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Diffuser design in concert halls using scale models

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ABSTRACT

Concert hall scale models with different scale factors were tested to investigate the locations and profiles of the diffusers. In-situ diffuseness of the scale models was measured by 'number of peaks (Np)' from the impulse responses recorded from the scale model halls. Diffuser locations and profiles were determined to yield maximum Np using 1:25 scale model, when omni-directional (hemisphere) diffusers were used. Scattering/diffusion coefficients of 1:10 diffuser specimen were measured and QRD-type horizontal diffusers were designed for the lateral walls close to stage in 1:10 scale model halls.

INTRODUCTION

Diffuser design for scattering treatments in reflective surfaces is one of the important factors to archieve good acoustics in concert halls [1]. Irregular surfaces prevent acoustic glare and coloration caused by strong and specular reflections [2]. However, highly diffusive surfaces do not always yield the best acoustics [3-5]; excessive diffusers could be harmful in terms of sound pressure level and reverberation time [6]. Though diffuser in auditoria contributes to smooth sound decay in impulse reponses, it tends to reduce loudness and reverberation.

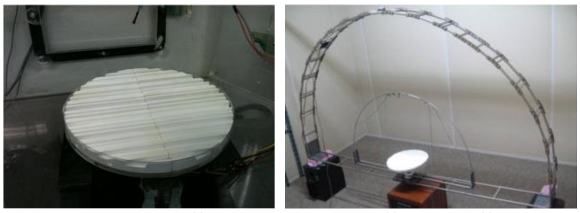
How can diffusers be designed accurately for better concert hall acoustics? Acoustical performance of diffuser profiles can be evaluated by measuring scattering and diffusion coefficients [7, 8]. However, the sound field in a concert hall, including scattered reflections, is different in the laboratory measurement conditions. There are little practical measuring methods for in-situ diffusivity in a viewpoint of acoustical design of concert halls. Recently, an in-situ diffusivity index calculated from impulse responses as *number of peaks* has been used for the design of a terraced hall [9].

In this study, a rectangular concert hall with 2,100-seats was tested in 1:25 and 1:10 scale models to investigate the location of reflecting surfaces and the diffuser profiles. Scattering and diffusion coefficients were applied to determine diffuser profile in terms of in-situ diffuseness. The design process of the diffuser in concert halls was also discussed with the measurement results from the different scale models.

METHODOLOGY

Scattering coefficient

As shown in Figure 1 (a), a scattering coefficient can be measured using motorized turntable in 1:10 reverberation chamber (volume of 0.253 m^3) based on ISO 17497-1 [7]. Circular diffuser specimen with a diameter of 30-cm was used. The sound sources were located at three positions, and the receiver was located at four positions in the chamber. The impulse responses were measured at 88 directions by rotating turntable and were synchronously averaged.



(a) Scattering coefficient (b) Diffusion coefficient

Figure 1. Measurement setup for scattering and diffusion coefficients for 1:10 scale specimen

Diffusion coefficient

As shown in Figure 1 (b), a diffusion coefficient can be measured using 1:10 goniometer in a test chamber based on AES-4id-2001 [8]. Circular diffuser specimen with a diameter of 30-cm was used as the same manner of scattering coefficient measurement. Multi-MLS was adopted for sound source. The sound source was located 1-m off from the specimen; at two indicence angles - 90° for normal incidence and 55° for oblique incidence. The receivers were half-radially located 0.5-m off from the specimen.

