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ACOUSTICAL DESIGN AND MEASUREMENT OF A CIRCULAR HALL, IMPROVING A SPATIAL FACTOR AT EACH SEAT

A. TAKATSU†, S. HASE‡, H. SAKAI, S. SATO AND Y. ANDO

Graduate School of Science and Technology, Kobe University, Kobe 657-8501, *Japan*

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A round-shaped multi-purpose-event hall with 400 seats (ORBIS Hall: Kobe, Japan) was designed based on the subjective-preference theory of sound fields. To maximize the total scale value of subjective preference at each seat, various is pieces of acoustical equipment were designed. One of the four orthogonal factors of a sound field, the *IACC* was taken into consideration to ensure the effects of the equipment by acoustical simulation in the design stage. After construction of the hall, acoustical measurements of *IACC* were conducted by use of two music motifs. The *IACC* using the music motifs was much improved due to scattered reflectors, which are installed at each sidewall, and near to and in ceilings, than that of the simulation in the design stage.

1. INTRODUCTION

Since ancient times in Greece and Rome, a round-shaped plan has enchanted many architects. However, there are a lot of particular problems in designing sound fields in round-shaped auditoria. For example, the round shape of walls causes sound concentration at the center of the hall and echo-disturbance leading to the "whispering gallery effect."

The ORBIS Hall in Kobe was designed as a medium size (400-seat) multi-purpose-event hall with a round-shaped plan in the Kobe Fashion Plaza that is an architectural complex (see Figure 1) [1]. The outside appearance of the hall was designed to be like an "unidentified flying object (UFO)", in order to embody the design concept of the Kobe Fashion Plaza. Thus, this hall was designed according to the round-shaped plan in order to create the unbroken impression of people entering a "UFO." In order to blend sound fields and all kinds of program sources, an additional hybrid system for the subsequent reverberation consisting of a small reverberation chamber an an electro-acoustic system was designed [1, 2].

† Also at Showa Sekkei Co., 1-2-1-800 Benten, Minato-ku, Osaka 552-0007, Japan
‡ Also at Theatre Design Co., 1-16-1, Shibata, Kita-ku, Osaka 530-0012, Japan.

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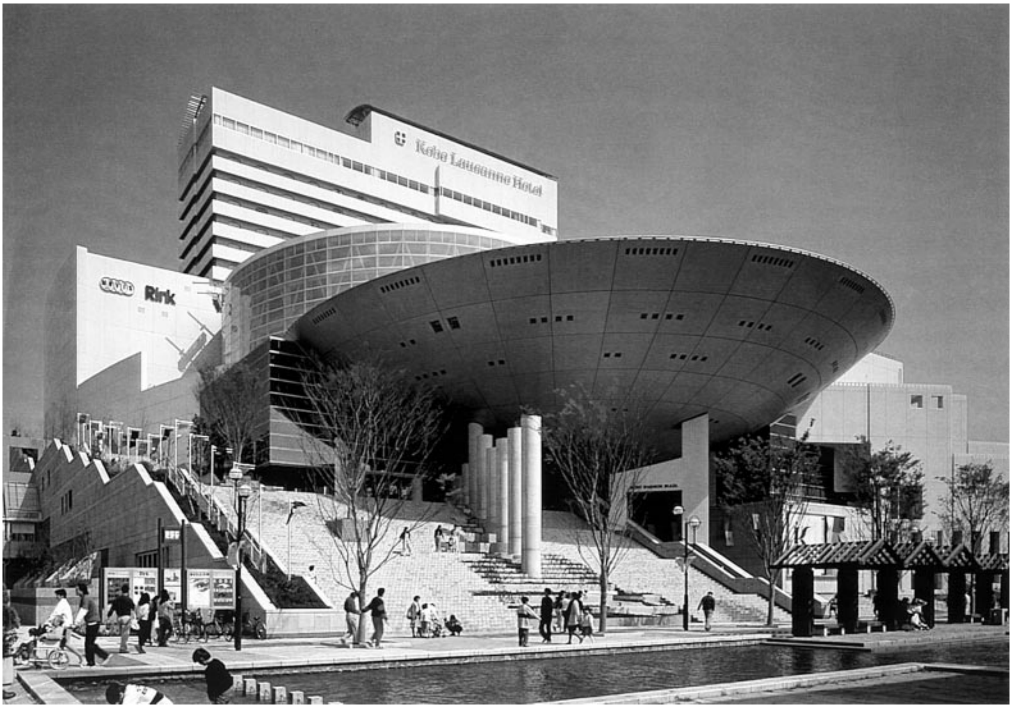

