ISSN1346-7824

Reverberance in relation to the orthogonal factors of sound field

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(Received 30 November 2009; accepted 7 December 2009)

As an application of theory of subjective preference, this paper discusses reverberance as a typical overall response of the sound field. The scale value of reverberance obtained by applying speech and music signals. Results show that the scale value of reverberance may well be expressed by the four orthogonal factors of the sound field. As similar manner to the scale value of subjective preference, we can calculate those of reverberance at every seating position in concert halls or opera houses.

Key words: Reverberance, orthogonal factors

1. INTRODUCTION

Reverberance is one of the subjective attributes which is experienced in the concert hall or opera houses. It is quite natural to consider that the reverberation time is deeply connected with the reverberance, however, other acoustical parameters may relate to the reverberance judgment. This paper confirms that the reverberance can be calculated by the orthogonal factors which are used to describe the subjective preference of the sound field. First, the scale value of reverberance was obtained in the synthesized sound fields. Then, the results obtained the synthesized sound fields were confirmed in the actual existing hall.

2. REVERBERANCE IN RELATION TO TEMPORAL FACTORS Δt_1 AND T_{sub}

First of all, effects of the temporal factor, the delay time of the first reflection Δt_1 and the subsequent reverberation time T_{sub} were examined [2]. The values of Δt_1 were controlled as 10 ms, 20 ms and 40 ms, and the values of T_{sub} as 0.25 s, 0.85 s and 1.25 s. In order to examine the effects of the temporal characteristics of different source signals which can be described by the minimum values of effective duration of the running autocorrelation function ACF, $(\tau_e)_{min}$, we also applied speech (11 ms) and music (59 ms) signals. The $(\tau_e)_{min}$ was obtained by the integration interval 2T = 2.0 s. The values of the interaural cross-correlation IACC and the sound pressure level SPL were fixed at 0.40 and 82 dBA at a peak level, respectively.

The paired comparison tests (PCT) with five subjects (36 pairs) were conducted. The session was repeated ten times for each subject. The signal duration of each stimulus was 5 s, and the silent interval between the stimuli was 1 s. Each pair of sound fields was separated by an interval of 4 s and the pairs were arranged in random order. The scale value of reverberance was obtained by applying the method, a modification of the Thurstone method [1]. Results of the PCT with all of five subjects are shown in Fig. 1 as a function of Δt_1 and a parameter of T_{sub}. The result of analysis of variance indicated that the effects of Δt_1 and T_{sub} on the scale value of reverberance are independent and significant on the scale value, so that

$$S(\text{rev.})_L \approx a_2x_2 + a_3x_3 \qquad (1)$$

where x_2 and x_3 are the normalized temporal factors, respectively. Coefficients a_2 and a_3 averaged for five subjects are 1.75 and 0.71, respectively. Calculated scale values by Eq. (1) fairly agree with measured ones for both speech and music signals ($r = 0.93$, $p < 0.01$). For each individual, coefficients a_2 and a_3 were obtained, and relationships between individual measured scale values and calculated values by Eq. (1) with individual coefficients are shown in Fig. 2, $r = 0.93$ ($p < 0.01$).

It is remarkable that contribution of the factors of Δt_1 with the speech signal to the scale value was much greater than that of T_{sub} for every individual in the range of this experiment, but this tendency was not clear with music signal. The fact may be clearly found in the slope difference of the scale value as a function of Δt_1 as shown in Fig. 1(a) with music signal and 1(b) with speech signal.

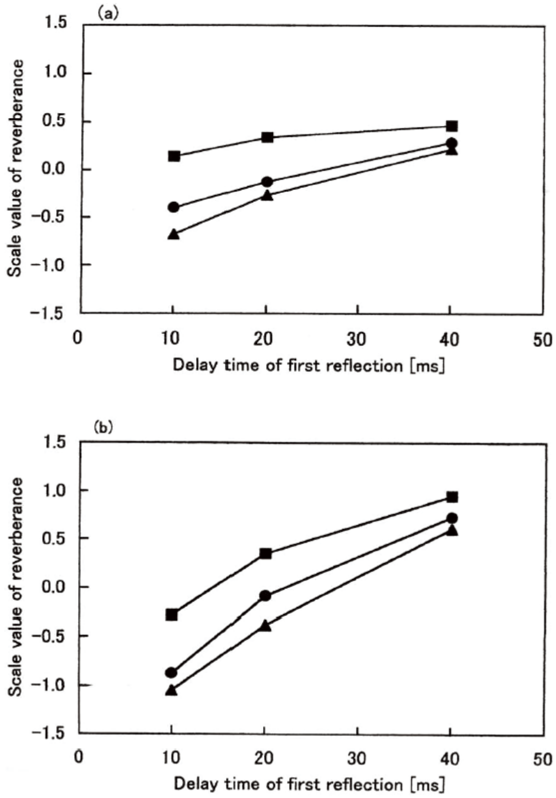

Fig. 3. Scale values of reverberance. (a) Music; (b) speech.

