IN-SITU MEASUREMENTS OF DIFFUSE REFLECTIONS FROM LATERAL WALLS IN CONCERT HALLS

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1 INTRODUCTION

Recent studies on sound diffusion have focused on quantifying the surface characteristics under laboratory conditions: 'diffusion coefficient' [1] and 'scattering coefficient' [2]. Scattering coefficient quantifies non-specular reflections relative to random incident sound energy based on RT measurements in a reverberation chamber, whereas diffusion coefficient quantifies the reflections from the autocorrelation function of polar responses in an anechoic chamber. The measurement methods for the coefficients have been standardized [1, 2], however evaluating the performance of diffusers under laboratory conditions is restrictive because the measured values indicate only the material characteristics of the diffuser surfaces.

Scattering characteristics of surface profiles have been investigated for concert hall design [3]: when diffusers are applied to the specular surfaces of rectangular halls, the RTs are reduced by more than 10%, depending on the surface coverage and structural heights of the diffusers [4]. Diffusers actually increase the linearity of the decay curves and decrease RT [5], whereas IACC decreased at seats close to circular columns in front of the walls [6]. Although some acoustical parameters have been found useful in evaluation of diffuse sound fields [7], they do not directly represent the diffusive reflection of surface materials; there is still no direct way to evaluate in-situ diffusion characteristics in a hall.

In this study, in-situ measurements of diffuse reflections from different wall conditions were carried out. First, a scale model hall with a stage enclosure was tested. Then, based on the results from the scale model testing, real hall measurements were carried out in the existing halls in Seoul and Grenoble.

2 DIFFUSE REFLECTIONS

In an enclosed space, the diffuse characteristics of a reverberation process are explored by considering the difference in temporal density of the impulse response. As shown in Figure 1, the degree of sound diffusion can be defined as the number of peaks (N_p) within the lapsed time of the effective amplitude drop. The peaks are in fact local maxima not reflections: they are arbitrary shapes in overlapping reflection components. As a simplified model for diffusion perception depends on audibility of the resultant waveform on a dB scale, the difference in the N_p values may represent the degree of diffusion.

Scattered reflections generally yield decrease of sound level and reverberation in concert halls [7], but promote spatial distribution of acoustical parameters. In this study, the sound fields resulting from different wall profiles were evaluated using related parameters such as Sound strength (G), Early decay time (EDT), Number of peaks (Np), and coefficient of variation (COV) of G and EDT.

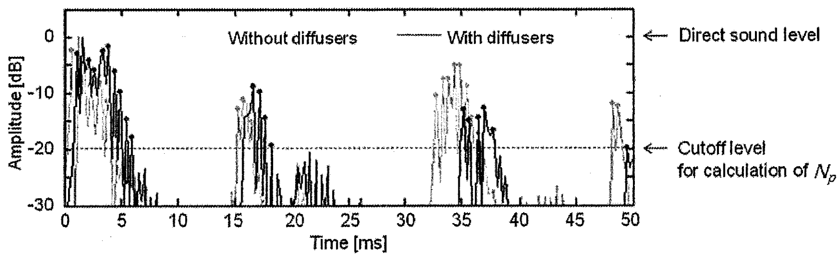


Figure 1. Comparison of the peaks (Np) from the impulse responses

3 SCALE MODEL EXPERIMENTS

3.1 The Lighthouse Concert Hall, Poole, UK

As shown in Figure 2, a model hall, the 1:25 scale model of the Lighthouse Concert Hall in Poole, UK, made by Mike Barron, was used for evaluation of lateral wall diffusion. The model was made of wood coated with water-based paint. The floor was covered with 20-mm thick polyurethane foam to simulate audience absorption. The rear wall of the audience area was open and the balcony front of the second floor was installed. There were scattering wall profiles on the rear-stage and lateral walls, which were made of reinforced plastic resin. In Figure 3, the existing walls are indicated A (stage rear), B (stage lateral) and C (audience).

Two source and six receiver positions were selected: an electric-spark generator for the sound source (S1 and S2) and 1/8 inch B&K microphones for the receivers (R1 to R6). As shown in Table I, to compare different wall profiles, the existing diffusive surfaces (D) were covered with wave-shaped (W) plastic boards, then with hard flat board (F). Using these treatments, three measurement cases were considered according to the treated wall configurations: from Case 1 (totally flat) to Case 3 (totally diffuse).

