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Perception of scattered sounds in rectangular concert halls

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ABSTRACT

This paper investigates objective and subjective responses on scattered sounds from rectangular concert halls. A concert hall with 450-seats and highly diffusive lateral walls was measured based on ISO 3382-1. Acoustical parameters such as RT, EDT, G, C80, LF and IACC were used for objective evaluation of scattered sounds. The impulse responses of the concert hall were selected according to the measurement results of 'Number of peaks' for in-situ diffusivity evaluation. Auditory experiments were performed with 8 auralized music sounds with normalized impulse responses. The effective diffusion parameter was discussed through the subjective test results.

INTRODUCTION

Sound diffusion is one of the important factors for evaluation of acoustical quality of concert halls. Scattered reflections by wall structures are major components to make sound fields diffusive. Laboratory evaluation methods on surface diffuseness of diffuser profile had been developed for scientific design of surface diffusion [1, 2]. However, it is required to develop in-situ diffusivity evaluation method because the sound fields including scattering sounds in laboratory condition are different from the actual sound fields in concert halls.

In the previous studies, scale models were employed to investigate objective effects of scattered sounds by diffusers on acoustical parameters [3-6]. It was found that the diffusive surfaces decreased *SPL*, *RT* and *IACC* as results of weakened strong specular reflections and smoothened sound decay. Scattered reflections by diffusers also yielded to decrease the level of specular peaks, and increase the peak density in time domain [7]. These effects were tried to be measured as a new parameter, *Number of peaks* (N_p), for the investigation of in-situ diffusion [8]. However, these parameters have not been fully verified through subjective evaluation on diffuseness impression. Ando reported that *IACC* was related to the subjective diffuseness [9]. Hidaka *et al.* found that $IACC_{L3}$ was related to listener envelopment [10]. Ryu and Jeon found the preference model of scattered sound as a function of *SPL*, *EDT* and $IACC_{L3}$ [6]. However, there is lack of studies on perception of scattered sound in order to develop objective parameters into in-situ diffusivity parameter for diffuser design of concert halls.

Therefore, in the present study, the scattered sounds from a rectangular concert hall with highly diffusive lateral wall surfaces were investigated objectively and subjectively. Coventional acoustical parameters such as *G* and *RT* including N_p were measured in the hall to investigate acoustical characteristics of the scattered sounds. Then, auditory tests with convolved music were carried out using the selected sound fields from the measurement.

Figure 1. Interior view of the hall

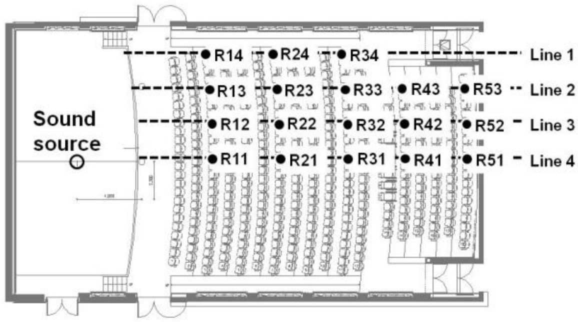


Figure 2. Source and receiver positions

MEASUREMENTS

Hall descriptions

As shown in Figure 1, a concert hall (450-seat) with highly diffusive lateral walls was introduced. The hall named 'Ceramic Palace Hall' was built in 2003, and designed through the scientific diffuser design procedure using scale models [11]. The lateral walls were covered by the cubic type ceramic tile diffusers with various heights.

Measurement set-up

Acoustical characteristics of the hall was measured based on ISO 3382-1 [12]. Figure 2 shows the measurement positions of sound source and receivers. The sound source was located at the center of the stage. Omni-directional dodecahedron loudspeaker was employed for the sound source. The 18 receivers were located at the audience area according to both the distance from stage and lateral wall. Receivers on the 'Line 1' were the furthest from the lateral wall, whereas receivers on the 'Line 4' were the closest. Both binaural (HATS) and monaural (AKG 414) microphones were employed for the measurements of *IACC* and *LF*, respectively. Conventional acoustical parameters were calculated from the binaural impulse responses. The height of sound source was 1.5 m, and that of receivers was 1.2 m in consideration of human dimension. Impulse responses were recorded at each receiver position using swept-sine signal with a sampling rate of 44,100 Hz.