Figure 1. Exterior of an architectural complex, Kobe Fashion Plaza, which includes the ORBIS Hall, Kobe City Fashion Art Museum, a hotel and movie theaters.

In order to eliminate the acoustical problems due to the round shape of all hall, various acoustic elements and pieces of equipment were designed and installed. The four orthogonal factors of the sound field were calculated, maximizing the total scale value of the subjective preference at each seat. After construction of the hall, acoustical measurements were conducted for the *IACC* using two music motifs.

2. ACOUSTICAL DESIGN

2.1. ACOUSTICAL DESIGN MAXIMIZING THE SUBJECTIVE PREFERENCE

The acoustical-design procedure maximizing the scale value of the subjective preference is shown in Figure 2 [3]. The final schemes of a concert hall is designed to maximize the scale values of both *SF*s and *TF*s in order to enhance the satisfaction of both human cerebral hemispheres. Here, the *IACC* is classified by the spatial factors.

2.2. CONTROL OF A SPATIAL FACTOR (*IACC*)

As a countermeasure to avoid the sound concentration caused by the dome portion of the ceiling, a large diffusion panel with a shape of a portion, cut from

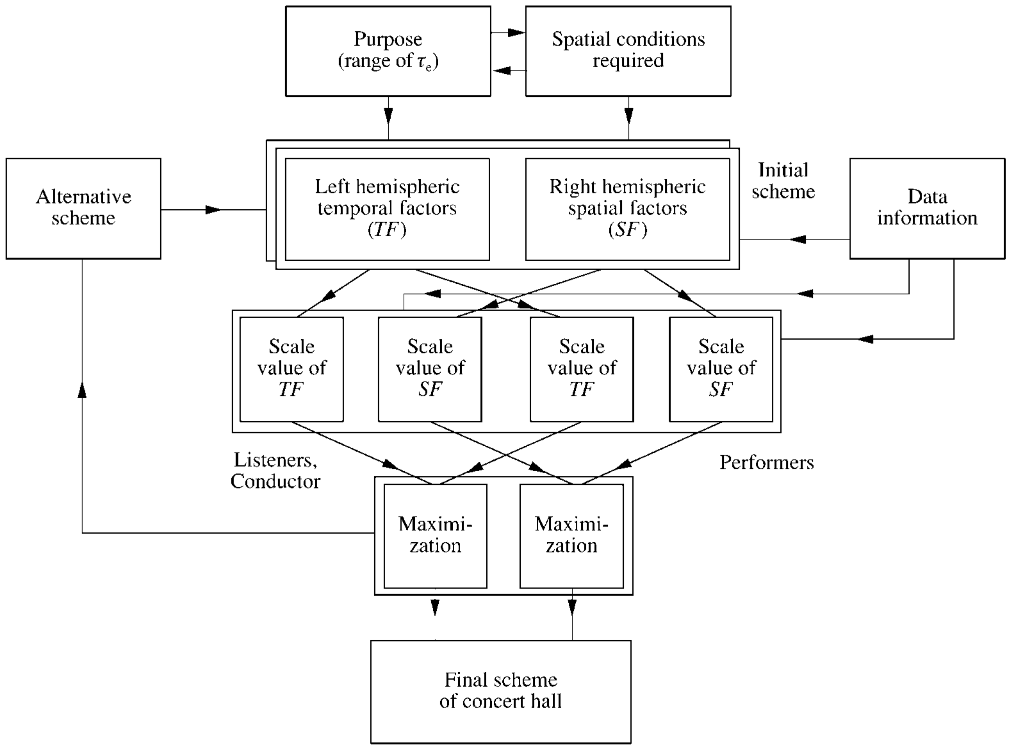

Figure 2. Acoustical-design procedure maximizing the scale values of spatial factors (*SF*s) and temporal factors (*TF*s) of a sound field in a concert hall, enhancing the satisfaction both human cerebral hemispheres.

a 26-m-diameter sphere, was installed in the central section of the ceiling as shown in Figures 3 and 4. The actual diameter of the panel is 9 m. A number of small diffusers shaped like UFOs with different diameters of about 0·9, 1·3 and 1·5 m were randomly installed around the central large panel from the center to the boundary walls (see Figures 3 and 4). These diffusion panels including the central large one are also used as lighting fixtures.

The acoustical design of concert halls has previously considered only the above-floor space. However, the sound field below the ears is equally important to the above one. So, the underfloor space was also taken into consideration in designing the sound field. In the area close to the stage equipped with movable chairs, perforated floors, in which the diameters of perforations were 5 mm and the holes were arranged in squares separated by 15 mm, were installed in order to link the above-floor space with the under-floor space. The seating area to the side and in the back have movable chairs that can be automatically lowered into the underfloor space. The movable chairs are raised up from the under floor when the hall is used for concerts. The floor around the chair legs has perforations with a perforation ratio 25% (see Figures 3(b)–6). These holes are designed to eliminate the *SPL*-dip in the low-frequency range centered on about 200 Hz due to the

