Design Proposal of an Opera House based on the Theory of Subjective Preference

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In the opera house, there are two different kinds of sound sources, i.e., the vocal source on the stage with a relatively short value of $(\tau_e)_{min}$, and the orchestra music in the pit with a long value of $(\tau_e)_{min}$. For these two quite different source signals, a proposal of designing an opera house using an acoustically transparent floor is made here.

Keywords: theory of subjective preference, temporal design for two different source signals, acoustically transparent floor

1. INTRODUCTION

First, the theory of subjective preference for the sound field based on the model of auditory-brain system is briefly reviewed. This theory consists of the temporal factors and spatial factors for the sound field, which are associated with the left and right cerebral hemispheres, respectively (Ando, 1985: 1998). The temporal criteria are the initial time delay gap between the direct sound and the first reflection (Δt_1) and the subsequent reverberation time (T_{sub}). These preferred conditions are related to the minimum value of effective duration of the running autocorrelation function (ACF) of source signals $(\tau_e)_{min}$. The spatial criteria are binaural listening level (LL) and the IACC, which may be extracted from the interaural crosscorrelation function (IACF). It is remarkable that this theory has been well based on neural activities in the auditory-brain system that is deeply related to subjective preference of the sound field (Ando, 1992; 1998; Soeta et al., 2002; 2003; Ando, 2003).

2. THEORY OF SUBJECTIVE PREFERENCE FOR THE SOUND FIELD

It has been well established that numbers of orthogonal acoustic factors, which are included in the sound signals at both ears of the sound field, are limited (Ando, 1983, 1985, 1998). Let x_i (i = 1,2... I) be such orthogonal factors of the sound field, then the scale value of any one-dimensional subjective response may be expressed by:

$$S = g(x_1, x_2, ..., x_I) \quad (1)$$

It has been found by a series of experiments that four objective factors influence independently on the scale value of subjective preference. To obtain the total scale value for sound field at each seat in a room under design, the unit of scale values obtained by the number of different experiments is almost constant, so that we may add scale values of the four factors (Ando, 1983), such that

$$\begin{aligned} S &= g(x_1) + g(x_2) + g(x_3) + g(x_4) \\ &= S_1 + S_2 + S_3 + S_4 \end{aligned} \quad (2)$$

where S_i (i = 1, 2, 3, 4) is the scale value of subjective preference of each orthogonal factor of the sound field. Equation (2) signifies a four-dimensional continuity.

Results of the scale value of subjective preference obtained from the different test series; using different music programs with the number of subjects, yielded the following common formula:

$$S_i \approx -\alpha_i |x_i|^{3/2}, \quad i = 1, 2, 3, 4 \quad (3)$$

where values of α_i are weighting coefficients for the orthogonal factors, as listed in Table 1. If α_i is small, then the corresponding orthogonal factor x_i has a lesser contribution on subjective preference.

Table 1. Four orthogonal factors or design criteria of the sound field and its weighting coefficients α_i in Eq. (3), which were obtained by a series of experiments (the paired-comparison test) on subjective preference with a number of subjects (Ando, 1983; 1998).

		α_1	
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	–

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

$$x_1 = 20\log P - 20\log[P]_p \quad (4)$$

P and $[P]_p$ being the sound pressure at a specific seat and the most preferred sound pressure that may be assumed usually at a center seating position in the room under investigation;

$$x_2 = \log (\Delta t_1 /[\Delta t_1]_p) \quad (5)$$

$$x_3 = \log (T_{sub} /[T_{sub}]_p) \quad (6)$$

$$x_4 = IACC \quad (7)$$

where the most preferred conditions of the temporal factors (the initial time delay gap between the direct sound and the first reflection, $[\Delta t_1]_p$, and the subsequent reverberation time $[T_{sub}]_p$) were obtained by a number of experiments may be formulated, respectively, by

$$[\Delta t_1]_p \approx (1\text{-}\log_{10}A)(\tau_e)_{\min} \quad (8)$$

$$[T_{sub}]_p \approx 23(\tau_e)_{\min} \quad (9)$$

where $(\tau_e)_{\min}$ is the effective duration of the running ACF of source signals, T_{sub} may be approximated by the well known Sabine's formula, A is the total amplitude of reflections, such that

$$A = [A_1^2 + A_2^2 + A_3^2 + ...]^{1/2} \quad (10)$$

A_n (n = 1,2, ...) being the nth reflection's amplitude.

Thus, the scale value of preference has been formulated approximately in terms of the 3/2 powers of the normalized objective parameter, expressed in the logarithm for the parameters, x_1, x_2 and x_3. The remarkable fact is that the spatial binaural parameter x_4 is expressed in terms of the 3/2 powers of its "real" value, indicating a greater contribution than those of the temporal parameters are. The scale value is not greatly changed in the neighborhood of the most preferred conditions, but decrease rapidly outside of this range. Since the series of experiments was conducted to find the optimal conditions, this theory holds in the range of preferred conditions for the four orthogonal factors. Acoustic design of an opera house and a concert hall is made by the maximization of Eq. (2) (Ando, 1998; Satoet al., 2002; Sato et al., 2004).

