Effect of absorption treatment with band-shaped absorber inside closed narrow rooms

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1. Introduction

Appropriate absorption treatment inside habitable spaces greatly contributes to the improvement of the sound environment. Providing enough absorption materials to wide areas on the surfaces of walls or ceilings leads to sufficient suppression of the reverberation in rooms; however, it is desirable that the total area of the absorber is kept to a minimum from the viewpoints of reduction of the installation cost, design, and functionality. To achieve this, maximizing the efficiency of absorption by using a fixed amount of absorption materials is necessary.

The reverberation in rooms with nonuniformly distributed absorption was investigated by Fitzroy [1]. Yasuda *et al.* studied the reverberation characteristics caused by unevenly distributed absorbers by using experimental and numerical schemes [2]. Caballol and Raposo studied the absorption effect by placing absorbent materials in pieces [3]. As mentioned in the above papers, the effect of nonuniformly distributed absorption materials on suppression of the reverberation of rooms has been investigated.

In this paper, the acoustical effect of absorption treatment with band-shaped absorber on the surrounding walls inside narrow rooms is investigated through numerical study based on the wave-based method of the finite-difference time-domain (FDTD) method. The numerical method was initially proposed by Yee [4] in the field of electromagnetics, and it has been applied to room acoustic problems [5]. By using the numerical method, the reverberation times with several different arrangements of band-shaped absorbers are calculated, and the effectiveness of the absorbers is discussed by comparing the numerical results.

2. Numerical study

Figure 1 illustrates the simulation models of rooms (a) and (b). The dimensions of room (a) are 5 m (W) $\times$ 4 m (D) $\times$ 2.5 m (H), whereas those of room (b) are 5 m (W) $\times$ 8 m (D) $\times$ 2.5 m (H). The floor area of room (b) is twice that of room (a). The acoustical effect of absorption treatment at the band-shaped wall part indicated by gray in the figure is investigated. To investigate how the absorption efficiency varies when the arrangement of the absorbers is changed, the reverberation characteristics inside the rooms with absorption conditions A, B, C, D, E, F, and G (Fig. 2) with fixed points of

the source S and receiver R are calculated. Note that Fig. 2 shows only the setting condition of the absorbers on one surface among the four surrounding walls in the room, and the other three surfaces of each wall also have the band-shaped absorber at the same heights as those in Fig. 2. From conditions B to G, the band-shaped absorbers having the same total area of absorption (10.8 m²) are shifted from the top to bottom of the room as shown in Fig. 2. Only for the split-type condition A, the absorption area is divided into two parts so that each part of the absorption surrounds the source or receiving point. To investigate the influence of the spatial relationship between the source point, the receiving point, and the height of the surrounding band-shaped absorber, the revised condition G is set by moving the absorber area up by 0.325 m from the position of condition C. Herein the absorbers of condition C spatially surround the source point whereas those of condition G do not. The spatial relationships between the source and receiving points are shown in Fig. 3. As shown in Fig. 3(a), the height of the receiving point is set to 1.6 m assuming the head position of a standing adult, whereas that of the source point is set to 1.0 m is set assuming that of a sitting adult.

The sound fields inside rooms (a) and (b) are calculated by using the three-dimensional FDTD method. In the simulation, the discrete spatial intervals and discrete time sampling are set as $\Delta x = \Delta y = \Delta z = 0.025$ m and 40,000 Hz, respectively. As the omnidirectional point source, a Gaussian sound source is adopted. As the boundary condition of the absorptive surface, the real-number acoustic impedances shown in Table 1 are given, which are equivalent to the normal-incidence sound absorption coefficients of Fig. 4, simulating typical characteristics of a glass fibrous material with a density of 25 kg/m³ and thickness of 50 mm, whereas the acoustic impedance of the non-absorptive surface is set to 15,500 Pa·s/m³, which is equivalent to a normal-incidence sound absorption coefficient of 0.1. To simulate the frequency characteristics in Table 1, the following calculation were performed. Firstly, five sound fields including the boundaries treated with band-shaped absorbers with the surface acoustic impedance in Table 1 were calculated. Secondly, the transient responses at frequencies of 125 Hz, 250 Hz, 500 Hz, 1 kHz, and 2 kHz were filtered by using an infinite impulse response (IIR) filter. Herein the data lengths of the adopted filters are sufficiently shorter than those of the transient responses under each condition. Lastly, the reverberation time in each

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Fig. 1 Details of the simulation models of rooms (a) and (b) with their dimensions and the source and receiving points.

