Spatial Distribution of Acoustical Parameters in Concert Halls: Comparison of Different Scattered Reflections

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Spatial distributions of orthogonal acoustical parameters were investigated in concert halls by the extensive acoustical measurements. The purpose of the measurements was to gain basic data about variation ranges, spatial dependencies, and interrelationships of the acoustical parameters, as well as to investigate local variation in parameters in neighboring seats. We measured two concert halls of similar size and shape, but with different scattered reflections. In one of halls, the array of circular columns is installed in front of walls. It was assumed that the local variation in parameters increases due to the scattering effect. The main results are the following.

1) Variation ranges of measured parameters are larger than their JND values, and most parameters vary systematically in the hall. Therefore, the seat positions in a hall can be divided into several groups in terms of each acoustical parameter. Listeners can choose a seat based on their preferences.

2) The local variations in SPL, the total amplitude of reflection (A-value), and the subsequent reverberation time (T_{sub}) in neighboring seats are quite small. A relatively small number of measurement points are sufficient to describe the spatial distributions of these parameters.

3) An array of columns installed in Tsuyama hall weaken the specular reflections from the sidewall by scattering them. As a result, the SPL and the A-value are decreased near the sidewalls. Also, the initial time delay gap (Δt_1) is prolonged throughout the hall and its local variation becomes large.

Keywords: acoustical parameters, spatial distribution, concert hall, subjective preference, seat selection

1.INTRODUCTION

Objective measures for describing the acoustic qualities are not the same throughout a hall. For example, the initial time delay gap is variable between the center of the hall and the seats close to the sidewalls. The sound pressure level (SPL) and direct-to-reverberant energy ratio are different between the front and rear seats. Measures for spatial impressions such as the inter-aural cross-correlation (IACC) and the lateral energy fraction (LF) also fluctuate in the hall (Bradley 1994, de Vries et al. 2001). Based on this knowledge, most workers measure these parameters at several positions scattered over a hall and calculate average values and standard deviations of those parameters to describe the hall's acoustical quality (e.g. Hidaka et al. 1995). However, the means of deciding the measurement points for taking an average are arbitrary, and the number of points that should be measured is unknown. Moreover, there is no justification for evaluating a hall by average values and deviations because it is not yet fully understood how the acoustic parameters are distributed within a hall (Pelorson et al. 1992).

In contrast, Ando stated that we need to evaluate the acoustical properties at particular seats in a hall in relation to the subjective preferences of the audience (Ando 1985). He found preferred values of four orthogonal acoustical parameters for many listeners (SPL, initial time delay gap, reverberation time, and IACC) and proposed a calculation method for the scale values of subjective preference at each seat. Furthermore, he found that the individual differences in subjective preference for the orthogonal acoustical parameters excluding the IACC are large and that all members of the audience can potentially find their preferred seat in a hall (Ando 1998). Based on these studies, a seat selection system was introduced in Kirishima

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International Concert Hall, Japan (Sakurai et al. 1997). In this system, the optimal seat for each audience member can be found by matching his/her preferred values and seat values of acoustical parameters.

Recently, we started the development of the Internet-based seat selection system as an extension of Ando's study. In our system, sound fields of concert halls are reproduced by using measured or calculated binaural impulse responses so that the users can experience the difference in sound at particular seats before buying tickets. Users can find their preferred acoustical conditions by comparing controlled music motifs. Users can also see their personalized seating maps showing available seat ranks based on their listening preferences. The usefulness of this reference for listeners who are reserving seats is readily apparent. In the project, we plan to construct a concert hall database, including binaural impulse responses for reproducing the sound fields of each seat and acoustical parameters for selecting seats. For an initial study, we performed extensive acoustical measurements in two concert halls to investigate spatial distributions of the acoustical parameters.

The purpose of our measurements was to investigate how much the acoustical parameters actually differ between the seats in concert halls. We wanted to know whether or not the variability of the acoustical properties inside a hall is objectively and subjectively important. We aimed to obtain basic data about variation ranges, spatial dependences, and the interrelationships of the acoustical parameters. The measurements were also intended to investigate local variation in the parameters. The distribution of the acoustical parameters was investigated in previous studies for roughly sampled measurement positions in concert halls and theaters because the parameters are assumed to change slowly with spatial displacements (e.g. Ando 1998). The global tendency of parameter distributions is captured by these measurements, but we have to examine how well the sampled measurement point can approximate the surrounding seats to describe the acoustical properties at every seat position. To address the issue, we measured the acoustical properties in two concert halls that have similar size and shape but different scattered reflections. As described later, an array of circular columns are installed close to the side and rear walls in one hall. It was assumed that the local variation in the acoustical parameters increases near the columns because the columns scatter sound waves into various directions and make early sound reflections more complicated. We also expected that comparing the distributions of the acoustical parameters in two halls would give insights about the effect of scattering on subjective preference.