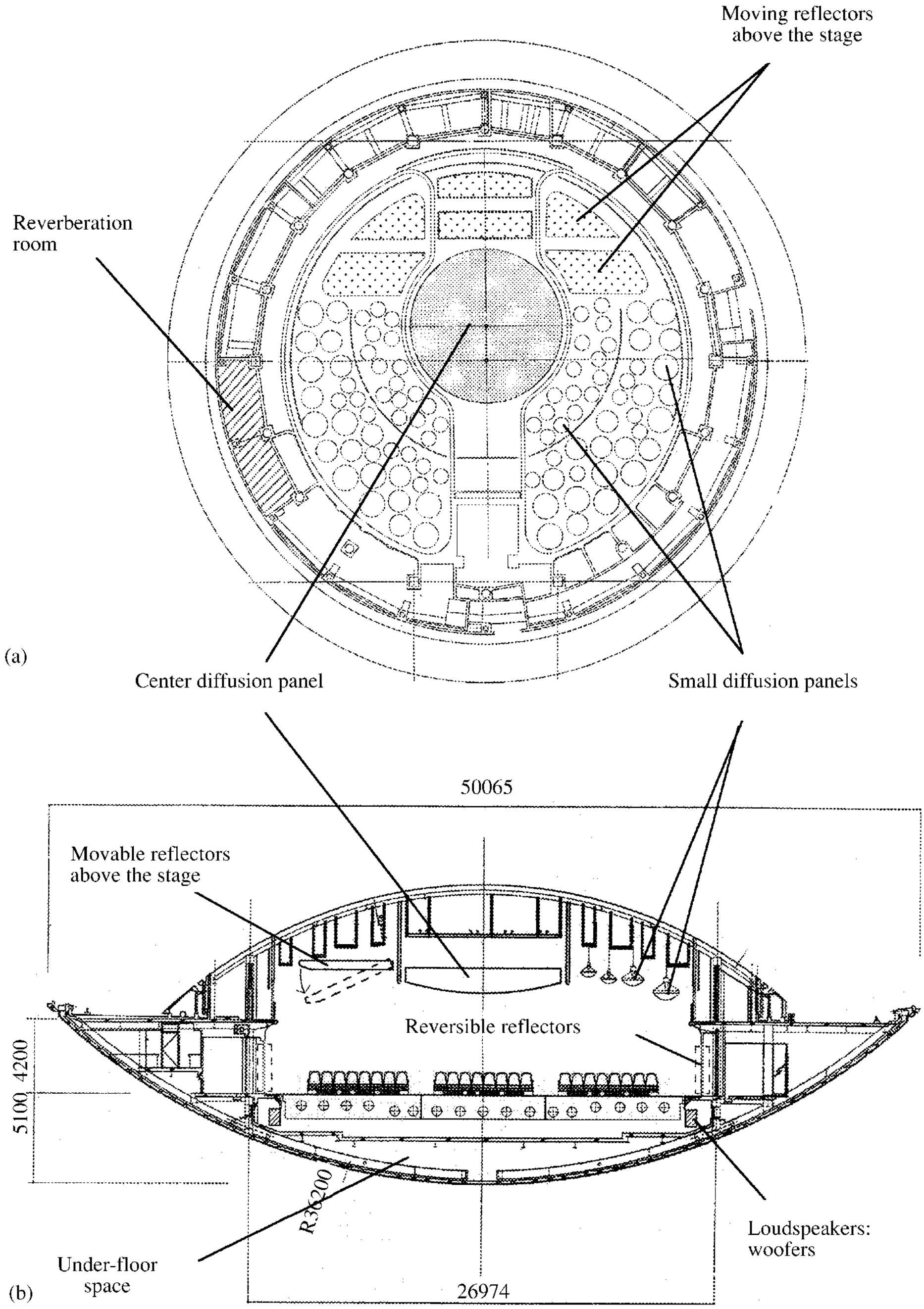

Figure 3. Ceiling plan (a); and cross-section (b) of the ORBIS Hall, A number of diffusing elements is designed for a spatial factor.

interference between the direct sound and the first strong reflection from the floor [4]. In addition, five heavy-bases loudspeakers were placed in the