Evaluation parameters

Acoustical parameters of *RT* (T_{20}), *EDT* and *G* for reverberance and loudness evaluations were averaged from 500 Hz to 1k Hz. *C80* and *IACC* for music clarity and spatial impression evaluations was averaged from 500 Hz to 2k Hz. LF measured from 'figure-of-eight' microphone was averaged from 125 Hz to 1k Hz. *Number of peaks* (N_p) was calculated in time domain as counting peaks within the lapsed time of the effective amplitude drop (-20 dB) from the amplitude of direct sound as shown in Figure 3.

Results

Figure 4 shows the measured acoustical parameters such as *G*, *EDT*, *LF*, $1\text{-}IACC_{E3}$ by source-to-receiver distance. *G* was ranged from 4.5 to 12.2 dB according to the distance from the sound source. As shown in Figure 4 (a), *G* in the Line 1 (close to the lateral wall) was higher than *G* in the Line 4 (far from the lateral wall). G_{80} (early sound level) also showed similar tendency with G. This was caused by the shorter delay time of the first reflections due to the near reflective surface. *EDT* was ranged from 1.74 to 1.94 s as shown in Figure 4 (b). *RT* showed the similar pattern with *EDT*, and ranged from 1.72 to 1.82 s. Range of *RT* (0.1 s) was shorter than that of *EDT* (0.2 s). *C80* was ranged from -1.8 to 0.5 dB. Figure 4 (c) indicates the distribution of *LF*. *LF* was ranged from 0.2 to 0.34. $1\text{-}IACC_{E3}$ was ranged from 0.52 to 0.76 as shown in Figure 4 (d). As shown in Figure 4 (d), $1\text{-}IACC_{E3}$ in the Line 1 was higher than $1\text{-}IACC_{E3}$ in the Line 4. Figure 5 shows the measurement results of N_{pE} and N_{pL}. N_{pE} was ranged from 187 to 484, whereas N_{pL} was ranged from 77 to 560. As results, acoustical characteristics were mainly depended on the distance from the source, but some differences by distance from the lateral walls were found for *G*, *EDT*, *IACC* and N_p values.

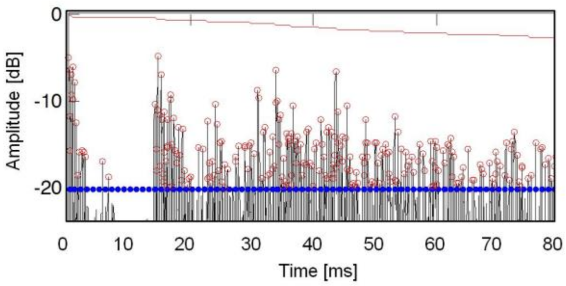
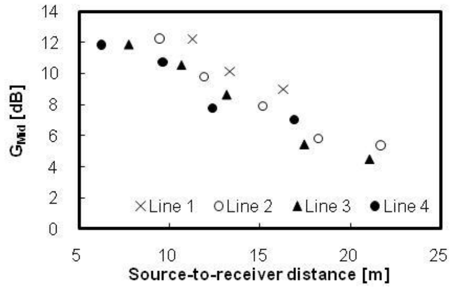
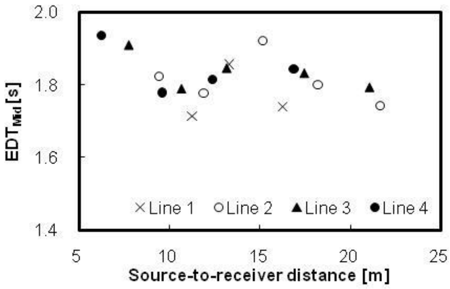