(a)

(b)

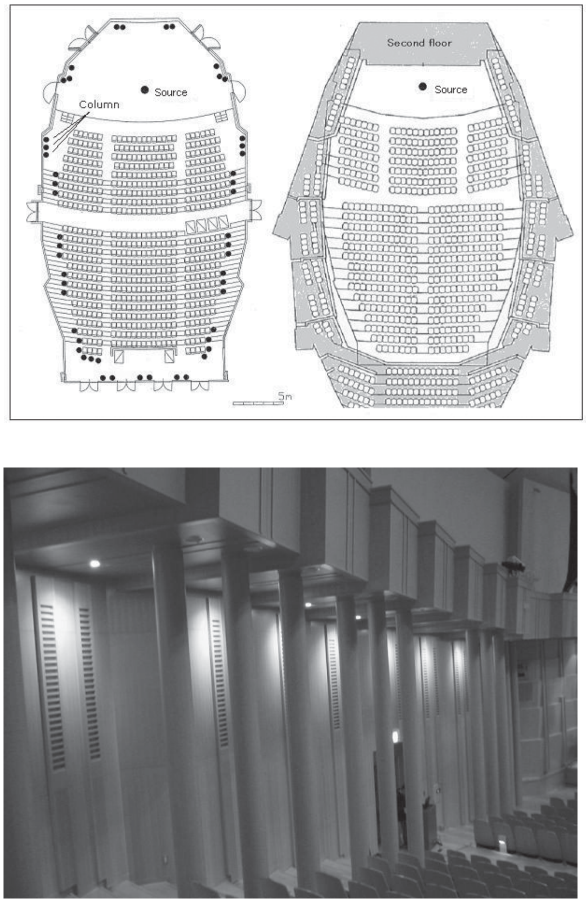

Fig. 1. (a) Floor plans of left: Tsuyama Cultural Music Hall and right: Kirishima International Concert Hall, (b) picture inside the Tsuyama hall.

2. PROCEDURES

2.1 Overview of the halls measured

Acoustical measurements were carried out in two concert halls in Japan, of which the acoustical design was done by consultants of the authors' group (Ando et al. 1997, Suzumura and Ando 2001). The halls are the Kirishima International Concert Hall in Kagoshima (8500 m^3, 770 seats), and the Tsuyama Cultural Music Hall in Okayama (6000 m^3, 600 seats). Both have a leaf-shape plan and a ship-bottom ceiling. The size and shape of these halls are quite similar except that the Kirishima hall has second floor seats. Floor plans are shown in Figure 1a. One big difference is that, in the Tsuyama hall, an array of a total of 52 circular columns (diameter = 300 mm) are installed close to the walls on the stage and in the audience area (Figure 1b). These columns were introduced to create a sound field similar to that of a forest, which has multiple scattering reflections and good acoustical qualities (Sakai et al. 1998). The array was found to actually improve the acoustical quality, especially the spaciousness. A scale model experiment and measurements taken after the construction confirmed this (Suzumura et al. 2000).

2.2 Measurement setup

Binaural impulse responses were measured using a sweep method. An omni-directional cylindrical loudspeaker with the diameter of 90 mm (Time domain, Yoshii-9) was used as the sound source. It was placed at the center of the stage as shown in Figure 1 in all measurements. A logarithmic sine sweep was employed as an excitation signal (Farina 2000). The frequency range of the sweep was between 40 and 20,000 Hz, and its duration was 10 s. On the receiving side, a dummy head (Neumann, KU100) was used. The dummy head was set in front of the audience seats. It faced the sound source, corresponding to the head position of the audience. The height of the microphones was set to 1.1 m. The microphone output was amplified and digitally recorded on a hard disk with a sampling frequency of 48,000 Hz and a bit rate of 32.

To investigate the spatial distribution of the acoustical qualities in detail, as many points as possible were required. Considering the symmetrical shape of the halls, all seat positions on only left side were covered in the measurement. The number of measurement positions was 259 and 316 for Kirishima and Tsuyama. All measurements were carried out in unoccupied conditions.

2.3 Acoustical parameters

Ando's orthogonal acoustical parameters were calculated from the measured binaural impulse responses. Four parameters that explained the subjective preferences of listeners in his experiments were SPL, reverberation time, initial-time-delay-gap (Δt_1), and inter-aural cross-correlation (IACC). Additionally, the total amplitude of reflections (A-value) was calculated in this study.

SPL is the primary criterion for listening to the sound in a concert hall. Though a uniform distribution of SPL is usually recommended, the preferred sound level depends on individual differences in hearing sensitivity, and its range is quite large (e.g., more than 20 dB among 106 listeners, in Ando (1988)). In actual halls, the SPL ranges between 5-10 dB mainly in proportion to the distance (Tachibana et al., 1989). It is generally said that the just noticeable difference (JND) of loudness is 1 dB (Bork 2000), thus the sound fields might be divided into several groups in terms of SPL. In this study, the relative SPL was calculated to investigate its spatial distribution inside the hall. The reference level was measured at 1.0 m from the sound source in all measurements.

Reverberation time is also an important acoustical parameter mainly related to reverberance or liveness of sound. The JND of the reverberation time is about 5% (Bork 2000), which means that a difference of 0.1 is distinguishable for a reference reverberation time of 2.0 s. It is assumed, however, that the reverberation time is almost uniform throughout the hall as it happens in a diffused sound field. Therefore, in comparing seats in the same hall, the reverberation time may not become a significant parameter. In this paper, the reverberation time is referred to as the subsequent reverberation time (T_{sub}) according to Ando (1998). T_{sub} was calculated by means of a linear regression over the decay curve between the arrival of the first reflection and -30 dB. Note that the calculated values are almost equal to T30.

The initial-time-delay-gap (Δt_1) is the time difference between the arrival of the direct sound and the first reflection. The first reflection is read directly from the impulse response as a reflection with maximum amplitude. The first (and strongest) reflection generally comes from the nearest sidewall (lateral reflections), and its value is mainly decided by the hall geometry. The overall tendency is that Δt_1 is at maximum for the center front seats and is decreased toward the side and rear seats. The preferred value of Δt_1 exists between the perception of coloration and echo disturbance. It has been found that the preferred Δt_1 is expressed as a function of the A-value and the effective duration of the autocorrelation function of source signals (Ando 1985).

