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PAPER

Experimental and numerical studies on reverberation characteristics in a rectangular room with unevenly distributed absorbers

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Abstract: The reverberation time in a room with unevenly distributed sound absorbers, such as a room having an absorptive floor and/or ceiling, is often observed to be longer in the middle- and high-frequency ranges than the values obtained using the Sabine/Eyring formula. In the present study, this phenomenon was investigated through a scale-model experiment and three-dimensional wave-based numerical analysis. The reverberation time in a room having an absorptive floor and/or ceiling was verified to be longer in the middle- and high-frequency ranges, and the arrangement of absorbers was found to affect the frequency characteristic of the reverberation time. The increase in the reverberation time is caused by the slow decay of the axial and tangential modes in the horizontal direction. The reverberation time is longer in the high-frequency range (in which the wavelength is sufficiently shorter compared with the height of the ceiling) than in the low-frequency range, even when the frequency characteristics of the absorption coefficients of the absorbers are flat. As a means of improving such an uneven reverberation time in a room, both the placement of diffusers in the vertical direction and the use of inwardly inclined walls (in rooms with highly absorptive floors) have been found to be effective.

Keywords: Reverberation, Absorption, Scale-model experiment, Numerical analysis, FDTD

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1. INTRODUCTION

In a room with unevenly distributed sound absorbers, the reverberation time calculated using the Sabine/Eyring formula is often observed not to agree with measurement results, which might be attributed to not satisfying the assumption of a diffuse sound field. In particular, when all of the floor and/or ceiling surfaces are absorptive, the reverberation time is often observed to be much longer than the values obtained using these formulae [1,2]. Examples of these sound fields include conference rooms, banquet halls in hotels, and classrooms.

A number of formulae have been proposed for calculating the reverberation time in such sound fields [3–6]. However, none of these formulae have been able to consistently predict the reverberation time with sufficient accuracy [7], because these formulae have the same energy-based form as Sabine's formula. The only difference between these formulae and Sabine's formula is that the absorption exponents are used in these formulae, rather than the average absorption coefficient, to express the characteristics of various types of rooms. In [7], the prediction accuracy of the reverberation time based on ray-based numerical analyses was also investigated, and ray-based numerical analyses were found to have difficulty in providing sufficient accuracy. These results indirectly indicate the necessity of wave-based analyses or experimental studies in order to simulate or investigate in detail the reverberation characteristics in a room with unevenly distributed absorbers.

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Wataya and Suga investigated these peculiar reverberation characteristics through a scale-model experiment [8]. They compared the reverberation times for various types of rooms having absorptive floors and/or ceilings with the values calculated by the reverberation time formula for two-dimensional sound fields. In addition, they examined measures to more closely approximate three-dimensional diffuse sound fields by 2D-like diffuse sound fields in these types of rooms.

In the present study, the reverberation characteristics in rectangular rooms with unevenly distributed absorbers are investigated in detail through a scale-model experiment and three-dimensional wave-based numerical analysis. In the experiment, the reverberation characteristics are verified and the effects of absorber arrangement, room shape and wall conditions on reverberation characteristics are examined. In the numerical study, this phenomenon is investigated more precisely in order to clarify its mechanism. In both the experiment and the numerical analysis, the effects of various measures to improve such characteristics are investigated.

2. ARRANGEMENT FOR STUDIES

2.1. Evaluation of Reverberation Time

Both in the scale-model experiment and in the numerical analysis, the room impulse response was first measured/calculated and the reverberation time was obtained from the result for each 1/3-octave band using the integrated impulse response method. For all cases, we evaluated the reverberation decay curves in the range from -5 dB to -25 dB in the scale model experiment (T_{20}), considering the S/N ratio, and from -5 dB to -35 dB in the numerical analysis (T_{30}).

Generally, reverberation decay curves do not show linear decreases in nondiffuse sound fields such as rooms where sound absorbers are unevenly distributed. In our studies, linear decreases were observed in many cases whereas nonlinear decreases were observed in some cases when only the floor was absorptive or the floor and the ceiling were absorptive. Figure 1 shows examples of reverberation decay curves, including a nonlinear case, obtained from the numerical study. As shown in this figure, there was a slight tendency for the line to bend as the frequency or the ceiling height h increased. Figure 2 shows the relationship between the evaluation range and reverberation time. The evaluation range affects the value of reverberation time when the ceiling is high and at high frequencies ($h = 12.0$, 500 Hz). In many cases, however, the reverberation time was more stable when obtained from a wider evaluation range than that from -5 to -25 dB. The reverberation time in the present study should be seen on the basis of these results.

