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Acoustical effects of columns, beams and furniture on sound fields in small enclosures

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ABSTRACT

In acoustic design of small enclosures, it is a considerably important matter to control eigenmodes at low frequencies, so that many researches have been done on the effect of overall shapes of rooms on the eigenmodes, such as optimization of room dimensions ratio. However, overall room shapes are usually restricted to rectangular forms due to easy construction, therefore it is desirable to improve sound fields only by changing partial elements in rectangular rooms. In the present paper, the effects of additional elements, such as columns, beams and furniture, on the sound field in a small rectangular room are investigated through wave-based numerical analysis. Supposing a room for listening use with a loudspeaker, the effects are evaluated regarding the flatness of frequency response and the uniformity of spatial distribution in a listening area. The results show that: the effect of columns is small but more than beams; that of closed-type shelves is relatively large but not so much as open-type shelves; the size and the arrangement of every element have unnegligible effects. It is also seen that the additional elements generally lead to positive effects in flatness of frequency response and special uniformity even at low frequencies, although in a specific case.

1. INTRODUCTION

In acoustic design of small enclosures, such as for audio listening, music practice and so on, it is a considerably important matter to control eigenmodes at low frequencies. The main factors affecting eigenmodes and distribution of eigenfrequencies are overall shapes of rooms, arrangement of absorbers (absorbing properties) and wall surface shapes (reflection properties). The effect of overall room shapes is most fundamental, so that many researches have been done on the effect on eigenmodes, such as optimization of room dimensions ratio [1-3]. However, overall room shapes are usually restricted to rectangular forms due to easy construction, therefore it is desirable to improve sound fields only by changing partial elements in rectangular rooms.

Regarding the unevenness of wall surfaces in small enclosures, it has been reported that small unevenness against wavelength has relatively large effect at lower frequencies [4,5]. In addition, it has been reported that a slight shape change of a mixing console affects acoustic properties in a studio [6,7]. Furthermore, Malsuki [8] has reported that furniture contributes to the control of peak and dip at low frequencies by arranging its pieces at the corners of a small room. The above reports generally suggest that there is a possibility to improve sound fields with partial elements even in small rooms. In the present paper, the effects of additional elements, such as columns, beams and furniture, on the sound field in a small rectangular room are investigated through wave-based numerical analysis.

2. NUMERICAL SET-UP

Supposing a small rectangular room for listening use, a normal analysis model of $2.7\times3.6\times2.4$ m^3 with one loudspeaker (left channel) is given as shown in Figure 1. In a listening area, 25 receiving points are fixed at intervals of 20 cm, and the center point R is considered as the representative point. This listening area generally follows the optimum relative dimentions of a listening room proposed by Olson [9]. Based on the normal case, a variation of 29 models is given by adding pillars, beams and furniture in some positions as shown in Figure 2.

Regarding the boundary conditions, a real part of normal impedance corresponding to the normal incidence absorption coefficient α = 0.15 is given to all wall surfaces; α = 0.01 is given to the surfaces of the speaker, and a vibration speed (piston vibration) is given to the vibrating plane. The theoretical reverberation time (Eyring) of the normal model is 0.47s; its Schroeder frequency is 282 Hz. In the following examination, frequency responses from 56 Hz to 280 Hz are calculated at intervals of 2 Hz using the fast multipole BEM. The obtained results are evaluated regarding the flatness of frequency response (SD_{f}, Eq. 1) and the uniformity of spatial distribution in the listening area (SD_{s}, Eq. 2). Moreover, the mean values of each receiving point for SD_{f}, and in each frequency band for SD_{s} are calculated to evaluate the sound fields in two dimensions. These values are denoted by $\overline{SD_{\mathrm{f}}}$ and $\overline{SD_{\mathrm{s}}}$, respectively. Additionally, a combined value to-evaluate the flatness characteristics in the domains of frequency and space ($SD_{f,s}$, Eq. 3) are calculated.