under-floor space. These create the sensation that the bass sound is rising up around the audience.

Figure 4. Interior of the ORBIS Hall.

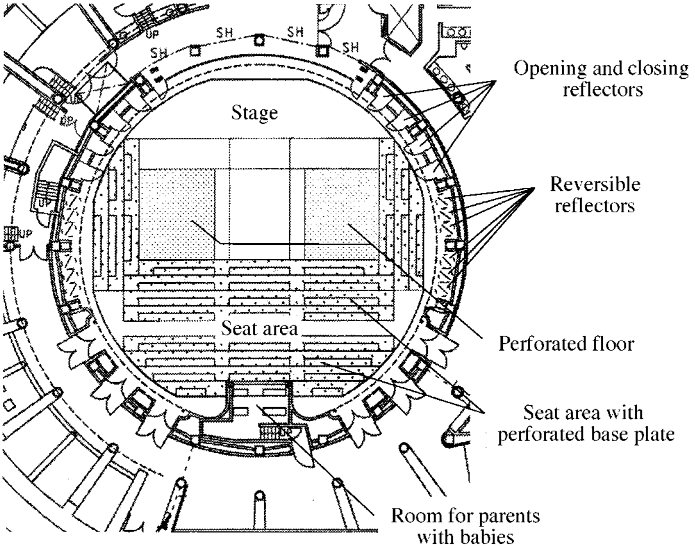

Figure 5. Plan of the ORBIS Hall with a number of elements improving sound fields, and a room for parents with babies cutting out long-path echoes.

