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Sound Diffusion Design for a Rectangular Concert Hall Using a 1:25 Scale Model

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ABSTRACT

To adequately evaluate sound diffusion in a rectangular concert hall, acoustic verification results from physical scale models and computer simulations are compared in this study. In these two verification methods, the researchers implemented three cases: the concert hall was finished without sound diffusers; sound diffusers were installed in a large area all along the back wall of the stage, side walls of the third floor in the audience area, and back walls of the second and third floors in the audience area; sound diffusers were installed on the side walls of the first and second floor in the audience area near the stage and all along the front of the balcony. These cases were virtually simulated using a computer program, and for the physical models, hemisphere diffusers were installed on the scale models. The sound diffusion effects were evaluated through relative standard deviations (RSD) among the seats depending on the arrangement of the sound diffusers. The computer simulations revealed that the RSD differences for reverberation time (RT) and early decay time (EDT) based on the arrangement of sound diffusers were small. Analysis of the values measured from the scale models indicated that the RSD differences were large depending on the existence and locations of the sound diffusers. This indicates that scale models are required for sound diffusion evaluations of rectangular concert halls. Further, an analysis of the scale model reveals that sounds are diffused better when the sound diffusers are installed closer to the sound source.

Keywords: Diffusion Design, Design Verification, Scale Model

1. INTRODUCTION

Acoustic consultants have been progressively making efforts to produce acoustically sound concert halls using objective indicators and subjective assessments by people. The standards for adequate sound environments have been developed from such activities, and to meet the expectations, acoustic consultants have aimed to predict acoustic performance and quantify acoustic indicators at concert halls. Two ways of assessing these acoustic values are via computer simulation and scale model measurement. Room acoustic scholars and consultants increasingly prefer computer simulations over scale model measurements owing to the former's lack of production cost, in addition to the convenience of modeling and freedom to adjust the variables influencing sounds, which are easily enabled by advances in software technology and algorithms.

Recent studies have utilized computer simulations to modify spatial configurations in a manner that would result in appropriate acoustic indicators suggested by previous studies, followed by auralization for assessment of the sounds (1). Diffusion evaluations in existing literature were conducted by perception tests in which the participants were asked to specify the location of a sound source after various diffusion surfaces in the concert hall were simulated to auralize sounds simultaneously generated from different locations (2). Shtrepi et al. (2016) utilized diffusion walls and reflection walls to assess sound diffusion in terms of distance in an actual variable acoustic environment by utilizing diffusion coefficients (3). Panels to adjust the sound diffusion were also predicted in another study using boundary element method (BEM)-based simulations. Shtrepi et al. (2015) generated simulation models of concert halls for listening tests of auralized sound sources with the goal of assessing the critical point for scattered audibility (4).

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Jeon et al. verified acoustic parameters (G, BQI, RT) through computer simulation and scale model for the design improvement of the hall with fan-type auditorium. (5)
Kim et al. produced three scale models (a 1:50 symphony hall, a 1:25 chamber hall and a 1:25 theater) to derive effective diffuser location and profile at the venue.(6)

Concert hall designs and sound diffusion assessments are often achieved via computer simulations, but there are limits to acoustic prediction software and algorithms with respect to precisely representing actual phenomena. Thus, there is a dearth of understanding concerning impact of sound diffusion as well as accurate prediction of other acoustic indicators.

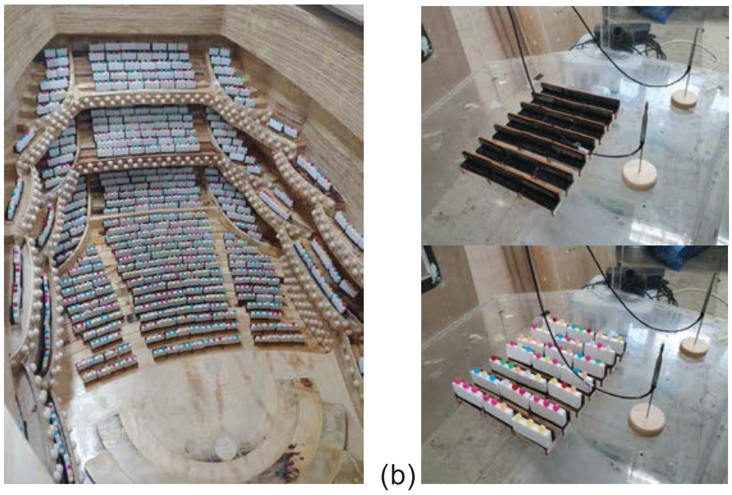
The current study aims to compare the acoustic parameter values for a rectangular concert hall generated by computer simulations and scale models. Moreover, sound diffusion depending on the arrangement of sound diffusers are evaluated for adequacy of the prediction methods.

