Investigation of sound diffusion characteristics using scale models in concert halls

J. Y. Jeon[1], Y. H. Kim[2]

[1] *Hanyang University, Seoul 133-791, Korea, Email: jyjeon@hanyang.ac.kr*
[2] *Hanyang University, Seoul 133-791, Korea, Email: kimyonghee@gmail.com*

Introduction

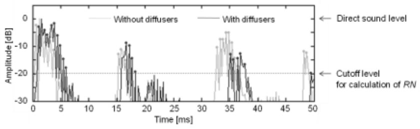
Recent studies on sound diffusion have mostly focused on quantifying the diffuser characteristics under laboratory conditions [1], namely ‘diffusion coefficient’ [4, 5] and, ‘scattering coefficient’ [2, 3], which are both necessary in evaluating early and late, respectively. The scattering coefficient quantifies the non-specular reflections (late energy) relative to random incident sound energy based on RT measurement in a reverberation chamber, whereas the diffusion coefficient quantifies the 2-D reflections from the autocorrelation function of polar responses (early energy) in an anechoic chamber. Although measurement methods for both coefficients have been standardized [3, 5], evaluating the performance of diffusers under laboratory conditions is restrictive because the measured values indicate the material characteristics from diffusion close to the diffuser surfaces. The audience in concert halls perceives not only the direct surface diffusion but the whole sound field, including the late sound reflections. Therefore, actual sound fields, which are affected by the geometrical shape of halls, diffuser profiles and source-receiver relationships, should be comprehensively evaluated using binaural impulse responses at each listener’s position.

The scattering characteristics of the surface profiles have been investigated for concert hall design [6-7]: when diffusers are applied to the side walls of rectangular halls, the RTs are often reduced by more than 10%, depending on the surface coverage and structural heights of the diffusers [7]. Diffusers actually increase the linearity of the decay curves and decrease RT [9], whereas IACC decreased at the seats close to the circular columns in front of the walls [8]. So far, in evaluation of diffuse sound fields, EDT, SPL and 1- $IACC_{L3}$ have been found as useful parameters [10]. However, the acoustical parameters do not directly represent the diffusive reflection of surface materials at each of the auditorium seats. There is still no direct way to evaluate in-situ diffusion characteristics in a hall, which may correlate with the surface diffusion parameters such as diffusion and scattering coefficients.

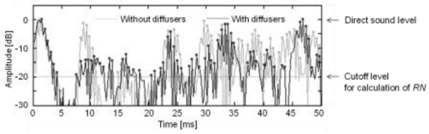
The expected phenomena for a sound field with appropriate diffuseness are: uniform distribution of sound pressure levels in both spatial and temporal domains, a smoother decay curve at the early part of reflections, and improvement in spatial impression, which results from scattered reflections with minimal loss of sound energy. Therefore, a sound diffusivity index should be evaluated from impulse response measurements, which contain information on the geometrical shape, surface absorption characteristics and source-to-receiver characteristics. In this paper, a new acoustical parameter which may characterize the diffuse elements from the impulse responses is introduced and validated through physical and auditory experiments using scale model concert halls.

In-situ diffusivity indices

Upon considering the differences in the temporal density of rays in the impulse responses, the degree of sound diffusion can be defined with indices: the number of reflected sound rays (RN) and the energy summation (RE) within the lapsed time of the effective amplitude drop. The lower limit of the amplitude level for calculating both RN and RE should be determined (see Fig. 1). Thus RN_{20} is defined as the number of reflected rays for which the level is within -20 dB of direct sound, and RE is defined as the summation of sound energies in the normalized impulse response measured in the auditorium. Both RN and RE are defined as early (0-80 ms) or late (80-200 ms) reflection values (for example, RN_{E20} indicates reflection numbers for early reflection with a -20 dB cutoff level).