The IACC is defined as the magnitude of the inter-aural cross-correlation function. It has been found that the IACC is a significant parameter in determining degrees of the subjective diffuseness and the subjective preference of sound fields. Ando and Kurihara (1986) found a strong negative correlation between the IACC and the subjective diffuseness. The IACC and subjective preference also show a negative correlation for all available data (Ando 1985). This means that listeners prefer the diffused sound field, which is produced by the uncorrelated signals reaching two ears.

In this study, the IACC was calculated from the measured binaural impulse responses. We adopted this analysis method because it is a convenient method and is effective to examine the physical properties of the sound field. But note that this may not be sufficient for relating these values to the subjective preference of sound fields, because an impulsive signal is quite different from the music signals produced in a concert hall. To measure the subjectively relevant IACC more appropriately, we should calculate it from the music signal recorded at the audience seats or the music signal convolved with the impulse response measured at the seat as suggested by Ando (1998).

Sensitivity to the small changes in IACC has been investigated by several researchers (Cox et al. 1993, Morimoto et al. 1995, Okano 2002). They determined JND values in the IACC by controlling the amplitude of the first few reflections in the sound field which simulated that of a concert hall. We take Okano's result as a reference value for JND of IACC, because he found the consistent results with other previous studies in a wide range of conditions corresponding to those in existing halls. He found the JND of $IACC_{E3}$ to be 0.06-0.08 with reference $IACC_{E3}$ between 0.3-0.6. Here, the $IACC_{E3}$ is the $IACC_{Early}$, which is calculated from only the early part of the impulse response, averaged for 3 bands of 500, 1000, and 2000 Hz. The reason of limiting the time range of the impulse response is to separate the early reflections from the late reverberant sound. Time ranges suggested by Hidaka et al. (1995) are 0 to 80 ms for $IACC_{Early}$, 80 ms to ∞ (length of impulse response) for $IACC_{Late}$, and 0 to ∞ for $IACC_{All}$.

The A-value was not included in the orthogonal parameters but was used for calculating the preferred Δt_1 in Ando (1985). The preferred Δt_1 was found to increase when the A-value decreases. The A-value represents the ratio between the total amplitude of the reverberant sound and the direct sound (the duration of the direct sound was set to 2.5 ms in this study). The A-value is considered to be strongly related to the other parameters such as clarity (C80) or definition (D50). The A-value is also considered as an important cue for auditory distance perception because it increases systematically with distance. Zahorik (2002) investigated the JND for the direct-to-reverberant energy ratio, which is the reciprocal of the A-value. From his results, the JND of the A-value is calculated as being about 3.0-4.0.

The SPL, T_{sub}, and IACC were calculated for six octave bands with center frequencies between 125 Hz and 4 kHz, and Δt_1 and the A-value were calculated from the all-pass impulse responses.

3. RESULTS AND DISCUSSION

3.1 Hall average values and variation ranges of acoustical parameters

The values of the relative SPL, T_{sub}, and IACC in 1/1 octave bands averaged for all measurement points in two halls are shown in Figure 2. Error bars indicate the maximum and the minimum values. We can see that both halls have quite similar acoustical qualities in terms of hall-averaged data, except

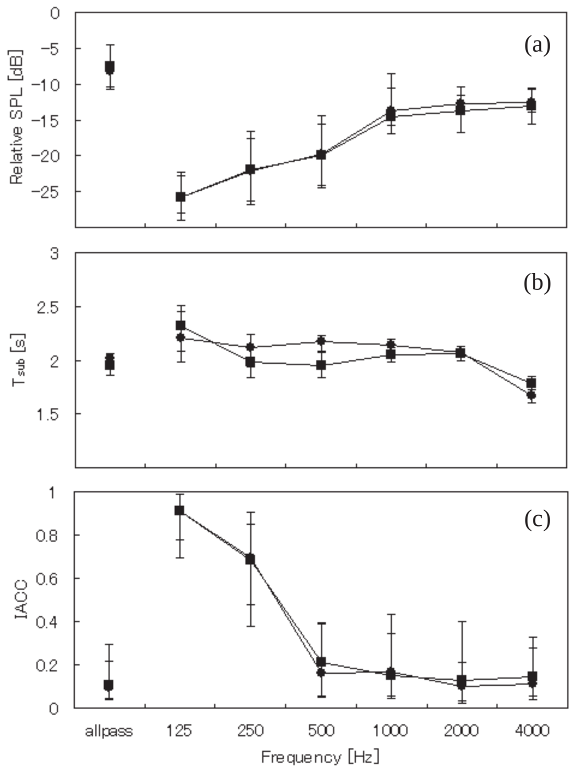

Fig. 2. The values of (a) relative SPL, (b) T_{sub}, and (c) IACC in 1/1 octave bands averaged for all measurement points in two halls (●: Tsuyama and ■: Kirishima).

that the reverberation time (T_{sub}) is slightly higher (about 0.2 s) for Tsuyama hall at a mid-frequency range. The results of the SPL and T_{sub} show that the frequency characteristics in the sound level and the reverberation in two halls are almost flat.

The variation ranges of the parameters are listed in Table 1. For the SPL, T_{sub}, and IACC, their ranges (differences between the maximum and minimum values) were averaged over all octave bands. The variation ranges are not much different in the two halls across parameters. In Table 1, the JND values for the parameters are also shown. The JND values were taken from the results of previous experiments. From Table 1, the variation ranges of the parameters within a hall are obviously much larger than their JNDs. By comparing those values, the sound fields in a hall can be classified into two to five categories in terms of each acoustical parameter.