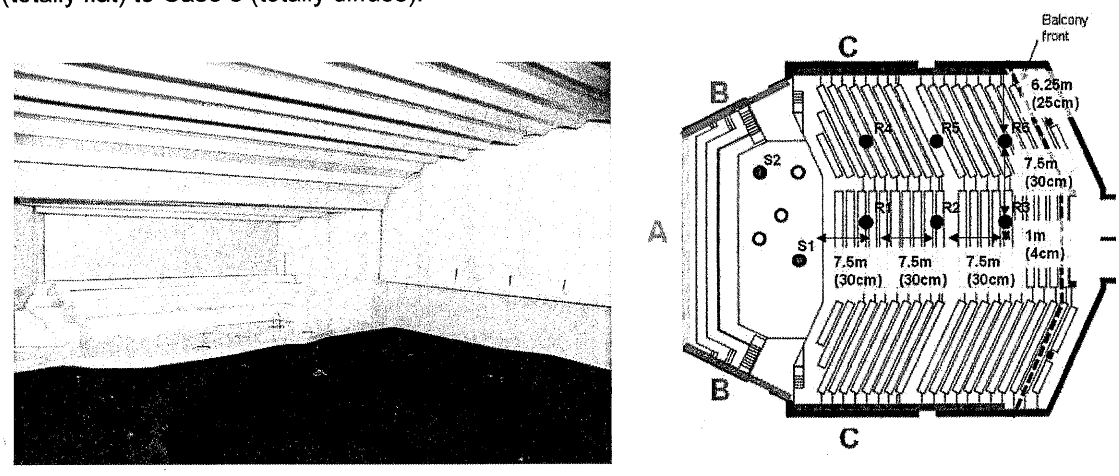
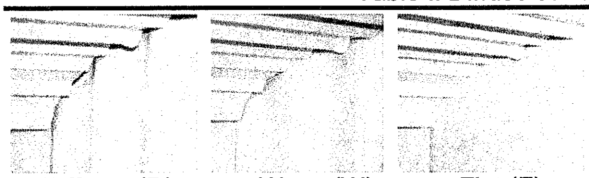


Figure 2. Measurement positions in the 1:25 scale model hall

Table I. Diffuse surface configurations

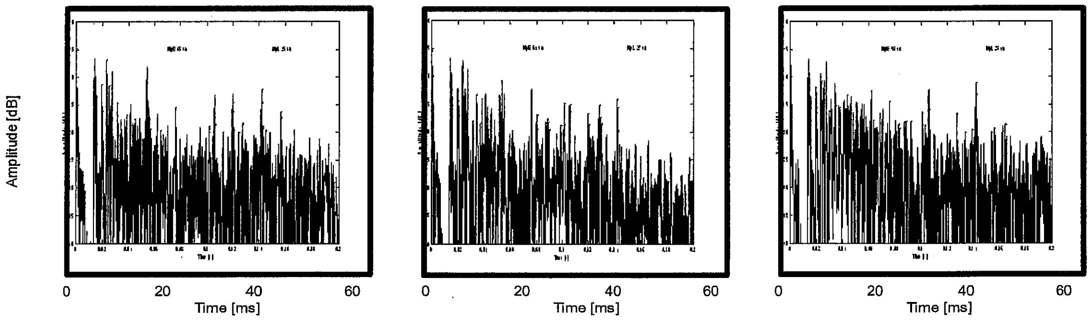


Diffuser (D) Wave (W) Flat (F)

Walls	Case 1	Case 2	Case 3
A (Stage rear)	F	F	D
B (Stage lateral)	F	W	D
C (Audience)	F	D	D

3.2 Results

Figure 3 shows the early parts of the measured impulse responses at positions R4 (with S2) according to the diffuser configuration. Major reflections at 20-60 ms are scattered due to the existing wall profiles. As shown in Figure 3 (a), clear specular peaks at 50 ms were found in Case 1 with all flat surfaces. However, with the increase of diffusive surfaces, these specular peaks disappeared and the reflection density increased as shown in Figure 3 (c).



