Reverberation Characteristics in a Room with Unevenly-Distributed Absorbers: Experimental and Numerical Studies

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Abstract It is often observed that the reverberation time in a room with unevenly-distributed sound absorbers, such as a room having an absorptive floor and/or ceiling, is often longer in middle- and high-frequency range than the values obtained using Eyring’s formula, since the assumption of diffuse sound field is not satisfied. In this study, this phenomenon was investigated through scale model experiment and three-dimensional wave-based numerical analysis. Reverberation time in a room having absorptive floor and/or ceiling was confirmed to be longer in the middle- and high-frequency range, and the arrangement of absorbers were also confirmed to affect the frequency characteristic of the reverberation time. The increase of reverberation time is caused by slow decay of axial and tangential modes in the horizontal direction. The frequency characteristic of reverberation time depends on the height of the room. The reverberation time is longer in high-frequency range (where the wavelength is sufficiently shorter compared to the height of the ceiling) than in low-frequency range when frequency characteristics of the absorption coefficients of the absorbers are flat. As a means to improve such an uneven reverberation time property in a room with highly absorptive floor/ceiling, the placement of diffusers in the vertical direction and inward-inclining walls (when in a room with highly absorptive floor) has been found to be effective.

1. INTRODUCTION

In a room with unevenly-distributed sound absorbers, it is often observed that the reverberation time calculated using the Eyring/Knudsen formula does not agree with the measurement results, which might be attributed to the dissatisfaction of the assumption
of diffuse sound field. Especially in the case where all surfaces of the floor and/or ceiling are absorptive, it is often observed that the reverberation time is much longer than the values obtained using these formulae [1, 2]. Several studies have been done on the reverberation characteristics in such sound fields: comparison among the sound fields in various types of room having unevenly-distributed absorbers through scale model experiments [3], comparison among the values calculated by different reverberation time formulae and using ray-based numerical analyses [4], etc.

In the present paper, the reverberation characteristics in rooms with unevenly-distributed absorbers are investigated through both of scale model experiment and three-dimensional wave-based numerical analysis. In the experimental study, such peculiar characteristics are confirmed and the effect of absorber arrangement, room shape and wall conditions on reverberation characteristics is examined. In the numerical study, this phenomenon is investigated more precisely to clarify its mechanism.

2. ARRANGEMENT FOR STUDIES

Both in the scale model experiment and in the numerical analysis, room impulse response was firstly measured/calculated and reverberation time was obtained from the result in each 1/3 octave band using the integrated impulse response method.

2.1 Measurement of Impulse Response in Experimental Study

The experimental study was performed using a 1/20 scale model of a rectangular room as shown in Fig. 1. In the experiment, impulse was radiated from a spark discharge source and the room response at a receiving point was detected with a 1/4-inch omnidirectional microphone by performing 32-times synchronous averaging to improve the S/N ratio. For sound absorption treatment, wool felt of 2 mm thick was used. The sound absorption coefficient of the felt measured in a scale model reverberation chamber is shown in Fig. 2.

![Figure 1: Arrangement in a rectangular room for experimental and numerical studies: (a) plan, and (b) cross section.](image)
2.2 Calculation of Impulse Response in Numerical Study

In the numerical study, the same room shape shown in Fig. 1 was assumed and room impulse response was computed using the three-dimensional FDTD method. For the boundary condition in the calculation, only the real part of the acoustic impedance was assumed so that the statistical sound absorption coefficient of the absorptive surfaces is 0.5 and that of the reflective surfaces is 0.05, respectively, over all frequencies.

2.3 Case Study

The parameters for experimental and numerical studies are as follows: room shape (height \( h \) [m] and floor area \( S_f = a \times b \) [m\(^2\)]), arrangement of absorbers, and wall type. Table 1 shows the conditions for the experimental and numerical studies. Five wall types were considered: normal flat walls (Type N) and the four types of walls shown in

<table>
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<th>Table 1: Conditions for experimental and numerical studies.</th>
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<td>height ( h ) [m]</td>
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<td>2.4, 3.0, 4.5, 6.0</td>
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<td>floor area ( S_f = a \times b ) [m(^2)]</td>
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<td>absorber arrangement</td>
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Fig. 3 (Types VD, HD, I and O). Types VD, HD, I and O are intended to make the sound field diffuse. For Type I and Type O rooms, only the condition where only the floor was absorptive was investigated. Figure 4 shows the location of the diffusing walls. In the following discussions, it is assumed that the floor area is $S_f = 24 \times 12$ and the wall type is Type N, unless noted otherwise.

