 ISSN1346-7824

Musical performance and the concert hall as a second instrument[a)]

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(Received 20 May 2007; accepted 15 December 2007)

When music is performed on a concert-hall stage, the concert hall acts as a second instrument. To blend music and the sound field in any given concert hall, temporal and spatial musical expressions should be taken into consideration and both expressions may play an important role in composition and interpretation promoting the further creation of music.

Keywords: music, sound field, temporal expression, spatial expression

1. INTRODUCTION

Since the theory of designing the sound field of a concert hall has been well established (Ando, 1985, 1998, 2007), we may discuss how music composition and performance can be conduced for a given concert hall as a second instrument. First of all, the theory of subjective preference for the sound field incorporating the temporal and spatial factors with optimal conditions maximizing subjective preference is reviewed in several provious studies. This theory has been well based on the specialization of human cerebral hemispheres, in which the most influential effects on subjective preference, i.e., the temporal factors and the spatial factors of the sound field are associated with the left hemisphere and the right hemisphere, respectively (Ando, 2003). After exploring an example of acoustic design for the concert hall, suggestions are made here for further musical expressivity in composition and interpretation, working with the temporal and spatial characteristics of human subjective response to music sound fields.

2. THEORY OF SUBJECTIVE PREFERENCE FOR THE SOUND FIELD

Subjective preference is the most primitive response in any subjective attribute of sensory input and entails judgments that steer an organism in the direction of maintaining and continuing *life*. Therefore, subjective preference may deeply relate to brain activities, and furthermore, to aesthetic issues.

It is known that subjective judgments for determining an absolute scale of sensory value presents a problem in reliability; rather, it is required to acquire judgment data in a relative manner such as by paired comparison tests. This is the simplest method, in that any person may participate, and the resulting scale values may be utilized in a wide range of applications.

From the results of subjective-preference studies in relation to the temporal factor and the spatial factor of a sound field, the theory of subjective preference is derived. Examples of calculating subjective preference at each listener's position has been demonstrated for both the global listener and the individual listener (Ando, 1998). The relationship between subjective preference judgments, conducted in existing rooms, and physical factors obtained has been well revealed by factor analysis (Sato et al., 1997; 2002).

2.1. Optimal conditions maximizing subjective preference

Optimam design objectives and a linear-scale value of subjective preference have been obtained from systematic investigation of simulated the sound field with multiple reflections and reverberation, with the aid of a computer, and through listening tests. Consequently, the optimum design objectives can be described in terms of the subjectively preferred sound qualities, which are related to the temporal and spatial factors (four orthogonal factors) describing the sound signals arriving at the two ears. They clearly lead to comprehensive criteria for achieving the optimal design of concert halls as summarized below (Ando, 1998).

2.1.1. Binaural listening level (LL) – spatial factor

The binaural LL is defined by

$$LL = 10 \log [\Phi(0)/\Phi(0)_{reference}] \quad (1)$$

[a)]This paper was presented as a special lecture at the Symposium of Kirishima Renaissance Conference held at the Kirishima International Music Hall, 19 May 2007.

where $\Phi(0) = [\Phi_{ll}(0)\Phi_{rr}(0)]^{1/2}$ is the geometrical mean of the sound energies arriving at the left and right ear entrances, which are obtained by the autocorrelation function (ACF) at $\tau = 0$, and $\Phi(0)$reference is the reference sound energy.

The LL is the primary criterion for listening to sound in a concert hall and is classified by one of the spatial factor due to right hemisphere dominance (Ando, 2003, see also Table 2). The preferred LL depends upon the music and the particular musical passage being performed.

Examples of the preferred level obtained with 16 subjects were surprisingly similar for two extreme music motifs: 77 −79 dBA in peak ranges for music motif A (Royal Pavane by Gibbons) at a leisurley adagio tempo, and 79−80 dBA for music motif B (Sinfonietta by Arnold) at a fast tempo.

2.1.2. Delay time of the strongest reflection after the direct sound (Δt_1) – temporal factor

An approximate relationship for the most preferred delay time has been described in terms of the ACF envelope of source signals and the total amplitude of reflections, A. From experimental results, it is expressed by $[\Delta t_1]_p = \tau_p$

$$|\phi_p(\tau)|_{envelope} \approx kA^c,\ \tau = \tau_p \quad (2)$$

where k and c are constants. If the envelope of ACF indicates an exponential decay, then

$$[\Delta t_1]_p = \tau_p = (\log_{10}1/k - c\ \log_{10}A)\ (\tau_e)_{min} \quad (3)$$

where $(\tau_e)_{min}$ is the minimum value of effective duration of the running ACF, representing a similar repetitive feature for a music piece, τ_e is defined in Fig. 1. The value of $(\tau_e)_{min}$ is observed at the most active part of a piece of music containing musically expressive information such as "vibrato", or a "quick tempo" in the music flow, and/or a very sharp sound signal. The value of A is the total pressure amplitude of individual reflections, combined (each reflection with an integer subscript). The expression for A is given by

$$A = |A_1^{\,2} + A_2^{\,2} + A_3^{\,2} + \ldots\ ]^{1/2} \quad (4)$$

Subjective preference and echo disturbance (for example), are controlled and determined for the music piece by the value of $(\tau_e)_{min}$. Even for lengthy music compositions, the minimum part of $(\tau_e)_{min}$ of the running ACF for the whole the music's performance, determines the preferred temporal condition. This value should be taken into consideration for the choice of music program to be performed in a given concert hall.

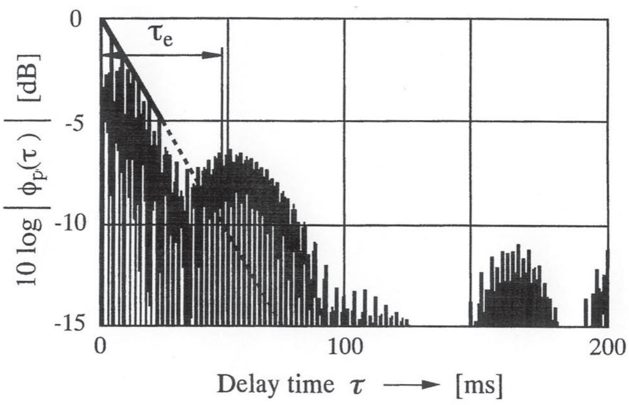

Fig. 1. Determination of the effective duration of running ACF, τ_e. The value of τ_e may be obtained by the delay at which the envelope of the normalized ACF becomes 0.1 or −10 dB (ten-percentile delay).

2.1.3. Reverberation time (T_{sub}) – temporal factor

It has been observed that the most preferred condition for frequency response to the reverberation time is a flat curve (Ando, Okano and Takezoe, 1989). The preferred reverberation time, which is equivalent to that defined by Sabine (1992) is expressed approximately by

$$[T_{sub}]_p \approx 23(\tau_e)_{min} \quad (5)$$

The total amplitude of reflections A, applied for Equation (5) and produced in sound simulation, ranged from 1.1 and 4.1, which covers the usual conditions of sound fields in a room. Recommended reverberation times for several sound sources are shown in Fig. 2. A lecture and conference room must be designed for speech signals: $[T_{sub}]_p \approx 0.5$ s. An opera house mainly for vocal music on the stage: $[T_{sub}]_p \approx 0.5$ −1.0 s but also for orchestra music in the pit: $[T_{sub}]_p \approx 1.0$ −1.8 s. An attempt at an acoustic design for an opera house has been made to accommodate these two quite different sound sources (Ando and Sakai, 2005). For orchestral music, there may be two or three types of optimum concert-hall designs with different reverberation times adapt to the effective duration of the ACF. For example, Symphony No. 41 by Mozart, The Rite of Spring by Stravinsky, and Arnold's Sinfonietta have short values of $(\tau_e)_{min}$ and fit orchestral music of type (A). On the other hand, Symphony No. 4 by Brahms and symphony No. 7 by Buckner are typical of orchestral music (B). Much longer ACFs are typical for pipe organ music, for example, by Bach.