3.2 Spatial distributions of acoustical parameters

Spatial maps of the acoustical parameters are shown in Figure 3-5. In these maps, measured values for one seat are plotted as one grid with different colors. The following observations were obtained from the maps.

SPL, A-value, and T_{sub}

Spatial distributions of the relative SPL in an A-weighted all-

Table 1. Variation ranges of acoustical parameters. Data of subjective limen is obtained from *Bork (2000),**Okano (2002), and ***translated from the data in Zahorik (2002).

	SPL [dB]	T_{sub} [s]	IACC	Δt_1 [ms]	A-value
Kirishima	6.4	0.22	0.33	30.6	4.8
Tsuyama	5.8	0.19	0.25	37.0	6.7
JND value	1.0*	5%* [0.1 s]	0.06-0.08**	no data	3.0-4.0***

pass band are shown in Figure 3 as seating maps. The SPL appears to decrease gradually from the front to the rear seats. Seat-to-seat variation in the SPL is relatively small, and by about four to five seat displacements, it reaches a noticeable difference of loudness of 1 dB. This overall tendency is the same for both the halls, but Tsuyama has a relatively larger reduction in SPL near the sidewalls (up to 8 or 9 seats).

The total SPL is divided into direct sound energy, early reflections, and reverberant sound energy. Considering that the direct sound energy decreases in almost a similar manner (according to the inverse-square law) and the reverberant sound energy is almost uniform in both halls, the attenuation of SPL might be caused by the weakening of specular reflections from the sidewalls. It can be considered that the array of columns in Tsuyama interrupts the strong early reflections of the sidewalls to reach listeners directly.

Maps of the A-value (total amplitude of reflection, or reverberant-to-direct energy ratio) are shown in Figure 4. As the source distance increases, the A-value increases in both halls. This is because the direct sound energy decreases according to the inverse-square law, though the reverberant energy remains roughly constant. Consequently, listeners can perceive a clear or "dry" sound in the front seats, and reverberant sound in the rear seats. Considering the JND for an A-value of 3.0-4.0, sound fields are divided into three and four groups in Kirishima and Tsuyama. The local variation of the A-value is quite small, but again, the reduction in A-value is larger near a sidewall in Tsuyama, perhaps because of the same reason affecting the SPL.

A map of T_{sub} for 500 Hz is shown in Figure 5. Though the variation range of T_{sub} slightly exceeds its JND value as shown in Table 1, no systematic variation pattern is evident and its spatial distribution is almost uniform in both halls as expected. Therefore, in comparing seats in the same hall, the reverberation time itself may not become a significant parameter. It would be interesting to compare the characteristics of T_{sub} with that of the early decay time (EDT), concerning perceived

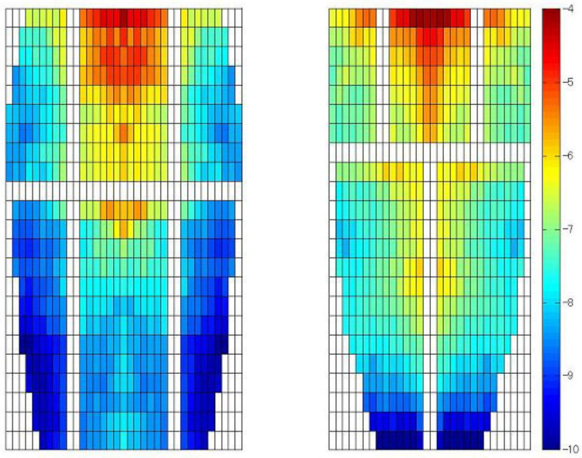

Fig. 3. Spatial maps of SPL for Tsuyama (left) and Kirishima (right).

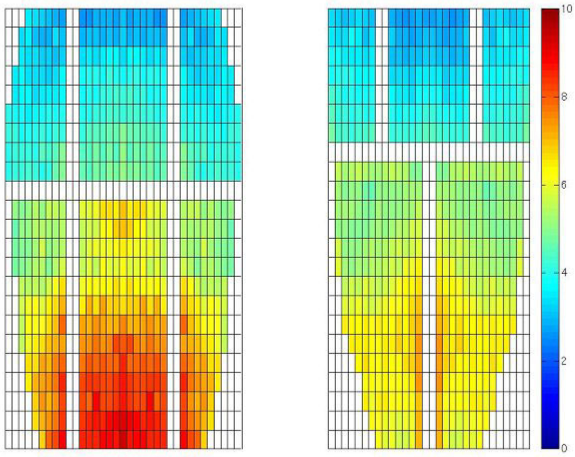

Fig. 4. Spatial maps of A-value for Tsuyama (left) and Kirishima (right).

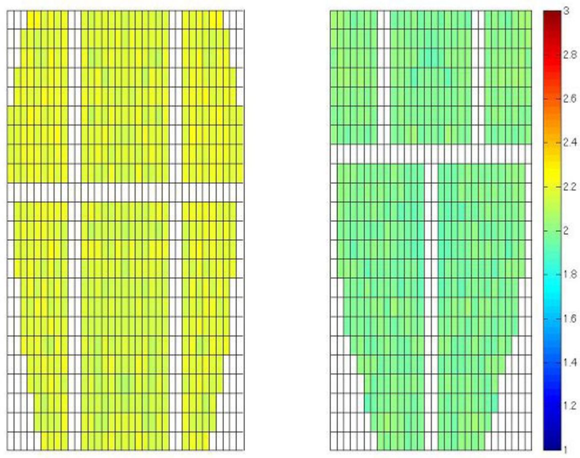

Fig. 5. Spatial maps of T_{sub} for Tsuyama (left) and Kirishima (right).

reverberance. The EDT might vary spatially because it depends on the initial part of the decay curve, which is influenced by the amount of early reflections. But this goes beyond the purpose of the paper.