In order to examine above mentioned subjective preference theory, the subjective preference judgments changing source locations on the stage in an existing hall were performed by the paired-comparison tests at each set of seats. The theory of subjective preference has been reconfirmed testing sound fields in an existing hall (Sato et al., 1997).

3. A DESIGN PROPOSAL BASED ON THE TEMPORAL AND SPATIAL CRITERIA

In an opera house, two temporal factors (Δt_1 and T_{sub}) for two different source signals, i.e., the vocal source on the stage and the orchestra music source in the pit should be carefully designed as indicated in Table 2, as well as two spatial factors (listening level (LL) and IACC) for the two sources.

3.1 Temporal acoustic criteria to be designed

1) By utilization of the under-floor space in addition to the above-floor space, we may control the temporal factors of two different source signals, i.e., the orchestra music with the value of $(\tau_e)_{\min}$ roughly 40 ms in the pit and the vocal sound with $(\tau_e)_{\min} \approx 20$ ms on the stage (Table 2). For the orchestra music in the pit, an acoustically transparent floor below auditorium and the orchestra pit realizes a large space, so that a longer preferred reverberation time $(T_{sub})_{music} \approx 1.0$ s can be obtained due to Eq. (9). For the vocal sound on the stage, acoustic design of the upper space of audience with a short initial time delay of early

Table 2. Temporal and spatial objectives of acoustic design to be optimized for an opera house under designing.

Source location and the value of $(\tau_e)_{min}$	Temporalfactors		Spatial factors	
	Δt_1	T_{sub}	LL	IACC
Stage (vocal) $(\tau_e)_{min} \approx 20$ ms[1]	$\approx$ 20 ms $\approx$ (A = 1.0)	$\approx$ 0.5 s	< 3.0 dB	< 0.5
Orchestra music in the pit $(\tau_e)_{min} \approx 40$ ms[2]	$\approx$ 20 ms $\approx$ (A = 3.0)	$\approx$ 1.0 s	< 3.0 dB	< 0.5

[1] The mean value for different vowels and pitches (Kato et al., 2004).

[2] A possible minimum value of the orchestra music (Ando, 1998).

reflection $(\Delta t_1)_{vocal}$ and a short reverberation time $(T_{sub})_{vocal} \approx 0.5$ s may be done at each seat.

2) In addition, it has been well known that there is the SPL-dip in low frequency in the seating-area. This is caused by the interference effect of the direct sound and the reflected sound of the floor in the audience area. The acoustic design of theatres has been made only the space above floor, except for the ancient Greek theatres (Vitruvius, ca. 25 B.C.). Since the acoustic field below the audiences' ears is equally important as one above the ears, we may take the under-floor space into consideration in designing sound field. To eliminate the SPL-dip in low frequency, as a matter of fact, it has been realized by utilizing the under-floor space (Takatsu et al., 2000). In the frontal area close to the stage, 5 mm diameter holes have been drilled through to the under-floor space in a 15 mm by 15 mm grid. A part of floor under the chair legs, there were drilled holes of a 25% ratio to the extent of strength permits. This allows sound wave to pass through to the under-floor space eliminating the dip of low-frequency-range due to the interference effect.

3) To obtain the preferred initial time delay of reflection according to Eq. (8) in the frontal seating area with the total amplitude of reflections A = 1.0 for vocal sound on the stage $(\Delta t_1)_{vocal} \approx 20$ ms, a canopy comprising triangular plates is installed. Also, this may play important role providing enough sound energy between the vocalist on the stage and the performers in the pit at the same time.

3.2 Spatial acoustic criteria to be designed

4) Also, it has been shown that such a canopy above the pit play important role to decrease the IACC for audience area (Nakajima et al., 1992).

5) In order to obtain a small value of the IACC at audience floor, a leaf shape of the plan can be applied as realized in the Kirishima International Concert Hall (Ando, 1998). The side walls may supply enough energy of early reflections for listeners arriving from about $\pm 55°$ measured from their median plane.

6) Another important factor is the balance of LL for listeners from both the singer on the stage and orchestra in the pit (Parati et al., 2004).

3.3 A design proposal

As shown in Fig. 1, we consider two different spaces for the temporal acoustic design. Supposing a certain degree of transmission loss of the floor and absorption of audience for the mid and high frequency components of vocal sound on the stage, temporal design in the space above the floor is made. For orchestra sound in the pit with low frequency components, on the other hand the transparent floor connects spaces under and above the floor to be one acoustically large space.

