MEASUREMENT OF SPATIAL INFORMATION IN SOUND FIELDS BY CLOSELY LOCATED FOUR MICROPHONES

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1. INTRODUCTION

Reverberation times and sound pressure levels are very important parameters in sound fields. But we often feel a quite different acoustic impression in the auditoriums which have about the same reverberation time and sound pressure level. This kind of difference might come from the difference of spatial information, especially in early reflection periods. So it is important to grasp spatial informations of sound fields. Many efforts have been done about this problem, for example to measure sound fields by the microphone which has sharp directivity.

In this paper measurement technique of spatial information in sound fields from impulse responses measured at closely located four points; the origin, and three points of the same distance (3 to 5 cm) from the origin on the rectangular coordinate axes; is discussed. From slight differences of these four impulse responses, the positions and powers of direct and reflected sound sources are calculated by correlation technique or intensity technique. It might be called three dimensional triangular surveying.

Concert halls, opera houses, theaters and many other sound fields are measured by this technique. The distributions of virtual image sources and directivity patterns of some concert halls are shown.

2. IMPULSE RESPONSE OF SOUND FIELDS

2.1 Impluse Response measurement

An impulse response of asound field consists of the direct sound and a number of reflections and represents the transmission characteristics from a certain source point to an observation point. Output signals for any input signals by the convolution with the impulse responses can be calculated, if the sound field is considered to be a linear and time invariant system. The four point method is developed to keep three more impulse responses to get the spatial information of a sound field.

Impulse responses can be measured by various methods. An electric spark or a loud speaker is used as the sound sources. In case of electric spark, the charge in $10\mu s$ capacitor with 2000 V is discharged through a narrow gap of 0.05 mm. A loudspeaker is driven by a unit sample pulse whose width is $5\mu s$ and amplitude is 100 V. In both cases the responses are averaged 32 to 256 times to improve the signal to noise ratio. The number of averaging is selected according to the background noise level with sufficiently long random intervals to improve the signal to noise ratio not only for random noise but also for periodical noise.

Recently, the time stretched pulse with real time convolution system, which is constructed over one thousand DSP chips and can convolve over three hundred thousand samples that is over 7 s, is introduced. Generally the duration of stretched pulse is not so long around 100 ms, so averaging is also necessary. [1),2)] We use 4 s duration stretched pulse. It is sufficiently long so we can get impulse response at once by real time deconvolution and by single measurement without averaging.

2.2 Reverberation TIme

Figure 1 shows impulse responses of Musikvereinssaal and Munchen Philharmonie Hall. Reverberation curve can be calculated by Schroeder's squared impulse response integration method,

$$\left\langle S^2(t)\right\rangle = \int_t^\infty h^2(t)dt \qquad (1).$$

Reverberation curves (500 Hz, 1 oct.) calculated by this method are shown in Fig.2.

2.3 Wigner Distribution

Wigner distribution is time-frequency function,

$$S_{ij}(\gamma) = \int_{ia}^{ia+j} \frac{h_i(t)\cdot h_j(t+\gamma)}{(h_i^2(t)\cdot h_j^2(t))^{1/3}}dt \qquad (2).$$

Time and frequency are orthogonal domain from the first. We must take note of the cross term to introduce wigner distribution. We can reduce cross terms by averaging time and frequency. Usually these cross terms are not desirable. Changing the point of view, we try to make positive use of cross terms to estimate sound fields. That is, the more sound fields are diffused, the more cross terms occur. These cross terms emphasize the room acoustics characteristics. Wigner distributions averaged by 1.5 ms in time domain and 1/3, 1/12, 1/24 oct. in frequency domain of Musikvereinssaal and Munchen Philharmonie Hall are shown in Fig.3.