The most preferred reverberation times for each sound

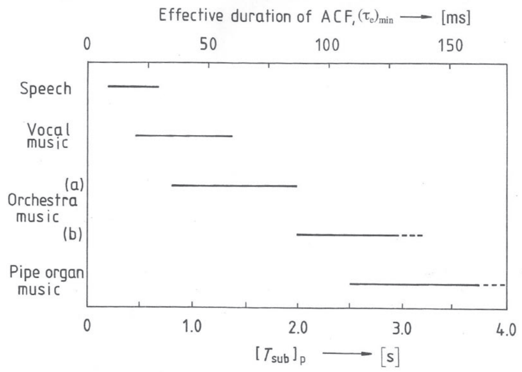

Fig. 2. Recommended reverberation times for several music/instrument sound programs.

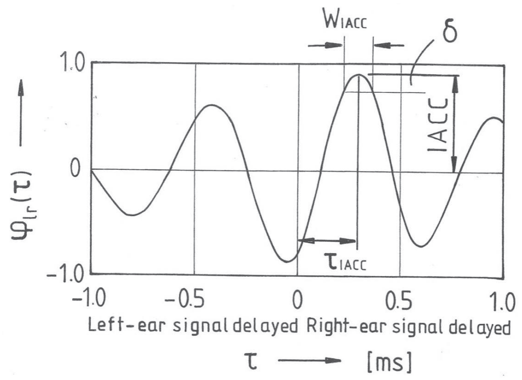

Fig. 3. Definition of the three spatial factors IACC, τ_{IACC} and W_{IACC}, extracted from the interaural cross-correlation function (IACF). The preferred condition is realized by the condition without any image shift of source location, τ_{IACC} = 0.

source given by Equation (5) might play an important role for selection of music motifs to be performed.

2.1.4. Magnitude of the inter-aural cross-correlation function (IACC) – spatial factor

All individual data indicated a negative correlation between the magnitude of the IACC (Fig. 3) and subjective preference, i.e., dissimilarity of signals arriving at the two ears is preferred. This holds under the condition that the maximum value of the IACF is maintained at the origin of the time delay keeping a balance of the sound field at the two ears, namely τ_{IACC} = 0. If not, then an image shift of the source may occur. To obtain a small magnitude of the IACC in the most effective manner, the directions from which the early reflections arrive at the listener should be kept within a certain range of angles from the median plane centered on 55 °. By definition, the sound arriving from the median plane 0 ° makes the value of IACC greater. Sound arriving from 90° in the horizontal plane is not always advantageous, because the similar "detour" paths around the head to both ears cannot decrease the IACC effectively, particularly for frequency ranges higher than 500 Hz. For example, the most effective angles for the frequency ranges of 1 kHz, 2 kHz and 4 kHz are centered on 55°, 36° and 18°, respectively.

2.2. Theory of subjective preference for the sound field

2.2.1. Theory

Since the number of orthogonal acoustic factors of the sound field that are included in the sound signals at both ears, is limited (Ando, 1998) the scale value of any one-dimensional subjective response may be expressed by

$$S = g(x_1, x_2, \ldots x_I). \tag{6}$$

It has been verified by a series of experiments that four objective factors act independently on the scale value when systematically changing two of four factors simultaneously. Results indicate that the units of the scale value of subjective preference derived by the series of experiments with different sound sources and different subjects have appeared to be constant (Ando, 1983), so that we simply may add the scale values to obtain the total scale value such as

$$S = g(x_1) + g(x_2) + g(x_3) + g(x_4)$$

$$= S_1 + S_2 + S_3 + S_4 \tag{7}$$

where S_i (i = 1, 2, 3, 4) is the scale value obtained relative to each objective parameter. Equation (7) indicates a four-dimensional continuity.

2.2.2. A common formula for the four normalized orthogonal factors

The dependence of the scale value on each objective parameter is shown graphically in Fig. 4. From the nature of the scale value, it is convenient to assign a value of zero as the most preferred condition, as shown in this figure. These results of the scale value of subjective preference obtained from the different test series, using different music programs, yield the following common expression:

$$S_i = -\alpha_i, \ i = 1, 2, 3, 4 \tag{8}$$

where values of α_i are weighting coefficients as listed in Table 1, and were obtained with a number of subjects. If αi is close to zero, then a lesser contribution of the factor xi on