In summary, the three acoustical parameters, the SPL, the T_{sub}, and the A-value, show no significant variations in neighboring seats. Spatial variations in these parameters are gradual, and a relatively small number of sampled measurement points are sufficient to describe the spatial distributions of these parameters. Since parameters other than T_{sub} are changed regularly and by a great degree in a hall, listeners can choose a seat based on their preferences. In the Tsuyama, the SPL and A-value were decreased near the sidewalls. It can be explained as a weakening of specular reflections by the array of columns. The effect of columns will be discussed in more detail below.

Initial time delay gap, Δt_1

Before showing the results, definition of Δt_1 is discussed. As described above, the first and strongest reflections generally arrive from the nearest sidewall in the hall (lateral reflection). Thus, the Δt_1 is read directly from the impulse response as the reflection with the maximum amplitude. However, in some cases, the amplitude of the lateral reflection is smaller than that of the other reflections from the ceiling, stage, etc. To investigate the distribution of the delay time of the lateral reflections, the Δt_1 was calculated as the first peak of the short-time integrated impulse response as shown in Figure 6. An integration time of 5 ms was chosen for the calculation.

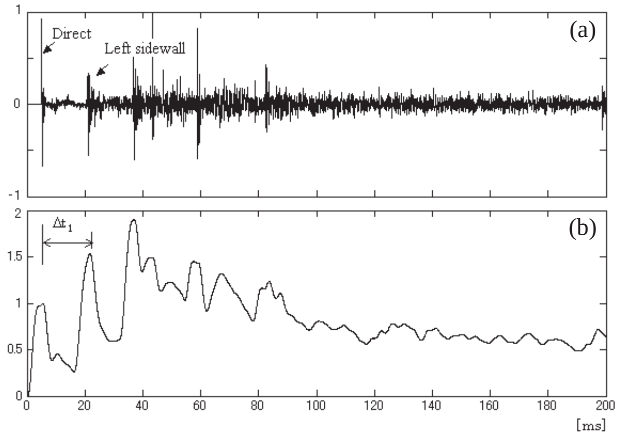

Fig. 6. (a) Example of the impulse response and (b) the integrated impulse response with integration time of 5 ms.

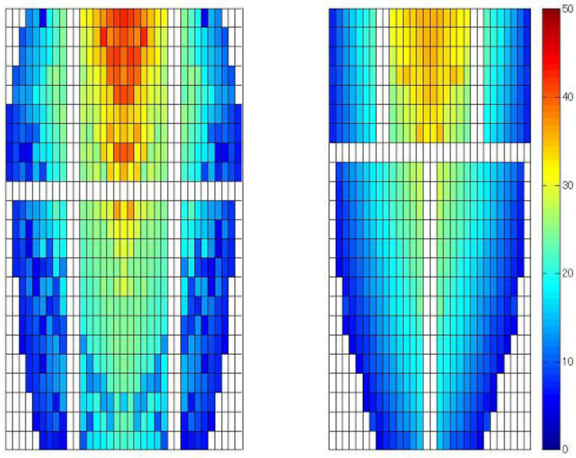

Fig. 7. Spatial maps of Δt_1 for Tsuyama (left) and Kirishima (right).

Spatial maps of Δt_1 are shown in Figure 7. The overall tendency of the Δt_1 distribution is the same for both halls. As expected, the Δt_1 becomes a maximum at the center front area and gradually decreases toward the side and rear. This demonstrates that we captured the delay of lateral reflections as Δt_1. By comparing maps, we can see that the Δt_1 is longer in Tsuyama. A local fluctuation of Δt_1 is also found around the sidewalls in Tsuyama. These findings imply the influence of the scattering from columns on the temporal distribution of early reflective sounds.

To understand the difference in early reflections in two halls, we compared examples of the impulse responses. In Figure 8, left ear impulse responses were taken from the fifth rows of seats in both halls, of which locations inside the hall are almost the same (see Figure 1). The effect of the scattering is clearly visible in the early part of the impulse responses. In each impulse response, a discrete lateral reflection found in Kirishima is masked by a dense temporal distribution of energy in Tsuyama. Because the arrival time of the lump of energy is almost the same as that of the discrete reflection in Kirishima, and it increases gradually as the distance from the sidewall increases, this energy is considered to be reflections from the sidewall scattered by the column array and is calculated as Δt_1.

It seems that the Δt_1 is prolonged because the columns interrupt the specular reflections from the sidewall, then scattering reflections from other columns or from other surfaces become the first major reflection arrived after the direct sound. Also, the time structure of the energy distribution is found to be different in neighboring seat positions. It is probable that the structure of early reflections is made different in neighboring seats by the complicated scattering reflections. Such scattered reflections by the columns must have affected the distribution of Δt_1 in Tsuyama.