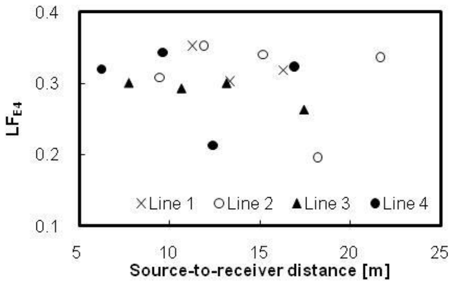
Figure 3. Calculation of *Number of peaks* in the measured impulse response



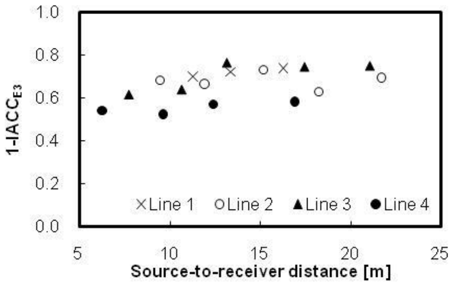
(a) Spatial distribution of G_{Mid}



(b) Spatial distribution of EDT_{Mid}

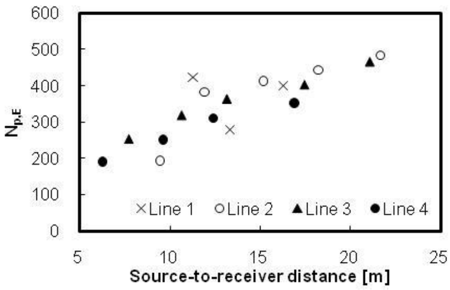


(c) Spatial distribution of LF_{E4}

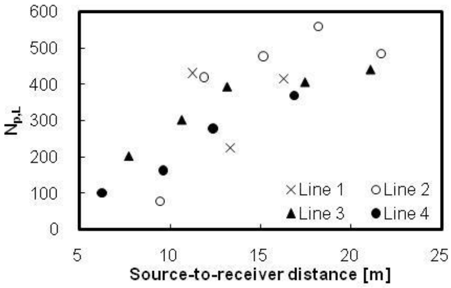


(d) Spatial distribution of $1\text{-}IACC_{E3}$

Figure 4. Measurement results of acoustical parameters



(a) Spatial distribution of $N_{p,E}$



(b) Spatial distribution of $N_{p,L}$

Figure 5. Measurement results of the *Number of peaks*

Table 1. Acoustical characteristics of the selected sound fields for auditory test (Experiment I)

No.	Posi-tion	*G* [dB]	*EDT* [s]	*C80* [dB]	LF_{E4}	**$1-IACC_{E3}$**	$1-IACC_{L3}$	**N_{pE}**	N_{pL}
A	R11	11.9	1.94	-0.3	0.32	**0.54**	0.89	**187**	101
B	R12	11.9	1.91	-0.5	0.30	**0.62**	0.85	**246**	201
C	R14	10.8	1.78	-1.6	0.34	**0.52**	0.84	**424**	163
D	R31	7.8	1.82	-1.6	0.21	**0.57**	0.85	**306**	278
E	R32	8.6	1.85	-1.8	0.30	**0.76**	0.82	**357**	394
F	R34	9.0	1.74	-0.5	0.32	**0.74**	0.81	**393**	416
G	R43	5.8	1.80	-1.0	0.20	**0.63**	0.84	**412**	560
H	R53	5.4	1.74	0.3	0.34	**0.70**	0.85	**468**	484