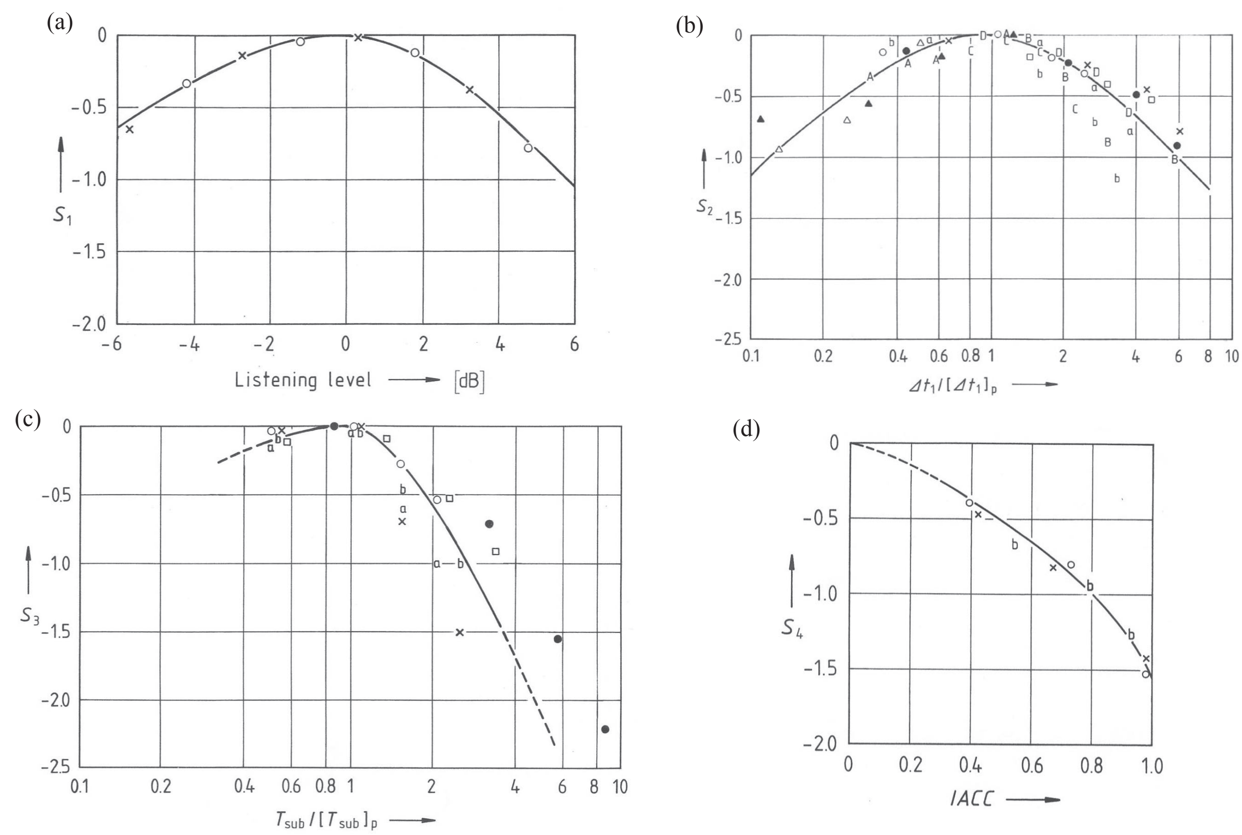

Fig. 4 Scale values of subjective preference obtained by the paired-comparison test for simulated sound fields in an anechoic chamber. Different symbols indicate scale values obtained from different source signals. Even if different signals are used, a consistency of scale values as a function of each factor is observed, fitting a single curve.
(a) As a function of listening level, LL. The most preferred listening level, $[LL]_p = 0$ dB.
(b) As a function of the normalized initial delay time of the first reflection by the most preferred delay time calculated by Equation (3), $\Delta t_1/[\Delta t_1]_p$.
(c) As a function of the normalized reverberation time by the most preferred one calculated by Equation (5), $T_{sub}/[T_{sub}]_p$.
(d) As a function of the IACC.

subjective preference is signified.

The factor x_1 is given by the sound pressure level (SPL) difference, measured by the A-weighted network, so that

$$x_1 = 20\log P - 20\log[P]_p \quad (9)$$

P and $[P]_p$, respectively, being the sound pressure at a specific seat and the most preferred sound pressure that may be assumed at a particular seat position in the room under investigation:

$$x_2 = \log (\Delta t_1 / [\Delta t_1]_p) \quad (10)$$

$$x_3 = \log (T_{sub} / [T_{sub}]_p) \quad (11)$$

$$x_4 = IACC \quad (12)$$

Thus, scale values of preference have been formulated approximately in terms of the 3/2 powers of the normalized objective parameters, expressed in the logarithm for the parameters, x_1, x_2 and x_3. Thus, scale values do not change in the neighborhood of the most preferred conditions, but decrease rapidly outside of this range. The remarkable find-

Table 1. Four orthogonal factors of the sound field and its weighting coefficients α_i obtained by the paired-comparison test of subjective preference with a number of subjects in the condition without any image shift of sound source, $\tau_{IACC} = 0$.

i	x_i	α_i	
		$x_i > 0$	$x_i < 0$
1	$20\log P - 20\log[p]_p$ (dB)	0.07	0.04
2	$\log(\Delta t_1/[\Delta t_1]_p)$	1.42	1.11
3	$\log(T_{sub}/[T_{sub}]_p)$	0.45 + 0.75A	2.36 - 0.42A
4	IACC	1.45	---

ing is that the spatial binaural parameter x_4 is expressed in terms of the 3/2 powers of its real values (non-logatithm), indicating a greater contribution than those of the temporal parameters.

2.2.3. Limitation of theory

Since experiments were conducted to find the optimal conditions, this theory of preference holds within the range of preferred conditions obtained by the sound field tests. In addition, the experiments performed in real rooms varying the sound-source locations on the stage indicate that the theory holds for the condition of $\tau_{IACC} = 0$.

3. SPECIALIZATION OF CEREBRAL HEMISPHERES FOR TEMPORAL AND SPATIAL FACTORS OF THE SOUND FIELD

The independent influence of the aforementioned temporal and spatial factors on subjective preference judgments has been achieved by the specialization of human cerebral hemispheres as indicated in Table 2 (Ando, 2003, 2006). It has been discovered that the listening level (LL) and the IACC are dominantly associated with the right cerebral hemisphere, and the temporal factors. Δt_1 and T_{sub} are associated with the left cerebral hemisphere. This implies that such specialization of the human cerebral hemisphere may relate to the highly independent influence between the spatial and temporal criteria on any subjective attribute. Additionally, experiments showed that spatial factors (LL and IACC) are independent on subjective preference and the same is true for temporal factors (Δt_1 and T_{sub}).

Table 2. Hemisphere specializations determined by analyses of AEP(SVR), EEG and MEG[1].

Factors changed	AEP (SVR) $A(P_1 - N_1)$	EEG ratio of ACF τ_e values of α-wave	MEG ACF τ_e value of α-wave
Temporal			
Δt_1	L > R (speech)[2]	L > R (music)	L > R (speech)
T_{sub}	—	L > R (music)	---
Spatial			
LL	R > L (speech)	---	---
IACC	R > L (vowel /a/) R > L (band noise)	R > L (music)[3]	---

[1] See also Ando (2003) for review of these investigations..

[2] Sound source used in experiments is indicated in the bracket..

[3] Flow of α-wave (EEG) from the right hemisphere to the light hemisphere for music stimuli in change of the IACC was observed by $|\phi(\tau)|_{max}$ between α-waves recorded at different electrodes (Sato, Nishio and Ando, 2003).

4. A DESIGN STUDY BASED ON A THEORY

After testing more than two hundred listeners, a small value of the IACC, which corresponds to strongly different sound signals arriving at two ears, was shown to be the preferred condition for individuals without exception. Due to this spatial factor, the IACC itself may be used to determine the shape of concert hall, minimizing it at each seating position. A practical application of this design theory was done for the Kirishima International Music Hall (Miyama Conceru), which was characterized by a "leaf shape" plan. It is worth noticing that optimization of a spatial form for the concert hall by use of a genetic algorithm also resulted in a shape similar to a "leaf" (Sato et al., 2002).

4.1. Temporal factors of the sound field for listeners

Referring to Fig. 2, when the space is designed for pipe organ performance, the range of $(\tau_e)_{min}$, which may be selected to be centered on 150 ms, determines the typical temporal factor of the hall, $[T_{sub}]_p \sim 3.5$ s by Equation (5). When it is designed for the performance of chamber music, the range is selected to be near the value of 65 ms, ($[T_{sub}]_p \sim 1.5$ s). The conductor and/or the sound coordinator (Appendix B) has the opportunity to select suitable music motifs with a satisfactory range of the effective duration of the ACF to achieve a music performance that blends the music and the sound field within the hall. To adjust the preferred condition for Δt_1, where the value of $(\tau_e)_{min}$ for violins is usually shorter than that of contrabasses in the low frequency range, the position of the violins can be shifted closer to a reflecting on the stage, and for a longer Δt_1 the position of the contrabasses can be located closer to the center.

4.2. Spatial factors of the sound field for listeners

As mentioned above, the IACC should be kept as small as possible, approching $\tau_{IACC} = 0$. This is realized by suppressing the strong reflection from the ceiling, and by appropriate reflections from the sidewall keeping a specific range of angles. Under actual hearing conditions, the perceived IACC depends on whether or not the amplitudes of reflection exceed the hearing threshold level. This may be one of the reasons why a more diffuse sound field can be perceived only with increasing power of the sound source. While the source is with just the direct sound above the thereshold, the actual IACC being processed in the auditory- brain system approaches unity, resulting in no diffuse sound impression.