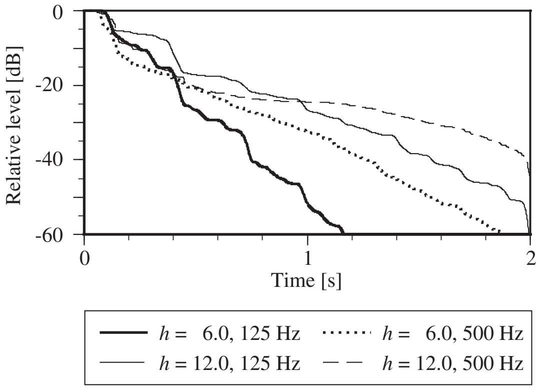

Fig. 1 Reverberation decay curves in normal rectangular room (floor area S_{f} is $24 \times 12\,\mathrm{m}^2$, floor and ceiling absorption, numerical results).

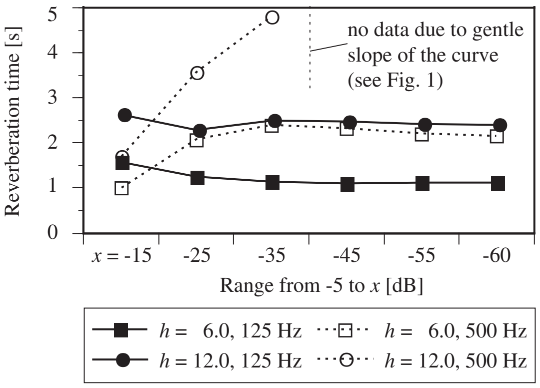

Fig. 2 Effect of the difference in evaluation range on reverberation time (corresponding to Fig. 1).

2.2. Measurement of Impulse Response in Scale-Model Experiment

The experiment was performed using a 1/20-scale model of a rectangular room, as shown in Fig. 3. In the experimental study, an impulse was emitted from a spark discharge source and the room response at the receiving point was detected with a 1/4-inch omnidirectional microphone through 32-times synchronous averaging to improve the S/N ratio. Two-millimeter-thick wool felt was used for sound absorption. The sound absorption coefficient of the felt, measured in a scale-model reverberation chamber, is shown in Fig. 4.

2.3. Calculation of Impulse Response in Numerical Study

In the numerical study, the room shape shown in Fig. 3 was assumed and the room impulse response was computed by the three-dimensional FDTD method [9]. For the boundary conditions in the calculation, only the real part of the acoustic impedance was assumed, so that the statistical sound absorption coefficient of the absorptive

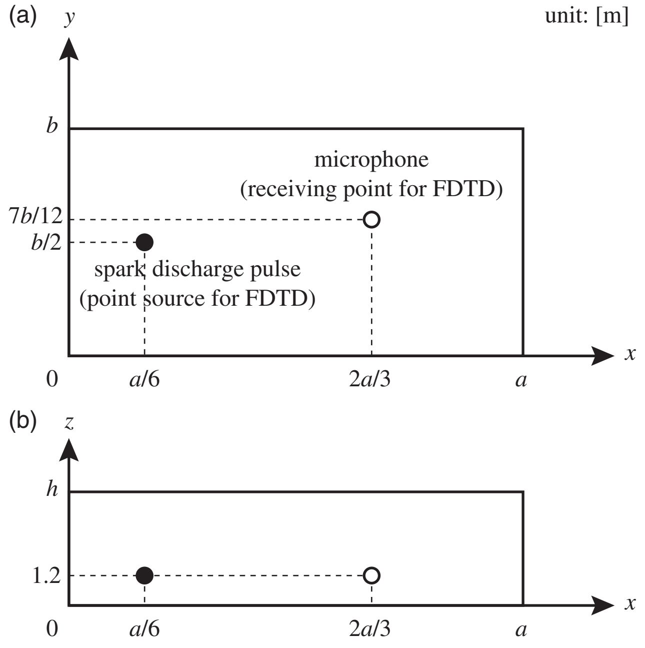

Fig. 3 Arrangement in a rectangular room for experimental and numerical studies: (a) plan and (b) cross section.

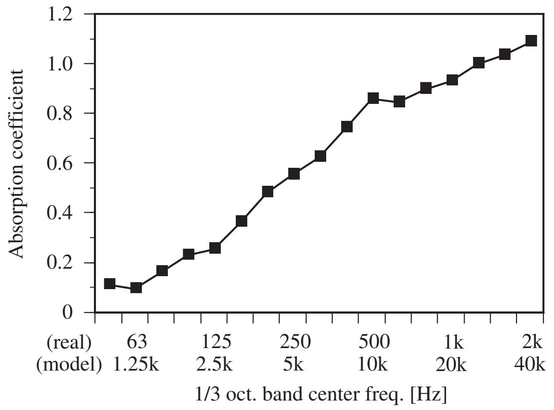

Fig. 4 Absorption coefficient of 2-mm-thick wool felt measured in a scale model reverberation chamber.