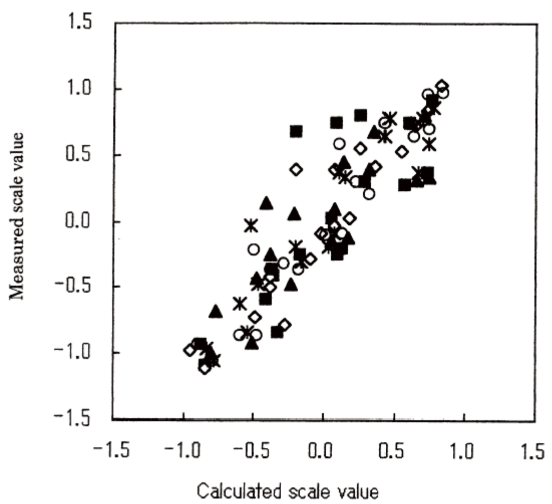

Fig. 2. Relationship between the calculated scale values of reverberance by Eq. (1) and measured scale values of reverberance. The correlation coefficient, $r = 0.93$, $p < 0.01$.

3. REVERBERANCE IN RELATION TO SPATIAL FACTORS SPL AND IACC

Second, in order to examine effects of the spatial factor associated with the right cerebral hemisphere, SPL and IACC were varied [1]. The values of SPL were controlled as 76, 82 and 88 dBA, and the values of IACC were controlled by changing horizontal angle of two early reflections $\xi = \pm 4^{\circ}, \pm 22^{\circ}$, and $\pm 54^{\circ}$, so that IACC = 0.60, 0.45 and 0.30 (music signal); IACC = 0.75, 0.60 and 0.40 (speech signal), respectively. In order to examine effects of different source signals also, we applied the same two signals of speech and music signals as the previous section. The values of Δt_1 and T_{sub}, respectively, were fixed at conditions in the range of most preferred value [1], so that 41 ms and 1.3 s (music signal); 8 ms and 0.3 s (speech signal). The reverberation time was controlled by the loudspeaker located at $\xi = 0^{\circ}$ that was the same location for the direct sound.

The PCT with nine subjects (36 pairs) were conducted. The session was repeated ten times for each subject. The signal duration of each stimulus was 5 s, and the silent interval between the stimuli was 1 s. Each pair of sound fields was separated by an interval of 4 s and the pairs were arranged in random order. The scale value of reverberance was obtained by applying the method, a modification of the Thurstone method [1]. Results of the PCT with all of nine subjects are shown in Figure 4 as a function of the IACC and a parameter of SPL. The result of analysis of variance showed that the Effects of LL and IACC on the scale value of reverberance are independent and significant on the scale value, so that

$$S(\mathrm{rev.})_R \approx a_1 x_1 + a_4 x_4 \qquad (2)$$

where x_1 = SPL−82 dBA in this experimental condition, and x_4 = IACC [1]. Coefficients averaged a_1 and a_4 obtained by nine subjects were 0.12 and −1.03, respectively. Calculated scale values by Eq. (2) fairly agree with measured ones for both speech and music signals ($r = 0.97$, $p < 0.01$). For each individual, coefficients a_1 and a_4 were. Resulting relationships between individual measured scale values and calculated values by Eq. (2) with individual coefficients are shown in Fig. 3 ($r = 0.98$, $p < 0.01$).

The scale value of reverberance increases with increasing LL and decreasing IACC It is remarkable that no significant differences may be found in the difference of source signals.

Since activities in the left and right cerebral hemispheres are independent, we assume that Eqs. (1) and (2) may be combined together obtaining overall response of reverberance as similar manner to subjective preference [1], such that

$$S(\mathrm{rev.}) = S(\mathrm{rev.})_L + S(\mathrm{rev.})_R = a_1 x_1 + a_2 x_2 + a_3 x_3 + a_4 x_4 \quad (3)$$

where $a_1 = 0.12$, $a_2 = 1.75$, $a_3 = 0.71$, and $a_4 = -1.03$.