$$SD_{\mathrm{f}} = \sqrt{\frac{1}{N_{\mathrm{b}}}\sum_{j}^{N_{\mathrm{b}}}\left(L_{ij}-\bar{L}_i\right)^2}\ ,\ \bar{L}_i = \frac{1}{N_{\mathrm{b}}}\sum_{j}^{N_{\mathrm{b}}} L_{ij} \tag{1}$$

$$SD_{\mathrm{s}} = \sqrt{\frac{1}{N_{\mathrm{r}}}\sum_{i}^{N_{\mathrm{r}}}\left(L_{ij}-\bar{L}_j\right)^2}\ ,\ \bar{L}_j = \frac{1}{N_{\mathrm{r}}}\sum_{i}^{N_{\mathrm{r}}} L_{ij} \tag{2}$$

$$SD_{\mathrm{f,s}} = \sqrt{\frac{1}{N_{\mathrm{r}}\times N_{\mathrm{b}}}\sum_{j}^{N_{\mathrm{b}}}\sum_{i}^{N_{\mathrm{r}}}\left(L_{ij}-\bar{L}\right)^2}\ ,\ \bar{L} = \frac{1}{N_{\mathrm{r}}\times N_{\mathrm{b}}}\sum_{j}^{N_{\mathrm{b}}}\sum_{i}^{N_{\mathrm{r}}} L_{ij} \tag{3}$$

where L_{ij} is the j-th octave band level at the i-th receiving point, N_b is the number of octave bands, N_r is the number of receiving points. The above evaluation is based on 1/12 octave band levels.

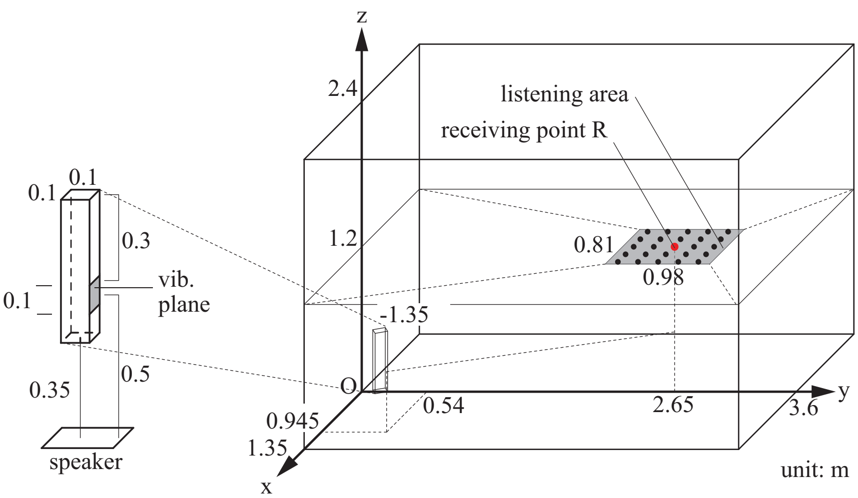


Figure 1 — A rectangular room with a source.

