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AN EVALUATION OF THE EFFECTS OF SCATTERED REFLECTIONS IN A SOUND FIELD

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In this paper we outline and apply a procedure to evaluate sound fields in a concert hall which involve scattered reflections. We adopted an experimental method and used a 1/10 scale model of the concert hall. Arrays of circular columns were placed in front of its walls to act as the scattering obstacles. The acoustic properties of the hall were measured both with and without the arrays of circular columns. Here, the quality of the scattered sound field was evaluated in terms of four orthogonal physical factors: sound pressure level (SPL), initial time-delay gap between the direct sound and the first reflection (Δt_1), subsequent reverberation time (T_{sub}), and magnitude of the interaural cross-correlation function ($IACC$). The $IACC$ at central seats near the stage and seating area near the columns were improved by the arrays of circular columns.

1. INTRODUCTION

The theory of scattering has been the subject of many studies, but the quality of a scattered sound field in a concert hall has not previously been evaluated. We have carried out such a study, during the design of a concert hall in Tsuyama City, Okayama Prefecture, which was opened in June 1999. It is called "Belle Forêt Tuyama", which means "Beautiful Forest". As the name suggests, the architectural and acoustic design concept was "beautiful sounds in a beautiful forest". The

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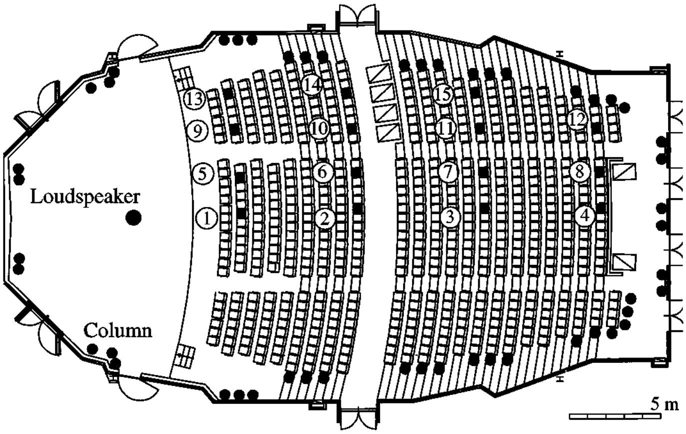

Figure 1. Floor plan of "Belle Forêt Tuyama" and measurement points: ■, measurement point (15 points).

concept has been studied [1], and was realized in Belle Forêt Tuyama, by using an array of circular columns (diameter = 300 mm) in front of the walls in the audience area and the stage. These circular columns simulate trees in a forest and scatter sound waves, both in the audience area and on the stage. The calculation of the effects of obstacles which cause scattering on the sound field in a concert hall is difficult to set up and would consume excessive computer processing time, so we adopted an experimental method to evaluate their effect.

The overall acoustic design process followed the sequence of steps outlined below.

1. The effect of the leaf-shaped floor plan (see Figure 1) and the shape of the ceiling were studied by sound field simulation on a personal computer [2].
2. A 1/10-scale model of the concert hall filled with ordinary air was used to evaluate the sound field that results from scattering by an array of circular columns installed in front of the walls.
3. The effect of triangular reflectors above the stage was studied, using the same 1/10-scale model [3].
4. The acoustic qualities of the real hall were measured after its construction.

In this paper, we report on the procedure of, and results for, the second step, prior to the installation of the triangular reflectors above the stage. The scattered sound field both with and without the array of circular columns was evaluated in terms of four orthogonal acoustic factors [4].