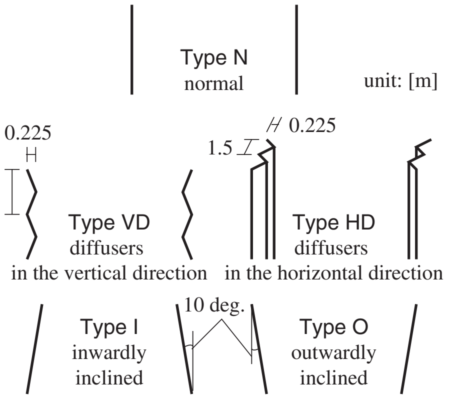

Fig. 5 Wall types (cross section). Only floor absorption is investigated in Type I and Type O rooms.

surfaces was 0.5 and that of the reflective surfaces was 0.05, over all frequencies. By adopting the flat frequency characteristics of the absorption coefficients, only the effect of an uneven distribution of absorbers on the reverberation characteristics could be investigated clearly. In the following discussions, the FDTD data for the high-frequency range are not shown because of limited computer memory (2 GB).

2.4. Case Study

The parameters for the experimental and numerical studies are as follows: room shape (height, h m, and floor area, $S_{\mathrm{f}} = a \times b$ m^2), arrangement of absorbers, and wall type. Table 1 shows the conditions used in the experimental and numerical studies. Five wall types were examined, normal flat walls (Type N) and the four types shown in Fig. 5 (Types VD, HD, I and O) to evaluate their effect on reverberation characteristics. For the Type I and Type O rooms, only one absorber arrangement, in which the floor was absorptive, was investigated. Figure 6 shows the location of the diffusing walls. In the following discussions, it is assumed that the floor area S_{f} is 24×12 and the walls are Type N, unless stated otherwise.

Table 1 Conditions in experimental and numerical studies. Figures 5 and 6 show the wall types used in the present study along with their designations.

		Experimental study	Numerical study
Height h [m]		2.4, 3.0, 4.5, 6.0	3.0, 6.0, 12.0
Floor area $S_{\mathrm{f}} = a \times b$ [m^2]		24×12	24×12, 12×12, 24×6, 6×6
Absorber arrangement		no absorp., floor absorp., floor and ceiling absorp., all absorp.	
Wall type	Type N	N	N
	Type VD	VD-a	VD-a
	Type HD	HD-a	HD-a
	Type I	I-a, I-l, I-s	I-a, I-e
	Type O	O-a, O-l, O-s	O-a

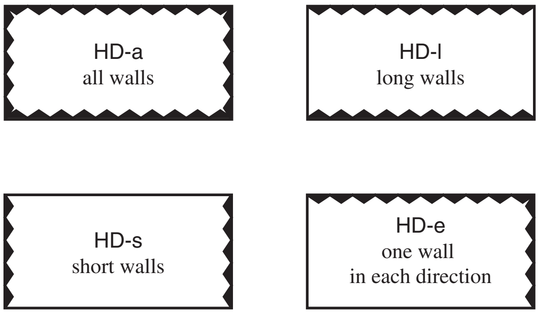

Fig. 6 Location of diffusing walls in rectangular room (plan).

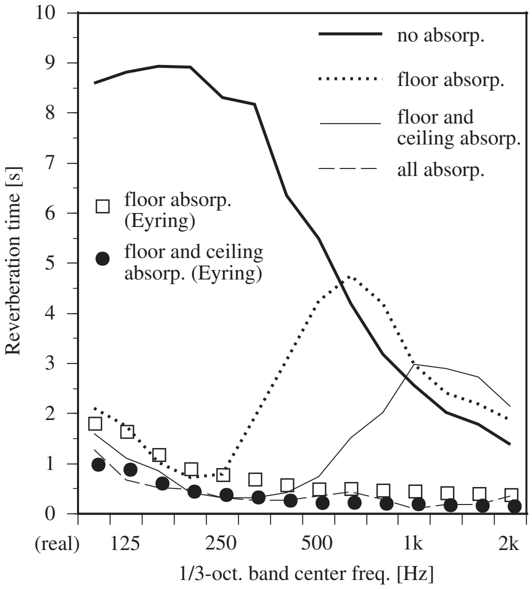

Fig. 7 Effect of arrangement of absorptive surfaces ($h = 3.0$, experimental results).

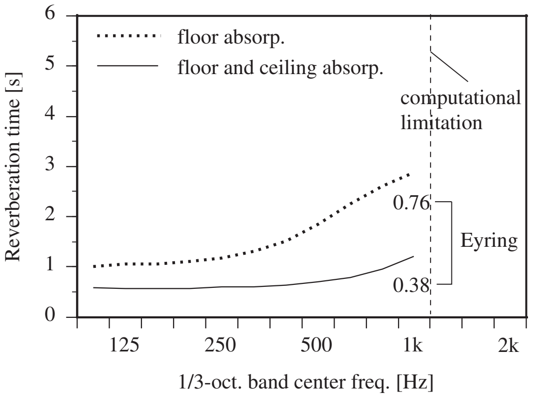

Fig. 8 Effect of arrangement of absorptive surfaces ($h = 3.0$, numerical results).