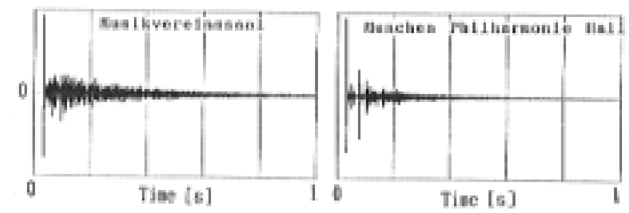

Fig.1. Impulse Response

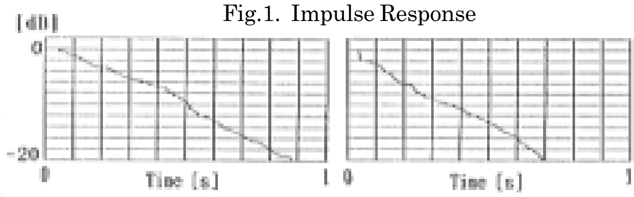

Fig.2. Reverberation Curves

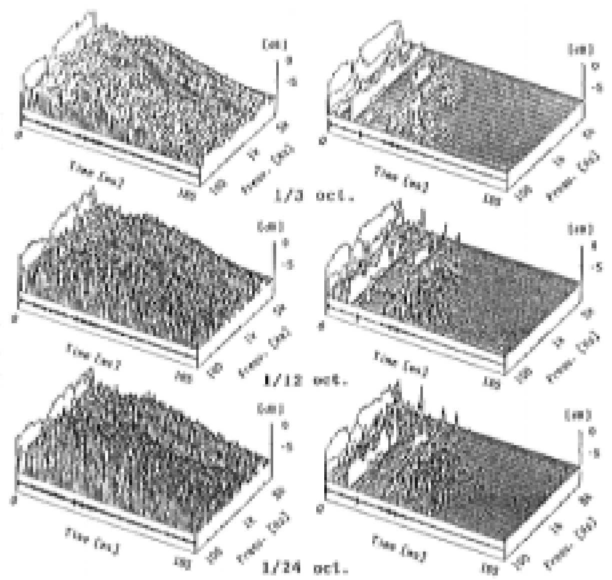

Fig.3. Wigner Distribution

3. FOUR POINT MICROPHONE MEASUREMTN [3),4),8)]

3.1 Microphone Arrangement

Theoretically four microphones should not be placed on the same plane and the distances of microphones should be sufficiently shorter than the wavelength of the sound. Four microphones are located at the origin of a coordinate and the three points on the rectangular coordinate axes at the same distance from the origin as shown in Fig.4.

Though the shorter the distances of microphones are the better in theory, actually we must decide the distance considering the accuracy in the mechanical set up and the numerical computation. We use the 8 mm diameter diaphragm electrostatic microphones with the distance of 50 mm for ordinary measurements, in the concert halls or opera houses. The distance is set 33 mm for the measurements in smaller rooms. 3 mm diameter microphones are used with 5 mm distance for scale model measurements.