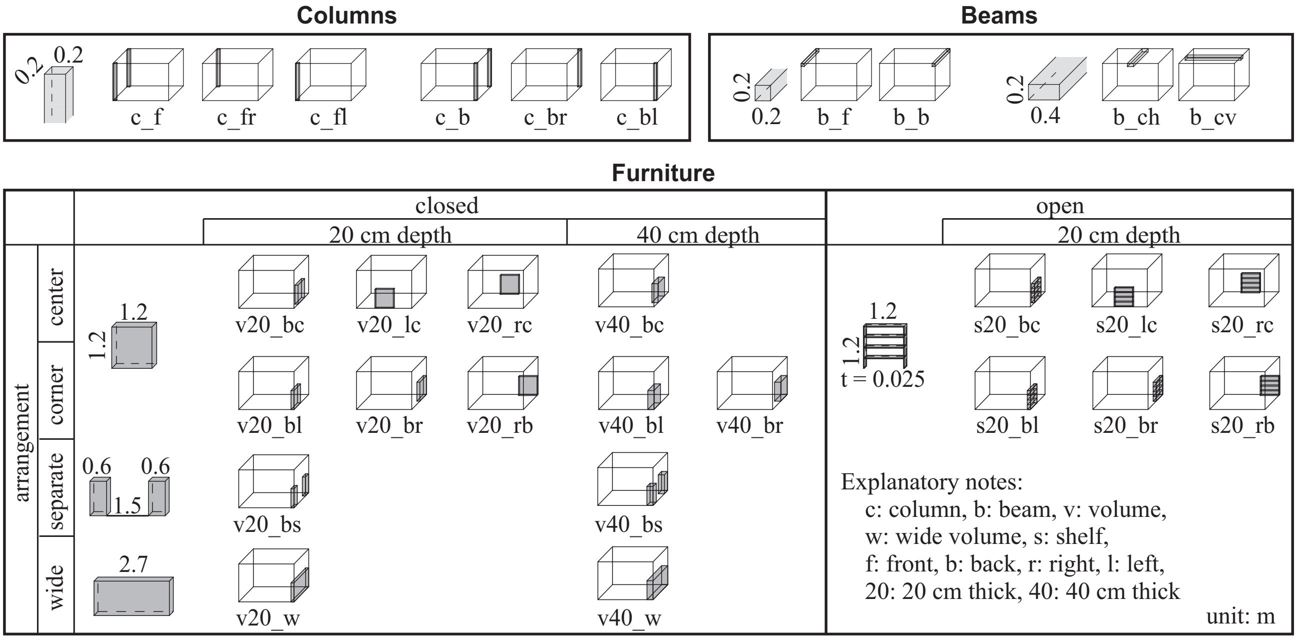
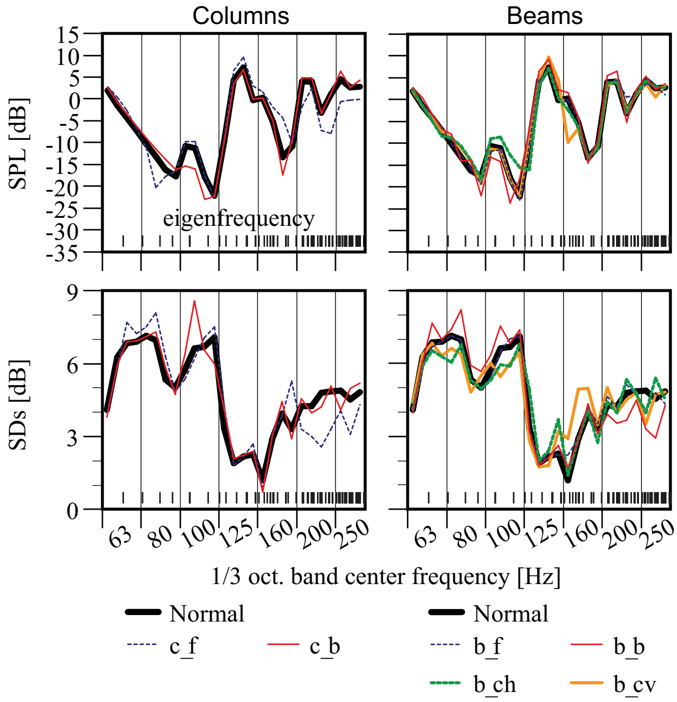


Figure 2 — The analysis cases.

3. RESULTS AND DISCUSSION

3.1. FREQUENCY RESPONSES AND SD_S

Figure 3 illustrates frequency responses at the center receiving point R, and SD_s of the listening area. As for the supplementation, to decide the evaluation area of SD_s, SD_s of the listening area have been compared with that of the space where the listening area was expanded in the cross-sectional direction by ±0.1 m. Though the graphs are omitted, the result shows that the tendency of both values have been almost resembled, so that we show SD_s calculated by one section.



Columns

Columns effect on the sound fields at high frequencies by arranging them near the sound source (c_f). The average value of difference in SD_s from the normal model is −1.30 dB. This means that columns contribute to improve uniformity of spatial distribution, but not so much as when the columns are arranged far from the sound source (c_b). It can be understand the results that elements effect largely when they are arranged near sound sources.

Beams

Even when beams are arranged where, they effect on the positions of peaks and dips of frequency responses, but the effects are small. The effects on SD_s are at the same level as columns, but it cannot be concluded that the elements improve the sound field.

Furniture

As for the closed-type shelves, it doesn't depend on the arrangement position, the effects are relatively large at wide range of frequency responses. Although the effects of thick furniture are large, the tendencies don't depend on their thickness. The effects of the defferences in the arrangement of the furniture indicate the similar tendency in the case arranged in corner position (bs) and the case arranged in back wall widely (w), but the in case of arranged in the center of walls (bc) is different. Moreover, a similar behaviour is admitted in Figure 4 that shows sound pressure distributions including the listening area. About the average values of the difference in SD_s from the normal model, it is 0.44 dB in v20_bc, it is 0.27 dB in v20_bs, and it is −0.60 dB. As mentioned above, the uniformity of spatial distribution is improved greatly when the furniture is arranged in corner of the room than center of walls.