AUDITORY TESTS

Procedure

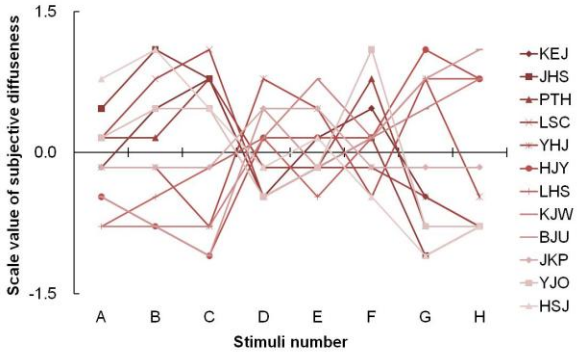
A total of eight scattered sound fields with different *IACC* and N_{pE} values were selected based on the objective measurement results. Table 1 showes the acoustical characteristics of the selected impulse responses. Among the selected sounds, $1\text{-}IACC_{E3}$ was varied from 0.52 to 0.76 by intervals of about 0.03, whereas N_{pE} was varied from 187 to 468 by internals of about 35.

The original impulse responses have large sound level difference up to 6.5 dB due to the different distances between source and receivers. Therefore, another set of normalized impulse responses was prepared to control effects of sound level because the loudness is the most dominant factor on sound perception generally. Accordingly, the following two sets of auditory tests were carried out to investigate subjective perception of diffuseness; 'Experiment I' with the original impulse responses, and 'Experiment II' with the normalized impulse responses.

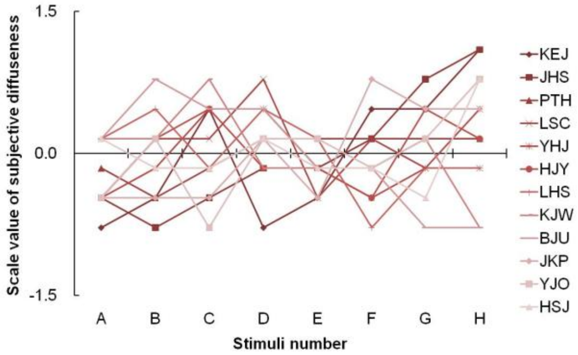
Auditory test was conducted using paired comparison method. Violin motif of 7 s as a dry source was convolved with the selected impulse response to be experimental music signals. Auralized music was presented to the subjects through headphone system (STAX SR-303) with randomized pairs. Scale values were derived from the percentile response by applying Thurstone's law of comparative judgment (case V) [13]. Significance of each individual response was examined through the consistency test procedure which calculates number of circular triads [14]. Averaged scale value for each test set was verified through the agreement test procedure [14]. Totally 12 subjects with normal hearing ability participated in the tests. All subjects were asked to judge which sound was heard as more subjectively diffused.

Results

All subjects took two auditory tests; 'Experiment I' and 'Experiment II'. Figure 6 shows the results of scale values of subjective diffuseness. Among 12 subjects, 9 subjects in the Experiment I (original sound fields) were passed the constancy test (under confident interval of 95%), and 6 subjects in the Experiment II (equalized sound level) were passed. However, for both Experiments I and II, the averaged scale values of the all significant individual results were not agreed statistically. Accordingly, cluster analysis for individual response was carried out to group subjects' response. Figure 7 shows the dendrograms of each test as a result of cluster analysis. As results, two groups for each test were derived. Table 2 showes the scale values of subjective diffuseness by the groups.

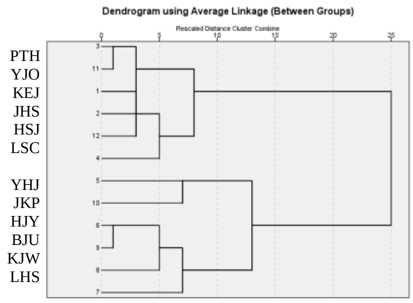


(a) Experiment I

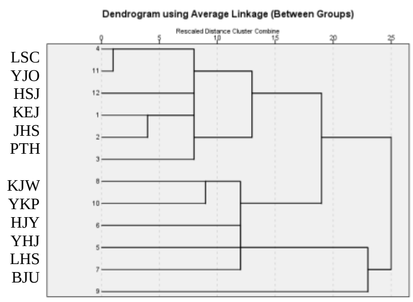


(b) Experiment II

Figure 6. Individual responses of the participated subjects for Set A and Set B tests in terms of scale values of subjective diffuseness. Legend indicates the name of each subject.