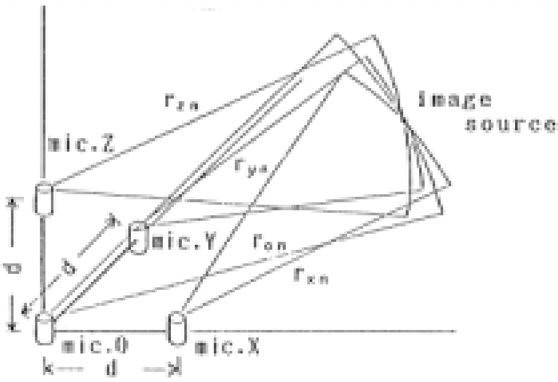

Fig.4 Microphone Arrangement

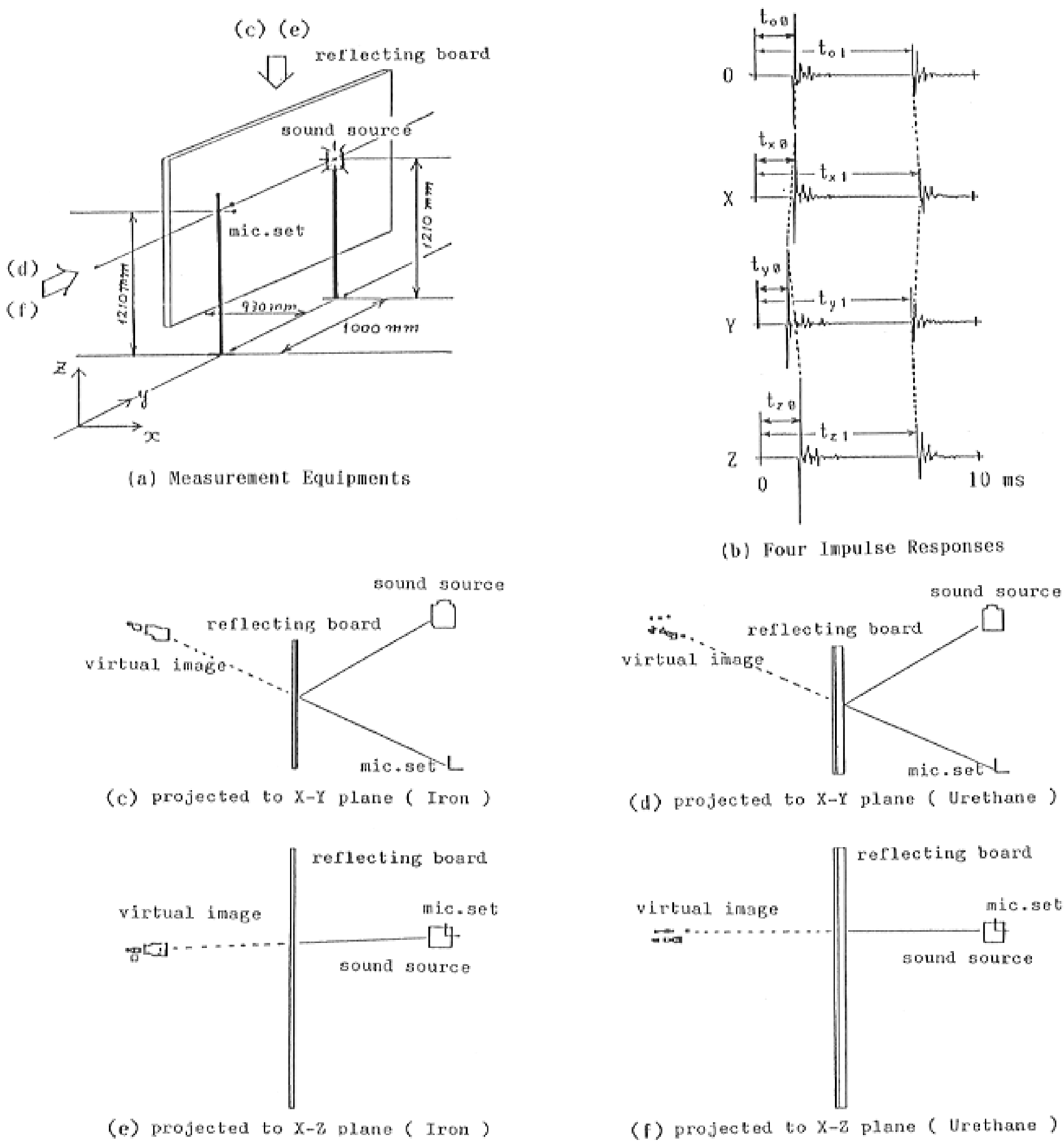

Fig.5 Four Point Microphone Measurement

3.2 Virtual Image Sources

From impulse responses observed at four closely located points we can calculate the coordinators of the virtual image sources, as follows;

Figure 5(a) shows the simple experiment in anechoic chamber with hard (iron) and soft (iron covered by urethane foam) walls. The local peaks in the impulse responses represent the traveling distance of the reflected sound as shown in Fig.5 (b). The sound source corresponding to each local peak should be on a spherical surface of radius r_{in} whose center is at the observation point as shown in Fig.5, where r_{in} (i=o,x,y,z) expresses the traveling distance from each microphone.

The four local peaks make the four spheres. The intersection of four spheres is the point of the sound source corresponding to the direct sound or the reflected sound. Of course, sound fields are very complicated, and we can calculate only the source points corresponding to the direct sound and a few reflections. As shown in the later part, calculated source points corresponding to the reflections are not always of the single reflection, but they are considered to be of the degenerated equivalent reflections. So we call them as virtual image sources.

In Fig.5 (b). t_{on}, t_{xn}, t_{yn} and t_{zn} correspond to the distances between a certain source and each observation point. The distances are

$$r_{on} = c \cdot t_{on}, \quad r_{xn} = c \cdot t_{xn}, \quad r_{yn} = c \cdot t_{yn}, \quad r_{zn} = c \cdot t_{zn} \tag{3}$$

where c is the velocity of the sound.

From spherical equations, the coordinates of a virtual image source (X_n, Y_n, Z_n) are

$$X_n = (d^2 + r_{on}^2 - r_{xn}^2)/2d, Y_n = (d^2 + r_{on}^2 - r_{yn}^2)/2d, Z_n = (d^2 + r_{on}^2 - r_{zn}^2)/2d \tag{4}$$

where d is the distance of microphones.

Figure 5(c) to (f) show the distritbutions of virtual image sources projected to $X-Y$ (floor) and $X-Z$ (wall) plane. The center of the squares represents the calculated coordinates of the virtual image source, and the area of each square represents the power of the corresponding source.