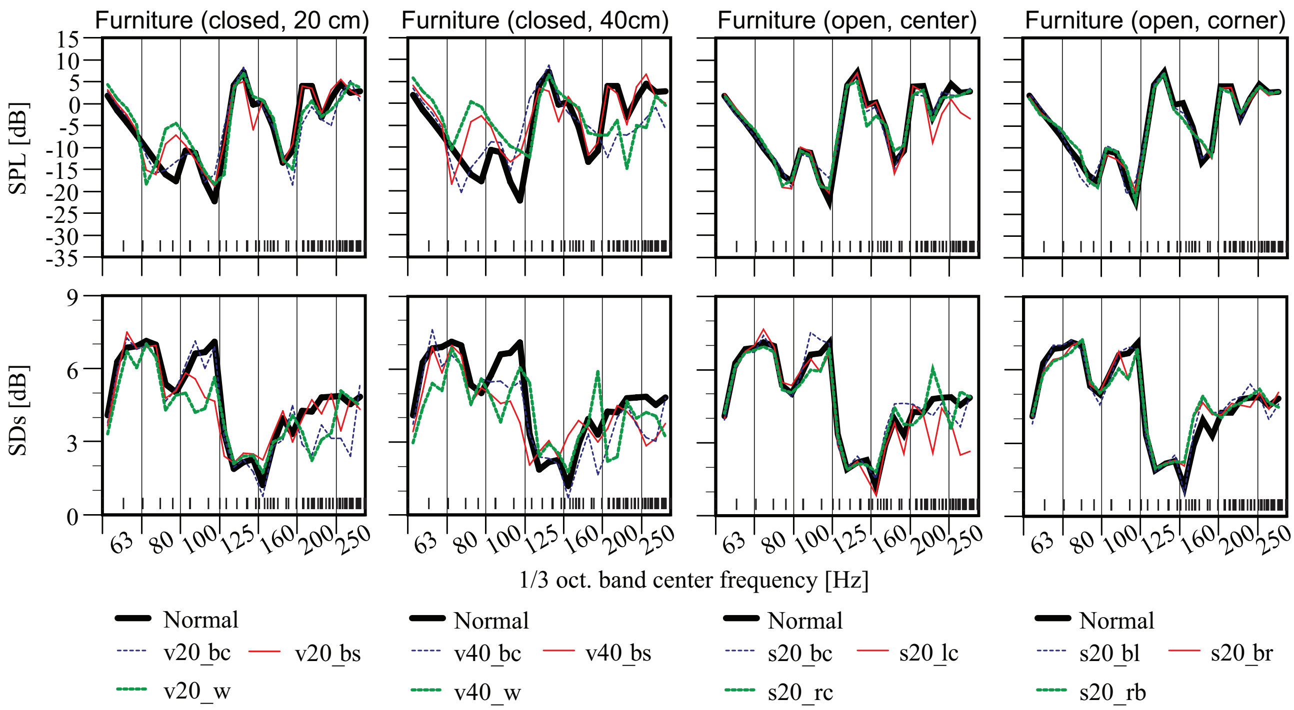


Figure 3 − Frequency responses at R, and SD_s in the listening area. Eigenfrequencies are calculated from room size ratio of the normal model.

3.2. SD_F

To evaluate the flatness of frequency responses, SD_f at the receiving points contained in listening area were calculated. Figure 5 shows that differences in SD_f from the normal model classified by 1 dB. The result shows the tendency that is almost similar to past examination. However, there are cases which the standard deviations are increased remarkably at a lot of receiving points around the representative receiving point R though the value at R is greatly decreased shown in the previous result like v40_w. Therefore, it can be concluded that the examination including not only a representative receiving point but also around the point for frequency responses is necessary even if the room has limited listening position.