3. RESULTS AND DISCUSSIONS

3.1 Effect of the Arrangement of Absorptive surfaces

Figure 5 shows the frequency characteristics of the reverberation time (R.T.) measured in the model for different arrangement of absorptive surfaces. In all cases, a decrease of R.T. is observed at high frequencies, owing to air absorption. In the case where all room surface is absorptive (all absorb.) the frequency characteristic of R.T. is almost flat, whereas in the cases where only the floor is absorptive and floor/ceiling is absorptive there is the tendency that R.T. is short at low frequencies and it increases as the frequency becomes higher. This fact indicates that uneven distribution of absorptive surface causes unnatural frequency characteristic of R.T. It is also seen that the frequency at which R.T. is the longest is different between the conditions where only the floor is absorptive and where the floor and ceiling are absorptive.

Figure 6 shows the results of the numerical study for the conditions where only the floor is absorptive and where the floor and ceiling are absorptive. In these cases, R.T. obtained using Eyring’s reverberation formula is 0.38 and 0.76, respectively, whereas the results of the numerical study are much longer than these values especially at middle and high frequencies. It is also seen that R.T. increases as the frequency increases as in the results of the experimental study mentioned above. The decrease of R.T. at high frequency observed in the scale model study is not seen in the results of the numerical
3.2 Effect of Room Shape

Ceiling Height

Figure 7 shows the result of the scale model study for the effect of the ceiling height on the frequency characteristics of R.T. under the condition where the floor and the ceiling are absorptive. Through all cases, the tendency is clearly seen that R.T. is relatively short at low frequencies and it increases with the increases of frequency. The frequency at which R.T. becomes maximum decreases with the increase of the ceiling height.

Figure 8 shows the result of the numerical study for the effect of the ceiling height, in which the similar tendencies are seen as in the result of the experimental study. It is also seen that the difference of the value of R.T. between the numerical study and the calculation using Eyring’s formula increase as the ceiling height becomes higher as is seen in the result of the experimental study. These facts observed in the experimental and numerical studies can be interpreted as follows: the increase of R.T. with the increase of 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 modes. That is, when the wavelength is much smaller than the ceiling height, the decay of the tangential modes is small, and accordingly the reverberation becomes long.

Area of the Floor

In the numerical study, the effect of the area of the floor of the rectangular room was examined under the same conditions of the room boundary and ceiling height. The result is shown in Fig. 9, in which it is seen that the change of R.T. by the difference of the floor area is very small.

From these results, it can be concluded that the frequency characteristic of R.T. much depends on the ceiling height in the case of a rectangular room of which floor or floor/ceiling study because the atmospheric sound absorption was not included in the calculation.
3.3 Effect of Wall Shape

Diffusion Treatment of Walls

As a measure to improve the frequency characteristic of R.T., the effect of diffusion treatment for walls was investigated by experimental and numerical studies and the results are shown in Fig. 11 and Fig. 12, respectively. These results are not necessarily in good agreement numerically, but show a similar tendency. That is, the tendency of the increase of R.T. at middle and high frequencies still remains in Type HD-a (diffusion treatment in horizontal direction). This is because the diffusion treatment in horizontal direction is not effective and the tangential modes still remain. On the other hand, the frequency characteristic of R.T. has been much improved in Type VD-a by the diffusion treatment in vertical direction.
Outward-Inclination of Walls

As another measure to improve R.T. frequency characteristic, the effect of inclination of wall were investigated by experimental and numerical studies and the results for outward-inclination of walls are shown in Fig. 13 and Fig. 14, respectively. In these results, it is seen that the inclination treatment is not so effective in the case where the two long-side walls are inclined (Type O-l) and in the case where the two short-side walls are inclined (Type O-s). This is because the axial modes still remain between the other couple of parallel walls. On the other hand, in the case where all walls are inclined (Type O-a), the R.T. frequency characteristic has much improved in both of the experimental and numerical results. In this case, however, R.T. calculated by the numerical study is much longer than the value calculated using Eyring’s formula. In the results of the numerical study, it is seen that the R.T. frequency characteristic becomes flatter with the increase of the inclination angle of the walls. This is because multiple reflection occurs between the rigid ceiling and walls when the angle of the outward inclining are small, as shown in Fig. 17.
absorbent floor
rigid

Figure 17: Sound rays in a room with outward-inclined walls.