The direct sound is displayed almost same but the reflections are observed clearly different. That is, the reflected image sources of a soft wall are much weaker and distributed widely because of the difference of reflection characteristics.

3.3 Calculation by Correlation Technique

The process to calculate the coordinate of the virtual image sources by correlation technique is as follows;

1) Four impulse responses are interpolated 256 times to keep high resolution.
2) The corresponding reflections are selected by use of the cross-correlation function.
3) The coordinate of the virtual image source is calculated by eq. (4) .

We used to interpolate impulse responses 256 times to keep high accuracy by main frame computers. For the convenience of field measurements, we introduce stand alone system with personal computers. The personal computer does not have enough speed for such a high rate interpolation. So we make some arrangement in softwares, that is to interpolate not whole impulse responses, but only within durations in which some reflections exist.

3.4 Short time Intensity Technique

Four microphones are arranged on the rectangular axes. So we can calculate intensity vector for three orthogonal directions. From short time intensity, we can decide the direction, the distance and the power of a virtual image source by polar coordinate. Strictly speaking this is not an image source, but the equivalent center of gravity of reflections of some moment. For the sake of convenience, we also call them virtual image sources. By intensity technique we can easily calculate virtual image sources within limited frequency bands.

4. DEVIELOPMENT OF VIRTUAL IMAGE SOURCES

4.1 Distribution of Virtural Image Sources

Figure 6(a) shows the impulse responses and (b) shows the distribution of virtual image sources projected to floor plane of four different kinds of sound fields, japanese and western living rooms, a concert hall (Boston Symphony Hall) and a cathedral (Munster in Freiburg). Directivity patterns with 1 degree open angle are also shown in (c).

The center of the circle represents the calculated points of the virtual image source, and the area of each circle represents the power of the corresponding source. The cross point of the two orthogonal lines is the observation point, From the projected virtual image sources, we can easily grasp the spatial information of the sound fields through eyes. The outlines of the rooms are also shown.

4.2 Time Divided Distribution

Time divided distributions of virtual image sources can also be displayed. Figure 7 (a) shows the image sources in the first 50 ms from the direct sound, (b) shows those between 50 ms and 100 ms, (c) shows those after 100 ms.

4.3 Distribution of Limited Space

We can also display distribution of the limited space. For example the space is divided to three sections by two planes which are paralleled to floor plane and 10 m above from the observation point. Figure 8 shows the virtual image sources projected to (floor) plane of above 10 m (a), from -10 m to + 10 m (b) and below -10 m (c).

4.4 Directivity Patterns (Hedgehog Patterns)

We can calculate directivity patterns by observing three dimensional distributions of virtual image sources through the limited input angle. Figure 9 shows directivity patterns, the total power of virtual image sources with horizontal open angle 1 and 10 degrees, vertical open angle 45 degrees, and 1 division represents 10 dB, with virtual open angle □}45 degrees as shown in Fig.10.

Fig.6(c)is the directivity patterns with open angle 1 degree for horizontal 45 degree for vertical.

4.5 Impulse Response of Limited Anle

Figure 11 shows impulse response through the limited angle, □}45 degrees both vertical and horizontal.

4.6 Frequency Band Limited Distribution

Figure 12 shows distribution of frequency and band limited virtual image sources of Musikvereinssaal and Munchen Philharmonic calculated by the intensity technique.

5. MEASUREMENT RESULTS OF AUDITORIUMS

We have measured many concert halls and opera theaters in Europe, the United States and Japan. Recently we introduce this technique to scale model measurements, too. We are trying to use these data bases to estimate the sound fields or to feed them back to the acoustic design.

Figure 13 shows impulse responses, wigner distributions, distributions of the virtual image sources and directivity patterns projected to three