It is clear that the qualitative inspection of the impulse re-

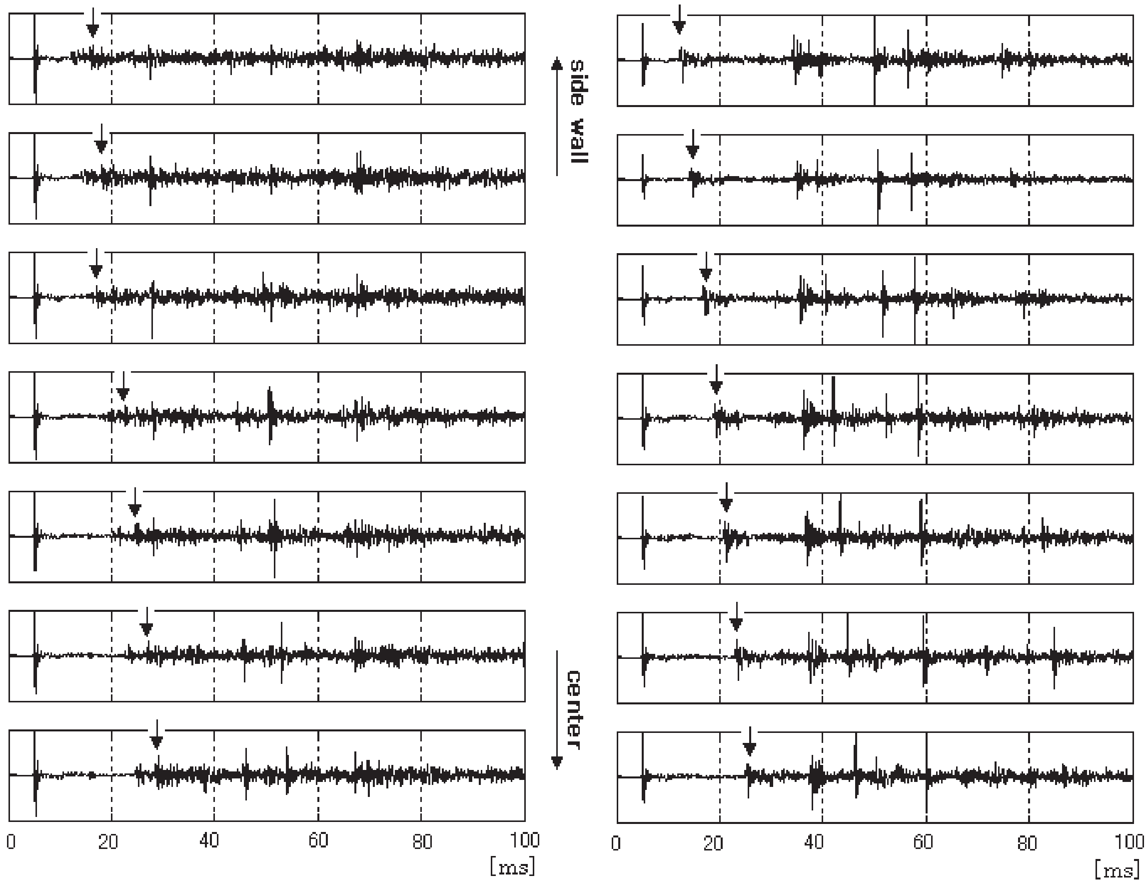

Fig. 8. Examples of left ear impulse responses measured at fifth rows of the audience seats in Tsuyama (left) and Kirishima (right). Arrows indicate the values of Δt_1.

sponses is not enough to fully understand the complicated physical properties of sound field by the insertion of scattering elements. One possible approach could be employing the analysis of the directional distribution of reflections (Guy and Abdou 1994). This would allow one to identify in more detail the contributions of various reflections depending on their arrival directions and their mutual relationship. Another problem is to investigate whether or not the discrete reflection and the scattered reflection influence the subjective preference in the same manner.

IACC

Figure 9 (a) shows the maps of the IACC averaged for three bands of 0.5, 1, and 2 kHz ($IACC_{A3}$). The overall tendency in both halls is that the IACC increases only around the center front area and decreases elsewhere. This is consistent with the previous measurement results in Kirishima (Ando et al. 1997) and in Tsuyama (Suzumura et al. 2000). It should be pointed out that the IACC increases extremely at the seats on the centerline in the Tsuyama hall (0.6 to 0.8). This tendency occurs because in the symmetrical hall, a coherent sound reflection will reach from both sides of the hall to any position on the centerline when the sound source is also on the center of the stage. This corresponds to the description in Ando (1985) and measurement results by Hidaka et al. (1995) and de Vries et al. (2001). Before the measurement, we assumed that the local variation in the IACC increases in Tsuyama because of the scattering effect of the column array. Seeing that there is no remarkable difference in the distributions of the IACC in two halls, we can say that the difference in the structures of early reflections found in the impulse responses does not strongly affect the IACC values.

Maps of $IACC_{E3}$ are shown in Figure 9 (b) that compare this measurement with the previous results about the sensitivity to the IACC. Based on the results of Okano (2002) that the JND of $IACC_{E3}$ is 0.05-0.08, measured values of $IACC_{E3}$ were rounded to the precision of 0.1, meaning that the seats with different color in the maps have discriminable differences. At a first glance of these maps, the behavior of $IACC_{E3}$ is more irregular than $IACC_{A3}$ in both halls. Even in neighboring seats have large differences in the $IACC_{E3}$. However, it is highly questionable whether such a difference is perceived in the actual halls. According to de Vries et al. (2001), the time win-