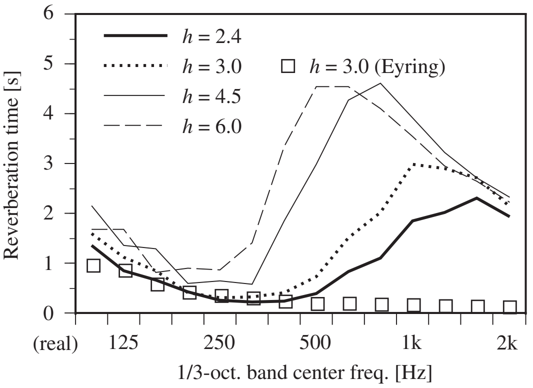

Fig. 9 Effect of ceiling height (floor and ceiling absorption, experimental results).

3. RESULTS AND DISCUSSION

3.1. Effect of Arrangement of Absorptive Surfaces

Figure 7 shows the frequency characteristics of the reverberation time (RT) measured in the scale model for the different arrangements of absorptive surfaces. In all cases, a decrease in the RT is observed at high frequencies, as a result of air absorption. In the case in which all of the room surfaces are absorptive (all absorp.), the RT frequency characteristic is almost flat, whereas in the cases in which only the floor is absorptive and the floor and ceiling are absorptive, RT tends to be short at low frequencies and increases with increasing frequency. In these cases, the RTs are not significantly different from the values obtained using Eyring's formula at low frequencies, whereas the difference is significant at high frequencies. This indicates that an uneven distribution of the absorptive surfaces causes an unnatural RT frequency characteristic. In addition, the frequency characteristic differs between the conditions in which only the floor is absorptive and in which both the floor and ceiling are absorptive.

Figure 8 shows the results of the numerical study for the conditions in which only the floor is absorptive and in which both the floor and ceiling are absorptive. In these cases, the RTs obtained using Eyring's reverberation formula are 0.38 and 0.76, respectively, independent of frequency, whereas the RTs obtained in the numerical study are much longer, particularly at middle and high frequencies. In addition, as with the results of the experimental study described above, the RT increases with frequency. The decrease in the RT at high frequencies, as observed in the scale-model study, is not observed in the numerical study because atmospheric sound absorption was not included in the calculation.

3.2. Effect of Room Shape

3.2.1. Ceiling height

Figure 9 shows the results of the scale-model study of the effect of the ceiling height on the RT frequency characteristics under the condition in which the floor and ceiling are absorptive. In all cases, RT tends to be relatively short at low frequencies and to increase with increasing

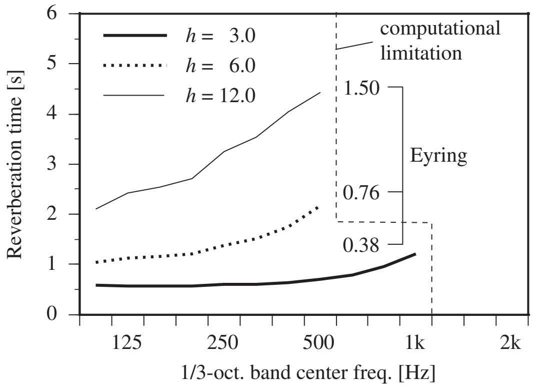

Fig. 10 Effect of ceiling height (floor and ceiling absorption, numerical results).

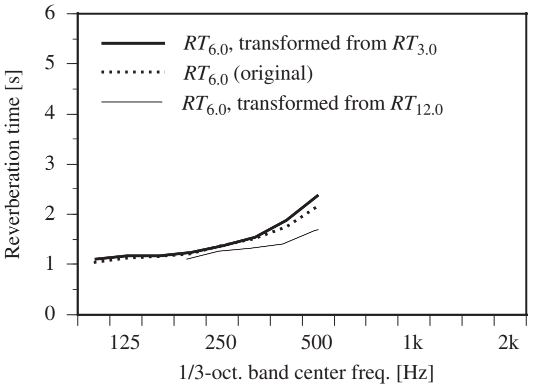

Fig. 12 Original RT and transformed RTs (floor and ceiling absorption, numerical results).

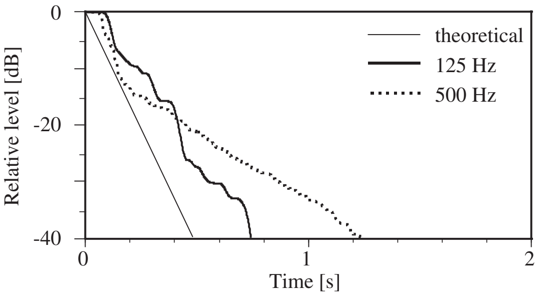

Fig. 11 Reverberation decay curves ($h = 6.0$, floor and ceiling absorption, numerical results).

frequency, even though the absorption coefficient of absorbers becomes larger. This tendency was also observed in [8]. The frequency at which RT becomes maximum seems to decrease with increasing ceiling height.

