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Objective assessment of a scattered sound field in simulated concert halls and scale model

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ABSTRACT

To propose an appropriate design for sound diffusion through the walls of concert halls, computer simulations and a scale model were used to investigate the effect of diffusion and diffusion arrangements on the acoustic parameters of the concert halls. Two types of models were constructed and analyzed: 1) the 12 concert halls included in an Odeon simulation with reflective surfaces, and 2) the same simulation models with existing scattering coefficients. The effect of the overall wall diffusion in the concert hall was examined by analyzing the room acoustic parameters. Specifically, the position, area, and height of the diffuser were determined using various scale models. Through auralization evaluation in the 1:10 scale model, acoustic disturbance and the improvement in acoustic response through diffusion design were evaluated. The results show that the relative standard deviation values of the acoustic parameters as well as the reverberation time, early decay time, and sound pressure were reduced by sound diffusion through the wall surfaces.

Keywords: Sound scattering, Computer simulation, Scale model, Auralization, Room acoustic parameter

1. INTRODUCTION

Many studies have investigated the positive effects of diffusion on the acoustic quality and verified that diffusion has a considerable effect on the uniform distribution of acoustic parameters and spaciousness experienced by audience in concert halls (1, 2). Furthermore, diffusion has been quantified to understand the effects of sound diffusion on objective acoustic parameters and subjective evaluation, and various indices have been suggested including scattering coefficient (S_c), directional scattering coefficient (D_c), number of peaks (N_p), and relative standard deviation (RSD) (3, 4).

The effects of sound diffusion on impulse responses and room acoustic parameters and the auditory effects of scattering coefficient in an actual hall and an auralized simulation hall have been studied.

First, studies on diffusion in actual halls have been conducted through field evaluation and the evaluation of various scale models. Kim et al. (5, 6) observed that diffusion influenced the reverberation time (RT) and early decay time (EDT) and increased clarity (C_{80}) in various 1:50 scale model halls. In a follow-up study, they observed that diffuse surfaces increased the EDT in a 1:25 scale model, but decreased EDT and C_{80} in a field evaluation. Jeon et al. (4) verified that the change patterns of parameters such as RT, EDT, G, and C_{80} vary by the shape of the hall. Thus, even for actual halls, it is very difficult to generalize the effects of diffusion on physical acoustic parameters or subjective evaluations owing to various acoustic factors influencing the diffusion sound field, such as the location of diffusers, the locations of sound-absorbing surfaces, and the shape of the hall.

Diffusion studies based on simulation models have been conducted as well. Significant differences in auditory perception depending on the existence or absence of wall diffusion were evaluated and the result confirmed the usefulness of diffusive surfaces in large concert halls (7). Furthermore, the accuracy of acoustic predictions was verified through a comparison of diffusion performances in various sound simulations, and the prediction results of the room differed by the acoustic tool (9). Therefore, even though the effect of diffusion on acoustic evaluations can be verified, there are limitations in investigating the concrete auditory causes because the diffusion simulation itself is considerably affected by the algorithm.

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Accordingly, to complement the limitations of scale model design and computer simulation, the effects of diffusion on the objective acoustic parameters of concert halls were examined by using these two methods together. Furthermore, the concrete causes of the effects of diffusion on subjective acoustic evaluation were examined through additional auditory test.

2. EXPERIMENT 1: CASE STUDY

2.1 Description of the case study

First, to examine the changes in acoustic parameters according to the changing scattering coefficient of the inner surface, the Boston Symphony Hall (BSH), a typical rectangular hall in the Odeon Simulation version 15 library, was used as a model. This hall had a volume of 18,750 m^2 and 2,625 seats. The internal materials of the model were fit similarly to the actual measurements of the hall based on the data provided by the simulation tool by default (10).

A total of 54 sound reception points were established at a height of 1.2 m with one receiver placed in each unit area of 2 × 2 m, and the sound source was placed at a height of 1.5 m at the solo position on the stage. The transition order was set as 2, the impulse response length as 5,000 ms, and the number of late rays as 15,000, which is higher than the recommended value.

2.2 Simulated alternatives

The sound absorption rates of the ceiling and walls were set identical in general except for the stage and balconies. The simulations were performed for two cases: a reflective surface (RS; $S_c = 0.05$) and a diffusive surface (DS; $S_c = 0.7$). The diffusion by frequency was not considered because the Odeon Simulation applies the same scattering coefficient for all frequencies based on the scattering coefficient of 707 Hz.

The room acoustic parameters i.e., the reverberation time ($RT_{20,\ occ}$), EDT, clarity (C_{80}), and lateral fraction (LF_{E4}) were analyzed as defined in ISO 3382-1. In addition, G_{early} was analyzed to examine the effect of sound diffusion on the initial sound pressure level.