In order to make decrease the *IACC* values, several kinds of reflectors as described below are implemented. Opening–closing reflectors were installed at either side of the stage at appropriate angles to create lateral reflection near 55° from the median plane (see Figures 5 and 7). For the same purpose, reversible

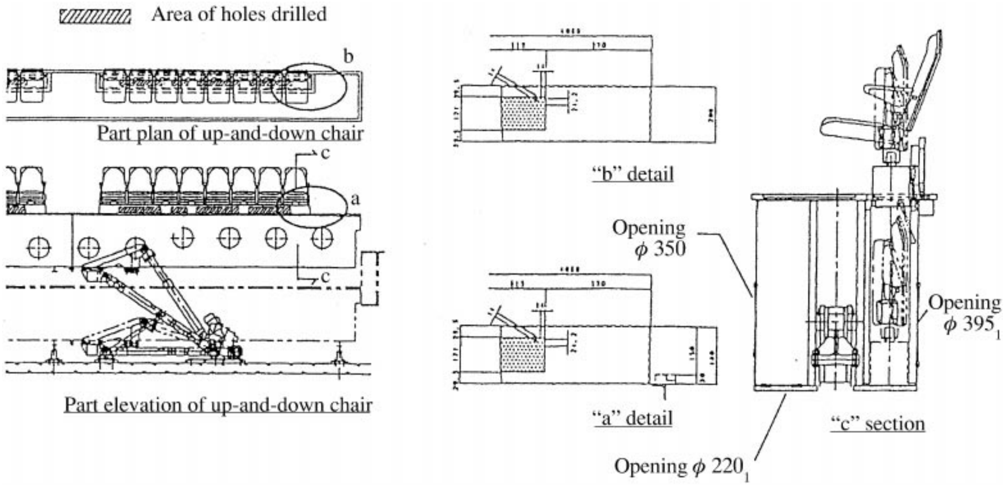

Figure 6. Configuration of up-and-down movable chairs, with holes under chairs reducing the low-frequency dip [2].

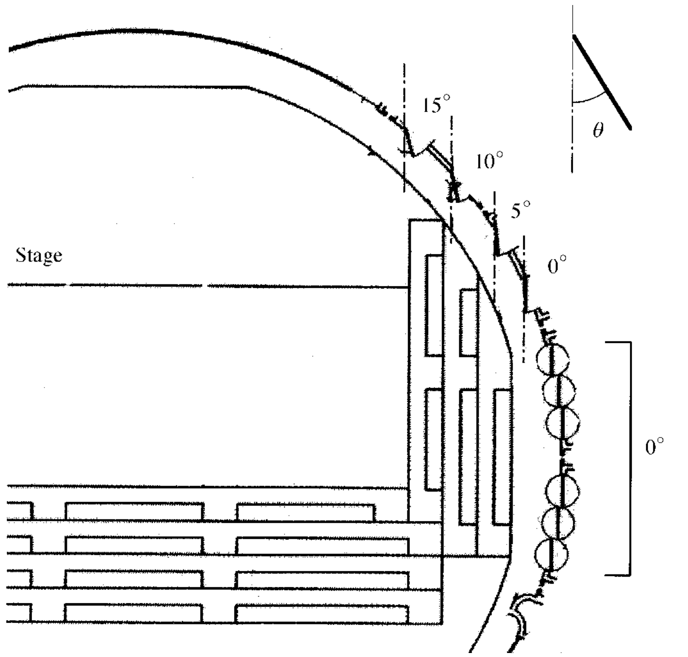

Figure 7. Conditions of the reflectors at the sidewalls in the simulation and the measurement.

reflectors were also placed on both sidewalls. One side of the reflector is absorptive, and the other is reflective. Above the stage, two reflectors are also installed to reinforce the initial reflection mainly for performers on the stage.