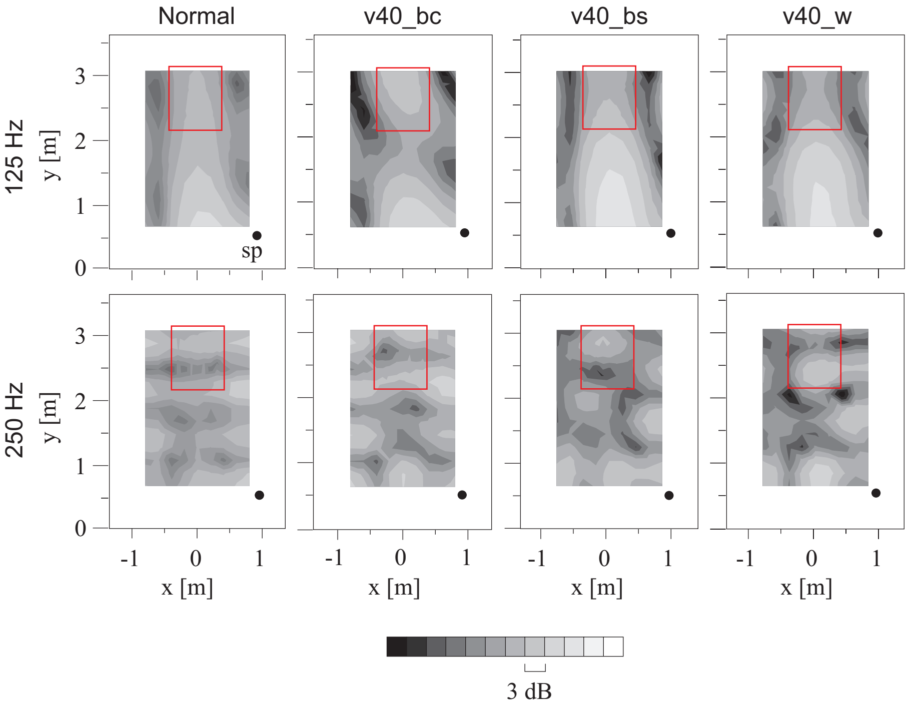


Figure 4 — Relative SPL distributions on a plane (z = 1.2).

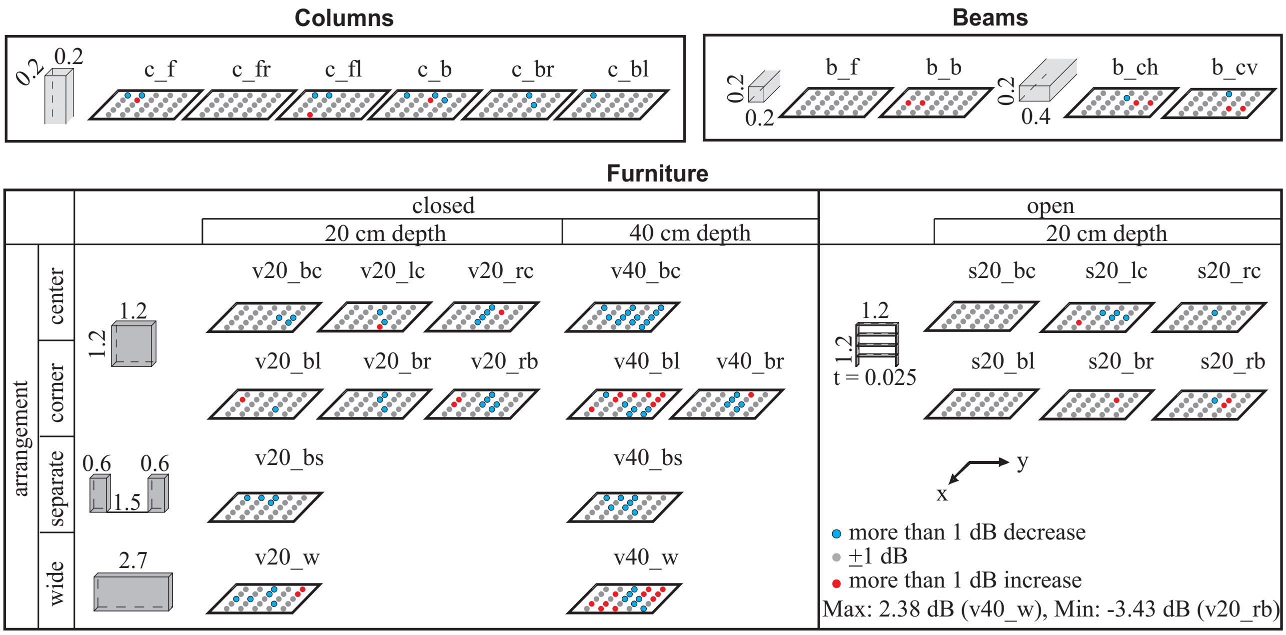


Figure 5 — Differences from the normal model in SD_f at 25 receiving points in the listening area.