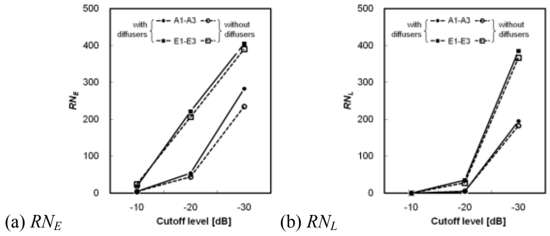
(a) Example of the frontal position (close to the source)



(b) Example of the rear position (far from the source)

Figure 1: Calculation examples of reflection numbers RN within the cutoff amplitude of ‘-20 dB’ at the impulse responses of specular or diffuse reflections from a shoebox scale model hall using hemisphere diffusers

Although the cut-off amplitude level in the impulse response was selected to be 20 dB for appropriate sensitivity, this selection must be validated in halls which have different size, absorption capacity and background noise level. Accordingly, several impulse responses were taken from a 1:10 scale model [10] and both RN and RE were calculated when the cut-off was varied from -10 to -30 dB. Several positions with or without diffusers on the side walls (A_{1-3} and E_{1-3}) were chosen from the orchestra seating to compare the early or late diffusivity values in impulse responses. Figure 2 (a) and (b) showed the calculation results of RN for positions A and E from the impulse responses in the real hall. The number of reflections at the rear seats (E_{1-3}) is much higher than the front (A_{1-3}) due to the lower amplitude level of direct sounds at rear positions. As shown in Fig. 3, when the cutoff limit is -30 dB, even the late RN value increases dramatically. It seems that the cutoff amplitude of ‘-20 dB’ is sufficient for the real hall and can be extended to ‘-30 dB’, if the reflection surfaces are much simpler just as the 1:10 scale model.



(a) RN_E (b) RN_L

Figure 2: Reflection number (*RN*) according to different cutoff levels in a 1:10 scale model. The results of Positions A and E were averaged from the measurements at A1-A3 and E1-E3, respectively

Scale model measurements

As both temporal and spatial aspects of diffusion phenomena are affected by scattered and redirected rays of sounds in halls, impulse responses from scale models may provide the optimum configuration of diffusers. The effect of location and profile of diffusers on the sound fields of halls was investigated through calculation of both *RN* and *RE*.

A. Hall shape

As shown in Fig. 3, two 1:50 scale model halls, one shoebox and another fan-shape, having a real volume of 12,000 m^3, were used to investigate the effect of diffusers on the impulse responses at the stage and auditorium of the halls. The diffusers used in this study were 15-mm diameter hemispheres made of lacquered wood. The walls were made of hard styrene board covered by paper coated twice with enamel and the seating area was covered with velvet to simulate the absorption of the seats and audience. All or half of the wall area close to the stage was covered by the diffusers with 43% coverage density. A spark source and a 1/8-in microphone were used. The diffuse fields from different geometrical hall shapes were investigated by calculating *ΔRN* and *ΔRE* in auditorium and on stage.

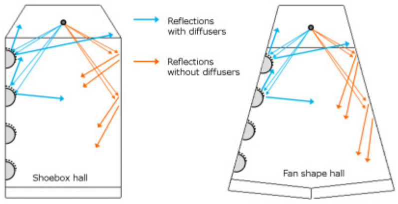


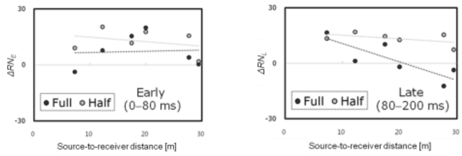
Figure 3: Diagram for specular and diffused reflection in the shoebox hall and the fan shaped hall. Lateral wall diffusers can contribute to reflect major sound energies to the stage area. The specular reflection in the fan shaped hall is facing toward the rear wall, while the specular reflection in the shoebox hall is facing toward the rear side wall.

The result shows that when the diffusers were installed for both shoebox- and fan-shaped halls, the acoustical parameters such as RT, EDT and SPL were reduced, whereas *RN* was increased (see Table 1). The *RE* decreased severely for the fan-type hall. As shown in Fig. 4, the reflection numbers increased in most cases, which is clearer for the walls half-covered with diffusers. When the side walls are half-covered with diffusers, both the early and the late reflection numbers increased. However, when the side walls are fully covered, the numbers for late reflections are reduced in the shoebox hall due to high increase of absorption with full diffusers, but the *RN* was remained unchanged in the fan-shaped hall.