4.3. Sound field for musicians

For music performers, the temporal factors are considered to be much more critical than the spatial factor (Nakayama, 1984, Nakayama and Uehara, 1988). Since musicians perform over a sequence of time, reflections with a certain delay in terms of the value of $(\tau_e)_{min}$ of the musical source signals are of particular importance. Without presence of spatial subjective diffuseness (Appendix A: Ando and Kurihara, 1986), the preferred directions of reflections are in the median plane of the musical performers, resulting in an IACC ~ 1.0. In order to satisfy these acoustic conditions, some design iterations are required, maximizing the scale values for both musicians and listeners and leading to the final scheme of the concert hall, as the example design process is shown in Fig. 5.

4.4. Sound field for the conductor

It is recommended that the sound field for the conductor on the stage should be designed in a manner for that of a "listener" with appropriate reflections of the sidewalls on the stage (Meyer, 1995).

4.5. Acoustic design in collaboration with architects

From the historical viewpoint, architects have been much more concerned with spatial criteria from the visual standpoint, and less so with temporal criteria, for blending human life and the environment with design. On the other hand, since the time of Sabine (1900), acousticians have mainly been concerned with temporal criteria, represented primarily by reverberation time. There existed no comprehensive theory of design including the spatial criterion as represented by the IACC, before 1977 (Ando, 1977), so that discussions between acousticians and architects were rarely on the same subject. As a matter of fact, both temporal and spatial factors are deeply interrelated with both acoustic design and architectural design (Ando, Johnson and Bosworth, 1996, Ando, 2004).

As an initial design sketch of the Kirishima International Music Hall, a leaf-like plan (Fig. 6) was presented at the first meeting for discussion with the architect Fumihiko Maki and associates, along with an explanation of the temporal and spatial factors of sound field. Following this design discussion, Maki and Ikeda produced a scheme for the concert hall as shown in Fig. 7 (Maki, 1997, Ikeda, 1997). Calculated results of the total scale value of subjective preference by Equations (7) and (8) for two music motifs as shown in Fig. 8, immediately demonstrated an excellent sound field (Nakajima and Ando, 1997, Ando, et al., 1997,

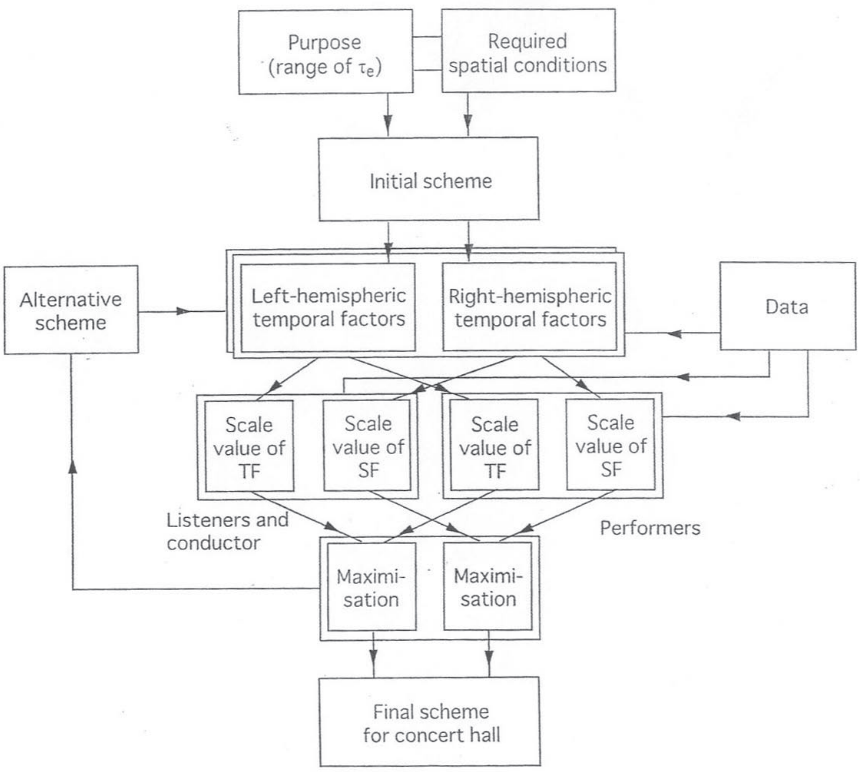

Fig. 5. Procedure for designing the sound field in a concert hall maximizing the scale values of subjective preference for listeners (including conductor) and performers. Data of global values for subjective preference may be utilized in designing a public performance hall.

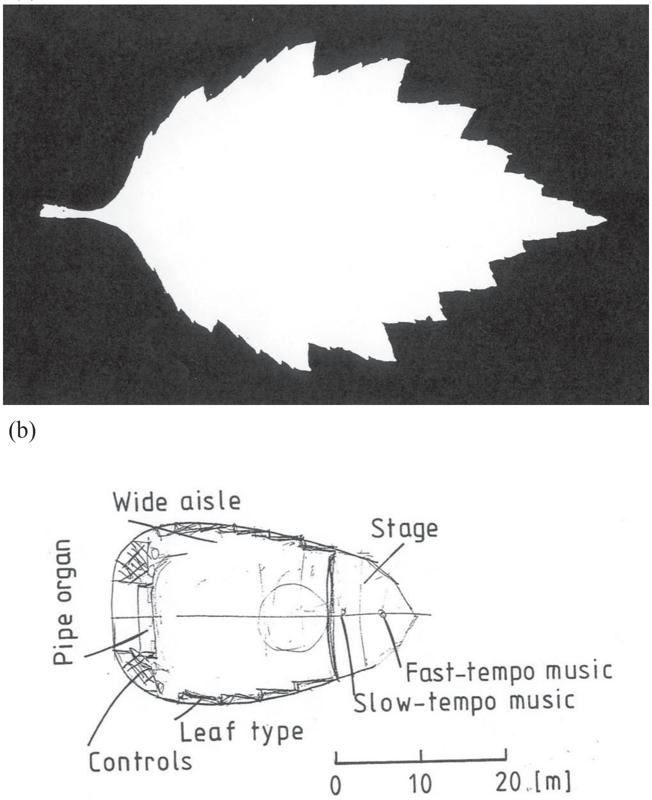

Fig. 6. A leaf shape for the plan proposed for the Kirishima International Concert Hall. (a) Original leaf shape found in a forest, Kobe, Japan. (b) Proposed shape for the plan by the author. In usual fashion, the sound field in circled seating area close to the stage (subject to be a large IACC value due to the strong direct sound) is carefully designed for obtaining reflections from the walls on the stage and tilted sidewalls tilted to produce a small IACC value.