3.3. $\overline{SD_f}$ AND $\overline{SD_s}$

In the above examination, SD_f were calculated for every receiving point and SD_s were calculated for every frequency band. In the following, to evaluate the sound fields more easily, it concerning the mean value of SD_f and that of SD_s. Figure 6 shows the results arranged two dimensions. In addition, both axes are normalized by the values of the normal model.

Columns

Although the effect of columns is small, in the cases which they were arranged near the sound source, both axes are in the tendency for the values to decrease. This means that both the uniformity of spatial distribution and flatness of frequency responses are improved.

Beams

The effects of beams are small, but show a tendency to change for the worse about uniformity of sound fields. Especially, when installing beams in the distance from the sound source, the tendency appeared strongly.

Furniture

The effects of closed-type shelves are larger than that of columns and beams, and improvement tendency is shown by all the cases. Although the effects of thick furniture are large, the tendencies don't depend on the thickness. On the other hand, the effects of open-type shelves are small and these are comparable as columns or beams. However, only when the open-type shelves are in the position where sound incident into the side of them directly, they effect on the sound fields comparable as closed-type shelves. Additionally, the correlation coefficient of SD_f and SD_s is 0.61 in this examination.

3.4. $SD_{F,S}$

Next, to evaluate the sound fields by the frequency domain and the spatial domain simultaneously, $SD_{f,s}$ were calculated. The results normalized by the value of the normal model are shown in Figure 7. It is shown that these results are similar to the aforementioned results in general; The effects of columns and beams are small; Although the effects of open-type shelves is small, an improvement tendency is indicated relatively large only s20_lc. The improvement effects of closed-type shelves are large, especially thicker one. However, the tendency to the effects is different in any case depending on their arrangement position.

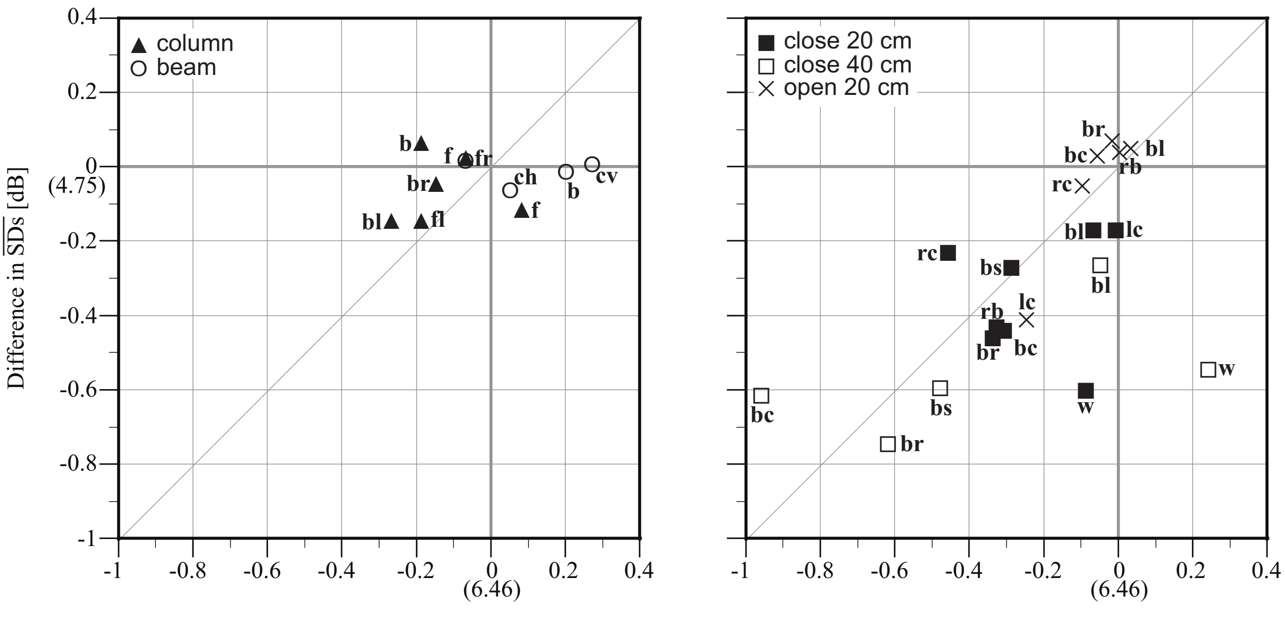


Figure 6—Differences in $\overline{SD_f}$ and $\overline{SD_s}$ from the normal model.