Figure 10 shows the results of the numerical study of the effect of ceiling height, which show similar tendencies to the results of the experimental study. In addition, the differences in the RTs of the numerical study and those of the calculation using Eyring's formula increase as the ceiling height increases, as shown by the experimental study. These observations can be interpreted as follows. The increase in RT with the increase in frequency is related to the tangential wave modes in the horizontal direction, and the relationship between the wavelength and the wall height affects the decay of the tangential wave modes. That is, when the wavelength is much smaller than the ceiling height, the decay of the tangential wave modes is small, and accordingly, the reverberation becomes long. Therefore, one can state that the decrease of the frequency at which RT becomes maximum in Fig. 9 is attributed to both atmospheric sound absorption and the increase of RT with ceiling height. Figure 11 shows examples of reverberation decay curves obtained by the numerical study. Although the 125 Hz curve is nearly straight, the slope of this curve is slightly gentler than that of the theoretical line because the room is not a diffuse sound field. For the 500 Hz curve, bending is clearly seen, which indicates the slow decay of the tangential wave modes in the horizontal direction.

Based on the above interpretation that the relationship between the ceiling height and the wavelength affects the RT, the following relationship concerning the RT can be assumed in the case of a rectangular room having rigid walls and a highly absorptive floor and ceiling (or only an absorptive floor) whose frequency characteristics of the absorption coefficients are flat: $RT_{h_1}(\lambda) \approx \frac{h_1}{h_2} RT_{h_2}(\frac{h_2}{h_1}\lambda)$, where λ is the wavelength, and RT_{h_1} and RT_{h_2} are the RTs in rectangular rooms having the same floor area and ceiling heights h_1 and h_2, respectively. $\frac{h_2}{h_1}\lambda$ expresses the relationship between the wavelength and the ceiling height. $\frac{h_1}{h_2}$ expresses the volume ratio of the rooms $\frac{V_1}{V_2}$, which is inserted according to the concept of the Sabine/Eyring reverberation formula that RT is proportional to the volume of the room. Figure 12 again shows the results of the numerical study for the case in which the floor and the ceiling are absorptive and the ceiling height h is 6.0. The thick and thin lines show the transformed RTs using the above relationship with $h_2 = 3.0$ ($RT_{3.0}$) and $h_2 = 12.0$ ($RT_{12.0}$), respectively. Although transformed values from those of $h_2 = 12.0$ differ from others at high frequencies due to the bending in the reverberation decay curves, good agreement is seen between the original and the transformed values on the whole. The same tendency is also seen in the cases in which only the floor is absorptive. These results sufficiently support the validity of the above interpretation of the relationship between the ceiling height, the wavelength and the RT.

3.2.2. Area of floor

Figure 13 shows the results of the numerical study of the effect of the floor area under the same room boundary conditions and ceiling height as each other. For completely rigid walls, the values obtained using Eyring's formula are the same in all cases shown. The change in RT due to differences in the floor area is very small.

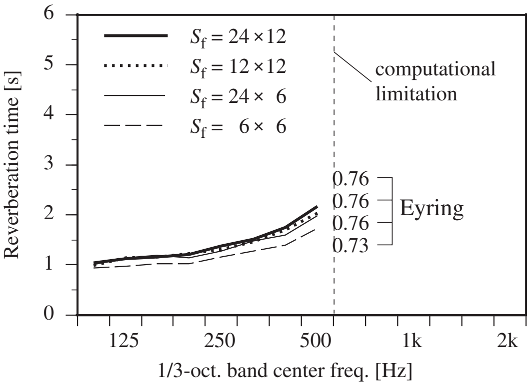

Fig. 13 Effect of floor area ($h = 6.0$, floor and ceiling absorption, numerical results).

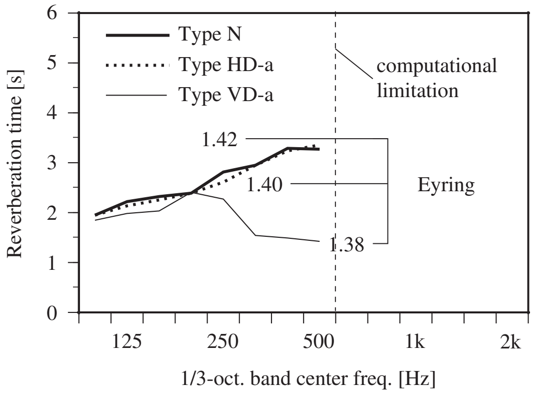

Fig. 15 Effect of diffusion treatment of walls ($h = 6.0$, floor absorption, numerical results).