2. METHODS

2.1 Scale model

As shown in Figure 1(a), a 1:25 scale model was produced using a hard wood material with a low sound absorption coefficient to create a sound field similar to that in an actual concert hall. To create a smooth surface, the material was coated with varnish. The model was produced in layers to ensure tightness, and the curvatures of the side walls and front of the balcony, which are special features of a concert hall, were implemented to closely resemble those of an actual concert hall. The sound absorption coefficients for the audience and chairs was measured at reverberation chamber (Figure 1(b)) and used in the scale model are shown in Table 1; these numbers are within the range of frequencies that can be measured with the scale model.

Twenty measurement points, with each pair of points separated by approximately forty seats, were established in the scale model. The sound-reception points were set 5 cm above the floor (1.2 m in the actual concert hall). The location of the sound source was set 6 cm above the soloist's position (1.5 m in the actual concert hall). A spark source was used as the sound source.



(a) (b)

Figure 1 – A 1:25 scale model : (a) unoccupied and (b) occupied

Table 1 – Absorption coefficients of the chairs in the scale model with a 1:10 reverberation chamber

		Frequency (Hz)			
		125	250	500	1000
Unoccupied	Scale Model	0.26	0.48	0.57	0.64
	Beranek (1960)	0.40	0.49	0.55	0.57
Occupied	Scale Model	0.45	0.67	0.78	0.76
	Beranek (1960)	0.54	0.66	0.78	0.85

2.2 Computer simulation

For comparison with the acoustic assessments from the scale model of the rectangular concert hall, Odeon Simulation Version 14 was used to virtually model the same concert hall. The sound absorption coefficients indicated in Table 2 were entered into the model, and the room acoustic parameters (RT, EDT, C80) were calculated. The location of the sound source and the sound-reception points at the audience seats were set at the same places as in the scale model to enable faithful comparison.

Table 2 – Absorption coefficients of materials in computer simulation

Design element	125	250	500	1000
Wall	0.05	0.05	0.05	0.05
Balcony front	0.18	0.13	0.1	0.07
Textured wall	0.20	0.20	0.15	0.10
Stage floor	0.25	0.30	0.10	0.07
Canopy	0.19	0.14	0.09	0.06
Canopy structure	0.20	0.30	0.40	0.45
Ceiling	0.02	0.02	0.02	0.04
Balcony floor	0.20	0.14	0.06	0.04
Audience occupied	0.47	0.58	0.70	0.72

2.3 Concert hall diffusion design

2.3.1 Sound diffusers

The sound diffusers used in this study are omnidirectional diffusers, which were chosen over 1D or 2D diffusers because of their ability to diffuse sounds in the horizontal and vertical orientations as well as in multiple crossed angles.

The results of a previous study (Kim et al., 2010) suggest that the most effective height for the diffusers is between 200 and 250 mm, and the most effective area of diffusion is 40–60% of the surface area. In the current study, the diffusers were installed such that their height was 250 mm and the effective area was 40% of the surface area. The scattering coefficient of the diffusion walls installed in the simulation is 0.5 for Table 3, and the sound absorption coefficients for each frequency is shown in Table 4.

Table 3 – Scattering coefficients of omnidirectional diffusers measured in the reverberation chamber (7)

Density	**Frequency bands (Hz)**									**Average**
(%)	**500**	**630**	**800**	**1000**	**1250**	**1600**	**2000**	**2500**	**3150**	
14	0.15	0.21	0.26	0.29	0.31	0.38	0.35	0.3	0.29	0.28
28	0.22	0.27	0.31	0.43	0.58	0.52	0.43	0.42	0.43	0.40
57	0.09	0.31	0.58	0.77	0.75	0.61	0.56	0.62	0.63	0.55
71	0.06	0.23	0.47	0.73	0.78	0.83	0.75	0.65	0.7	0.58

Table 4 – Absorption coefficients of omnidirectional diffusers

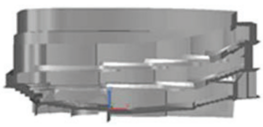
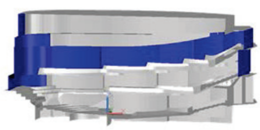
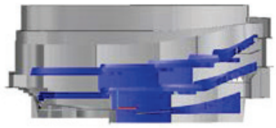
Frequency bands (Hz)				
125	**250**	**500**	**1000**	**Aver.**
0.20	0.20	0.15	0.10	0.16

2.3.2 Arrangement of the diffusers

Multiple cases were developed to understand how the distance between the sound source and diffusers, as well as the locations to which the sounds are directly delivered via the diffusers, affect the diffusion performance.