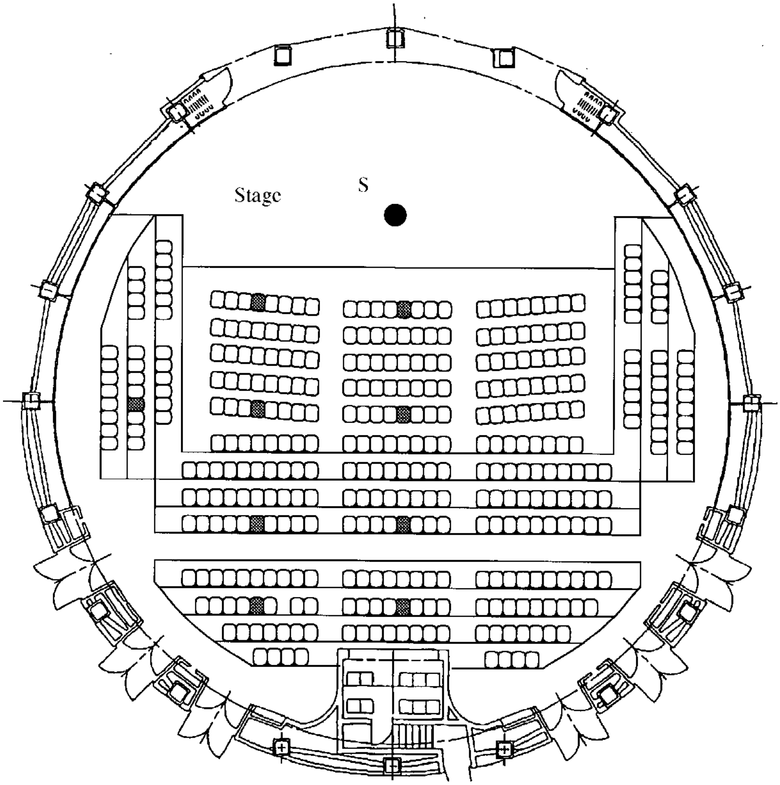

Figure 8. Location of the omni-directional-dodecahedron loudspeaker *S* as a sound source, and receiving points in the seating area.

3. ACOUSTIC MEASUREMENT AFTER CONSTRUCTION

3.1. MEASUREMENT SET-UP

An omni-directional-dodecahedron loudspeaker *S* as a sound source, and receiving points were arranged as shown in Figure 8. The height of the center of *S* was 1·5 m above the stage floor. Two microphones of the 0·5-in condenser types were placed at the ear entrances of a real person who sat on a seat (see Figure 9).

In order to compare the results between the acoustical simulation in the design stage and measurement, the conditions of the simulation and the measurement are indicated in Table 1. Although the effect of the center big reflector at the ceiling was considered, the effect of the small diffusers shaped UFO, under-floor space and excess attenuation over seat lows were not considered in the simulation. In the simulation using an image method, the number of reflections was two, an omni-directional sound source with its height of 1·5 m was placed on the stage, and measurement points were 35 positions with the height of 1·1 m, directed towards the source on the stage. The other conditions were almost same between the simulation and the measurement. The pattern of the hall was an end-stage type. Reflectors at the sidewall were reflective with appropriate angles (15, 10, 5, and 0°

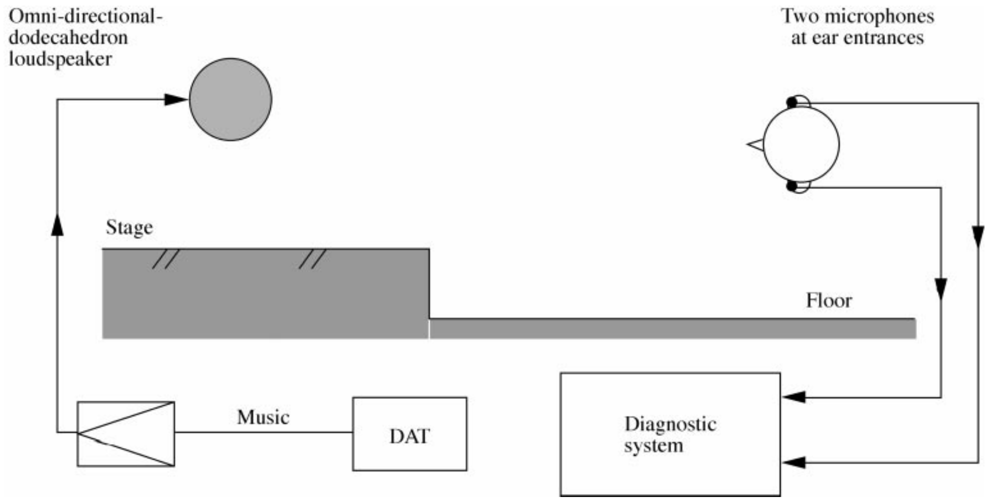

Figure 9. Block diagram of acoustical measurement.