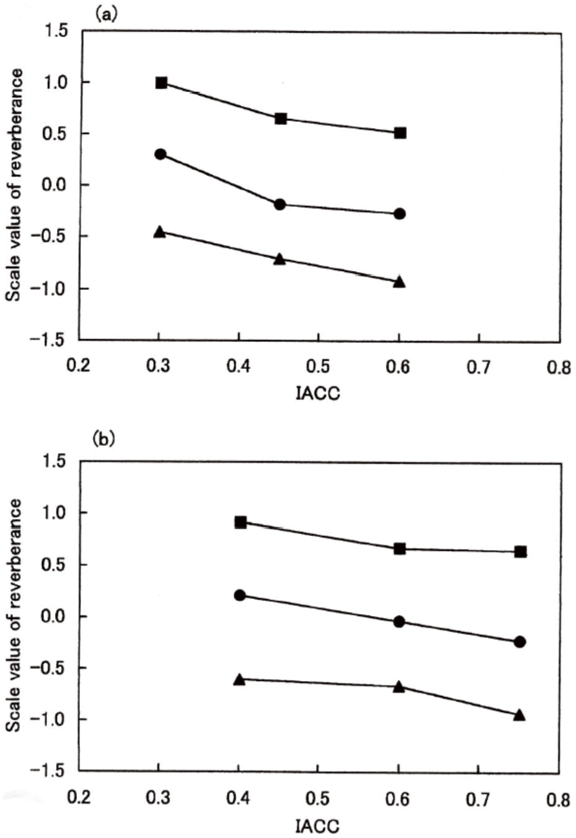

Fig. 3. Scale values of reverberance. (a) Music; (b) speech.

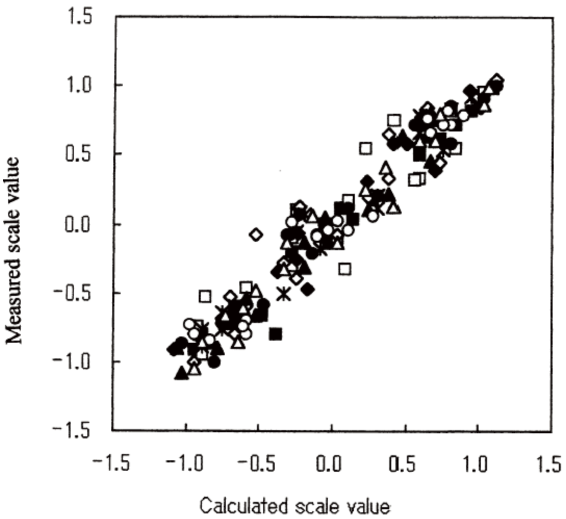

Fig. 4. Relationship between the calculated scale values of reverberance by Eq. (1) and measured scale values of reverberance. The correlation coefficient, $r = 0.93$, $p < 0.01$.

4. REVERBERANCE JUDGMENT IN AN EXISTING HALL - RECONFIRMATION

In order to reconfirm Eq. (3), we controlled SPL and T_{sub} in an actual existing hall. The sound field at the seating positions in the Orbis Hall (with 400 seats), Kobe (Fig. 5) was applied [2]. The same music and speech as the above experiments were used. The value of T_{sub} was adjusted by a hybrid system, consisting of an electroacoustic system and a small reverberation chamber, which reproduced fine structured reflections in the decay, as shown in Fig. 6. Sound signals were reproduced from a dodecahedral loudspeaker located on the stage (1.35 m above the stage floor, and 2.20 m from the front edge of the stage) and picked up by a microphone on the stage for use of the hybrid system (0.50 m from the loudspeaker and 1.10 m above the stage floor). The signals radiated from the loudspeakers distributed near the ceiling were delivered through the hybrid reverberator and were superposed on the sound field in the hall. The frequency characteristic of measured Tsub without reverberation system was almost flat around 1.0 s. When the reverberation was superposed, on the other hand, the averaged value of T_{sub} was increased to about 1.4 s.

The PCT was conducted as T_{sub} and SPL were changed. Twenty-one subjects were divided into six groups and seated at the specified positions as shown in Fig. 5. To avoid effects of other senses including visual and tactile senses on judgments, the subjects were asked to remain in their seats [3], and judge which of two sound fields they perceived to have more reverberance. The test consisted of 6 pairs of stimuli, in total. The signal duration of each stimulus was 9 s, and the silent interval between the stimuli was 1 s. Each pair of sound fields was separated by an interval of 4 s and the pairs were arranged in random order.

The scale value of reverberance was obtained by applying the method, a modification of the Thurstone method. Because there was no significant difference in the scale value of reverberance among the seats, scale values of the six groups of seats were averaged. As shown in Fig. 9, the scale value of reverberance for the sets of both sound signals increased as SPL or T_{sub} increased. Results of the analysis of variance for the scale values of reverberance indicate that the factors SPL and T_{sub} are significant ($p < 0.01$), and the interaction between SPL and T_{sub} are not significant. Thus, we can superpose the scale value due to two factors only in Eq. (3), so that

$$S(\text{rev.}) = S(\text{rev.})_L + S(\text{rev.})_R = a_1x_1 + a_3x_3 + c \qquad (4)$$

where $a_1 \approx 0.12$ and $a_3 \approx 0.71$, and c is eliminated without losing any generality due to the property of the scale value. Figure 10 shows the resulting relationship between the measured scale value of reverberance and the scale value calculated by Eq. (4) ($r = 0.87$, $p < 0.01$).