2.3 Results

Table 1 outlines the sound simulation results for the two models of RS and DS. When a high scattering coefficient was applied, the RT decreased by 0.43 s, and the RSD decreased by 50% to 0.05, thus decreasing the deviation between seats. The EDT also showed a decreasing tendency similar to the RT, but the RSD did not change much. C_{80} and LF increased by 0.3 dB and 0.01, respectively. The G, which indicates loudness in the hall, decreased by 0.45 dB owing to the increased scattering coefficient, but the RSD increased by 0.15, and G_{early} also showed a similar tendency as G. These results were similar to the results of the scale model evaluation for a rectangular hall by Ryu and Jeon (12) in terms of average values, but the RSD values were not consistent with each other. Furthermore, our results were in contrast to the results of a previous study (9) in which the RT and EDT increased as the scattering coefficient increased, but C_{80} decreased. This is because the BSH is much larger than the hall in the previous study (N = 480 seats, V = 2380 m^3), and the ratio of side walls and ceiling areas of the BSH is much higher than that in the previous study. Thus, even if the Oblique Lambert is compensated for, the energy loss owing to the increased scattering coefficient is high (13).

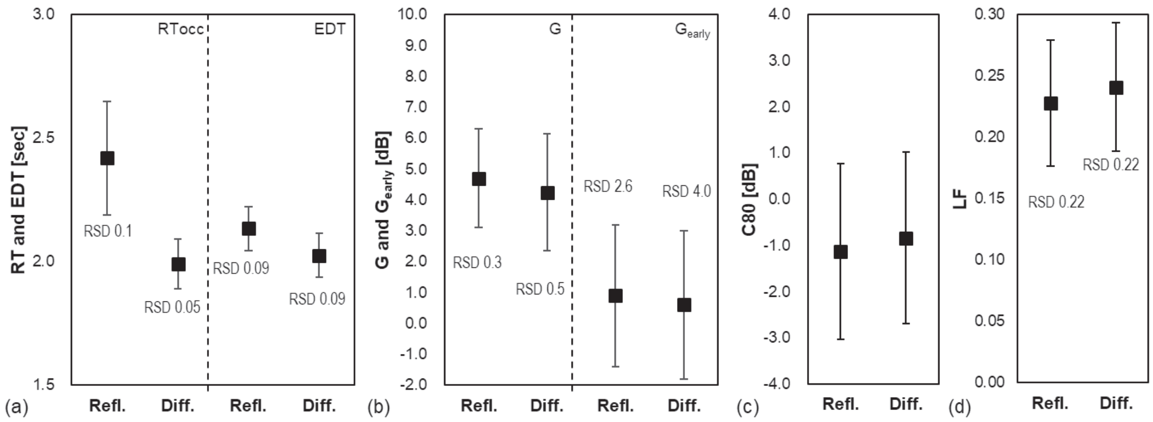

Figure 1 – Acoustical parameter with RSD according to cases (a) RT and EDT, (b) G and G_{early}, (c) C_{80}, (d) LF in Boston Symphony Hall

3. EXPERIMENT 2: REAL HALL

3.1 Computer simulation

3.1.1 Hall description

Based on the case study results, computer simulation and a scale model experiment were performed for an actual concert hall. For this purpose, the Art Center Incheon (ACI) with 1,750 seats and a volume of 18,500 m^3 was selected. The ACI is a fan-type hall with lateral walls formed as vineyard terraces for acoustic and visual intimacy.

3.1.2 Simulation setup

The basic setup of the simulation was identical to that of Experiment 1. For the materials, the sound absorption rates of the actual design materials were applied. The stage and some surfaces were adjusted similarly to the actual measurement data by applying the data provided by the Odeon Combined 15 library. A total of 41 sound reception points were specified with one reception point per 2 × 2 m grid, and the sound source was specified as a solo position. The RS and DS models were evaluated, and the scattering coefficients of 0.05 and 0.7 were applied, respectively, to all walls and ceiling except for the stage floor and surrounding walls and balcony fronts.

3.1.3. Results

Figure 2 shows the results of acoustic parameters for the two simulation models. The DS model showed larger RT than that of the RS model, and the deviation between seats was higher by 0.01. When the scattering coefficient was higher, the EDT decreased, but the RSD increased. Furthermore, the G increased as the scattering coefficient increased, and not only did the average value of G_{early} increase, but the RSD also decreased, indicating a smaller deviation between seats. C_{80} increased by 0.7 dB, but the LF changed very little. In particular, RT, G, and G_{early} showed opposite change patterns to those of the BSH. The reason for this appears to be that the ACI has a larger area of balconies, and the area of walls affected by the changed scattering coefficient of the walls is very small. Consequently, not only is the energy loss by the diffusion algorithm small, but there is also an effect of the secondary source of the image source for the initial sound field.