A proposed scheme of opera house is shown in Fig. 2. In the plan of opera house (Fig. 2a), frontal panels of boxes form a leaf-shape as similar to the Kirishima International Concert Hall supply the useful reflections centered roughly on $\pm 55°$. This kind of shapes realizes to make decrease the IACC at each seating position of audience floor controlling

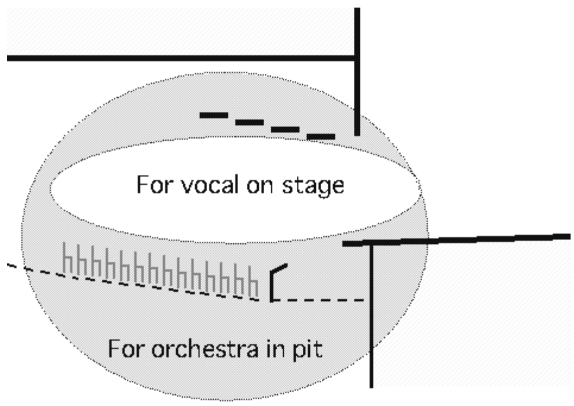

Fig. 1. A proposal of acoustic design for the two different sound sources, the vocal on the stage and orchestra in the pit.

its angles for early reflections to listeners (Ando, 1985; 1998). As shown in Fig. 2b, the canopy array above frontal areas of stage and a reflector in front of pit can control the balance of the LL of the vocal sound and the orchestra sound for audience. This may produce the relatively short initial delay time of reflection, $(\Delta t_1)_{vocal}$, at the same time. These may provide enough sound energy from the pit to the stage performers and vice versa. Fig. 2c demonstrates one large acoustic space with the transparent floor for the orchestra music in the pit

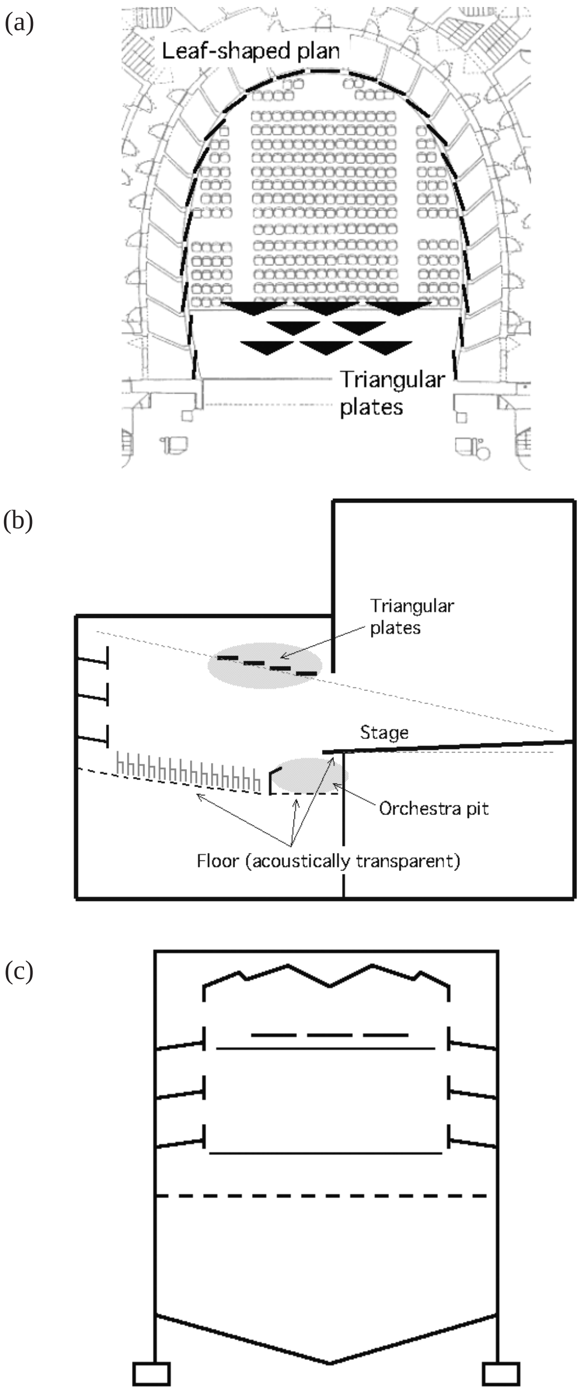

Fig. 2. Proposed scheme of an opera house. (a) Plan. (b), (c) Cross-sections.

obtaining the relatively long reverberation time, $(T_{sub})_{music}$. The ship-shaped bottom of the house also may act to reduce the IACC.

4. REMARKS

So far, we proposed a new type of opera house taking the four orthogonal factors of sound fields. Particularly, a method of controlling two temporal factors (Δt_1 and T_{sub}) for the vocal sound on the stage and the orchestra music in the pit is offered.

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