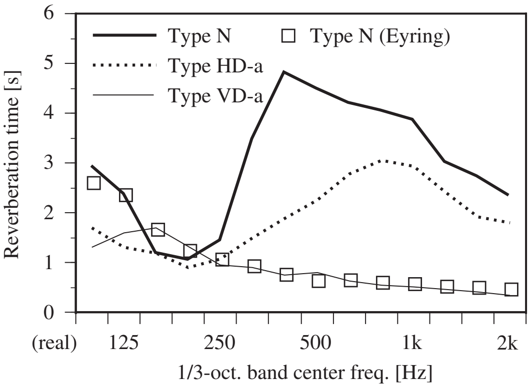

Fig. 14 Effect of diffusion treatment of walls ($h = 4.5$, floor absorption, experimental results).

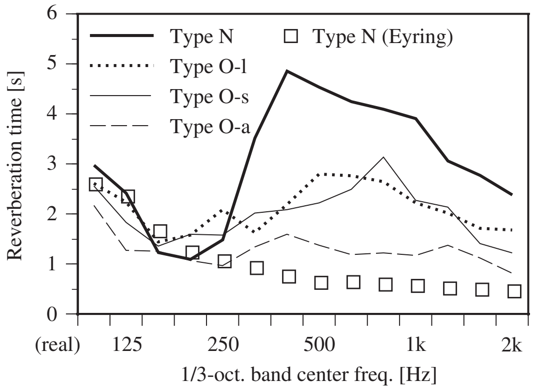

Fig. 16 Effect of outward inclination of walls ($h = 4.5$, floor absorption, experimental results).

3.3. Effect of Wall Shape

In order to improve the RT frequency characteristic, sound absorption treatment of walls is often applied and is considered to be effective. For many practical cases, however, the surfaces on which absorption treatment can be undertaken are limited. We investigated the effect of the variation of wall shape only, shown in Table 1, assuming such sound fields where it is difficult to undertake absorption treatment on the wall surfaces.

3.3.1. Diffusion treatment of walls

The experimental and numerical results for the effect of diffusion treatment of walls (Types VD and HD) on RT are shown in Figs. 14 and 15, respectively. Although the results are not in good agreement numerically, they show similar tendencies. That is, the tendency of an increase of RT at middle and high frequencies is also observed for the Type HD-a wall. This is because the arrangement of the diffusion treatment in the horizontal direction is not effective and the tangential wave modes remain. On the other hand, the RT frequency characteristic in the Type VD-a wall is greatly improved by the diffusion treatment in the vertical direction. In this case, however, RT decreases only at frequencies above 250 Hz, which is clearly seen in the numerical results. This might be attributed to the size of the diffusers, and thus, the reverberation time may be decreased over a broader frequency range if various types of diffuser are used in conjunction.

3.3.2. Outward inclination of walls

The experimental and numerical results for outwardly inclined walls (Type O) under the condition that the floor is absorptive are shown in Figs. 16 and 17, respectively. These results show that the inclination treatment is not very effective in the cases in which either the two long-side walls are inclined (Type O-l) or the two short-side walls are inclined (Type O-s). This is because the axial wave modes between the noninclined pair of parallel walls remain. On the other hand, in the case in which all walls are inclined (Type O-a), the RT frequency characteristic is much improved in both experimental and numerical results. In this case, however, the RT is much longer than that calculated using Eyring's formula. The results of the numerical study show that the RT frequency characteristic becomes flatter with increasing inclination angle of the walls. This is because multiple reflection occurs between

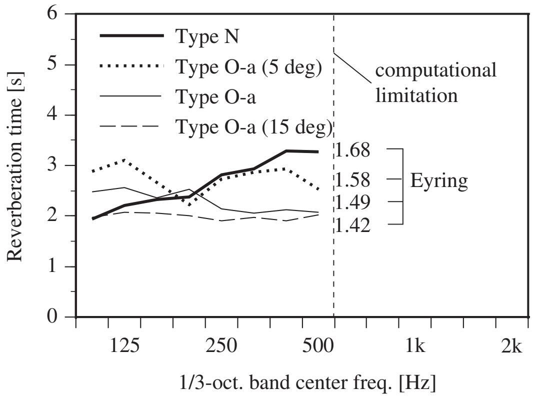

Fig. 17 Effect of outward inclination of walls ($h = 6.0$, floor absorption, numerical results).

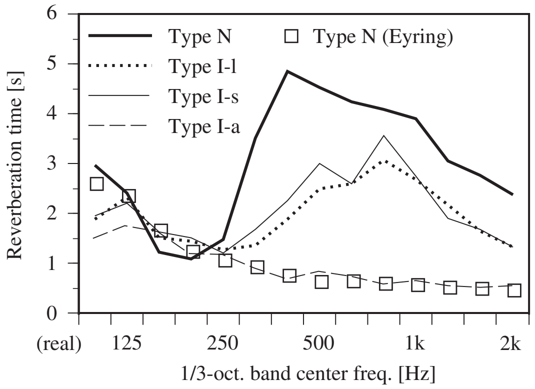

Fig. 18 Effect of inward inclination of walls ($h = 4.5$, floor absorption, experimental results).

the rigid ceiling and walls when the angle of outward inclination is small, as shown in Fig. 20.