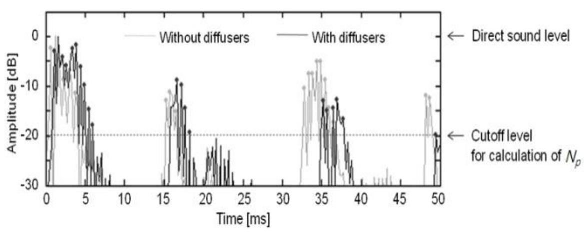


Figure 2. Calculation of *Number of peaks* (N_p) in the impulse responses

In-situ diffusivity index

Upon considering the differences in temporal density of the impulse response rays, the degree of sound diffusion can be defined as *Number of peaks* (N_p) within the lapsed time of the effective amplitude drop (-20 dB). Figure 2 shows a calculation example of N_p in the impulse reponses. Actually, peaks (local maxima) in the impulse response are not "reflections" but arbitrary maxima in overlapping reflection components after filtering. When filtering is applied, Dirac pulses form a specific wave form, the octave filter impulse response. This response involves an onset, two/three maxima, and then an offset. When room reflections meet at similar delay times, the resulting impulse response has some peaks at which the maxima coincide, resulting in cancellation when the two intersecting peaks have opposite phases. Because humans perceive the resultant wave form on a dB scale, not the phase itself, it is assumed that the number of peaks represents the degree of sound diffusion. $N_{p,E}$ is calculated for early reflections (0 to 80 ms), and $N_{p,L}$ is calculated for late reflections (80 to 200 ms).

SCALE MODEL HALL

Hall description

A rectangular hall with 2,100-seats was selected as shown in Figure 3. The volume is 19,500 m^3, and the stage area is 214 m^2. The rearmost seat was located at 34.5 m from the center of stage front. Two balcony floors were designed. A large over-stage reflector and a rear-stage pipe organ were included.

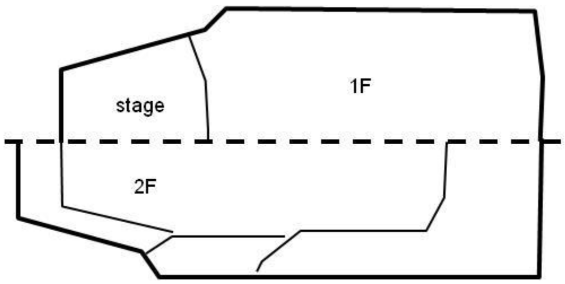


Figure 3. The floorplan of the model hall: the width (W) x height (H) x length (L) was 24.3 x 20.9 x 31.5 m.

Figure 4. Picture of the 1:25 scale model hall without ceiling reflector

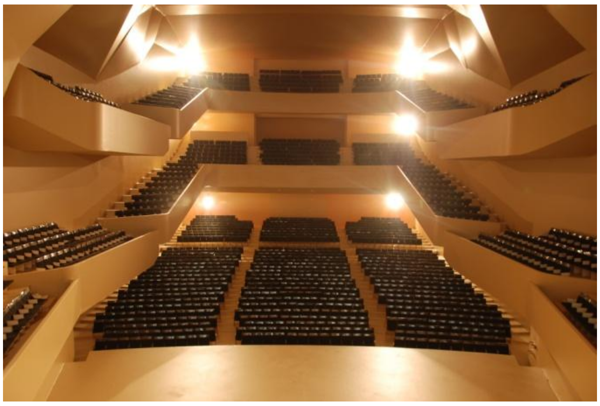


Figure 5. Picture of the 1:10 scale model hall

1:25 scale model hall

1:25 scale model hall was built to determine diffuser location and profile as shown in Figure 4. The model hall was made of varnished MDF boards and miniature chair models based on absorption coefficients of the model hall and real hall materials. High-voltage spark source and 1/8 inch monaural microphones were used. Receivers were located at 14 positions in the audience area. *SPL*, *RT*, *EDT*, C_{80}, $N_{p,E}$ and $N_{p,L}$ were measured as acoustical parameters. Air absorption of the measured RT was corrected based on ISO 354.

1:10 scale model hall

1:10 scale model hall was built to investigate as shown in Figure 5. The model hall was made of water-painted MDF boards and miniature chair models based on absorption coefficients of model and real hall materials. Reverberation time of the unoccupied model hall without diffusers was 2.5 s at mid-frequency bands. 1:10 miniature dodecahedron loudspeaker and miniature dummyhead were employed as a sound source and receiver. *SPL*, *RT*, *EDT*, C_{80}, $N_{p,E}$, $N_{p,L}$, $IACC_{E3}$ and $IACC_{L3}$ were measured as acoustical parameters.