The three cases(Reflective/Diffusive /Diffusive II) shown in Table 5 were established to measure the impact of diffusion depending on the locations of the sound diffusers. These three cases may be summarized as follows: all walls are reflective, the diffusers are installed farther away from the sound source (wide area), and the diffusers are installed closer to the sound source (small area).

Table 5 – Sound diffusion design cases

	Reflective	Diffusive I	Diffusive II
Design			
Diffuser area [m^2]	-	880.4	520.3
Area ratio [%] (Diffuser area/wall area)	-	29.3	16.7

3. RESULTS

3.1 Acoustic parameters

In all the frequency bands between 125 and 1000 Hz, the RT and EDT of the scale model were 1.5–2.0 s longer than those from the computer simulations. This is because the simulation utilized the sound absorption coefficients of the finishing materials used in an actual concert hall, whereas the scale model had a uniform wood material with a lower sound absorption coefficient than the simulations.

After implementing the diffusion and sound absorption coefficients given in Tables 4 and 5 to Diffusive I and Diffusive II, the analysis indicated that larger diffuser installation areas resulted in smaller RT and EDT, both in the scale model and the computer simulation. However, owing to the increased sound absorption caused by the diffusers, the scale model had greater RT and EDT reduction from larger diffuser installation areas, whereas the reduction was smaller for the computer simulation, which resulted in poor reflection of the increased sound absorption.

3.2 Assessment of Sound Diffusion

The deviations in the acoustic parameters between the seats for different concert hall diffusion designs are shown in Table 6. The diffusion force values were calculated by multiplying the diffusion coefficient (0.5) with the area of the installed diffusers. This is the same as the sound absorption area for the installed diffusers.

Observing the relative standard deviations (RSDs) of RT and EDT for the twenty measurement points in the audience area, the diffusion performance of the configuration without diffusers was exaggerated in the computer simulation compared to the scale model. The significance of the reduction in RSD by installation of the diffusers was larger in the scale model, and the simulation was not able to implement the effect of diffusion in Diffusive II. Because diffusion has a strong influence on the initial sound field in the scale model, the RSD reduction from installation of the diffusers was greater for EDT than for RT. The RSD was the smallest for the case with the largest area of installed diffusers (Diffusive I) and largest for the case without diffusers (Reflective). The RSD for the case in which the diffusers were installed in a smaller area, on the side walls of the first and second floors in the audience area and the front of the balcony near the stage (Diffusive II), was in the middle.

Table 6 – Comparison of acoustic parameters from computer simulation with those of scale model according to the diffusion design

		Computer simulation			Scale model		
Parameter		**Reflective**	**Diffusive I**	**Diffusive II**	**Reflective**	**Diffusive I**	**Diffusive II**
Diffusing Power (m^2)		-	440.2	260.2	-	440.2	260.2
RT (s)	Mean	2.05	1.99	2.03	3.86	3.32	3.45
	SD	0.08	0.06	0.06	0.30	0.10	0.14
	RSD	0.04	0.03	0.03	0.08	0.03	0.04
EDT (s)	Mean	2.21	2.07	2.19	3.72	3.54	3.50
	SD	0.19	0.15	0.19	0.52	0.30	0.37
	RSD	0.09	0.07	0.09	0.14	0.08	0.11

4. DISCUSSION AND CONCLUSION

The RSD variations for different diffusion design cases (Reflective/Diffusive I/Diffusive II) were small in the simulation but large in the scale model. Thus, it is concluded that the scale model has a higher prediction accuracy, while the computer simulations using diffusion algorithms do not have adequate ability to predict the acoustic performance of a concert hall.

Because the reduction of RSD for RT and EDT between seats for the area of the installed diffusers is larger in Diffusive II, it is more advantageous to install sound diffusers on the walls near the sound source (but not on the walls around the stage, to prevent the sound pressure of the sound source from decreasing). Further, installing diffusers to extend the sound farther into the concert hall from the sound source increases the sound absorption excessively, thus potentially reducing the RT under adequate sound levels.

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