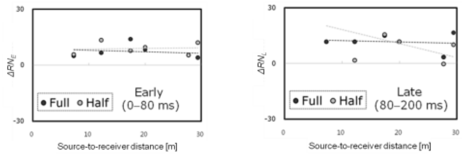
	ΔRT [s]	ΔEDT [s]	ΔSPL [dB]	ΔC_{80} [dB]	*ΔRN*	*ΔRE* [dB]
Shoe-box	-0.25 (1.99→1.75)	-0.17 (1.74→1.56)	-1.2	+0.3 (0.1→ 0.4)	+17 (219→236)	-0.5
Fan-shaped	-0.29 (1.97→1.68)	-0.36 (1.79→1.42)	-1.2	+1.0 (-1.5→ -0.5)	+20 (223→243)	-4.2

* Difference (no diffuser → with diffuser)

Table 1: Variation in acoustical parameters from installing diffusers on the lateral walls



(a) ΔRN_E for shoebox hall (b) ΔRN_L for shoebox hall



(c) ΔRN_E for fan shaped hall (d) ΔRN_L for fan shaped hall

Figure 4: Mea Variation in reflection numbers (early and late) by diffuser installation in shoebox and fan shaped halls

B. Location of diffusers

The effect of a diffuser and its location on diffuseness of a shoebox hall was investigated using a 1:50 scale model concert hall which was modeled from the basic interior dimension of the Boston Symphony Hall. An absorption banner was put in the rear wall to fit the reverberation time of the model hall, around 2.0 second. The balconies were not installed in the scale model to observe the total diffusing aspects of lateral walls to the audience on the floor. The structural walls and ceiling were made of 10 mm thick acryl board and the floor was made of wooden board. The model seats were made from wooden board upholstered with velvet and the audience was made from polystyrene board upholstered with nonwoven fabric. A spark source was used on the stage floor. Nineteen receivers with 1/8 inch microphones were located in the audience area (15 positions) and on the stage (4 positions). The effect of diffuser location, especially audience side walls and stage walls, on diffuseness of the hall was investigated using a hemisphere diffuser (Cases 1-3 and 5). The effect of the semi-cylindrical diffuser (Case 4) was compared with that of the hemisphere diffuser. The hemisphere and semi-cylindrical diffusers made of lacquered wood were both 7.5 mm in structural height with surface coverage of 43%.

The measurement results with the deviations from the reference (no diffuser) are shown in Tables 2 (audience area) and 3 (stage area). The reflection number (*RN*) and reflection energy (*RE*) were calculated with integration periods of 0-80 ms (early) and 80-200 ms (late). The results show that *RN* was increased both in the audience area and on stage in most of the cases of side wall diffusers (Cases 1-4), among which maximum diffusivity was found in Case 2 (hemispheres in half). On the contrary, *RE* was decreased in the audience area in Cases 3-4 (hemispheres in full and semi-cylinders). Comparing the results of Case 2 with Case 4, the hemispheres provide higher diffusivity than semi-cylinders. The hemispheres (Case 5) are effective for diffuseness on the stage but not in the audience area.

	ΔRN		*ΔRE* [dB]	
	ΔRN_E (0-80ms)	ΔRN_L (80-200 ms)	ΔRE_E (0-80 ms)	ΔRE_L (80-200 ms)
Case 1	+14 (75→89)	–	+0.2	-0.3
Case 2	+14 (75→89)	+7 (137→144)	+0.3	–
Case 3	+8 (75→83)	–	-0.3	-0.1
Case 4	+9 (75→84)	+4 (137→141)	-0.1	-0.3
Case 5	+6 (75→81)	–	–	-0.1

* Difference (no diffuser → with diffuser)