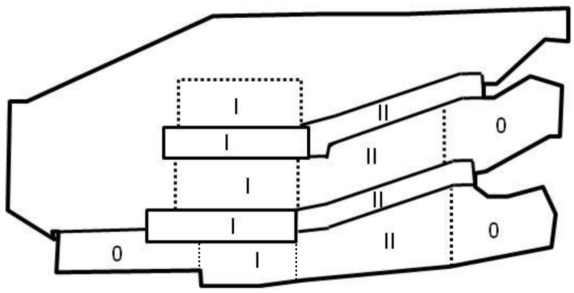


Figure 6. The section of the model hall with design concept of diffuser location: "Type 0" indicates flat surface, "Type I" indicates the most diffusive surface and "Type II" indicates the medium diffusive surface.

Design concept of diffuser location

Optimum diffuser location was determined based on the previous study on a rectangular concert hall [10]: the study reported that the most important location for diffusers in rectangular halls was a half of lateral walls close to stage [10]. Figure 6 shows the design concept of diffuser location for the model hall. In Figure 6, "Type I" diffuser is designated for the diffuser profile with a maximum structural height; "Type II" is profiled with medium height of Type I.

EVALUATION OF THE DIFFUSER LOCATION IN 1:25 SCALE MODEL HALL

Measurement set-up

Acoustical measurements were carried out in four conditions according to diffuser installation. "Case A1" indicates the flat surfaces as a reference. "Case A2" indicates the omni-directional diffusers on lateral walls, whereas "Case A3" indicates the horizontal diffusers on lateral walls. In "Case A4", omni-directional diffusers were installed on the balcony fronts based on "Case A3". Sound source was located at the typical soloist position. Structural height of diffusers was 7.5-mm (180-mm in real scale) for omni-directional diffusers (both Type I and II), 10-mm (250-mm in real scale) for Type I horizontal diffuser, and 5-mm (125-mm in real scale) for Type II horizontal diffuser. All parameters were averaged at 500-1,000 Hz except for C_{80} (500-2k Hz). Air absorption was corrected

Results

Table 1 shows the measurement results of the acoustical parameters. By installing diffusers, *SPL*, *RT* and *EDT* were decreased but C_{80}, $N_{p,E}$ and $N_{p,L}$ were increased as shown in the previous studies [4-6]. In case of the omni-directional diffusers (Case A2), *SPL* and *RT* decreased, whereas N_p values did not significantly increase. On the other hand, the horizontal diffusers on lateral walls (Case A3 and A4) provided high N_p values (more than 10% as for the early reflections) as compared to the omni-directional diffusers (Case A2). This suggests that the strong lateral reflections are necessary for spreading sounds horizontally. Therefore, the horizontal diffusers were selected for the lateral walls. In addition, there was increase in the early reflection numbers ($N_{p,E}$) due to the diffusers at the balcony front. It is shown that the diffusing surface on the balcony front is essential for ealy scattering sounds in the auditorium.

Table 1. Measurement conditions of the 1:25 scale model hall and the measured acoustical parameters which were averaged from 14 receiver positions.

Case	A1	A2	A3	A4
Wall I	Flat	O.D.	H.D.	H.D.
Wall II	Flat	O.D.	H.D.	H.D.
Balcony front	Flat	Flat	Flat	O.D.
SPL [dB]	76.2	74.8	74.5	74.2
RT [s]	2.06	1.95	2.01	1.96
EDT [s]	2.10	1.95	1.97	1.99
C_{80} [dB]	-0.5	0.5	1.6	0.7
$N_{p,E}$	55.3	58.7	63.0	65.8
$N_{p,L}$	86.7	87.5	91.8	91.9

* O.D.: Omni-directional diffuser (Hemisphere type), H.D.: Horizontal diffuser (QRD type)

EVALUATION OF DIFFUSER PROFILE IN 1:10 SCALE MODEL HALL

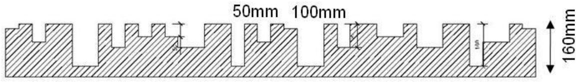
Diffuser profile design

Based on Quadratic Residue Diffuser (QRD) [2], the horizontal diffuser profiles were designed as shown in Figure 7. Scattering coefficient of Type I diffuser (structural height: 160 mm in real scale) was measured as 0.52 (averaged at 500 to 3,150 Hz). This result corresponds to the hemisphere type diffuser with structural height of 200-mm and occupied density of 50% or more. The frequency characteristics of the scattering coefficient for Type I diffuser was shown in Figure 8. The diffuser has the effective scattering coefficient over 0.4 above 1,000 Hz.