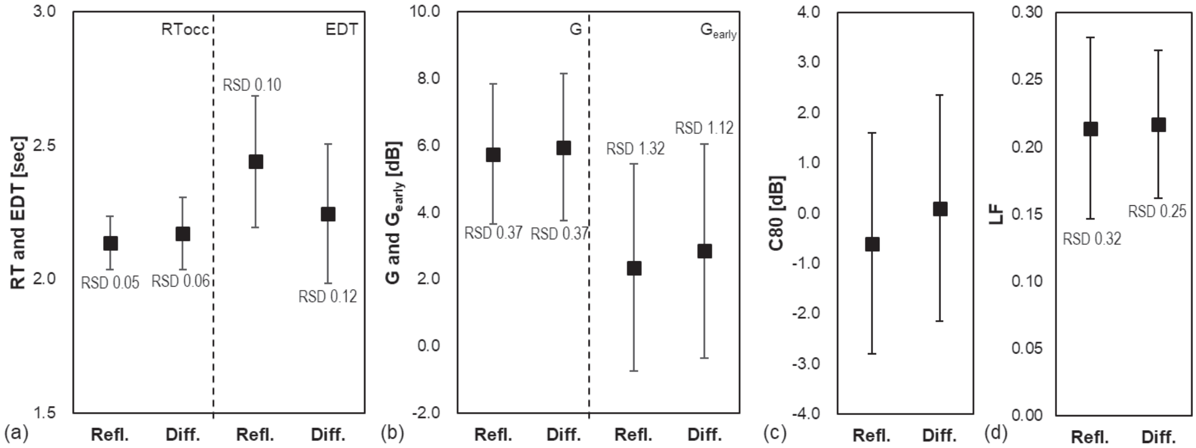

Figure 2 – Acoustic parameters with RSD according to cases (a) RT and EDT, (b) G and G_{early}, (c) C_{80}, (d) LF in Art Center Incheon

3.2 1:10 Scale Model

3.2.1 Measurement

A 1:10 scale model with the same shape as the model used in the computer simulations was fabricated and the acoustic parameters were measured according to the existence or absence of diffuser. The location of the diffuser was based on the evaluation results of various scale models (14). Consequently, a higher diffusion was applied to the walls closer to the stage and a lower diffusion was applied to the walls farther from the sound source. A miniature loudspeaker (a speaker with a diameter of 13 mm) and a miniature dummy head, which were produced using a 3D printer, and 1/8-inch microphones (B&K) were used as sound sources and receivers. The sound source point was selected as a solo position, and the locations of receivers were selected near the side walls, which are affected considerably by the diffuser of the wall. A sampling rate of 192 kHz was used for the analysis considering down sampling, and the measurement results were analyzed using Adobe Audition Software 1.5 version.

3.2.2 Result – effect of sound diffusion on objective acoustic parameters

Table 1 outlines the measurement results of acoustic parameters according to the existence or absence of diffuser. The RT decreased in general and the EDT increased as the diffuser was deployed. Furthermore, C_{80} and G decreased at all points. This is a different change pattern from the simulation result using the same model. One cause of this difference appears to be that, in the case of the 1:10 scale model, the scattering coefficient of the diffuser profile attached to the surface is different from that of the simulation, and the primary cause is the increased sound absorption rate owing to the increased surface area by the attachment of the diffuser. Another cause is that the Odeon Simulation cannot reflect a realistic reflection directivity that is similar to the real value because it only applies the scattering coefficient to the surface without directly modeling the diffuser profile (7).

Table 1 – Comparison of the acoustic parameters measured in diffusive and non-diffusive cases

	R1		R2		R3		R4		R5		Ave	
Diffuser	-	√	-	√	-	√	-	√	-	√	-	√
RT (sec)	2.25	1.99	2.10	2.05	2.22	1.98	2.19	2.02	2.13	2.01	2.18	2.01
EDT (sec)	2.30	2.46	2.05	2.16	2.11	2.33	2.33	1.82	2.41	2.24	2.41	2.20
C_{80} (dB)	-0.0	-2.3	-1.6	-2.1	-0.9	-0.5	-2.5	-0.8	-2.2	-1.9	-1.4	-1.0
G (dB)	7.1	6.6	6.4	5.9	5.8	5.4	3.9	3.6	3.8	3.4	5.4	5.0

3.3 Subjective evaluation

3.3.1 Design of auditory test

A 15-s-long soprano sound was used as a sound source for evaluation. Ten stimuli in total were created by performing convolution of the impulse responses measured at the reception points R1 to R5 before and after installing the diffuser. This experiment was conducted with 30 audio engineers and college students with normal hearing. The same sound source was played repeatedly 10 times through headphones (Sennheiser HD 650). The background noise was very low at 25 dBA.