Table 2: Measurement results of *ΔRN* and *ΔRE* at the audience area

	ΔRN		*ΔRE* [dB]	
	ΔRN_E (0-80 ms)	ΔRN_L (80-200 ms)	ΔRE_E (0-80 ms)	ΔRE_L (80-200 ms)
Case 1	+9 (31→40)	+11 (5→16)	+0.8	+2.3
Case 2	+10 (31→41)	+10 (5→15)	+0.8	+2.4
Case 3	+1 (31→32)	+4 (5→9)	–	+1.0
Case 4	+8 (31→39)	+10 (5→15)	+0.2	+2.2
Case 5	+11 (31→42)	+3 (5→8)	+0.3	+0.8

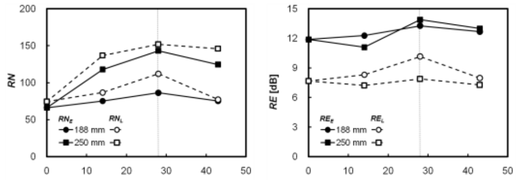
* Difference (no diffuser → with diffuser)

Table 3: Measurement results for *ΔRN* and *ΔRE* at the stage area

C. Diffuser profiles

The next scale model experiment was conducted to investigate the effect of the shape, structural height and surface coverage of diffusers on diffusivity in a 1:25 scale model concert hall. The body of the 1:25 scale model hall is the same as the previous 1:50 scale model, but the dimension of the audience and the chair model are changed due to the scale factor. In addition, the balcony was installed. The height of the hemisphere diffusers was 7.5 or 10 mm, which are 188 or 250 mm respectively at full scale. The surface coverage was varied to be 14, 28 and 43% and the diffusers were located in the half of the side walls near the stage for all six cases - two diffuser sizes and three surface coverage percentages.

The model seats were made from aluminum angled chairs upholstered with velvet cloth and the audiences were made from polystyrene board clothed with velvet. The measurement setup is the same as in the previous experiment. A spark source and a 1/8 inch microphone were used as the sound source and receiver, respectively. The sound source was recorded at 12 receiver positions, 9 receivers were located in the stalls, and 3 receivers were located in the balcony. Each receiver was positioned as if it were 1.2 m high at full scale. The measurements were conducted under fully occupied conditions with a model audience.



(a) Reflection number (*RN*) (b) Reflection energy (*RE*)

Figure 5: Measurement results of *RN* and *RE* by surface coverage and structural height of diffusers.

As shown in Fig. 5 the values of *RN* and *RE* were generally increased by installing diffusers and the number of late reflections was greater than that of early reflections. The values of *RN* and *RE* with 10 mm high (250 mm at full scale) diffusers were greater than the values with 7.5 mm (188 mm in real scale) diffusers. It was also found that both *RN* and *RE* are affected significantly by the surface coverage of the diffusers and the 28% surface coverage is most effective for increasing diffuseness, whereas the previous study [6] showed that the scattering coefficient becomes higher when the coverage reaches about 50%.

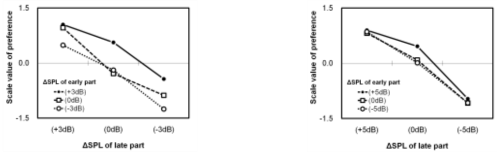
Perception of scattered sounds

A. Experimental procedure

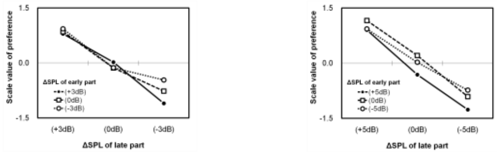
Auditory experiments have been conducted to evaluate subjective responses to the variation in the diffusivity indices in an auditorium. The impulse responses were obtained using binaural microphones in the previous 1:10 scale model experiments [10] and both *RN* and *RE* were obtained from impulse response measurements, when the cutoff level was reduced to -30 dB. Comparing the direct sounds of the reflections at different positions, both the front (A1) and rear (E1) seats were chosen to be manipulated for auralization due to their representative source-to-receiver relationship. The measures were related to early (10-80 ms after the direct sound) and late (80-200 ms after the direct sound) time periods so that the impulse responses were treated as three cases of different level adjustments (of 1, 3, and 5 dB) for perceivable level differences. A violin solo piece was convoluted to be delivered to the subjects for assessment. Twenty-five (21 male and 4 female) subjects with self-reported normal hearing aged from 22 to 30 participated in a paired comparison test using an open-type headset in a test booth with a low background noise level (less than 20 dBA).