(a) Experiment I



(b) Experiment II

Figure 7. Dendrograms of each auditory test between groups from the cluster analysis. Legend indicates the name of each subject.

Table 2. Scale values of subjective diffuseness by group

Exp.	Group (no. of subjects)	A	B	C	D	E	F	G	H
I	I-1 (5)	0.48	1.06	1.02	-0.48	-0.12	0.43	-1.22	-1.17
	I-2 (4)	-0.84	-0.90	-1.37	0.61	0.51	0.00	1.13	0.86
II	II-1 (3)	-0.83	-0.06	0.58	-0.83	-1.17	0.70	0.48	1.12
	II-2 (3)	-0.36	-0.06	-1.17	0.83	0.70	-0.06	0.95	-0.83

Table 3. Correlation coefficients between the scale values of subjective diffuseness by group and the measured objective parameters. Dotted values (*) are indicates p<0.05

Group	*G*	*EDT*	*C80*	LF_{E4}	$1-IACC_{E3}$	$1-IACC_{L3}$	N_{pE}	N_{pL}
I-1	0.94*	0.41	-0.14	0.51	-0.33	0.10	-0.48	-0.80*
I-2	-0.92*	0.42	0.02	-0.57	0.55	-0.35	0.45	0.87*
II-1	-0.37	-0.73*	0.51	0.28	0.12	-0.28	0.71*	0.42
II-2	-0.34	0.18	-0.43	-0.85*	0.28	-0.25	-0.18	0.42

Discussions

In order to clarify the perception model of scattered sounds, the results of the scale values of subjective diffuseness were compared to the results of acoustical parameters. Table 3 shows the results of correlation analysis between the scale values of subjective diffuseness by group and the measured objective parameters.

In case of Experiment I, most of subjects perceived the original scattered sound fields in terms of *G* values, firstly, and N_{pL} value was the second influential factor for determining diffuseness. However, each group reacted in direct opposition on the subjective diffuseness. Group I-1 perceived loud sound more diffusive. Contrarily, Group I-2 perceived many numbers of late reflections (N_{pL}) more diffusive with lower sound level. Dominance of sound level on perception of scattered sound was similarly appeared in the previous study [6].

In case of Experiment II with the controlled sound level, *EDT* and N_{pE} were found as the important factors on subjective diffuserness for Group II-1. Group II-1 perceived many numbers of early reflections (N_{pE}) with low reverberance (*EDT*) more diffusive. However, Group II-2 perceived the sound fields in terms of only LF_{E4}. In particular, subjects of Group II-2 perceived sound fields with low lateral energy more diffusive. These results indicate that the perception model of scattered sounds can be divided into two groups according to subjects: a number of reflections group and a lateral energy group.

CONCLUDING REMARKS

In this paper, perception of scattered sound fields was investtigated in a rectangular concert hall, objectively and subjectively. From the acoustical measurement, distribution ranges of acoustical parameters including in-situ diffusivity indices (N_{pE} and N_{pL}) were measured. With highly diffusive lateral wall surfaces, sound level, binaural dissimilarity, number of reflections were varied according to distance from sound source and lateral wall.

From the subjective evaluation, sound pressure level was found as the dominant parameter to judge subjective diffusion. However, one perceives louder sounds more diffusive, whereas the other perceives oppositely. When sound level was fixed and the other parameters were changed, one perceives many early reflections more diffusive, whereas the other perceives low lateral reflections more diffusive. Because the experiments were carried out as a pilot test with only 12 subjects, the results should be verified with sufficient number of individual responses.

Sound level is the most dominant factor to perceive preference or sound diffusion. However, this paper demonstrated that N_{pL} and N_{pE}, number of peaks, could be effective paramters to evaluate sound diffusion subjectively. In further study, perceptible limen of N_p parameters and range of N_p values by different concert halls are needed to be investigated.

ACKNOWLEDGEMENT

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