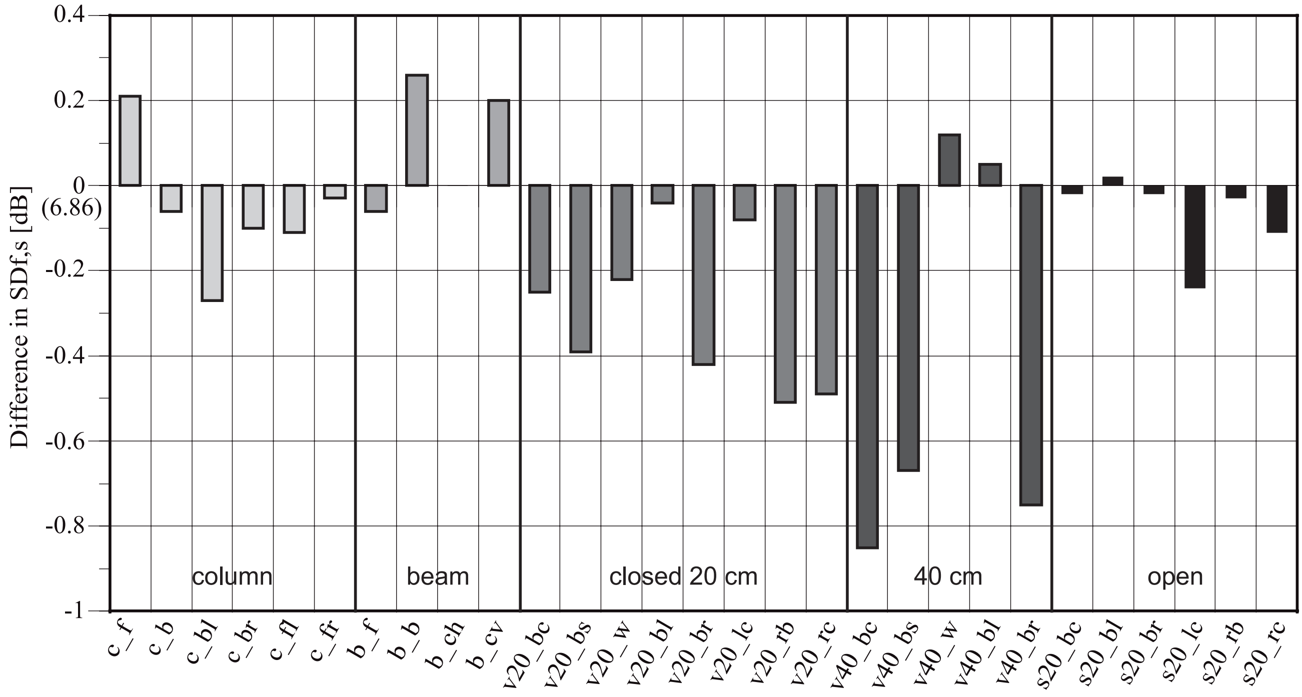


Figure 7－Differences in $SD_{f,s}$ from the normal model.

4. CONCLUSIONS

In the present paper, the effects of additional elements, such as columns, beams and furniture, on the sound fields in a small rectangular room are investigated through wave-based numerical analysis. The results show that: the effect of columns is small but more than beams; that of closed-type shelves is relatively large but not so much with open-type shelves; The size and the arrangement of every element have unnegligible effects. It is also seen that the additional elements generally lead to positive effects in flatness of frequency response and spatial uniformity even at low frequencies, although in specific case. Especially, when the elements are large or arranged near a sound source, the effects come to be large. Therefore, from these results, it is desirable to examine in detail the effects of arrangement of partial room elements in acoustic design of small enclosures.

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