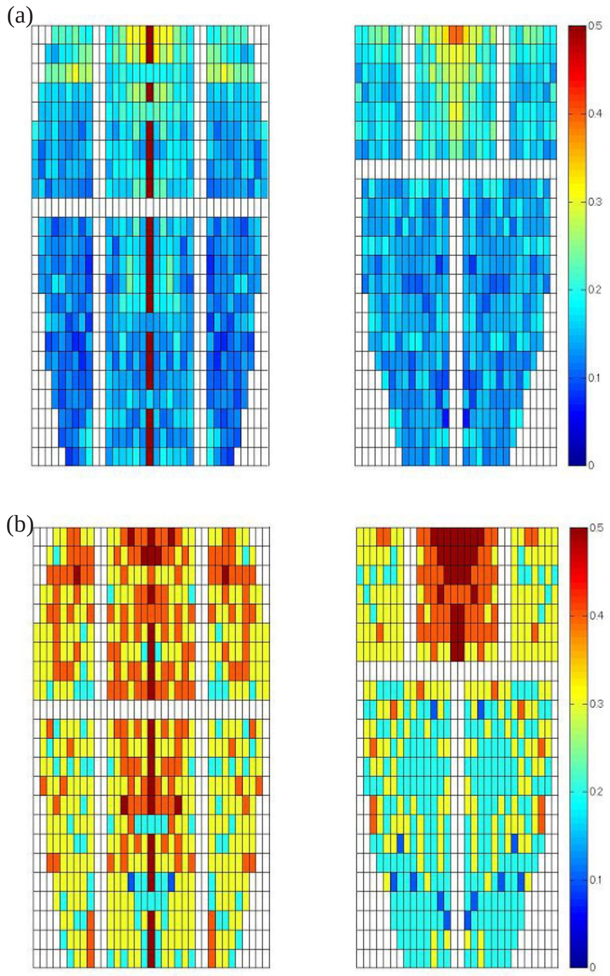

Fig. 9. Spatial maps of (a) $IACC_{A3}$ and (b) $IACC_{E3}$ for Tsuyama (left) and Kirishima (right).

dow boundary of 80 ms used for calculating $IACC_E$ may cause a discontinuity in the results, because the strong early reflections may suddenly disappear from the “windowed” impulse response when moving to the next position. They reported that the $IACC_{E3}$ shows significant variation with quite small spatial displacements of the measuring points even within a single seat. If this is the case, large local fluctuations found in the $IACC_{E3}$ could be caused by the definition of the $IACC_E$ itself. In Okano (2002), the listening tests were performed in the simulated sound fields, by controlling the amplitude of only a small number of reflections. If such a simplified sound field is quite different from the situation in the real concert hall, their JND values could not be taken as reference in this measurement. The question on the perceptual relevance of the fluctuation in the IACC (i.e. about the degree at which the observed variations in the IACC produce relevant effects on the subjective attributes) cannot be unambiguously answered at this point.

By comparing the maps of $IACC_{A3}$ and $IACC_{E3}$, another line of discussion is possible. The overall distributions of these two values look similar in Kirishima. But in Tsuyama, two versions of the IACC seem to show somewhat different distributions. For example, $IACC_{A3}$ is decreased near the sidewalls, but $IACC_{E3}$ is not. Correlation coefficients between $IACC_{A3}$ and $IACC_{E3}$ (r = 0.90 for Kirishima and r = 0.74 for Tsuyama) back up this observation. Secondly, the $IACC_{E3}$ in Tsuyama is larger than in Kirishima throughout the hall. Because the $IACC_A$ is calculated by integrating all range of the impulse responses, the effect of all of reflections is included, whereas the $IACC_E$ is affected only by the early reflections within first 80 ms. As stated before, the SPL and A-value showed a large reduction near the sidewalls in Tsuyama, which means that the lateral reflection is weakened in this area. By combining these results, the following assumption can be made: in Kirishima, the strong lateral reflections within 80 ms work effectively for lowering $IACC_E$ and $IACC_A$ in a same manner, and in Tsuyama, the diffuse reflections mainly contribute to decrease the $IACC_A$, but not to the $IACC_E$. According to Bradley and Soulodre (1995), the spatial impression can be characterized by two attributes: apparent source width (ASW) and listener envelopment (LEV), the former related to the strength of early lateral reflections, and the latter related to the strength of late arriving lateral energy. If this distinction were effective in the real hall, a large difference in the spatial impression would arise in Tsuyama and Kirishima (compare $IACC_{E3}$). But if it were not the case, the difference becomes small (compare $IACC_{A3}$).

3.3 Interrelation between acoustical parameters

From the spatial maps, we can see that some of the parameters have similar variation patterns in the hall. Measured values of these parameters were plotted with each other in Figure 10 to investigate these interrelations in more detail. The scatter of each parameter is large, so they can be considered as independent to some extent. Even though the correlation coefficients became “statistically” significant as shown in Table 2, such correlations may be due to a large amount of data points. Of course, each parameter expresses a different acoustical property, and they can affect the subjective preference independently. There is no doubt about the orthogonality of these parameters in these meanings. The results, however, urge caution when selecting a preferred seat by combining the preferences for each acoustical parameter. For example, if a listener prefers a long Δt_1 and a low SPL, it may cause a contradiction because Δt_1 and SPL are highly correlated. No seat