B. Results

The subjective response was not consistent when the level was adjusted by 1 dB, but almost all the responses to either 3 or 5 dB adjustment (higher level difference) passed the consistency tests. Seventeen of 25 subjects were consistent on the A1 sound source and 14 subjects among 25 subjects were consistent on the E1 sound source. Through agreement tests, it was found that the answers were statistically not different between subjects. As shown in Fig. 6, the increase in the late sound level increases the preference for the violin performance at the positions (A1 and E1).



(a) 3-dB adjustment case for Seat A1 (b) 5-dB adjustment case for Seat A1



(c) 3-dB adjustment case for Seat E1 (d) 5-dB adjustment case for Seat E1

Figure 6: Scale values of preference derived from the auditory tests

When the relationship between subjective evaluation and physical parameters was determined, it was found that the correlation coefficients between the acoustical parameters such as C_{80}, T_s, EDT, RT, RN_L, RE_L and preference (see Table 4) were high and statistically significant for both A1 and E1 seats. However, in the case of A1, 'SPL' was found to be highly correlated to subjective response. Using the results of high correlation coefficients (above 0.81) for RN_L and RE_L, we confirm that the diffuse reflection of late sounds is an important aspect of sound preference. Compared with the cut-off level of diffusivity indices, there is a higher correlation between *RN* (or *RE*) and the scale value when the cut-off level is -30 dB.

Sound source	Adjust level	SPL	C_{80}	T_s	EDT	RT	Reflection number				Reflection energy	
							20 dB Cutoff		30 dB Cutoff			
							RN_{E20}	RN_{L20}	RN_{E30}	RN_{L30}	RE_E	RE_L
A1	3dB	0.93*	-0.82*	0.91*	0.56	-0.92*	0.39	0.81*	0.38	0.89*	0.39	0.90*
E1	3dB	0.16	-0.85*	0.89*	0.74*	-0.28	-0.12	0.94*	-0.12	0.97*	-0.12	0.97*

Table 4: Correlation coefficients between subjective preference and objective parameters (* $p<0.05$)

The preference model for in-situ diffuse fields adopts EDT and SPL as the acoustical parameters influencing perception of in-situ diffusivity. Alternatively, a linear regression analysis was undertaken with *RN* and *RE*.

$$\text{Model 1: S.V.} \approx a_1[\text{EDT}]+C \quad (1)$$

$$\text{Model 2: S.V.} \approx a_1[\text{EDT}]+a_2[\text{SPL}]+C \quad (2)$$

$$\text{Model 3: S.V.} \approx a_1[RN_{\text{E30}}]+a_2[RN_{\text{L30}}]+C \quad (3)$$

$$\text{Model 4: S.V.} \approx a_1[RE_{\text{E}}]+[a_2[RE_{\text{L}}]+C \quad (4)$$

As a result, adjusting 3-dB level in two time periods (early/late) provides higher deterministic coefficients for the models using controlled music signals. The models with *RN* and *RE* are more determinative (R^2 = 0.77-0.97), whereas the models with normal acoustical parameters such as EDT and SPL have R-squared values ranging between 0.57 and 0.77. The late sound reflection contributes more to surface diffusivity, as shown by higher standardized regression coefficients (0.89-0.97) in the regression analyses. The energy model shows more accuracy in predicting the diffuseness of a space.

Summary

The reflection number *RN* is defined by the number of reflection rays with a critical amplitude level within -30 dB after direct sound. Reflection energy *RE* is defined by the integrated energy of the normalized impulse response measured in the auditorium. Both *RN* and *RE* have been used as an in-situ diffusivity index, which is sensitive to installation of diffusers in a scale model hall.

