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1/16 SCALE MODEL EXPERIMENT FOR ROOM ACOUSTICS
PHYSICAL PROPERTIES AND AURALIZED SOUND QUALITY

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ABSTRACT
This paper describes a new potential of a 1/16 scale model experiment as a room acoustic simulation method. First, acoustic physical parameters such as reverberation time, echo diagram and transmission frequency responses were investigated both in 1/10 and 1/16 scale models simulating a small hall of 132 seats. As a result, it was confirmed that the various physical parameters obtained by the 1/16 model agreed well with those obtained by the 1/10 model which had already been admitted as a practical simulation method. Next, the sound quality of the 1/16 scale model was investigated through a psychological experiment on "Smoothness of reverberant decay" and "Beauty of the room sound". Impulse responses of the 1/16 model simulating a concert hall of 399 seats were measured in several interior conditions, and the test sounds were produced by convoluting the impulse responses with dry sounds of piano, strings and white noise pulse. In the psychological experiment, four students from a music academy participated as subjects and reliable differences were detected by diffusion processing on the interior walls. Through these investigations, it became clear that the acoustical experiments by the 1/16 scale model have sufficient effectiveness as a method of room acoustic simulation.

1. INTRODUCTION
A model experiment for room acoustics is an effective means of confirming the physical characteristics and sound quality in rooms on the design stage of a concert hall etc. It was developed by H. Tachibana [1, 2] as a practical technology mainly adopted to 1/10 scale. The model experiment of 1/10 scale has so far been performed when constructing many major concert halls in Japan. However, the length of the 1/10 scale models of the large halls of 1,500-2,000 seats will amount to 5-6m; therefore the 1/10 scale model is sometimes difficult to adopt because of the model manufacture cost and the installation space, either. In such a case, it is common to adopt a 1/20 scale instead of the 1/10 scale conventionally. However, the 1/20 scale model experiment is unable to cover 5.6 kHz, since the upper frequency limit of a microphone or microphone amplifier that can usually be obtained is generally about 100 kHz. The 5.6 kHz is the high end frequency of 1 octave band with a center frequency of 4 kHz which is significant for room acoustic design. For these reasons, we focused on a new model scale of 1/16. A model of 1/16 scale is 62.5% of the size in the case of 1/10 scale, so the installation space and the manufacturing cost are similar to that in the case of the 1/20 scale model. Moreover, the 1/16 scale model experiment covers the frequency of 5.6 kHz. In addition, since the 1.6 times is equivalent to two steps of the 1/3 octave series, it is possible to obtain 1/3 octave band data on sound absorption of interior material or inner air of the 1/16 scale model from the 1/10 scale model data that has already been provided. Recently, a sound card for digital audios with a sampling frequency of 192 kHz has become available with the spread of DVDs, and in the 1/16 scale experiment, this card enables 5.6 kHz to be covered.

This paper first describes the acoustic physical characteristics observed in the 1/10 and 1/16 scale models simulating the same hall. Next, the method and results of a psychological experiment are reported in connection with an evaluation of the quality of the sound auralized through the 1/16 scale model. Finally, the potential of the 1/16 scale model experiment as a room acoustic simulation method is investigated based on these results.

2. PHYSICAL CHARACTERISTICS BY TWO TYPES OF ACOUSTIC SCALE MODEL

2.1 Acoustic Models and the Measurement of Impulse Responses

Room acoustic measurement for the same conditions was carried out in the models of the 1/10 scale and the 1/16 scale simulating the same hall specifications. The acoustic models simulate a small hall having 132 seats, the volume of 1,050 m^3 and a surface area of 659 m^2. The inside dimension of the 1/10 scale model is 1.58 m (D) × 1.12 m (W) × 0.65 m (H), and that of the 1/16 scale model is 0.99 m (D) × 0.70 m (W) × 0.41 m (H). Both models use plywood as the base, and the sound diffusing walls are laminate lumber or chipboard. On the seats of the 1/10 scale model, the human models for 1/10 scale [3], that are already in practical use, were set. And, on the seats of the 1/16 scale model, human models for 1/16 scale [4], which have newly been developed by us, were set.

