.25 m. (a) (1) 2-D BEM and (2) Measurement for the absorber using the membrane A. (3) 2-D BEM and (4) Measurement for the absorber using the membrane B. (b) (5) 2-D BEM and (6) Measurement for the absorber using the membrane C.

much larger in the cases of the absorbers with membrane C [Figs. 7(b) and 8(b)], which has the highest flow resistance and surface density.

On the whole, the 2-D BEM overestimates the absorptivity in all cases. This infers that, due to the nature of the two-dimensional model which is equivalent to assuming the absorbers as infinitely long, a stronger standing wave is present in the model than in the actual absorber which has a finite (1 m) height. This is emphasized more when the membrane is heavy and of high flow resistance, because high flow resistance and surface density makes the membrane in the opposite side work as a back wall more significantly than the frontal surface. Therefore, in the absorbers with membrane C, there are significant peaks corresponding to the standing wave peak similar in the porous material with a rigid backing.

In the experiment, it is considered that standing wave effects are rather weak because of its finite height and the sound incident from the opening at the top of the

absorbers. In order to clarify this point and to establish a more accurate prediction system, three-dimensional BEM analyses will be necessary, which will be the focus of the next step of this work.

5 CONCLUDING REMARKS

In this study, as a pilot study to research the feasibility, three-dimensional (cylindrical and rectangular) space sound absorbers with permeable membrane are presented and their sound absorption characteristics are examined experimentally. In addition a computational study is presented. In the experiments, the random incidence sound absorption coefficient is measured in a reverberation chamber and the absorption coefficients are compared with 2-D BEM results.

From the experimental results, the absorption coefficient of the proposed absorbers is low at low frequencies and increases with frequency to converge to around 0.5 at a maximum. The absorption coefficient is slightly higher in the cylindrical cases than in the rectangular cases at low to middle frequencies. In the experiments three types of permeable membrane are used: among the three membranes the membrane with large mass and high flow resistance shows the highest absorptivity. Considering the results of previous studies⁶⁻⁸ there may be an optimal value.

In order to confirm the effect of the sound incidence from the top end opening of the specimens, the effect of a cover on the open top end of the specimen to close the opening is also explored with the experimental results. Although the cover on the top opening is somewhat effective in the three-dimensional MPP absorber cases, its effect is small in the present cases.

For the practical applications of these membrane absorbers, we also tried to predict the absorption characteristics by using a two-dimensional wave-based numerical method. In this paper, as a pilot study, the 2-D BEM, which has been used for analysing three-dimensional MPP space sound absorbers (CMSA and RMSA)⁴, is employed by changing the boundary condition to that of a permeable membrane. Although the BEM analyses show a similar tendency when the membrane's flow resistance and surface density are low, the simulated results overestimate the absorptivity of the proposed absorbers. These discrepancies are assumed to be due to the limitation of the two-dimensional model. For this purpose it is required to employ a more sophisticated three-dimensional BEM model and its development will be presented in subsequent papers.

6 ACKNOWLEDGEMENTS

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