Inward-Inclination of Walls

The effect of inward-inclination of walls was also examined by the experimental and numerical studies and the results are shown in Fig. 15 and Fig. 16, respectively. Similar to the case of outward-inclination, it is seen that the inclination treatment is not so effective in the case where the two long-side walls are inclined (Type I-l) and in the case the two short-side walls are inclined (Type I-s), whereas in the case where all walls are inclined (Type I-a), the R.T. frequency characteristic has much improved in both of the experimental and numerical results. It should be noted that R.T. for Type I-a obtained in the numerical study agrees well with the value calculated using Eyring’s formula; this is different from the case of outward-inclination of walls. In the result of the numerical study, we can also see a sufficient effect of 3-degrees inclination of one long-side wall and one short-side wall (Type I-e (3 deg)).

To see the difference between Type N, basic room shape, and Type I-a, the best room shape, from a viewpoint of sound field diffusion, steady-state sound fields were analyzed using the fast multipole BEM (FMBEM) [5]. Figure 18 shows the sound pressure level in distance (x-direction) from a point source for 500-Hz octave band. Theoretical values of the relative sound pressure level of diffuse sound fields are also shown, which was calculated by the following equation:

\[ L = 10 \log_{10} \left( \frac{1}{4\pi r^2} + \frac{4}{R} \right), \]  

where \( r \) is the distance from the point source and \( R \) is the room constant. Here, the sound pressure level distributions obtained by the FMBEM were calculated by energy summation of the results at 1/12 octave band center frequencies. The sound pressure level in Type N is found to be higher than the theoretical values on the whole, whereas that in Type I-a is found to be closer to the theoretical values.

3.4 Impulse Response and Energy Decay in Respective Frequencies

To see the difference of transient property between Type N and Type I-a, Fig. 19 and Fig. 20 shows the impulse response and its spectrogram for these two conditions mea-
sured in the scale model experiment. Also in Fig. 21 and Fig. 22 the results obtained by the FDTD calculation are compared. In the case of Type N (Fig. 19 and Fig. 21), it is seen that the sound energy is kept long. In contrast, in the case of Type I-a (Fig. 20 and Fig. 22), the decay of the impulse response is fast and the sound energy at middle and high frequencies diminishes fast.

4. CONCLUSIONS

The reverberation characteristics in a room having unevenly-distributed sound absorbers were investigated through scale model experiment and three-dimensional wave-based numerical analysis. Reverberation time in a room having absorptive floor and/or ceiling was confirmed to be longer in the middle- and high-frequency range compared to that calculated using Eyring’s formula, and the arrangement of absorptive surfaces was also confirmed to affect the frequency characteristic of reverberation time. The increase of reverberation time is caused by slow decay of axial and tangential modes in the horizontal direction, and the decay of these modes depends on the height of the room and on the frequency. The reverberation time is longer in high-frequency range (where the wavelength is sufficiently shorter compared to the ceiling height) than in low-frequency range, even when frequency characteristics of the absorption coefficients of the absorptive surfaces are flat. When making the walls diffusive shape or outward/inward inclined to improve the frequency characteristic of reverberation time, it is important to reduce the tangential and axial modes. Inward-inclined walls (when the floor is absorptive) and diffusers in the vertical direction were found to be effective for flat frequency characteristic, when taken careful attention to the positions of the placement.

ACKNOWLEDGEMENTS

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REFERENCES

Figure 19: (a) Measured impulse response, and (b) its spectrogram ($h = 3.0$, floor absorption, Type N).

Figure 20: (a) Measured impulse response, and (b) its spectrogram ($h = 3.0$, floor absorption, Type I-a).

Figure 21: (a) Calculated impulse response, and (b) its spectrogram ($h = 3.0$, floor absorption, Type N).

Figure 22: (a) Calculated impulse response, and (b) its spectrogram ($h = 3.0$, floor absorption, Type I-a).