3.3.3. Inward inclination of walls

The effect of inwardly inclined walls (Type I) under the condition that the floor is absorptive was also examined by experimental and numerical studies, and the results are shown in Figs. 18 and 19, respectively. Similar to the outward-inclination case, the inclination treatment is not very effective when either the two long-side walls are inclined (Type I-l) or the two short-side walls are inclined (Type I-s), whereas when all of the walls are inclined (Type I-a), the RT frequency characteristic is greatly improved in both experimental and numerical results. It should be noted that the RTs for Type I-a obtained in both experimental and numerical studies agree well with the values calculated using Eyring's formula. This was not the case for the outwardly inclined walls. Figure 21 shows examples of reverberation decay curves obtained by numerical study. In the case of Type O-a (5 deg), the curve bends, and the slope at later times is gentler than that of Type N. This indicates that other slow-decay modes not seen in Type N exist in the case of Type O-a (5 deg). In contrast, the slope of the Type I-a curve agrees well with that of the theoretical line for the diffuse sound field. It is also seen from the results of the numerical study (Fig. 19) that a sufficient effect is achieved with a 3-degree inclination of one long-side wall and one short-side wall (Type I-e (3 deg)).

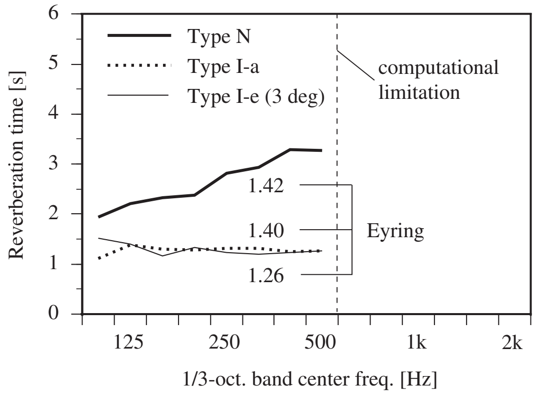

Fig. 19 Effect of inward inclination of walls ($h = 6.0$, floor absorption, numerical results).

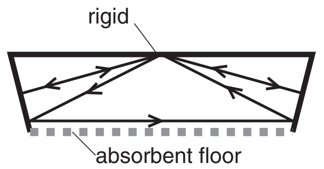

Fig. 20 Sound rays in room with outwardly inclined walls.

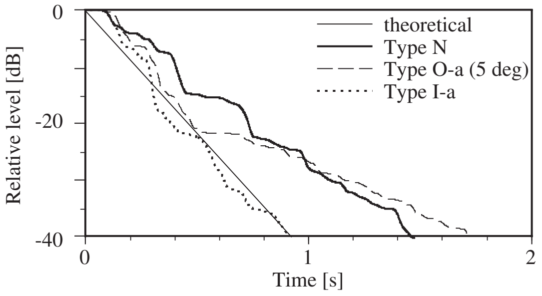

Fig. 21 Reverberation decay curves ($h = 6.0$, floor absorption, 125 Hz, numerical results).

3.4. Impulse Response and Energy Decay for Respective Frequencies

We also examined the difference in the transient property between Type N and Type I-a walls. Figures 22 and 23 show the impulse responses and their spectrograms for these two conditions measured in the scale-model experiment. In Figs. 24 and 25, the results obtained by FDTD calculation are compared. In the case of the Type N wall (Figs. 22 and 24), the sound energy remains for a

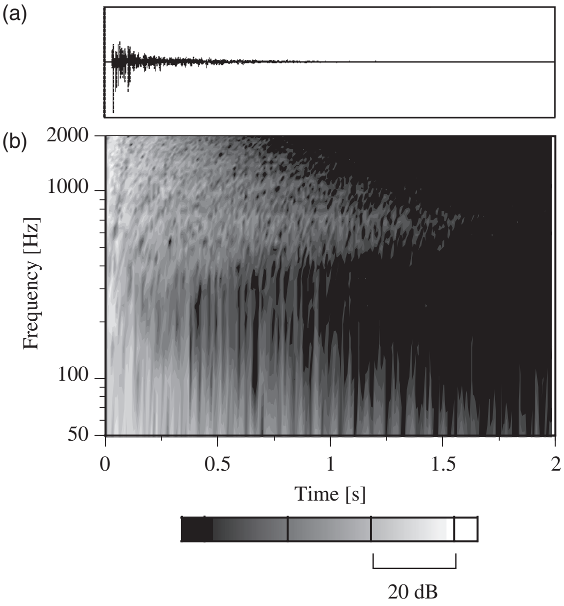

Fig. 22 (a) Measured impulse response and (b) its spectrogram ($h = 3.0$, floor absorption, Type N).