from rear of the stage) and reflectors above the stage had angles so as to be parallel to each other, as shown in Figure 7. Electroacoustic systems including reinformcenet systems and reverberation control-rooms are not used both in the simulation and measurement.

3.2. METHOD OF ANALYZING *IACC*

In order to obtain *IACC* values, two music motifs were fed into the omni-directional loudspeaker on the stage. These two dry sources are music motifs A (Royal Pavane; composed by O. Gibbons) and B (Sinfonietta, Opus 48; IV movement; composed by M. Arnold). Then, the signals, received by the two microphones at the ear entrances, were analyzed by use of a cross-correlation function. After obtaining the signals at both the ears, $p_l(t)$ and $p_r(t)$, we calculated the *IACC*.

The magnitude of the interaural cross-correlation function, *IACC*, is defined by the following normalized interaural cross-correlation function:

$$\phi_{lr}(\tau) = \frac{\Phi_{lr}(\tau)}{[\Phi_{ll}(0)\Phi_{rr}(0)]^{1/2}}, \qquad IACC = |\,\phi_{lr}(\tau)|_{\max}, \quad |\tau| < 1\text{ ms}, \qquad (1,2)$$

where

$$\Phi_{lr}(\tau) = \frac{1}{2T}\int_0^{2\mathrm{T}} p_l(t)\,p_r(t+\tau)\,\mathrm{d}t. \qquad (3)$$

This represents the degree of similarity between sound waves incident to the two ears, and is a significant factor in determining the degree of subjective diffuseness and apparent source width (*ASW*) as well as subjective preference in a sound field [3, 5].

TABLE 1

Conditions of acoustical simulation under designing and measurement after construction

	Simulation	Measurement
Large diffusion panel	Included	Included
Small diffusion panels	Excepted	Included
Perforated floor (under floor space)	Expected	Included
Loudspeakers system	Excepted	Expected

4. RESULTS OF MEASUREMENT AND DISCUSSION

Measured values of the *IACC* at each seat are shown in Figures 10(a–d). Long-pass echoes were not found in impulse response measurements using the maximum length sequence (MLS) signal [6, 7]. Measured *IACC* values for music motifs were better than the values calculated using the image method, excluding effects of the diffusers, in terms of spatial distributions.

As the calculation of *IACC* using the music motifs A and B, the values of the all-pass band of measured *IACC* are shown here. As shown in Figure 10(a)–(d), calculated values of the *IACC* in the front seating area were between 0·7 and 0·9 for both motifs. But measured values of the *IACC* in the same area were decreased to between 0·4 and 0·7 for motif A, and between 0·5 and 0·8 for motif B. At the rear and side of the hall, the values of *IACC* were decreased.

Generally, the values of *IACC* in the front seating area are large because of the strong direct sound with relatively weak initial reflections from the sidewall. Thus, the calculated *IACC* values were larger than 0·5 in front of the stage as shown in Figures 10(a) and 10(c). However, the measured *IACC* values were much improved even in the front seating area (see Figures 10(b) and 10(d)). This may be caused by the small diffusers on the ceiling, which were not considered in the simulation. The reflectors above the stage with appropriate angles were also considered to decrease the *IACC* value for performers on the stage.

In this measurement, the loudspeaker systems were not used as described before. If they are properly tuned up, it is expected that the *IACC* values and the subjective preference would be much improved.