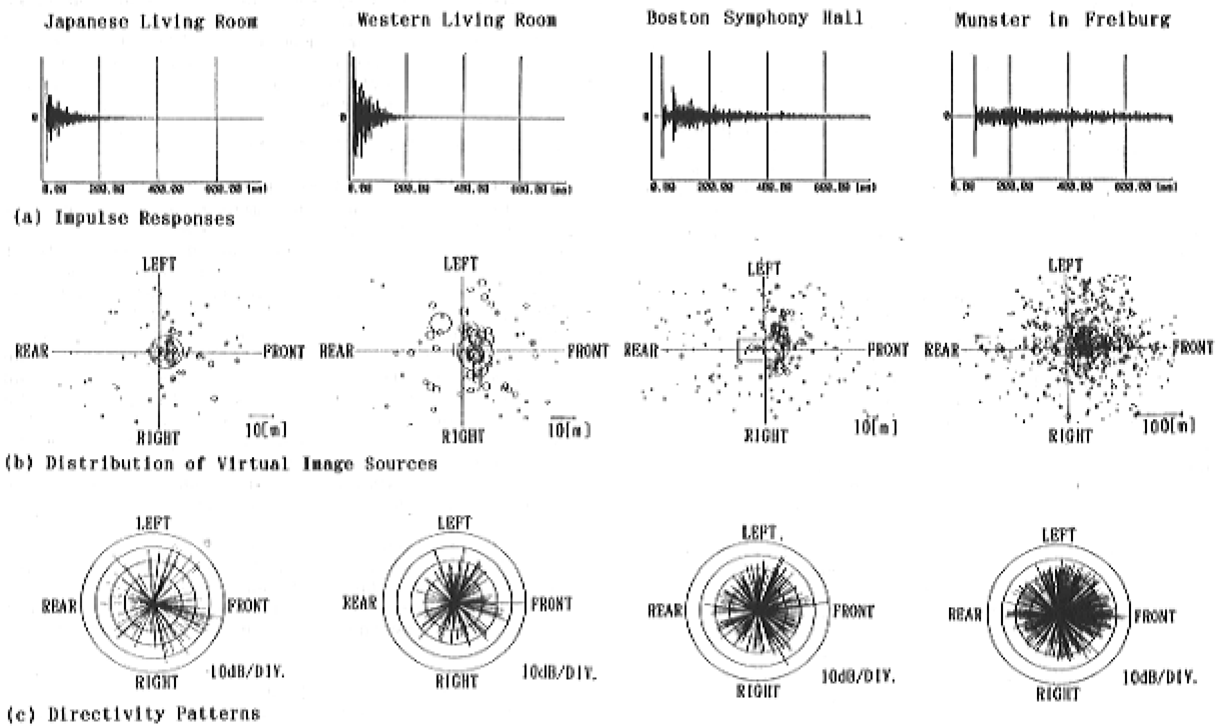

Fig. 6 Developments of Virtual Image Sources

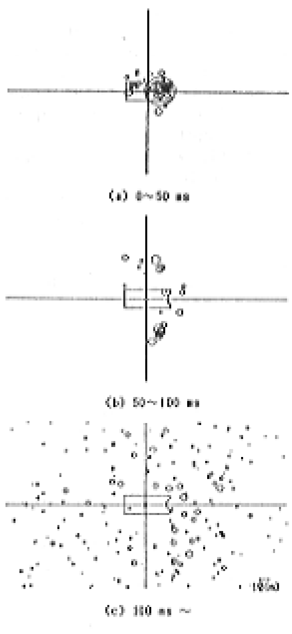

Fig. 7 Time Divided Distribution

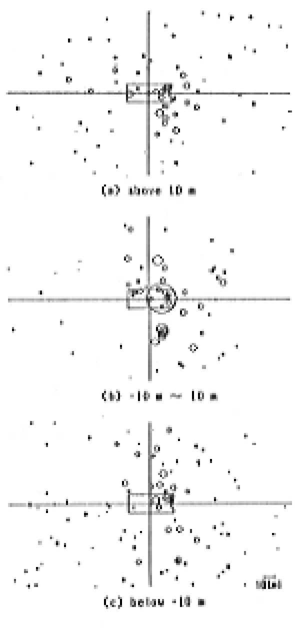