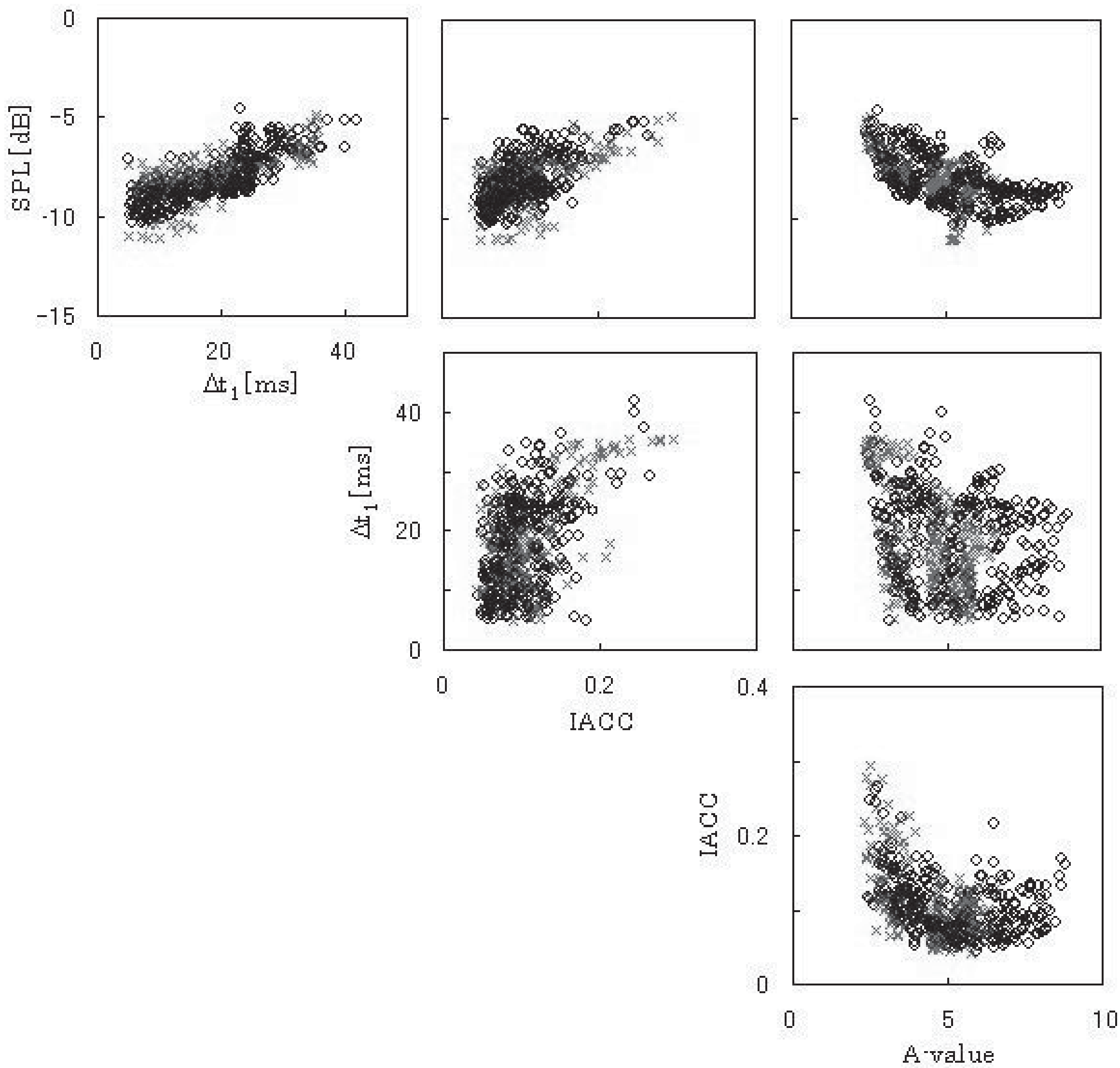

Fig. 10. Scatter plots between acoustical parameters SPL, Δt_1, IACC, and A-value for all values in ○ : Tsuyama and ✕ : Kirishima

Table 2. Correlation coefficients between the acoustical parameters calculated for all measurement points in (top) Kirishima, and (bottom) Tsuyama (*p<0.01).

	Δt_1	T_{sub}	IACC	A-value
SPL	0.73*	-0.05	0.54*	-0.66*
	0.79*	0.02	0.60*	-0.55*
Δt_1		-0.23*	0.59*	-0.46*
		-0.16*	0.45*	-0.22*
T_{sub}			0.01	-0.28*
			0.04	-0.42*
IACC				-0.57*
				-0.35*

satisfies these conditions simultaneously. To deal with such a situation, we need to consider both the preferred values of the acoustical parameters and the relative contribution of particular parameters to the total preference.

4. CONCLUSION

Spatial distributions of acoustical parameters were investigated in two concert halls by extensive acoustical measurements. Local variations in the parameters of neighboring seats were measured in two concert halls with different scattered reflections. From the results, the following conclusions were drawn.

1) Variation ranges of measured parameters are larger than

their JND values, and therefore, the seat positions in a hall can be divided into several groups in terms of each acoustical parameter.

2) For SPL, A-value, and T_{sub}, local variations in neighboring seats are quite small. A relatively small number of measurement points are sufficient to describe the spatial distributions of these parameters. Because SPL and A-value vary systematically in a hall, listeners can choose a seat based on their preferences. T_{sub} is almost uniform throughout the hall. Therefore it may not be a significant parameter when selecting preferred seat.

3) An array of columns installed in Tsuyama hall weakens the specular reflections from the sidewall by scattering them. As a result, the SPL and A-value are decreased near the sidewall. Also, the scattering from the columns causes a longer Δt_1 throughout the hall and makes its local variation large.

4) Some of the orthogonal acoustical parameters have similar variation patterns in the hall. In searching for the optimal seats for each listener, both the preferred values of the parameters and their relative contributions to the total preference should be taken into account to avoid any contradiction between parameters.

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