(a) Case 1 (FFF) (b) Case 2 (FWD) (c) Case 3 (DDD)

Figure 3. Temporal characteristics of early scattered reflections by diffuse surfaces (R4)

Table II shows the average value of EDT at mid frequencies, the standard deviation of EDT as a function of COV, and Np in the early parts (0 to 80 ms). Both diffusive cases (Cases 2 and 3) provide longer EDT and less COV of EDT than those in the flat surface case (Case 1). In terms of spatial distribution, lower COV indicates even characteristics. Np increases about 20% with full diffusive surfaces. Because the scale model is incomplete in the rear, some limitation for the full evaluation of acoustical parameters does exist.

Table II. Measured acoustical parameters in the 1:25 scale model hall

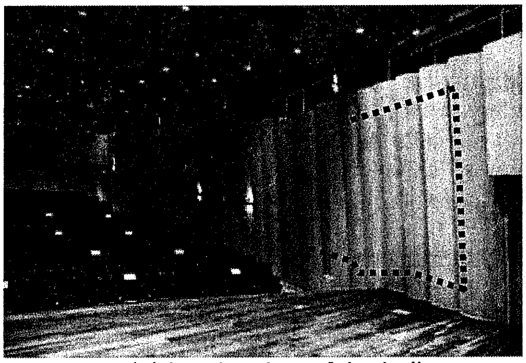
	Case 1 (FFF)	**Case 2 (FWD)**	**Case 3 (DDD)**
$EDT_{500\text{-}1kHz}$ [s]	1.10	1.16	1.16
COV_{EDT}	0.13	0.11	0.12
$Np_{E,20dB}$	78	75	92

4 IN-SITU EXPERIMENT I

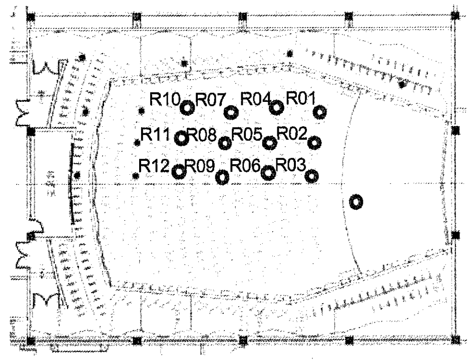
4.1 Sejong Chamber Hall, Seoul, Korea

Based on the experience of the above scale model testing, in-situ measurements of diffuse reflections from lateral walls in the Sejong Chamber Hall, Seoul were planned. The hall has 443 seats with a volume of 3,212 m^3. The main usage is for recital and chamber music. The hall has a rectangular floor plan with reverse-fan shaped stalls. Lateral walls are designed as saw-tooth shaped diffuser made of GFRC (Glass-fiber reinforced concrete). Maximum depth of the diffuser is 300 mm and the average height of the lateral walls is around 4 m.

Figure 4 (b) shows the measurement positions on the first floor. An omni-directional dodecahedron loudspeaker, a dummy head and AKG-414 microphones were used for both measuring and recording. RT, EDT, C80, $IACC_{E3}$ and Np_E were derived from the impulse responses.



(a) Interior view of the hall



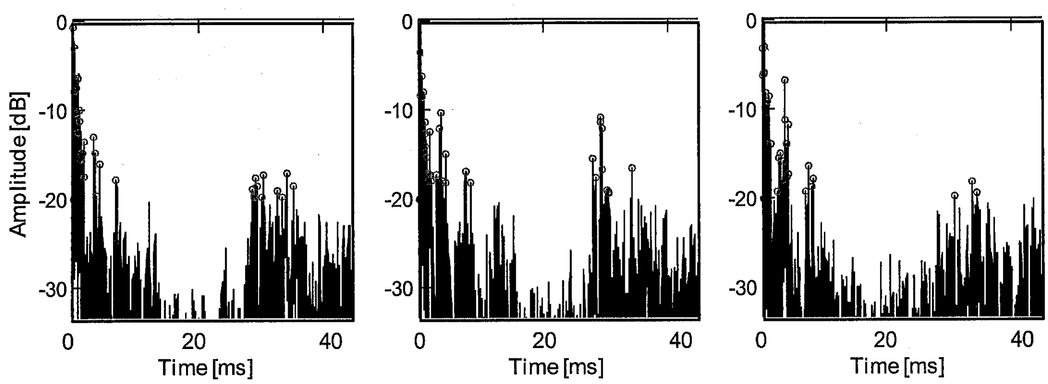
(b) Measurement positions

Figure 4. Picture and measurement position of the Sejong Chamber Hall. Dotted line on the picture indicates the area for installation of plastic boards