2. EXPERIMENTAL PROCEDURE

The walls, floor and ceiling of the scale model were made of plywood panels at a scale of 1 : 10 to their planned counterparts. In the model studies, the frequency range examined was 5–20 kHz, corresponding to 500–2000 Hz in the real dimension. Considering the air absorption above 20 kHz in the model, we concentrate on the 500–1000 Hz range in this paper. The reverberation time at

500 Hz was adjusted to match that of the planned hall (1·6 s) by placing urethane foam on the seats.

An omni-directional loudspeaker was placed at a height of 1·2 m (12 cm) above the center of the stage. Sound signals were received by two microphones which acted as the ears of a 1/10-scale dummy head at a given seat number, and were recorded on a computer. After the impulse responses were obtained, four orthogonal acoustic parameters listed below were analyzed: (1) the relative sound pressure level (SPL); (2) the initial time-delay gap between the direct sound and the first reflection (Δt_1); (3) the subsequent reverberation time (T_{sub}); (4) the magnitude of the interaural cross-correlation function ($IACC$).

These four factors were obtained both with and without the columns to ascertain the effects of placing arrays of columns in front of the side and rear walls of the concert hall.

3. EXPERIMENTAL RESULTS ANS DISCUSSION

Table 1 shows values of the four parameters (SPL, Δt_1, T_{sub} and $IACC$) measured across the 1/3 octave bands centered at 1000 and 500 Hz. Cases 1, 2, and 3 as listed below are shown for each parameter. All measurements were made without a canopy above the stage.

Measurements conditions were as follows: case 1, without columns; case 2, with arrays of columns only around the audience area; case 3, with arrays of columns around the audience area, and on the stage.

(a) *Relative sound pressure level—the listening level* (SPL)

For all three cases, the maximum difference between SPLs in all of the frequency ranges that were investigated (500 Hz–2 kHz), at different seats, was within 7 dB as indicated in Table 1. It thus follows that the SPL does not decrease greatly with the distance; rather it is a relatively flat distribution in this hall. This may be due to the leaf-shaped floor plan, similar to that of the Kirishima International Concert Hall [5].

(b) *Initial time-delay gap between the direct sound and the first reflection* (Δt_1)

The effect of the arrays of columns appear clearly in the Δt_1 as measured using delay from the direct sound to the time of the reflection which has second energy [3]. The value of Δt_1 is lengthened by the columns (cases 2 and 3), particularly at seats near the side wall (points 14 and 15) for both frequencies, 500 and 1000 Hz. This shows that the columns scatter the sound which is reflected from the walls. They thus decrease the coloration due to the interference effects which occur at short distances and values of Δt_1 that lead to coherence [4].

(c) *Subsequent reverberation time* (T_{sub})

The arrays of columns have little effect on T_{sub} at 500 Hz, as can be seen in Table 1(b). On the other hand, at 1000 and 2000 Hz (not indicated in the data here) the columns decrease the fluctuation in T_{sub} throughout the audience area leading to a more diffuse sound field. It is worth noticing that the wavelength of sound in the 1000 and 2000 Hz range is shorter than and of a similar order to the diameter of the columns.

(d) *Magnitude of the interaural cross-correlation function* ($IACC$)

TABLE 1

(*a*) *Four parameters measured across the* 1/3 *octave band centered at* 1000 Hz

		Seat number														
Factor	Condition	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
Relative *SPL*	Case 1	− 12	− 13	− 16	− 17	− 15	− 14	− 16	− 17	− 15	− 16	− 17	− 18	− 15	− 16	− 17
	Case 2	− 12	− 13	− 16	− 17	− 15	− 14	− 16	− 17	− 15	− 16	− 17	− 17	− 15	− 17	− 18
	Case 3	− 11	− 13	− 16	− 17	− 14	− 14	− 16	− 17	− 15	− 15	− 17	− 17	− 14	− 16	− 18
Δt_1	Case 1	37	30	25	20	32	24	20	15	25	29	15	30	12	12	9
	Case 2	37	30	30	26	31	24	20	25	25	29	37	31	12	21	37
	Case 3	37	30	29	28	31	27	19	25	25	29	33	30	14	24	37
T_{sub}	Case 1	1·2	1·2	1·4	1·3	1·5	1·3	1·3	1·4	1·7	1·5	1·4	1·3	1·5	1·5	1·4
	Case 2	1·2	1·2	1·4	1·3	1·5	1·3	1·3	1·4	1·6	1·5	1·4	1·3	1·6	1·5	1·5
	Case 3	1·2	1·3	1·4	1·4	1·5	1·4	1·4	1·4	1·5	1·5	1·5	1·4	1·6	1·6	1·5
IACC	Case 1	0·52	0·14	0·39	0·26	0·10	0·26	0·18	0·04	0·14	0·09	0·21	0·16	0·25	0·26	0·34
	Case 2	0·56	0·17	0·37	0·24	0·13	0·28	0·27	0·06	0·14	0·12	0·29	0·05	0·23	0·22	0·22
	Case 3	0·45	0·19	0·21	0·23	0·09	0·22	0·33	0·10	0·12	0·05	0·23	0·20	0·30	0·22	0·15