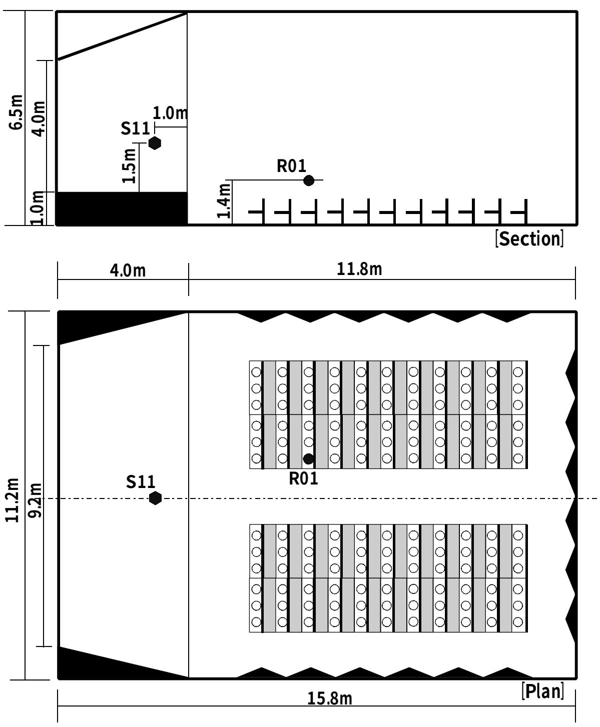

Fig.1. Plan view and section view of the simulated hall (by actual size). “S11” is a sound source position and “R01” is a representative receiver position in the model experiment.

Fig.2. 1/10 scale model (left side) and 1/16 scale model (right side) simulating the same hall of 132 seats.

Fig.3. Human models of sitting for 1/10 scale of 80 mm tall (rear) and 1/16 scale of 50 mm tall (front).

Fig.1 shows the plan view and section view of the hall model by actual size (1/1 scale). In this figure, the sound source position is shown as “S11”, and a representative of the receiver position is shown as "R01". The two types of scale models are shown in Fig. 2, and the human models for 1/10 and 1/16 scale models are shown in Fig. 3. The sound source equipment by the electric discharge pulse developed for the model experiment was installed at the center of the stage front, and the impulse response was recorded at the representative point of the seat using two 1/4-inch capacitor microphones turned to the direction of the sound source at intervals of 40 cm of the actual scale. The recorded data were downloaded to the computer through a sound card of 192 kHz of sampling frequencies, and the impulse responses were determined by 32 times synchronous addition processing. The impulse responses obtained in the scale models were compensated by convoluting the reverse characteristic of the electric discharge pulse obtained in the anechoic room. The corrected impulse responses were converted to the actual time scale (1/1 scale) by interpreting sampling frequency as 12 kHz that is one sixteenth of the original. The temperature of the air in the models was kept at about 24 degrees C and relative humidity was approximately maintained from 50 to 60% throughout the acoustic model experiments, although the nitrogen substitution was omitted.

2.2 Physical Acoustic Parameters

Figure 4 shows average reverberation times, converted to the actual time scale, measured at three points of the two scale models including "R01". Three interior conditions on audience are adopted; one is completely vacant (no chair and no audience), the second is that 132 wooden model chairs are only set up and the last is that the wooden chairs are full occupied by the human models.

According to Fig. 4, the reverberation characteristics obtained by the 1/16 scale model agree well with those obtained by the 1/10 scale model, especially under the full occupied conditions. It suggests that the reverberation times in the 1/16 scale model can be simulated precisely as almost equivalent to the 1/10 scale model.

Figure 5 shows initial impulse responses within the first 200 ms, which were observed at the point of "R01". According to this figure, waveforms of the impulse responses, at right and left channels, obtained by the 1/16 scale model agree very well with those obtained by the 1/10 scale model.

Figure 6 shows the frequency characteristics of impulse responses, that is, the transmission frequency characteristic between a stage center (S11) and a representative seat (R01), in the form of 1/3 octave-band spectrum. According to this figure, the transmission frequency characteristics by the 1/16 scale model and the 1/10 scale model are in good agreement on the whole except for part of the low frequency range. From the above results, it can be thought that the 1/16 scale model experiment has an almost equal simulation accuracy to that of the 1/10 scale model experiment on the observation of physical acoustic parameters. The influence of the air absorption can be avoided by nitrogen substitution in the case of the 1/10 scale experiment [1, 2]. Although description in this paper is omitted, the numerical simulation confirms that the influence of air absorption can be reduced to a practical level by the nitrogen substitution in also the 1/16 scale model experiment [4].