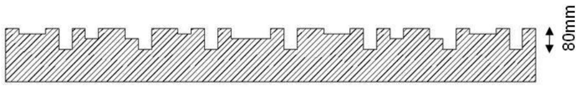
Diffusion coefficient of Type I diffuser was measured as 0.40 (0.26 for flat surface). Figure 9 shows the polar response of Type I diffuser for both normal and oblique incidence sound sources. As the diffuser profile spreaded reflections horizontally, the specular reflection of the normal incident sound source was decreased by about 5 dB while the scattered reflections were increased by only 3 dB. However, as for the oblique incident sound source, the diffuser profile increased the scattered reflections by about 5 dB without reducing the level of the specular reflection.

Measurement set-up

Two measurement cases by presence of diffusers were considered. As shown in Figure 10, Type I and II diffusers were installed on the lateral walls and the balcony fronts according to the determined diffuser locations and profiles. Binaural measurements were carried out in the model hall. All parameters were averaged at 500-1,000 Hz except for C_{80} and *IACC* (500-2k Hz).



(a) Type I diffuser profile



(b) Type II diffuser profile

Figure 7. The horizontal diffusers designed for the model hall

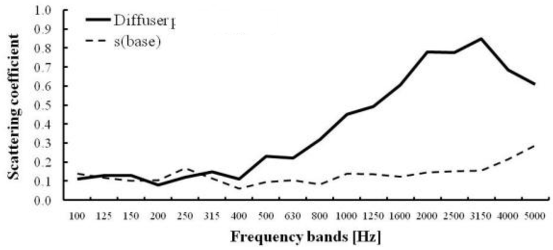
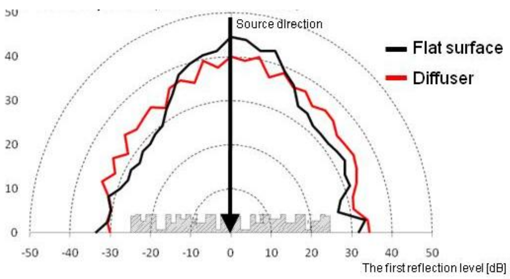
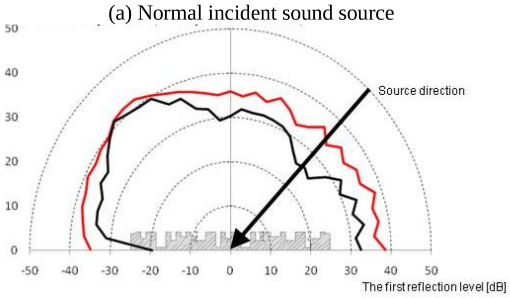


Figure 8. Frequency characteristics of the measured scattering coefficient of Type I diffuser



(a) Normal incident sound source



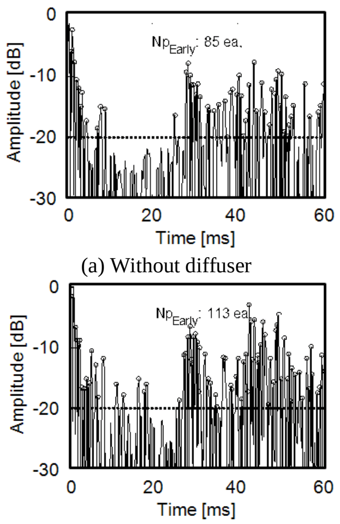
(b) Oblique incident sound source

Figure 9. Polar responses of Type I diffuser

Figure 10. The horizontal diffusers installed in the 1:10 scale model hall

Table 2. Acoustical parameters of the 1:10 model hall by diffuser installation (averaged from 24 receiver positions)