To control diffusive lateral walls, hard plastic boards and sound-absorbing fabric (microfiber) were installed on the lateral walls as shown in Figure 4 (a). Before application of these treatments, the absorption characteristics of the plastic board and fabric were measured according to ISO 354; the plastic board was 5-mm thick with an averaged absorption coefficient of 0.08. The average absorption coefficient of the microfiber with the plastic board underneath increased up to 0.44 with 300 mm air gap. The total area of the installed flat board was 77 m^2. In each case, acoustical parameters were measured with the same methods.

4.2 Results

Figure 5 shows the early parts of the measured impulse responses within 40 ms at the near wall position (R01) according to diffuser configuration. Major reflections at 30 ms around are scattered due to lateral wall profiles in the same manner as the scale model results. As shown in Figure 5 (b), specular peaks at 28 ms are found for the flat wall case with plastic boards on the near-stage lateral walls. Both Diffusive and Absorbing Cases decrease the specular peaks, but for the Diffusive Case, the sound level of scattered reflections was not much decreased compared with the Absorbing Case.



(a) Diffusive Case (b) Reflective Case (c) Absorbing Case

Figure 5. Temporal characteristics of the early scattered reflections by diffuser configuration received at R01 position

Figure 6 shows the results of EDT and COV of EDT by frequency bands according to diffuser configuration. EDT was decreased for the Absorbing Case, but the Diffusive Case showed the highest EDT at 250 Hz band. This indicates that the saw-tooth profile has large diameters (0.6 to 1.2 m) which correspond to the low frequency diffusion. Contrarily, relative standard deviation of EDT (COV of EDT), showed lower values in both Diffuse and Reflective Cases than Absorptive Case. However, at high frequency bands, the Diffusive Case showed the lowest values among the measurement cases.

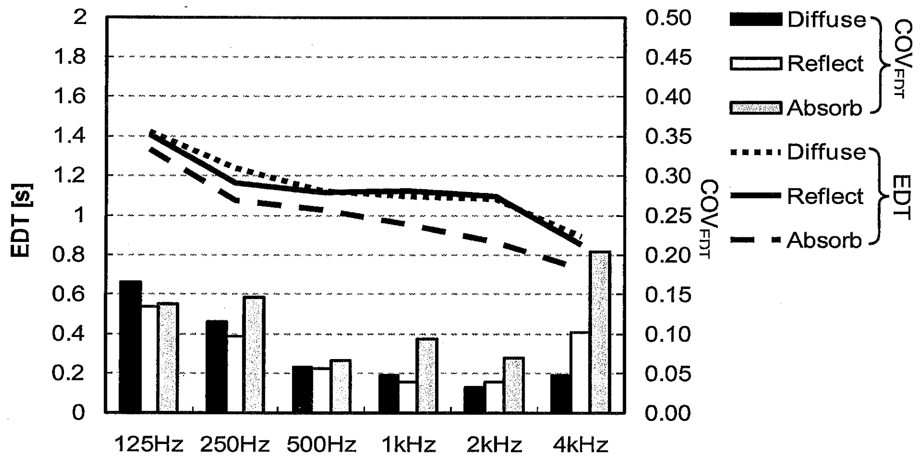


Figure 6. Average and COV of EDT according to diffuser configuration in the Sejong Chamber Hall

Table III shows the average values of RT and EDT at mid frequencies, C80 and $IACC_{E3}$ at 500 Hz to 2 kHz bands and Np in the early parts. For RT and EDT, spatial distributions were evaluated using COV, and for C80 and IACC, standard deviation was applied. There were little differences between Diffusive and Reflective Cases for averaged RT and EDT. C80 and $IACC_{E3}$ also showed little difference between the Diffusive and Reflective Cases. However, Np showed a clear difference between Diffusive and Reflective Cases.