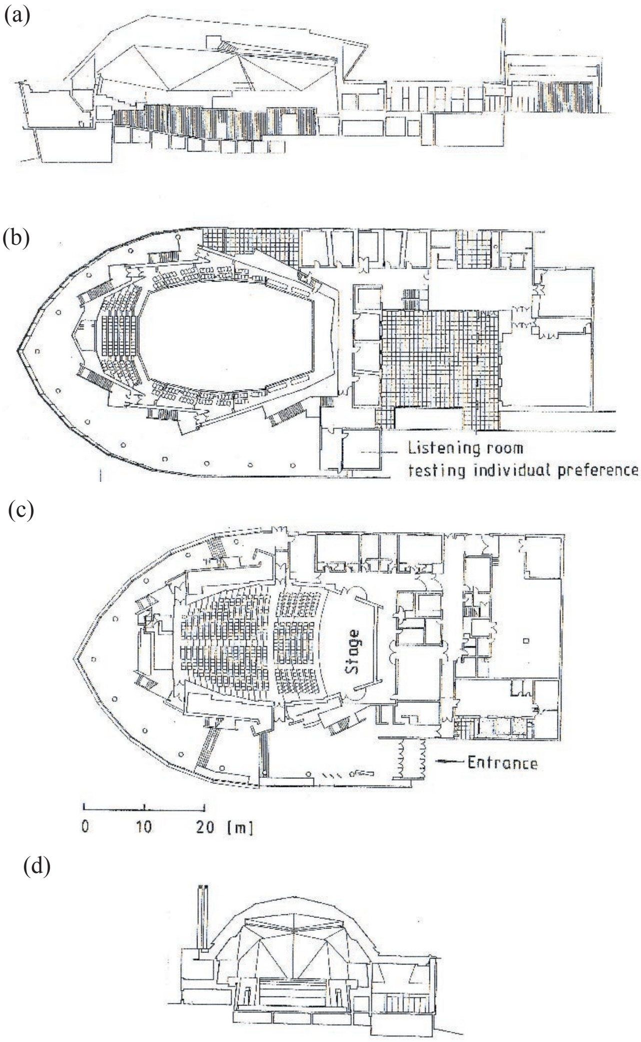

Fig. 7. Final scheme of the Kirishima International Concert Hall; Kagoshima, Japan designed by the architect Maki (1997) and associates. (a) Longitudinal section. (b) Plan of balcony level. (c) Plan of audience level. (d) Cross-section.

Ando, 1998).

The final architectural schemes for this hall, together with the special listening room for testing individual preference of sound field, (used for selecting the appropriate seats to maximize individual sound field preference), are shown in Fig. 7. In these figures, an outdoor concert courtyard, small concert hall, several rehearsal rooms, and dressing rooms are also shown. The concert hall while under construction is shown in Photo 1, in which the overall “leaf shape” may be seen as expressed in the exterior form, and the concert hall opened in 1994, and the inside of the hall with a ceiling consisting of triangular panels is shown in Photo 2. This ceiling design produces a small value of IACC due to reflections arriving from different angles centered on roughly 55° from the median plan for each listening position in the audience seating area.

Photo 1. The Kirishima International Concert Hall, Kagoshima, under construction. The leaf shape can be seen.

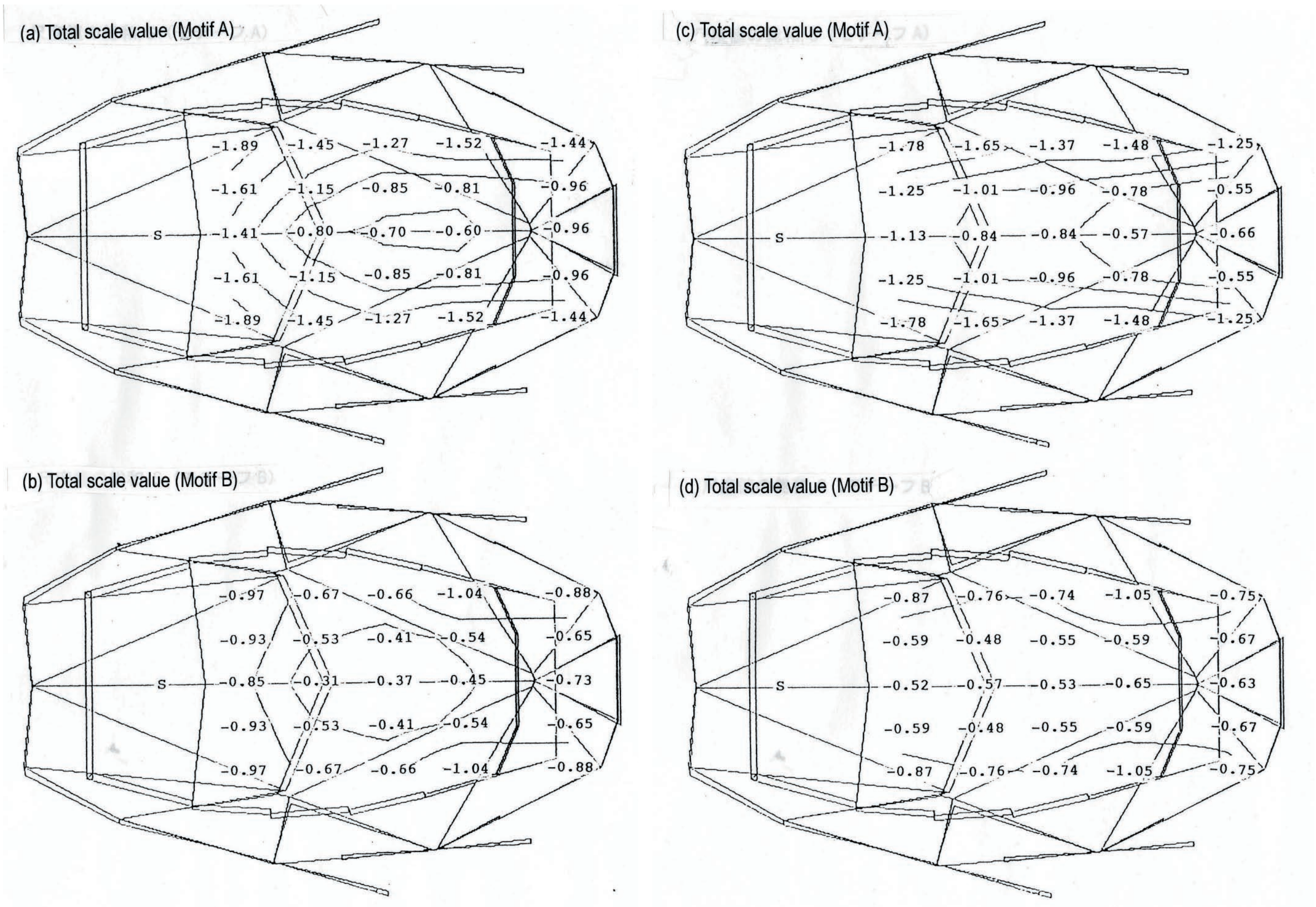

Fig. 8 Calculated total scale values of subjective preference at each seat for Music motif A (Royal Pavane by Gibbons; $(\tau_e)_{min}$ = 125 ms) and Music motif B (Sinfonietta, Opus 48; IV movement by Arnold; $(\tau_e)_{min}$ = 35 ms) (Ando, 1998).
(a) Performing position: Stage front with music motif A; (b) Performing position: Stage front with music motif B; (c) Performing position: Stage rear with music motif A; (d) Performing position: Stage rear with music motif B.
Seating areas with the total scale value greater than −0.6 for Music motif B are much wider than those for Music motif A. This demonstrates that Music motif B is blending much better than Music motif A due to the temporal factors of the sound field of this concert hall. According to the seating areas with the total scale value greater than −0.6, the performing position at the stage-rear near the wall is recommended for both music motifs.