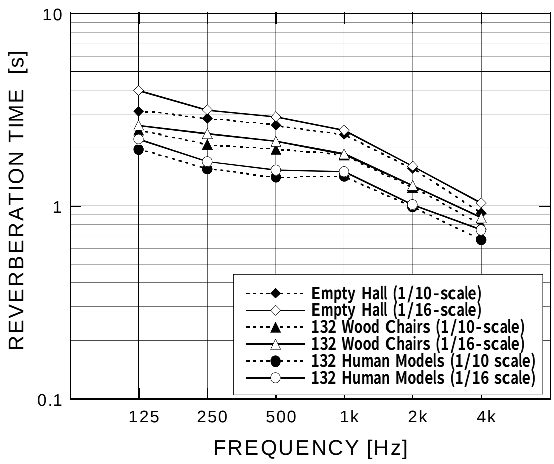

Fig.4. Average reverberation times converted to the actual time scale, measured at three points of the two scale models including "R01".

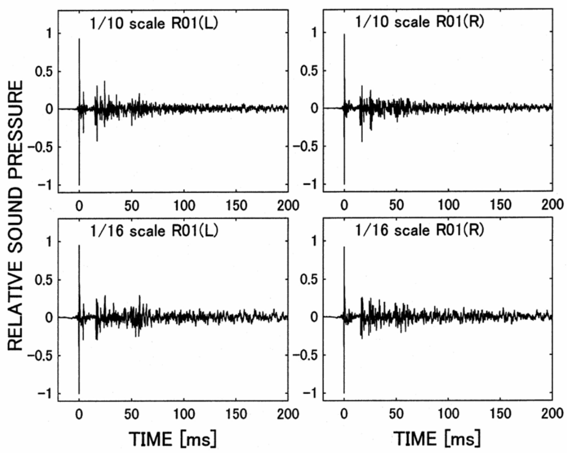

Fig.5. Initial impulse response waveforms converted to the actual time scale obtained by 1/10 and 1/16 scale models.

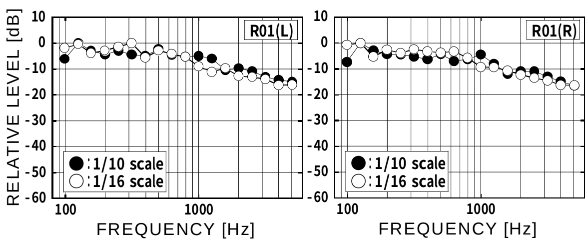

Fig.6. Transmission frequency characteristics between a stage centre (S11) and a seat (R01) converted to the actual time scale, measured in the 1/10 and 1/16 scale model halls.

3. PSYCHOLOGICAL EXPERIMENT ON QUALITY OF ROOM SOUND

3.1 Outline of Experiment

In order to investigate the potential of the sound quality by the 1/16 scale model, a psychological experiment using auralized sound through the 1/16 scale model was carried out. A virtual hall having the volume of 4,280 m^3 and 399 seats was simulated in the 1/16 scale, by newly using the same model frame as the 1/10 scale model in the former experiment. The plan view and section view of the model hall are shown in Fig. 7 in actual size.

The reverberation time and average sound absorption coefficient at 500 Hz of the model hall by actual scale is 1.75 second and 0.23 respectively, which are almost realized the optimal values as a concert hall. The shape of interior boundaries was changed to four patterns and impulse responses were measured using the same method as the former experiment at one source point (S21) and two receiving points (R21 and R22) in Fig. 7. The test sounds for the psychological experiment including the room sound were produced by convoluting the impulse responses of the actual time scale with dry sources; a passage of music for piano, strings, violin and white noise pulse.

3.2 Experimental Method and Conditions

A psychological experiment by Scheffe's method of paired comparisons was carried out with four conditions of interior boundaries by four students from a music academy as subjects. The combination of four types of interior conditions becomes 4×(4-1) = 12 pairs. In the experiment, a total of 72 pairs of test signals containing the six same comparison pairs were provided to each subject. The subjects compared the quality of sound of two signals provided with a pair, and answered which is excellent in five steps. "The smoothness of reverberant decay" and "the beauty of the room sound" were used to evaluate the quality of sound.

The four types of interior conditions (Condition D31-D34) are shown in Table 1, the section views of the diffusion panels are shown in Fig. 8, the inside views of the model hall are shown in Fig. 9 and the conditions of the psychological experiment are shown in Table 2 respectively.