The questionnaire consisted of 10 questions including five questions about acoustical impression (clarity, reverberance, envelopment, intimacy, and loudness), four questions about brilliance and warmth, which indicate balance, and diffusion (density of reflection, smoothness of decay curve, smoothness of reflection, and isotropy directivity), and overall satisfaction. Every question was answered based on an 11-point scale.

3.2.2 Results - effect of sound diffusion on subjective acoustic quality

Table 2 outlines the changes in the evaluation parameters before and after attaching the diffuser. Subjective responses increased after installing the diffuser in all parameters except reverberance and bass ratio. Notably, the overall impression increased after installing the diffuser. It can be observed from examining the detailed results that clarity and intimacy increased significantly. As the clarity and intimacy increased, the loudness increased to some extent, even though the physical sound pressure index decreased. The diffusion-related indices also increased in general, even though the amount of increase is not large.

Table 2 – Mean value of subjective impressions in reflective and diffusive cases

	Diffuser	Cl	Rev	Env	Int	Loud	Br	Wa	DoR	SoD	SoR	ID	OI
R1	-	2.9	7.4	5.0	3.7	6.5	5.3	6.4	5.4	4.3	4.5	5.0	3.0
	√	6.5	5.7	6.6	6.7	7.5	6.9	5.4	6.9	5.8	5.3	6.8	6.2
R2	-	1.5	7.7	3.5	1.6	4.8	3.1	6.9	4.6	4.1	4.5	5.6	1.6
	√	4.6	6.4	5.7	4.8	5.9	6.0	4.9	5.2	4.7	4.9	6.7	4.6
R3	-	2.1	7.2	4.1	2.6	5.0	3.7	6.6	4.6	4.5	4.1	5.6	2.4
	√	5.8	4.8	6.5	6.0	6.5	6.5	5.0	6.0	6.0	5.9	6.7	5.5
R4	-	4.3	6.0	4.8	4.3	4.6	4.9	4.9	5.1	5.0	5.3	3.5	3.9
	√	5.5	5.6	4.8	4.6	4.8	5.2	5.8	5.9	5.2	5.7	4.8	4.9
R5	-	2.4	7.4	4.2	2.4	3.8	3.6	6.0	4.4	5.5	4.6	3.5	2.2
	√	6.6	4.1	4.7	6.3	5.5	6.2	4.8	5.5	6.2	6.2	4.4	5.9
Avg.	-	2.6	7.1	4.3	2.9	4.9	4.1	6.2	4.8	4.7	4.6	4.7	2.6
	√	5.8	5.3	5.7	5.7	6.0	6.2	5.2	5.9	5.6	5.6	5.9	5.4

*Cl: Clarity, Rev: Reverberance, Env: Envelopment, Int: Intimacy, Loud: Loudness, Br: Brilliance, Wa: Warmth, DoR: Density of reflection, SoD: Smoothness of decay, SoR: Smoothness of reflection, ID: Isotropic directivity, OI: Overall impression.

4. DISCUSSION AND CONCLUSION

In the case study, the change patterns of acoustic parameters were verified through sound simulation according to the existence or absence of diffusion in the rectangular-shaped BSH. The results showed that, the higher the scattering coefficients of the inner walls and ceiling of the concert hall, the lower were the RT, EDT, and G, and the higher were the C_{80} and LF. In addition, the diffusion algorithm of the Odeon Simulation and the effects of the wall and balcony areas were examined through a simulation of the same environment in the fan-shaped ACI hall. The evaluation results of the effects of diffusion in the two halls reconfirmed that it is difficult to generalize the effects of diffusion on the acoustic parameters owing to various factors such as the limitation of the diffusion algorithm of the Odeon Simulation, the shape and volume of the hall, and the shape and placement of the diffuser (5, 7). This could be verified from the different tendencies of the acoustic parameters owing to the differences in the attachment position and shape of the diffuser as well as the difference in the scattering coefficient between the computer simulation and the scale model of ACI. In the auralization evaluation results according to the existence or absence of the diffuser, a large loudness was perceived owing to the sound absorption effect of the diffuser and the overall impression increased even though the RT and G increased. This suggests that there is a limitation in evaluating the acoustic quality of concert halls only through the results of physical parameters. Therefore, scale model evaluation must be considered together with computer simulation for the design of an appropriate diffusion level in concert halls. However, in this study, the effects of diffusion were examined for specific small halls. Thus, in future studies, the effects of diffusion on the sound field of concert halls need to be examined through experiment results for more diverse halls. Nevertheless, the findings of this study are meaningful in that they provide a design process for the simultaneous consideration of simulation and modeling for the diffusion of newly designed or remodeled concert halls.

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