Through the scale model measurements, it was found that half of the side walls near the stage were important for the diffuseness of sounds both in the auditorium and on stage. When the diffusers were installed on the whole side walls, the created diffuse field became less effective as the average reflection energy decreased. This is an adverse effect which is different from the computer simulation. The diffuser surfaces keep the sound power and reverberation time decreased due to the sound absorption of diffusers. Generally, the scattering coefficients are affected by the structural height of diffuser profiles in reverberation room measurements, and the surface coverage for the highest scattering coefficients was found to be 43% [6]. However, for in-situ diffusivity in this study, the optimum surface coverage decreased to 28% because *RN* decreased when the surface absorption increased. However, as indicated from the impulse responses at different source-to-receiver positions shown in the present study, both the cut-off amplitude level (-20 or -30 dB) and the *RN* itself are very much affected by the sound pressure level of the direct sounds. Therefore, the present method of handling in-situ diffusivity is useful for considering the relative amount of reflection for diffuseness perception, which is subject to the level of the direct sounds. However, for the general selection of preferred diffuseness at different room volumes, more theoretical background needs to be established for determining the effective reflection level in each sound field. To provide the absolute values for *RN* and *RE* and to recognize the optimum level of diffuseness for standard testing and evaluating methods, correction factors such as attenuation of SPL and effective perceptual SPL based on the source-to-receiver distances should be further developed.

Designing concert halls (whether rectangular or fan-shaped or vineyard with balcony overhang) benefits from using scale models at 1:50 (for appropriate location of diffusers) or 1:25 (for designing diffuser profiles) scales, which are useful for calculating both RN and RE. By varying the values, the optimum diffuser profiles can be determined. All the surface characteristics related to binaural information should be treated with scale models of 1:10 (for detailed design of diffuser profiles and surface coverage).

References

[1] T. J. Cox, B. I. L. Dalenback, P. D'Antonio, J. J. Embrecht, J. Y. Jeon, E. Mommertz, and M. Vorländer, A tutorial on scattering and diffusion coefficients for room acoustic surfaces, Acta Acustica united Acustica, 92(1), pp. 1-15, 2006.

[2] M. Vorländer and E. Mommertz. Definition and measurement of random-incidence scattering coefficients. Appl. Acoust. 60, pp. 149-165, 2000.

[3] ISO 17497-1, Acoustics-Sound-scattering properties of Surfaces, Part 1: Measurement of the random- incidence scattering coefficient in a reverberation room, 2004.

[4] T. J. Hargreaves, T. J. Cox, Y. W. Lam and P. D'Antonio, Surface diffusion coefficients for room acoustics: Free-field measures, J. Acoust. Soc. Am. 108 (4), pp. 1710-1720, 2000.

[5] AES-4id-2001, Characterisation and measurement of surface scattering uniformity, J. Audio Eng. Soc., 49(3), 149-165, 2001.

[6] J. Y. Jeon, S. C. Lee, and M. Vorländer, Development of scattering surfaces for concert halls, Appl. Acoust. 65, pp. 341-355, 2004.

[7] S. Sato, Y. H. Kim, H. M. Lee and J. Y. Jeon, Objective evaluations of sound scattering by using scale models and computer simulation, Proc. 19th ICA, 2007.

[8] Y. Suzumura, M. Sakurai, Y. Ando, I. Yamamoto, T. Iizuka, and M. Oowaki, An evaluation of the effects of scattered reflections in a sound field, J. Sound and Vib., 232, pp. 303-308, 2000.

[9] S. Chiles, Scattering Surfaced in Concert halls, Proc. New Zealand Acoust. Soc., Wellington, 2004.

[10] J. K. Ryu and J. Y. Jeon, Subjective and objective evaluations of a scattered sound field in a scale model opera house, J. Acoust. Soc. Am. 124 (3), pp. 1538-1549, 2008.