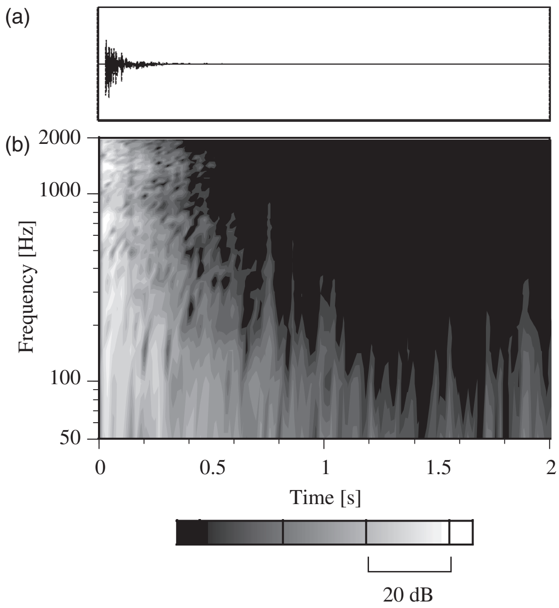

Fig. 23 (a) Measured impulse response and (b) its spectrogram ($h = 3.0$, floor absorption, Type I-a).

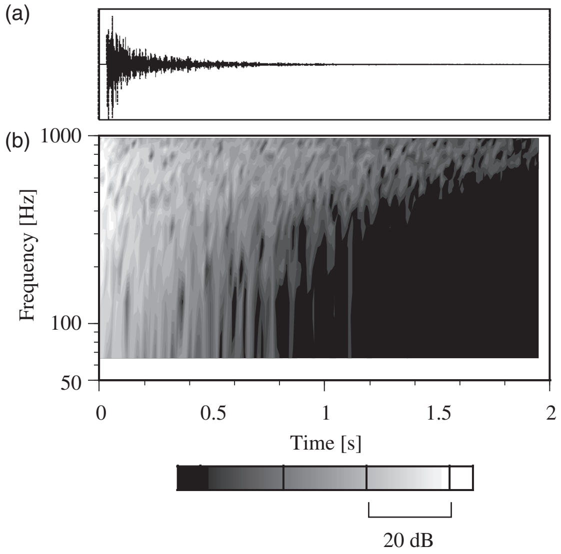

Fig. 24 (a) Calculated impulse response and (b) its spectrogram ($h = 3.0$, floor absorption, Type N).

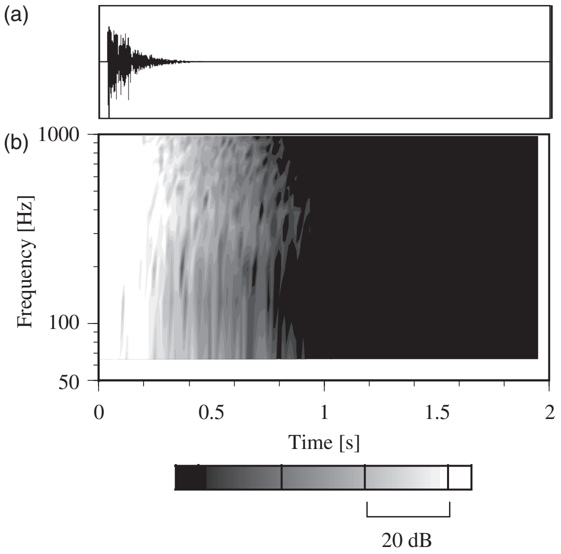

Fig. 25 (a) Calculated impulse response and (b) its spectrogram ($h = 3.0$, floor absorption, Type I-a).

longer time. In contrast, in the case of the Type I-a wall (Figs. 23 and 25), the decay of the impulse response is faster and the sound energy at middle and high frequencies diminishes more quickly.

4. CONCLUSIONS

The reverberation characteristics in a rectangular room having unevenly distributed sound absorbers were investigated through a scale-model experiment and three-dimensional wave-based numerical analysis. The reverberation time in a room having an absorptive floor and/or ceiling was verified to be longer in the middle- and high-frequency ranges compared with that calculated using Eyring's formula, and that the arrangement of absorptive surfaces affects the frequency characteristic of the reverberation time. The increase in reverberation time is caused by the slow decay of the axial and tangential wave modes in the horizontal direction, and the decay of these modes depends on the height of the room and the frequency. The reverberation time is longer in the high-frequency range (in which the wavelength is significantly shorter compared with the ceiling height) than in the low-frequency range, even when the absorption coefficients of the absorptive surfaces in the high-frequency range are greater than those in the low-frequency range, as is generally the case for normal rooms. In order to reduce the tangential and axial wave modes in the horizontal direction, acoustic treatment of walls for sound diffusion is important. Inwardly inclined walls (when the floor is absorptive) and diffusers in the vertical direction were found to be effective for flattening the frequency characteristic of the reverberation time, when careful consideration was given to the arrangement of the treatment.

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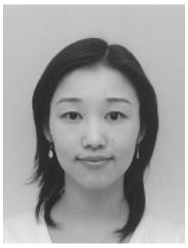

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