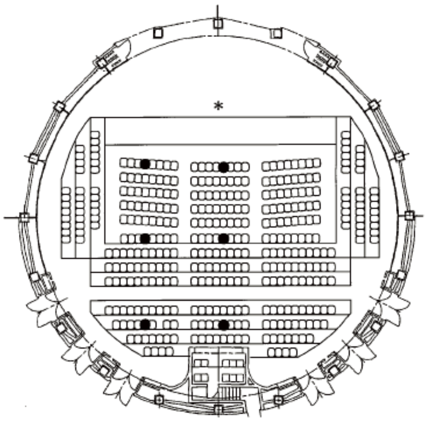

Fig. 5. Plan of ORBIS HALL, Kobe: ∗, Sound source; ●, listener's location (6 positions).

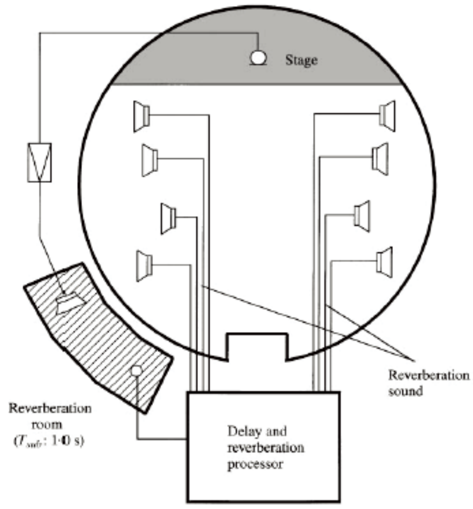

Figure 6. Block diagram of a hybrid reverberation system.

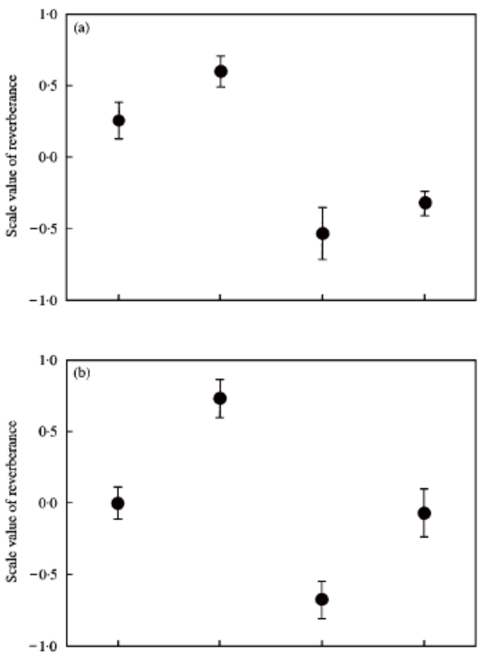

Fig. 7. Average scale values of reverberance (six seats) with 95% reliability. (a) Music; (b) speech: *On, with the reverberation system; Off, without the reverberation system.

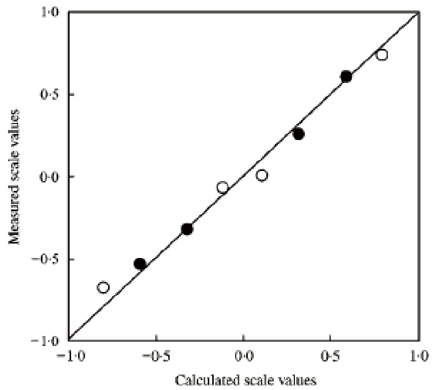

Fig. 8. Relationship between the calculated scale values of reverberance by Eq. (1) and measured scale values of reverberance. The correlation coefficient, $r = 0.99$, $p < 0.01$: ●, Music; ○, Speech.

5. REMARKS

The scale values of reverberance were confirmed in both synthesized and the actual existing sound field. Eq. (3) may be reconfirmed by the bridge of the two hemispheric independent activities well. Effects of the SPL on reverberance may be related to the sensation level of reverberation decay, so that the higher SPL could result in greater values of reverberance. Also, source signals with the shorter $(\tau_e)_{min}$ value may result more reverberance. Theory of subjective preference, therefore, may be applied for reverberance as an overall response of the sound field.

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