4.6. Details of acoustic design

4.6.1. For listeners on the main floor

In order to provide a small value of the IACC for most listeners, ceilings were designed using a number of triangular plates with adjusted angles as mentioned above, and the side walls were given a 10% tilt with respect to the main-audience floor, as shown in Fig. 9. Diffusing elements were incorporated into the sidewalls to avoid an image shift of the perceived sound source location on the stage, which is caused by the strong reflections in the high frequency range above 2 kHz. This treatment also contribute to the goal of τ_{IACC} = 0. These diffusers on sidewalls were designed as a modification of the Schroeder diffuser (Schroeder, 1984), removing the wells, as shown by the detail in Fig. 10.

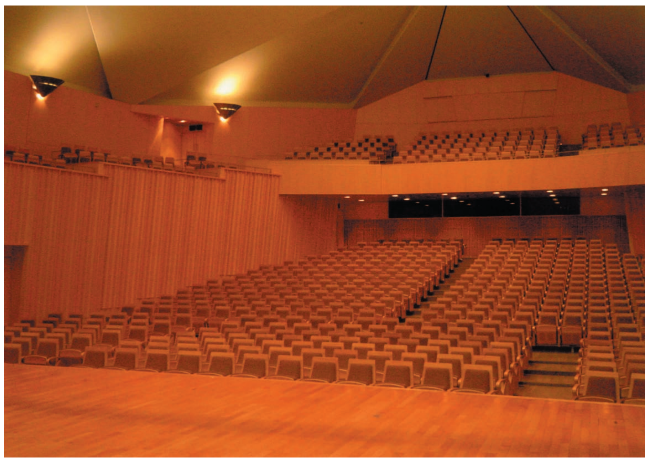

Photo 2. Tilted sidewalls and triangular ceilings after construction of the hall.

4.6.2. For music performers on stage

To provide reflections from places near the median plane of each of the performers on the stage, the back wall on the stage was carefully configured as shown in Fig. 7a and Fig. 9. The tilted back wall consists of six sub-walls with angles adjusted to provide appropriate reflections within the median plane of the performer. It is worth noticing that the tilted sidewalls on the stage provide good reflection to the audience sitting close to the stage, and at the same time resulting in a decrease of the IACC. Also, the sidewall on the stage of the left hand side looking from the audience may provide useful reflection arriving from behind for a piano or other soloist.

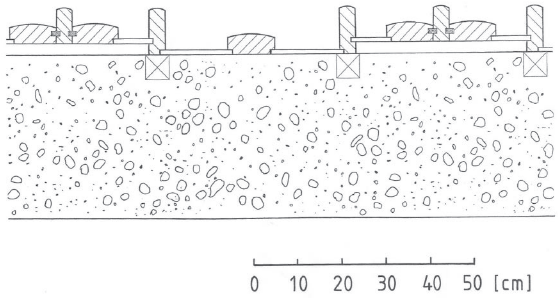

Fig. 10 Detail of the diffusing sidewalls effective for the higher frequency range above 1.5 kHz, to prevent an image shift of the sound source on the stage, $\tau_{IACC} = 0$. The surface is deformed from the Schroeder diffuser (1984) by removal of the well partitions.

4.6.3. Stage floor structure

For the purpose of suppressing anomalous sound radiation from the stage floor during a performance, the stage floor joists form triangles without neighboring parallel structure, as shown in Fig. 11. The thickness of the floor is designed to be relatively thin, 27 mm, in order to radiate sound effectively through the vibration from instruments like the cello and contrabass. During rehearsal, musical performers may control the radiation power somewhat by adjusting their sitting position or by use of a soft pad between the floor and the instrument.

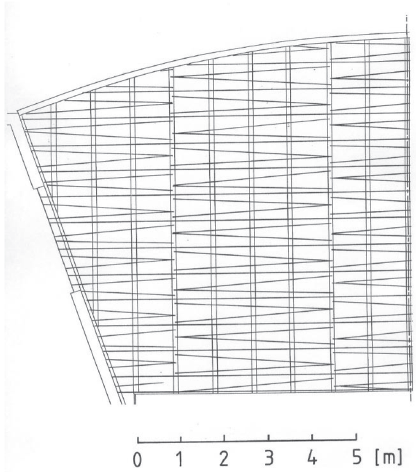

Fig. 11. Detail of the triangular joist arrangement for the stage floor, preventing anomalous radiation due to the normal modes of vibration from music instruments, which contact the floor.

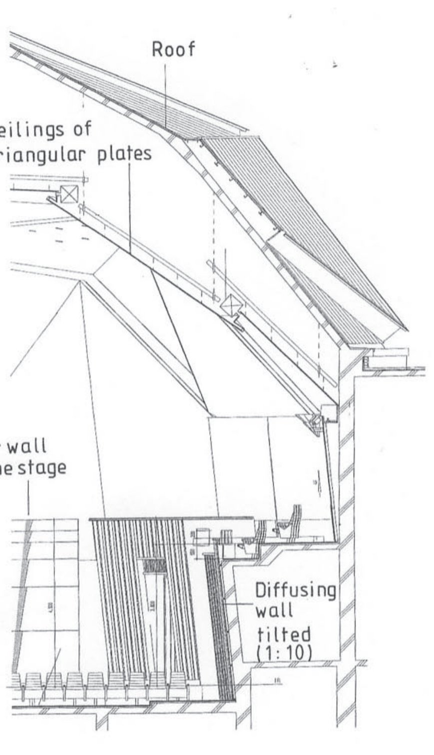

Fig. 9. Details of the cross section, including a sectional detail of the rear wall on the stage, at the lower left of the figure. The stage enclosure design provides appropriate reflections from both rear wall and sidewalls with the tilt angle of 10° and benefitting performers on the stage. At the same time the sidewalls provide reflections roughly 55° from the median plan for each listening position in the audience area.

5. MUSICAL COMPOSITION AND PERFORMANCE DUE TO TEMPORAL AND SPATIAL EXPRESSIONS

When performers on the stage play an instrument, the concert hall acts as a second instrument. Let us now discuss what kind of musical expressions the second instrument can produce. As previously described, there are temporal expressions related to the temporal factor of the sound field and spatial expressions in relation to the spatial factor.

Table 3 summarizes musical composition and performance of temporal and spatial expressions blending and utilizing the temporal and spatial factor of a given concert hall.

5.1. Musical composition blending with the temporal factor of the sound field -

5.1.1. Matching the temporal factor of the sound field using source music $(\tau_e)_{min}$

In music composition, a composer can consider the reverberation time of anticipated spaces housing the music's performance, whether performed in a church, with a long reverberation time, or in a small room with a short reverberation time. For example, Mozart-style motifs at a fast tempo might be composed while imagining guest entry hall in a Court with a reverberation time of about 1.5 s, but not intended for a church of over 4 s or a lecture room of below 1 s. The scientific expressions needed for blending the source signal with the temporal factor of the sound field are described by Equations (3) and (5). For example, when the acceptable reverberation time is defined by the scale value $S = -0.1$ in reference to $S = 0$ at the most preferred reverberation time $[T_{sub}]_p$, then the reverberation time should be restricted to a range of $T_{sub} = 0.5-1.3\ [T_{sub}]_p$.