Fig. 2 Spatial relationship between receiving and source points, and the absorptive area.

frequency band was evaluated using the integrated impulse response method over a 30 dB decay range in the reverberation curve from -5 to -35 dB below the starting level.

Fig. 3 Spatial relationships of the source and receiving points in the cross sections of the simulated rooms in the (1) x - z plane and (2) x - y plane. The values enclosed by parentheses in (2) indicate the distances in room (b), whereas the other values indicate those in room (a).

Table 1 Frequency characteristic of the normal-incidence acoustic impedance on the absorptive surface.

Frequency [Hz]	125	250	500	1k	2k
Sound abs. coef. [—]	0.3	0.5	0.9	0.9	0.9
Acoust. Impedance [Pa·s/m ³]	4,600	2,390	788	788	788

Fig. 4 Frequency characteristics of the normal-incidence sound absorption coefficient of the absorptive and non-absorptive surfaces.

3. Results and discussion

3.1. Effect of the band-shaped absorber in different-size rooms

The frequency characteristics of the reverberation time of room (a) are shown in Fig. 5. In the figure, the theoretically calculated reverberation times based on the Eyring's theory are also shown. As the frequency increases, the difference between the reverberation times for each absorption condition

Fig. 5 Frequency characteristics of the simulated reverberation times of room (a).

increases. Firstly, comparing absorption condition A and the other conditions, the reverberation time of condition A is shortest above 250 Hz. Secondly, the reverberation times of conditions B and F, in which the absorbers are set directly under the ceiling or over the floor, are much longer than those of the other conditions, especially in the 1 and 2 kHz bands. Thirdly, the numerically calculated results in the entire frequency ranges are larger than the theoretical values. These results indicate that the band-shaped absorbers with different shapes, such as single or split types, or different heights result in significantly different reverberation characteristics of the rooms, whereas all the absorbers have the same total area of absorption. It should also be noted that the higher absorption effect for the split-type condition A could be caused by the area effect, which can be made more prominent by splitting the absorbers into smaller pieces. Schroeder's reverberation decay curves calculated from the numerically obtained impulse responses of conditions A and F in each 1 octave band are shown in Figs. 6(a) and 6(b), respectively. In the frequency bands of 500 Hz, 1 kHz, and 2 kHz, the curves slightly bend at an early time of around 0.05 s. Comparing conditions A and F, the reverberation in the former case decays slightly faster than that in the latter case after 0.2 s. Next, the frequency characteristics of the reverberation time of room (b) obtained by the FDTD calculation and the theoretical estimation are shown in Fig. 7. In the frequency range above 500 Hz, the results show larger differences between each condition than those of room (a) in Fig. 5. Similar to the characteristics of room (a), the reverberation time of condition A is shorter than that of the other conditions above 500 Hz. The tendency of the longer reverberation time of conditions B and F is also observed in this room. In addition, these numerically obtained values are larger than the theoretical values, similarly to in the case of room (a).

3.2. Effect of the height of arrangement of the absorber

Figure 8 shows the simulated results of the reverberation time of room (a) as a function of the height of the arrangement of each absorber. Note that condition A is excluded from this figure. Whereas the reverberation times of 125, 250, and 500 Hz have relatively flat characteristics regardless of

Fig. 6 Reverberation decay curves of the calculated impulse responses.

Fig. 7 Frequency characteristics of the simulated reverberation times in room (b).

the height of the absorber, those of 1 and 2 kHz have longer reverberation times for conditions B and F and shorter ones for conditions of C, D, E, and G. In addition, the reverberation times of conditions C and G have different values, especially at 2 kHz, despite only a slight difference in the height of the absorber for the two conditions. The results show that differences in the height of the band-shaped absorbers have a noticeable influence on the reverberation time of narrow rooms at relatively high frequencies range. At the higher frequencies, especially at 2 kHz, it is also observed that the reverberation times are shortened when the band-shaped absorbers are set at the same height as the receiving point.

Fig. 8 Spatial distribution characteristics of the simulated reverberation times of room (a).

4. Conclusion

The reverberation characteristics in a narrow room with band-shaped absorbers attached on the surrounding walls were investigated through three-dimensional wave-based numerical analysis. The results confirmed that the frequency characteristics of the reverberation times of the rooms with

the band-shaped absorbers are significantly influenced by the relative positions of the source and receiving points, the arrangement height of the band-shaped absorber, and whether a single- or split-types arrangement is used. The findings of this study can be applied to the sound design of relatively narrow rooms in case that the sound source and receiving points are located at fixed positions inside the rooms.

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