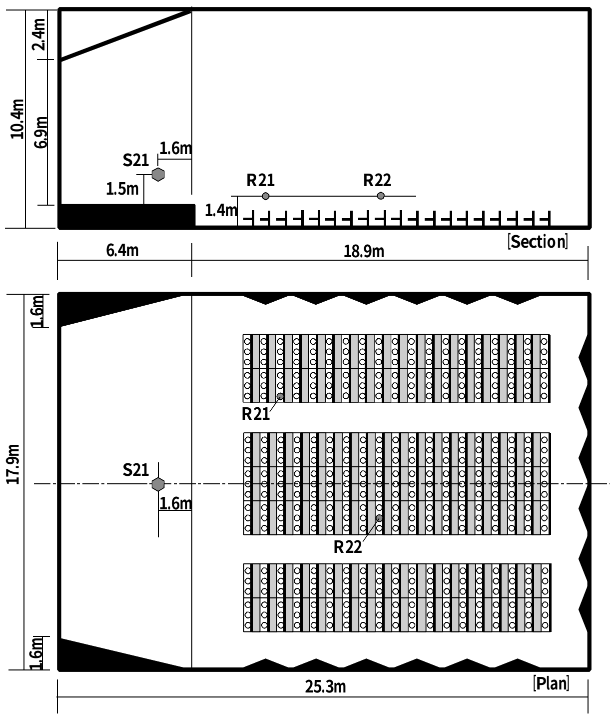

Fig.7. Plan and section views of the simulated hall (by actual size) used for the evaluation of sound quality by the 1/16 scale model.

Table 1. Details of four types of interior conditions.

		Condition Code			
		D31	D32	D33	D34
Stage	Ceiling	Flat (horizontal)	Reflection Panel (inclined)		
	Side Walls	Flat (parallel)	Inclined (non-parallel)		
	Back Wall	Flat			Diffusion Panel II
Audience Area	Side and Back Walls	Flat		Diffusion Panel I	
	Ceiling	Flat			Diffusion Panel III

Table 2. Experimental conditions of the psychological experiment on the quality of room sound.

Experimental Code	Receiving point	Dry Source	Evalution Measure
Wnp1S21R21C1A	R21	White Noise Pulse	Smoothness of Reverberant Decay
Str2S21R22C1B	R22	String Quartet	Beauty of Room Sound
Vln1S21R22C1B	R22	Violin Solo	
Pia1S21R21C1B	R21	Piano	

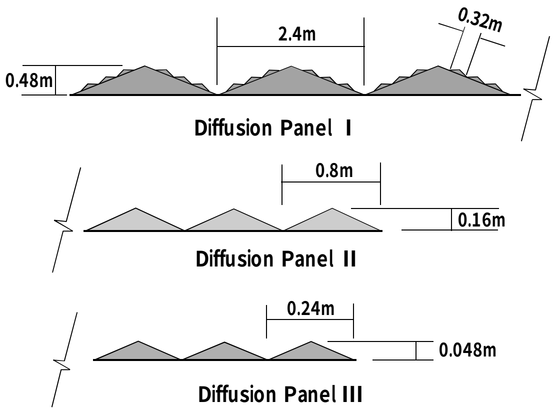

Fig.8. Section views of diffusion panels (by actual size) used for changing acoustical conditions of the model halls.

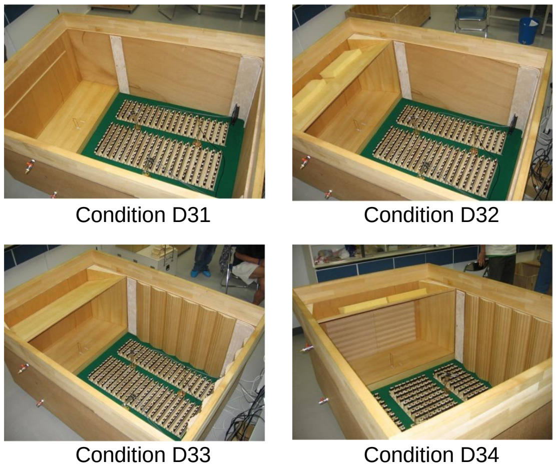

Fig.9. Inside views of the model hall with four types of interior conditions.