If the room has a shorter reverberation time than $[T_{sub}]_p$, then the music can be adapted to consist of a rapid movement without any repetitive features, so that the value of $(\tau_e)_{min}$ would then tend to be smaller. On the other extreme, if a music source is a slow tempo and with a long duration of tones - like pipe organ music- then performance space with a long reverberation time would be well blended with this musical composition (Fig. 2).

5.1.2. Spatial expression due to ASW of the sound field

It has been shown that the apparent source width (ASW) may be described by both spatial factors W_{IACC} and IACC as shown in Fig. 12 (Appendix A, Sato and Ando, 1999). If the value of the W_{IACC} is a large, due to the low-frequency-component of the music signal particularly below 200 Hz (Fig. 13 see also the definition of W_{IACC} in Fig. 3), then the sound source will be perceived as "wide." For example, The Moldau composed by Bedrich Smetana (1824-1884), consists of high frequencies in the early portion of the piece, producing a "narrow" image of two upper valleys, both small sources of water. Then, as piece develops, it becomes an expression of the joining of both streams into one, and consists of increasing low-frequency spectral component producing, a wide image of the downstream flows, into a broad valley.

Another example is Piano Sonata No.14 in C sharp minor, Op.27 No.2 ("Moonlight") by Ludwig van Beethoven, in

Table 3 Musical composition and performance of temporal and spatial expressions blending and utilizing the temporal and spatial factor of a given concert hall.

	Temporal expression	Spatial expression
Composition	Tempo, Note (whole note – sixteenth), Meter, Selection of musical instrument for ACF $(\tau_e)_{min}$ of music source due to the temporal factor of a given concert hall.	(1) Frequency component for the spatial sensation (AWS); (2) Dynamics (*ppp – fff*) for subjective diffuseness & envelopment.
Performance	(1)Selection of music program to be performed in a given concert hall; (2) Selection of performing position on the stage for ease of performance due to music program; (3) Style such as vibrato extent, staccato - supper legato for ACF $(\tau_e)_{min}$ of music source due to the temporal factor in a given concert hall.	(1) Selection of performing position on the stage for decrease of IACC at each seating position; (2) Source strength as an interpretation of music for subjective diffuseness, envelopment or "embracement" with full sound surrounded of listeners.

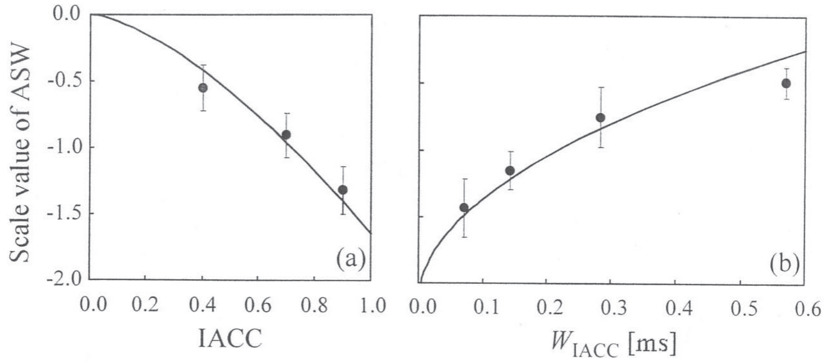

Fig. 12. Scale values of ASW for the 1/3 octave-band pass noises with 95% reliability as a function of (a) the IACC and (b) the W_{IACC}. Note that The regression curves are expressed by $S = f(IACC) + f(W_{IACC}) \approx \alpha(IACC)^{3/2} + \beta(W_{IACC})^{1/2}$ with $\alpha = 1.64$ and $\beta = 2.44$.

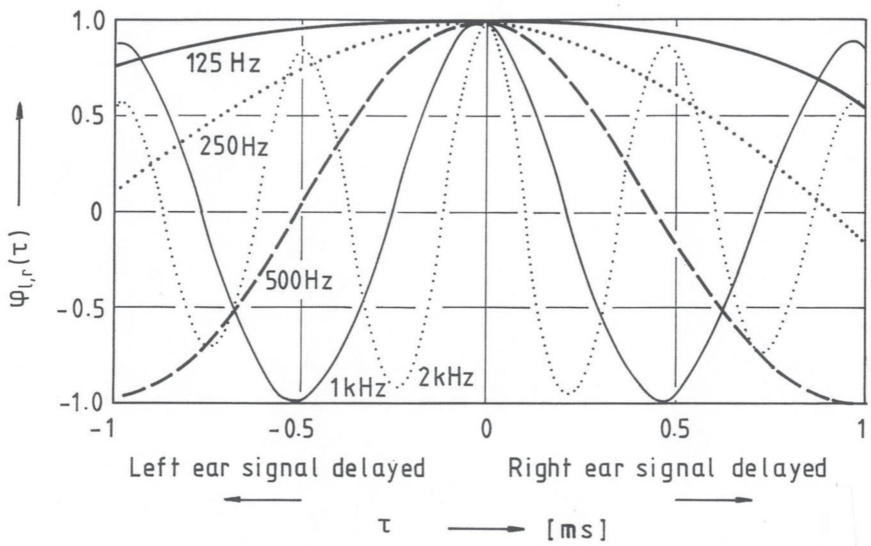

Fig. 13. The interaural cross-correlation function of the 1/3 octave-band pass noise with difference center frequencies. The value of W_{IACC} is defined in Fig. 3. It is clear that W_{IACC} increases with decreasing component frequency. For the frequency component below 200 Hz, for example, the W_{IACC} value maintains a large value for all horizontal directions expressed in term of the interaural delay.

which there are heavy low frequency components composed to represent an ambient vision of a big-blue sky with a big water and spacious ground (large ASW), while accompanimg this with high frequency components representing a focused vision of the moon.

5.1.3. Spatial expression due to the strength of music in the sound field

If the acoustic design for IACC at each seat in a concert hall is small enough, then the strength of stage sound sources at volumes; "*ppp*" to "*fff*" can utilized to control subjective diffuseness (Appendix A) as well as envelopment (Damaske, 1967/68). Musical dynamics and the resulting sound amplitude of directional reflection, which are above the concert hall's prevailing the threshold level will decrease the perceived IACC, resulting in subjectively diffuse sound, while intentional produced low dynamic levels can be used by the composed to produce a narrowing of sound field environment.

5.2. Music performance due to temporal and spatial factors of the sound field

5.2.1. Selection of performing position on the stage and control of the source strength

Soloist should select a position on the stage, which is intended to control the initial delay time of reflection, Δt_1, according to the music program. This in turn is mainly related to the range of the $(\tau_e)_{min}$ value (Ando, 1998, Sato, Ohta and

Ando, 2000, Noson, et al., 2002). The soloist may select a location on stage at the time of rehearsal, adopted both to ease of performance and to enhanced listener satisfaction. It is further recommended that a soloist situate near the middle or rear of the stage, rather than close to the front, in order to produce a small value of IACC at each seating position in the audience area.