Fig. 8 Limited Space Distribution

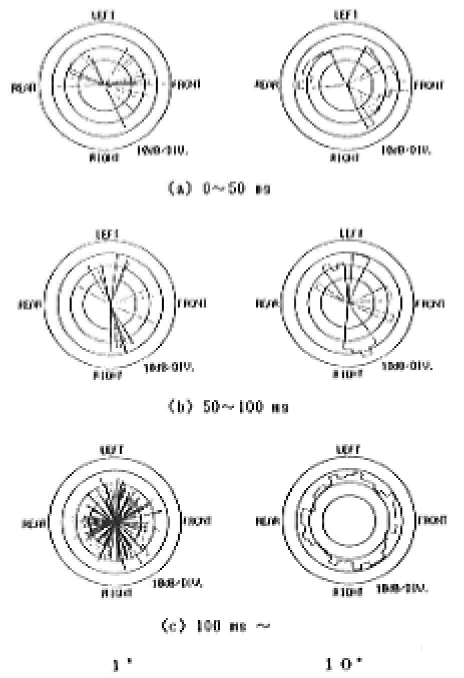

Fig. 9 Directivity Patterns

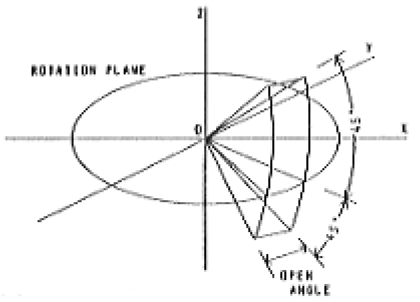

Fig. 10 Directivity Measurement

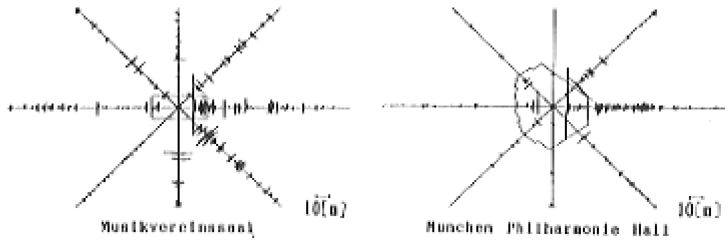