Condition	Without diffusers	With diffusers	Difference (W/ - W/O)
SPL [dB]	75.3	74.6	-0.7
	1F: 76.0	1F: 75.2	1F: -0.8
	2F: 74.1	2F: 73.5	2F: -0.6
	3F: 74.9	3F: 74.3	3F: -0.6
	Max: 80.5	Max: 79.1	Max: -1.4
	Min: 72.5	Min: 72.5	Min: 0
	Range: 8.0	Range: 6.6	Range: -1.4
RT [s]	2.55	2.34	-0.21
	1F: 2.57	1F: 2.33	1F: -0.24
	2F: 2.49	2F: 2.34	2F: -0.16
	3F: 2.54	3F: 2.35	3F: -0.19
EDT [s]	2.44	2.17	-0.27
	1F: 2.40	1F: 2.12	1F: -0.28
	2F: 2.58	2F: 2.30	2F: -0.29
	3F: 2.38	3F: 2.16	3F: -0.22
C_{80} [dB]	-1.8	-1.5	+0.3
	1F: -0.8	1F: -0.7	1F: +0.1
	2F: -2.7	2F: -1.9	2F: +0.8
	3F: -2.5	3F: -2.6	3F: -0.1
$N_{p,E}$	111.6	120.4	+8.8
	1F: 94.3	1F: 107.7	1F: +13.5
	2F: 123.6	2F: 130.6	2F:+ 7.0
	3F: 144.0	3F: 142.3	3F: -1.8
$N_{p,L}$	171.2	183.8	+12.1
	1F: 147.5	1F: 162.5	1F: +15.1
	2F: 186.8	2F: 197.8	2F: +11.0
	3F: 217.0	3F: 222.0	3F: +5.8
1-IACC$_{E3}$	0.59	0.63	+0.04
	1F: 0.53	1F: 0.59	1F: +0.05
	2F: 0.66	2F: 0.67	2F: +0.01
	3F: 0.63	3F: 0.69	3F: +0.06
1-IACC$_{L3}$	0.87	0.87	-



(a) Without diffuser

(b) With diffuser

Figure 11. Reflectogram of the measured impulse responses with and without diffusers at the same position

Results

Table 2 shows the measurement results of the acoustical parameters. After diffuser installation, overall *SPL*, *RT* and *EDT* were decreased by 0.7 dB, 0.21 s and 0.27 s, respectively, whereas C_{80} was increased by 0.3 dB. In comparison with the results from the 1:25 scale model, *SPL* was not much reduced, but *RT* and *EDT* were reduced more by almost 10%. This was caused by the increased absorption from the detailed diffuser profiles, although the diffuser surfaces were properly varnished. *SPL* and *RT* of 1F receivers were largely decreased by diffusers than those of other floors. Consequently, deviations of *SPL* and *RT* distribution were reduced relatively after the diffusers were installed. The maximum *SPL* was decreased by 1.4 dB. In particular, the average *RT* at each floor was ranged from 2.33 to 2.35 s. As for clarity factor, C_{80} at the 2nd balcony was largely increased by diffusers.

Both $N_{p,E}$ and $N_{p,L}$ were increased by 8.8 (+7.8%) and 12.1 (+7.1%) , respectively, according to the diffuser installation. Especially, N_p at the 1st floor was largely increased. Figure 11 confirms that the early reflections were added by diffusers in the impulse responses. However, $N_{p,E}$ at the 3rd balcony was rather decreased after installing diffusers because most of the laterall walls consisted of flat surfaces except for small area near stage. In terms of binaural dissimilarity, *1-IACC*$_{E3}$ was increased by 0.04 after installing diffusers, whereas *1-IACC*$_{L3}$ did not change. Because the diffusers were intensively placed near stage, only *1-IACC*$_{E3}$ values at 1st and 3rd balconies were mainly increased.

CONCLUDING REMARKS

In this study, diffuser profile and location in an actual concert hall were objectively investigated using different scale factored models. Small scale models could help to determine diffuser concept using in-situ diffusivity parameters (N_p); Np can be calculated from any monaural measurements, and the results are well corresponded to the change of surface diffusivity. Then, as scale factor becomes larger, more detailed acoustical analysis is possible. As for designing diffusers in concert halls, scale model testings is essential to determine effective diffuser location, proper amount of diffusion, and directivity of diffuser shape. Furthermore, diffuser design can be completed by subjective evaluation based on perceptible limen of diffusion.

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