The performing position that minimizes the IACC of the sound field for the listener's seats is demonstrated here by means of an example. The values of IACC are calculated with Music motif B (Arnold; $(\tau_e)_{min}$ = 35 ms) at 112 listener positions in a Bekesy Courtyard (Bekesy, 1934). For simplicity, the directivity of the sound source is assumed to be uniform in this calculation. The height of the sound source is 80 cm from the ground level, and the height of the listeners' ears is 110 cm. The contour lines of equal average values of the IACC for 112 listener positions, are calculated to find the optimum performing position, and are then plotted in Fig. 14. The effective positions for performance may be found in the area minimizing IACC for all listening positions within the area of IACC < 0.5. A more effective procedure is that this positioning could be suggested by a " sound coordinator" of each concert hall (Appendix B).

5.2.2. Performance Blending of the Temporal Factor of the Sound Field

When the reverberation time (T_{sub}) is short and the dimensions of a given hall are small, a method of blending music with a sound field is of a pianist, for example, who makes a decrease in the $(\tau_e)_{min}$ value by introducing staccato instead of legato, supper legato and full pedal (Taguti and Ando, 1997). A method of controlling the minimum value of $(\tau_e)_{min}$ in vocal performance, which determines the preferred temporal condition for vocal music has been discussed as a means for blending the sound source and a given concert hall (Kato and Ando, 2002; Kato et al., 2004, 2006). When vibrato is introduced during singing, for example, it decreases $(\tau_e)_{min}$, blending the sound field with a shorter reverberation time.

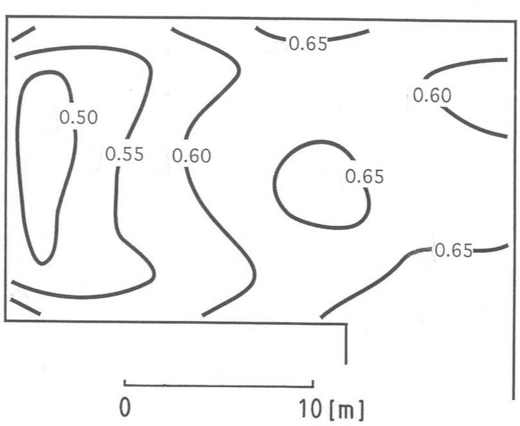

Fig. 14. Contour lines of equal averaged IACC calculated to find optimum performing position. The value was averaged for 112 listening positions. The most effective location of performance is found in the area IACC < 0.5.

Since a characteristic of vibrato depends on the individual performer, the individual performer can be strongly urged to attain a skill for controlling the $(\tau_e)_{min}$ value by use of a real time ACF analyzer of music signals (Kato et al., 2006). In the same manner, any performer may also play with a certain amount of vibrato or its equivalent for the particular instrument.

Conversely, if the reverberation time is long and the dimension of a given hall is large, then the $(\tau_e)_{min}$ value should be controlled to be long. For example, the pianist may produce a long $(\tau_e)_{min}$ value by legato, super legato and full sustain pedal instead of staccato. The vocalist and the violinist, for example, may perform with less vibrato.

In July 2004, the author requested that Tsuyoshi Tsutsumi present an invited special paper on blending cello music and the sound field in a concert hall. He immediately accepted this invitation, and said that it is a "musical lifeline". Tsutsumi (2006) has shown how cello music can be blended with the specific case of the sound field at the Kirishima International Music Hall. On the Internet, his music performance is avaiable (Journal of Temporal Design in Architecture and the Environment, Vol. 6, No. 3, (2006) 78-81, http://www.jtdweb.org/).

6. REMARKS TOWARD FUTURE CREATIONS OF MUSIC AND PERFORMANCE

The scientific approach made here suggests that further dimensions of musical temporal and spatial expressions in composition can be based on a concert hall's acoustics (Table 3). In blending music sources performed on the stage with the temporal factor of the sound field in a given concert hall, we may take the effective duration of the autocorrelation function of the source signal into account, both for practical considerations (satisfaction of audience) and for artistic purposes (expressivity of the composer and performer). For spatial expression, the frequency component and the strength of music source enhancing spatial sensations, due to the perceived IACC, could be carefully included in the production of each musical note.

After selecting a suitable performing position on the stage, music sources and the sound field in a concert hall may be fully blended by control of the temporal and the spatial expressions. For the temporal expression of the performer, methods of blending the temporal factor of the sound field have been proposed based on the effective duration of ACF of the sound source. For spatial expression, minimum source energy is needed to realizing subjective diffuseness or envelopment for each listener.

It is hoped that the survey presented here will encourage musicians, researchers and students in their future work, and encourage furtherance of artistic creations in music composition and performance - utilizing simultaneously the two primary instruments, soloist's musical instrument and the given concert hall enclosure.

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APPENDIX A. Spatial sensations of the sound field

The spatial sensations of the sound field may be classified into following three (Ando, unpublished):

1) Localization of the sound source

A well-defined direction is perceived when the normalized interaural crosscorrelation function (IACF) has one sharp maximum with a large value of IACC, and with a narrow value of W_{IACC} due to the high frequency components above 2 kHz.

2) Apparent Source Width (ASW) (Sato and Ando, 1996).

Listeners judged which of two sound sources were perceived to be more wider (Sato and Ando, 1996). More generally (Ando, unpublished), the ASW may be expressed by

$$S_{ASW} = f(IACC) + f(W_{IACC}) + f(LL) \approx \alpha(IACC)^{3/2} + \beta(W_{IACC})^{1/2} + \gamma(LL)^{3/2} \quad (A1)$$

where $\alpha \approx -1.64$, $\beta \approx 2.42$, $\gamma \approx 0.005$.

3) Subjective Diffuseness

Listeners judged which of two sound fields were perceived as more diffuse (Ando and Kurihara, 1986). Thus, subjective diffuseness is defined by spatial impression of being surrounded by the sound field including the direct sound. This condition can be produced by the small value of the IACC as well as the large value of the LL. It is worth noticing that listener envelopement (LEV) defined by Gade (2007) is deeply related to subjective diffuseness. Both of these spatial sensations are expressed by the spatial factors extracted from the IACF.

According to experimaents, subjective diffuseness are inversely proportional to the IACC, and may be formulated in terms of the 3/2 power of the IACC in a manner similar to the subjective preference values, i.e.,

$$S_{\text{subjective diffuseness}} = -\alpha(IACC)^{\beta} \quad (A2)$$

where $\alpha = 2.9$, $\beta = 3/2$.

The most effective horizontal angles of reflections depend on the frequency range. These are about for the 500 Hz range and the frequency range below 500 Hz, around for the 1 kHz range (that is the most important angle for the music), and smaller than for the 2 kHz and 4 kHz ranges.

It is considered, when the listening level is increased, the scale value of subjective diffuseness of the sound field is increased also.

APPENDIX B. Sound coordinator as a specialist for each concert hall

In order to enhance both temporal and spatial expressions in a given concert hall as a second musical instrument, it is highly recommended to establish a position as a specialist for each concert hall, who is an expert of concert hall acoustics and music acoustics. The sound coordinator suggest, for instance, appropriate music programs to be performed in a given concert hall, positioning and style of performance of each music performer on the stage. This assigment for the facility should be based on a result of examination after attending a professonal school course or a university/college course of concert hall acoustics and music acoustics similar to the specialist of an art museum.

Such a new position may play important role for furtherance of artistic creations in music composition and performance - utilizing simultaneously the two primary instruments: soloist’s musical instrument and the given concert hall enclosure.