Fig. 11 Impulse Response of Limited Angle

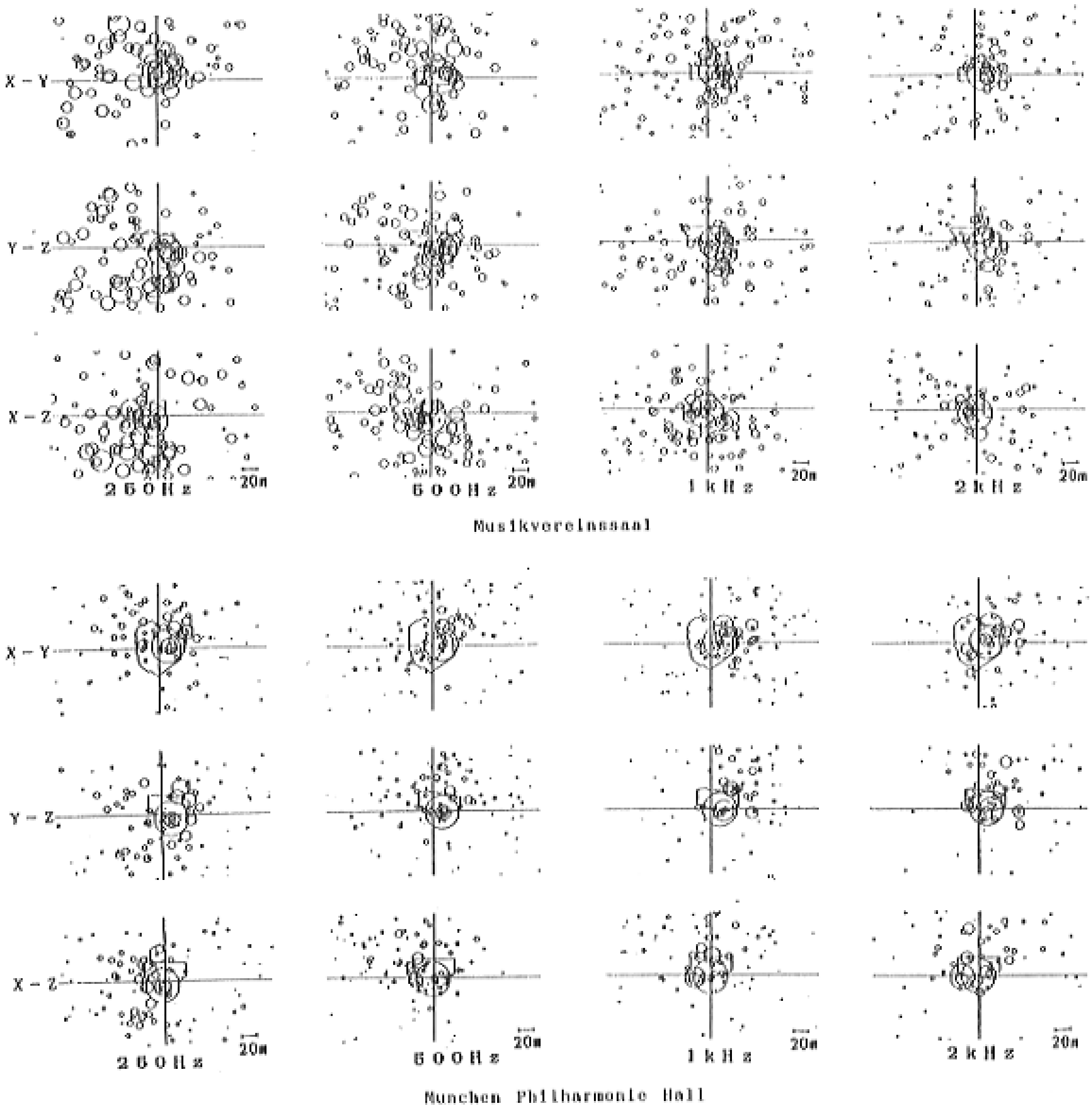

Fig. 12 Band Limited distribution by Intensity

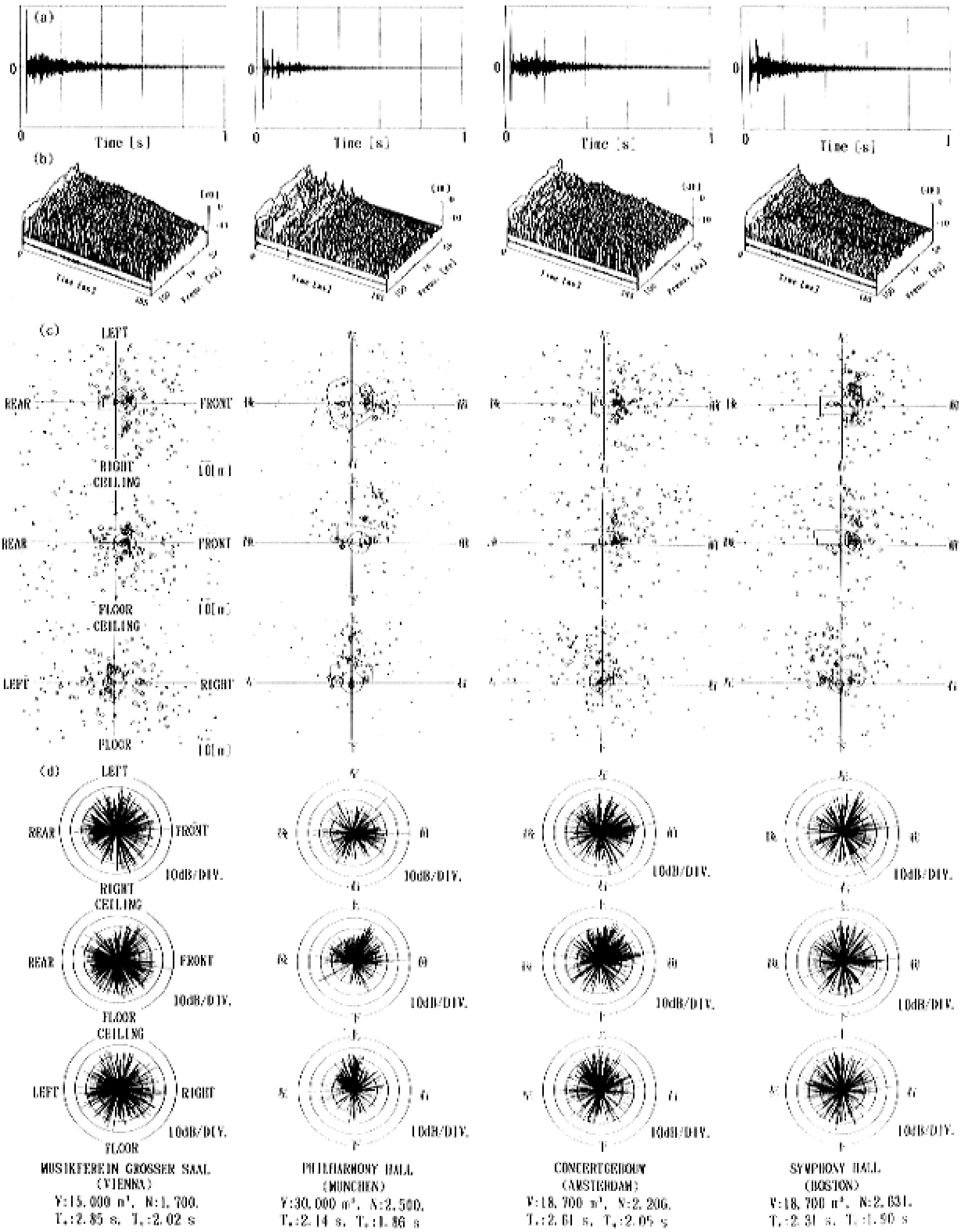

Fig. 13 Measurement Result of Auditorium (1)