Previously, in Kirishima International Concert Hall in Japan, the orthogonal factors were also calculated during the design phase and measured after construction [8]. It was found that the measured *IACC* corresponded to the calculated ones because no additional diffusers were needed. In the case of the ORBIS Hall, the calculated results do not coincide as well with the measured results as in the case of the Kirishima Concert Hall. This is due to the effects of many distributed elements, which were not taken into account in the calculation.

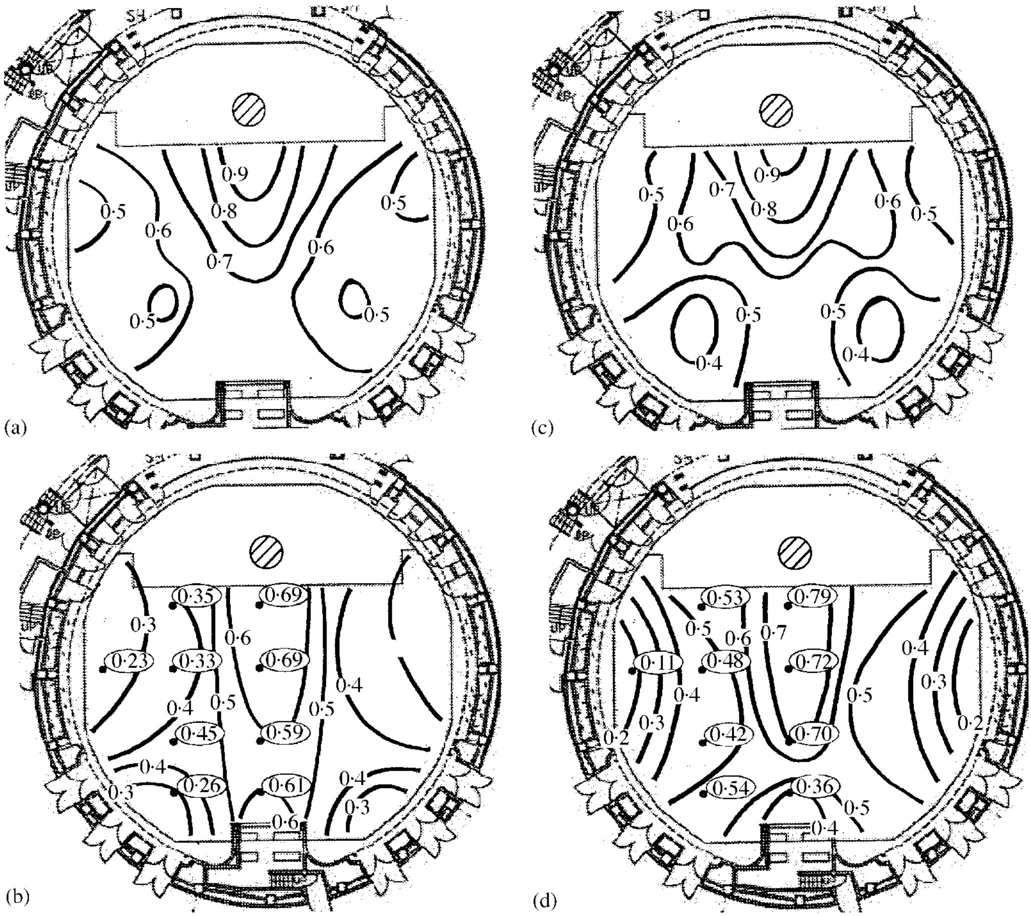

Figure 10. Results of the *IACC* in all-pass band. Calculated values of the *IACC* for music motif A at the design stage (a); and measured values (b); calculated values for music motif B at the design stage (c); and measured values (d).

5. CONCLUSIONS

The acoustical design of a circular hall was examined by *IACC* measurement by use of two music motifs. Values of the *IACC* were much improved by the acoustical treatments. This is thought to be because the effects of small diffusion panels, which were not taken into account in the calculation, greatly improved the results.

The effects of each acoustical device including the small diffusion panels, the perforated floor and the under-floor space were made clear by other acoustical measurements. The measurement results and their discussions will be taken up in another treatise in near future.

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