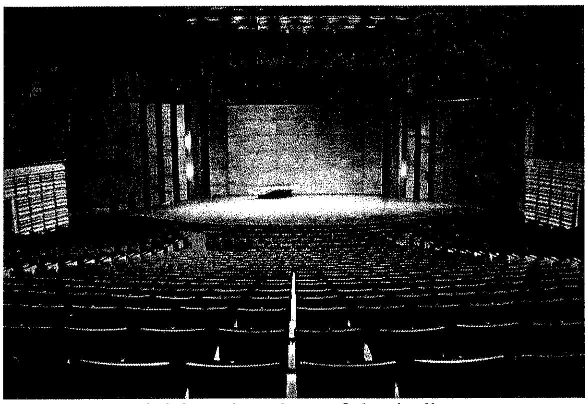
Table III. Measurement results of acoustical parameters in the Sejong Chamber Hall

Acoustical parameter	Diffuse Case	Flat Case	Absorb Case
$T30_{500\text{-}1kHz}$ [s]	1.18	1.18	1.01
COV_{T30}	0.02	0.02	0.01
$EDT_{500\text{-}1kHz}$ [s]	1.11	1.12	0.99
COV_{EDT}	0.05	0.05	0.08
$C80_{3B}$ [dB]	2.9	3.0	4.4
St. Dev.C80	0.48	0.47	0.37
$1\text{-}IACC_{E3}$	0.64	0.64	0.54
St. Dev.$1\text{-}IACC_{E3}$	0.43	0.35	0.30
$Np_{E,20dB}$	307	201	197

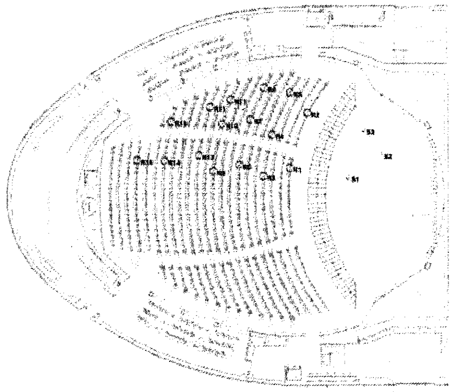
5 IN-SITU EXPERIMENT II

5.1 MC2 Concert Hall, Grenoble, France

Another hall with diffuse lateral walls has been measured to study the in-situ characteristics of diffuse reflections. This venue is the MC2 Concert Hall located in Grenoble, France shown in Figure 7. It is a 998 seats auditorium of 11,500 m^3 mainly used for classical music concerts. The hall has an oval shaped plan with diffusing elements made of concrete (lower part of lateral walls) or wood (upper part of lateral walls), as shown in Figure 8 (a). We focus here on the concrete diffuser on one side of the symmetric auditorium which is located close to the audience. Therefore the effect of the diffuser on the seats close to the side wall was expected to be the most significant. The maximum depth of the concrete diffuser is 11 cm.



(a) Interior view of the hall

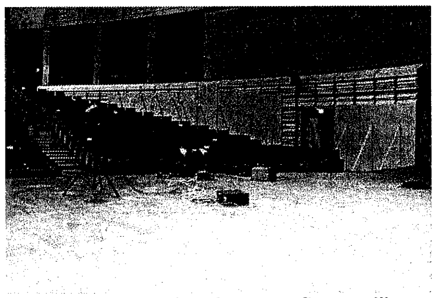


(b) Measurement positions

Figure 7. Picture and measurement position of the MC2 Concert Hall

To control the diffusivity of the lateral walls, hard medium wood MDF boards were temporally installed on one side as shown in Figure 8 (b). Then, only the half of the hall close to the modified wall has been measured to study the effect of the covering of the diffuse wall. Figure 7 (b) shows the measurement positions in the stalls. An omni-directional dodecahedron loudspeaker was used at three stage source positions. Impulse responses have been measured in total of sixteen receiver positions. The results were recorded with a Sennheiser MKH 80-P48 microphone and processed according to ISO 3382-1. RT, EDT, Np_E and Np_L were derived from the measured impulse responses.