3.3 Experimental Results and Discussions

Experimental results are shown in Figs. 10-13. The horizontal axis of these figures shows four types of interior conditions, and the vertical axis shows the evaluation score by the Scheffe's method of paired comparisons. The experimental values by four subjects almost agreed with each other, and the evaluation scores tended to become high in accordance with the progress of diffusion processing of the interior boundaries. According to the results of integrated analysis of the reply by four subjects, a significant difference with 5% confidence level was detected between the evaluation scores of conditions D32 and D33 for three sound sources except the piano. In the case of the piano sound, a significant difference of 5% was detected between conditions D31 and D32, but the tendency is different from that of other sound sources. That is, in the case of the piano sound, there is no significant difference between D32 and D33, and the evaluation score decreases in the condition D34 which is the most diffusive condition; a significant difference of 5% was detected between D33 and D34. These results suggest an interesting supposition especially for the piano sound that the diffusion treatment of the interior boundaries that participate in reinforcement of direct sound is not necessarily effective for the quality of room sound.

While the results provide information about the relation of the interior boundary shapes and the quality of room sound, at the same time, it is shown that the simulation on the quality of room sound is sufficiently possible by the 1/16 scale model experiment.

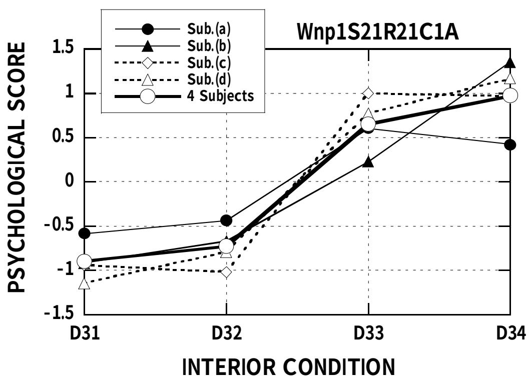

Fig.10. Experimental results on "Smoothness of reverberant decay" by a white noise pulse.

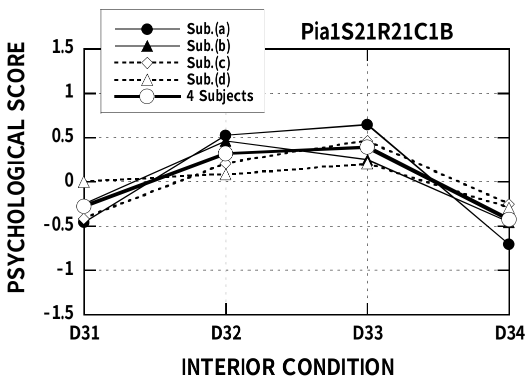

Fig.11. Experimental results on "Beauty of the room sound" by a passage of music for a piano.

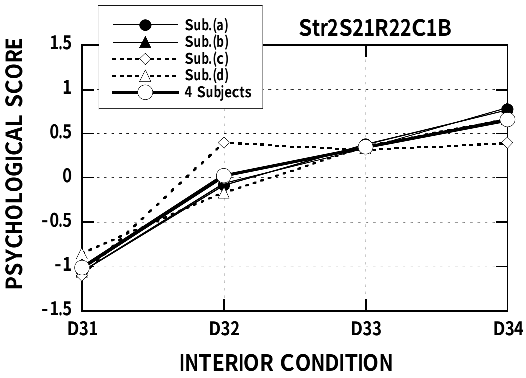

Fig.12. Experimental results on "Beauty of the room sound" by a passage of music for a string quartet.

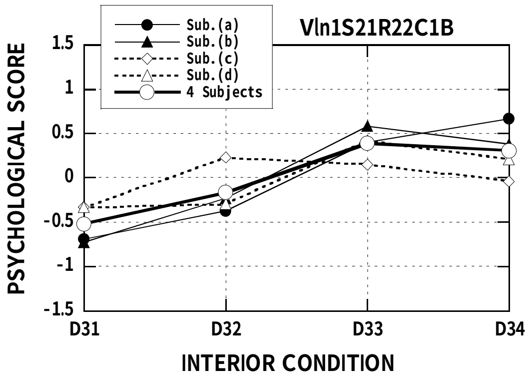

Fig.13. Experimental results on "Beauty of the room sound" by a passage of music for a violin solo.

4. CONCLUSIONS

As described above, the 1/16 scale model experiment has almost equal potential to observe the physical acoustic parameters as the 1/10 scale model experiment, which is generally in practical use, and the auralized sound by the 1/16 scale model sufficiently reflects the difference in the quality of room sound accompanying the change of interior conditions.

These results indicate that the acoustic experiment by the 1/16 scale model, which is 62.5% size of the 1/10 scale model, has sufficient effectiveness as an acoustic simulation means on the design stage of a concert hall etc.

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