(*b*) *Four parameters measured across the* 1/3 *octave band centered at* 500 Hz

		Seat number														
Factor	Condition	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
Relative *SPL*	Case 1	− 14	− 16	− 17	− 16	− 16	− 17	− 16	− 16	− 17	− 16	− 18	− 15	− 16	− 17	− 17
	Case 2	− 15	− 16	− 17	− 16	− 16	− 17	− 17	− 15	− 16	− 16	− 18	− 16	− 16	− 18	− 17
	Case 3	− 14	− 15	− 16	− 17	− 15	− 17	− 17	− 15	− 17	− 15	− 18	− 16	− 16	− 18	− 17
Δt_1	Case 1	37	30	25	20	32	24	20	15	25	29	15	30	12	12	9
	Case 2	37	30	30	26	31	24	20	25	25	29	37	31	12	21	37
	Case 3	37	30	29	28	31	27	19	25	25	29	33	30	14	24	37
T_{sub}	Case 1	1·7	1·7	1·7	1·5	1·9	1·8	1·6	1·5	1·9	1·7	1·8	1·4	2·0	1·8	1·7
	Case 2	1·6	1·6	1·7	1·5	1·8	1·7	1·6	1·4	1·8	1·6	1·8	1·3	1·9	1·9	1·6
	Case 3	1·6	1·7	1·6	1·6	1·8	1·8	1·6	1·4	1·8	1·5	1·7	1·5	1·9	1·9	1·7
IACC	Case 1	0·53	0·35	0·54	0·59	0·20.	0·30	0·42	0·63	0·19	0·56	0·47	0·60	0·27	0·40	0·16
	Case 2	0·55	0·33	0·61	0·67	0·26	0·32	0·52	0·66	0·29	0·64	0·42	0·55	0·31	0·47	0·28
	Case 3	0·54	0·39	0·49	0·58	0·20	0·40	0·53	0·70	0·22	0·69	0·48	0·40	0·17	0·38	0·33

Here, the values of Δt_1 are equal to those in Table 1(a) because the values are measured at all-pass frequency range.

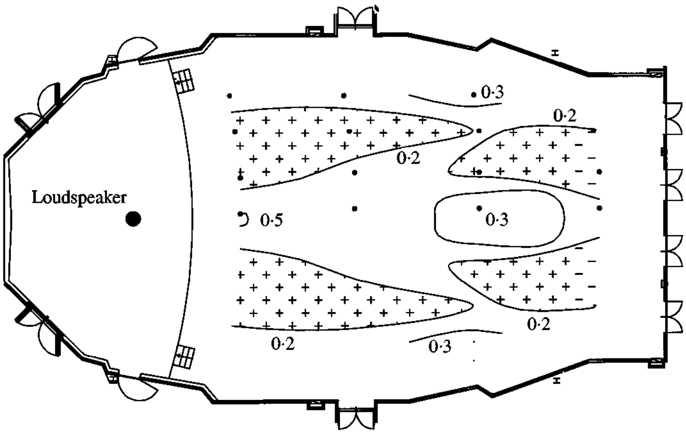

Figure 2. Conterminous values of the *IACC* for case 1 at 1000 Hz: + + +, the seating area with *IACC* < 0·2.