(a) Case 1 (Diffusive wall)



(b) Case 2 (Reflective flat wall)

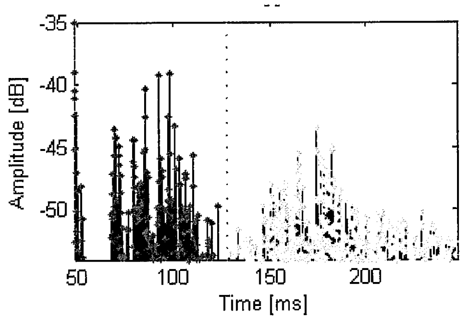
Figure 8. Two measurement cases by different diffuser configurations on lateral walls

5.2 Results

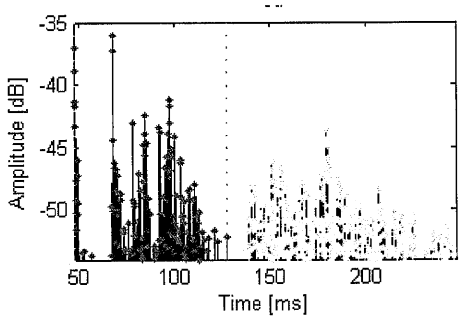
Figure 9 shows the echogram until 200 ms for the dynamic range of 20dB at a seat located in the middle of the stalls. One can note that reflections at 70 ms for the early part and at 140 ms and 205 ms for the late part are diffused.

Table IV shows the averaged values of RT and EDT at middle frequencies, Np_E and Np_L (80 to 200 ms). The coefficient of Variation (COV) or standard deviation has been also used here to study spatial distribution. The figures show that RT is very constant for all seats between the Diffusive and the Reflective Case. The EDT value is slightly higher for the Diffusive case which can be explained by the diffuser material (concrete, $\alpha s \sim 0.02$) reflecting more energy than medium boards.

The Np in the early part of the impulse response (0 to 80 ms) is shown as an average of sources S2 and S3. Compared to the Sejong Chamber Hall Np values are lower. One reason is that the ratio area of diffuser to total area of the wall is smaller for the MC2 which means that only a small diffusion effect can occur. Another reason is that the MC2 Hall's volume is larger than the Sejong Chamber Hall which induces that reflections arrive later in time. This means that there are less peaks if the same cutoff level (dynamic range of 20dB) is considered for the calculation of Np_E. Therefore the Np_L parameter is then investigated which is 24% higher for the Diffusive Case compared to the Reflective Case. In both cases (Np_E, Np_L) the parameter Np gives an indication of diffusivity of the hall.



(a) Diffusive Case



(b) Reflective Case

Figure 9. Temporal characteristics of the early scattered reflections by diffuser configuration received at R10 position, S2 source in the MC2 Hall. Red dot: early part, green dots: late part.

Table IV. Measurement results of acoustical parameters in the MC2 Concert Hall

Acoustical parameter	Diffuse Case	Reflective Case
$T30_{500\text{-}1kHz}$ [s]	2.21	2.22
$EDT_{500\text{-}1kHz}$ [s]	2.12	2.09
COV_{EDT}	0.07	0.08
$Np_{E,20dB}$(S2, S3)	157	137
$Np_{L,20dB}$(S2, S3)	127	100

6 CONCLUDING REMARKS

In this study, scale model and real halls were investigated according to the different lateral wall profiles in terms of in-situ diffusion. In the 1:25 scale model testing, although the model has only stage enclosure, Np changed sensitively according to the amount and configuration of diffusers. These results were confirmed through the field measurements in both Sejong Chamber Hall and MC2 Concert Hall. Because diffusers tend to decrease sound level and reverberation, it is required to develop the application methods of the conventional acoustical parameters to evaluate the diffuser configurations. From the results of the Sejong Chamber Hall experiments, EDT and its relative spatial deviation seem to be another positive indicator in addition to Np.

This study has been limited to the objective investigation of the acoustical parameters, but more studies in the perception of scattered sounds in concert halls may indicate the amount of diffusion. As a further study, in-situ diffusivity of more concert halls is needed to establish a guideline for proper diffusion.

7 ACKNOWLEDGEMENT

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