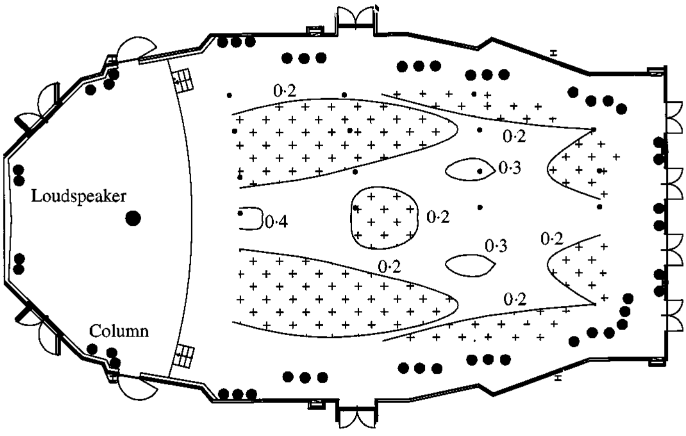

Figure 3. Conterminous values of the *IACC* for case 3 at 1000 Hz: + + +, the seating area with *IACC* < 0·2.

Figures 2 and 3 show conterminous values of the *IACC* at 1000 Hz for cases 1 and 3 respectively. Usually, it is difficult to improve the quality of the sound field at seats in the center of the hall near the stage. However, the *IACC* is markedly decreased, particularly at points 1 and 3, when arrays of columns are placed on the stage (the difference between cases 2 and 3 in Table 1(a). Subjective quality [5] may, therefore, be improved at seats in the central area of the hall by the addition of arrays of columns (case 3) on the stage, and at seats near the side walls by the placement of arrays of columns around the audience area (case 2). It is also shown that the values of the *IACC* are decreased at the seats near the side wall (points 14 and 15) by the existence of arrays of columns around the audience area (cf. cases 2 and 3). Results of the *IACC* at 500 Hz are somewhat different. As indicated in Table 1(b), values of the *IACC* at 12 seats are increased by arrays of columns around the audience area (cf. cases 1 and 2). This may be caused by change of directional reflections to the listener from the desired lateral reflections at ± 90° for the 500 Hz range [5]. However, when the columns on the stage are added (cases 2 and 3), then the values at 8 seats are decreased. It is emphasized that the columns on the stage are effective to decrease the $IACC$ for these frequencies investigated.

4. CONCLUSIONS

In this acoustic modelling experiment, we studied the effect of the arrays of columns on sound fields in a concert hall via four physical parameters. The result of the experiment shows that an array of columns particularly, on the stage, can improve the sound field in a concert hall, in terms of the $IACC$ and Δt_1. It is considered, therefore, that the method used in this paper, is useful to evaluate a sound field in a concert hall.

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REFERENCES

1. H. Sakai, S. Sato and Y. Ando 1998 *Journal of the Acoustical Society of America* **104**, 1491–1497. Orthogonal acoustical factors of sound fields in a forest compared with those in a concert hall.
2. Y. Ando and Y. Suzumura 1999 *Proceedings of the 2nd Convention of the European Acoustics Association*: *Forum Acusticum.* Acoustic design of the Tsuyama Music Cultural Hall based on the preference theory.
3. M. Sakaurai, S. Aizawa, Y. Suzumura and Y. Ando 1999 *Proceedings of the 16th International Congress on Acoustics*, *Seattle* Vol. 1 19–20. A diagnostic system measuring orthogonal factors of sound fields in a scale model of concert hall.
4. Y. Ando and H. Alrutz 1982 *Journal of the Acoustical Society of America* **71**, 616–618. Perception of coloration in sound fields in relation to the auto-correlation function.
5. Y. Ando 1998 *Architectural Acoustics*; *Blending Sound Sources, Sound Fields, and Listeners.* New York: AIP Press/Springer-Verlag.