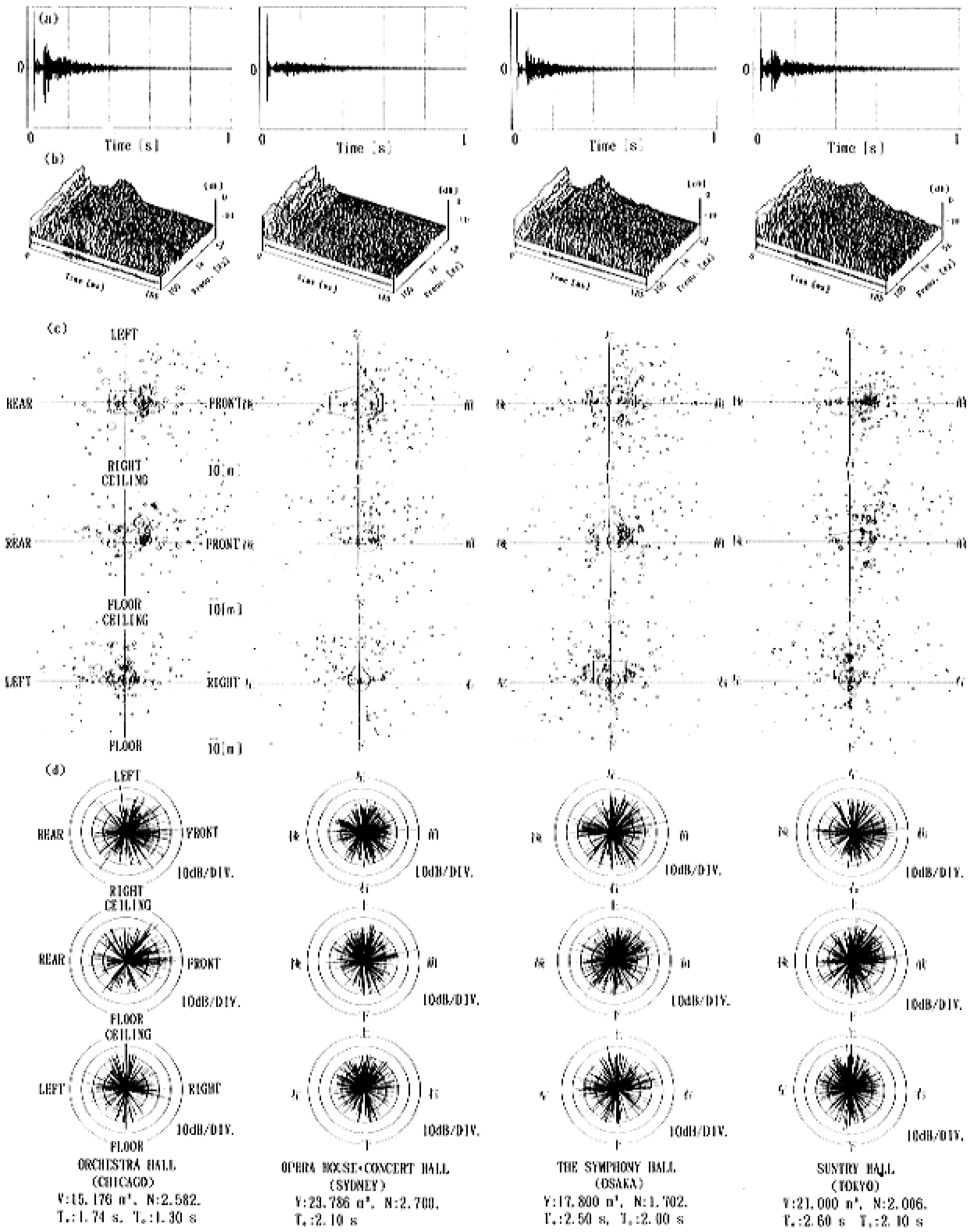

Fig. 13 Measurement Results of Auditoriums (2)

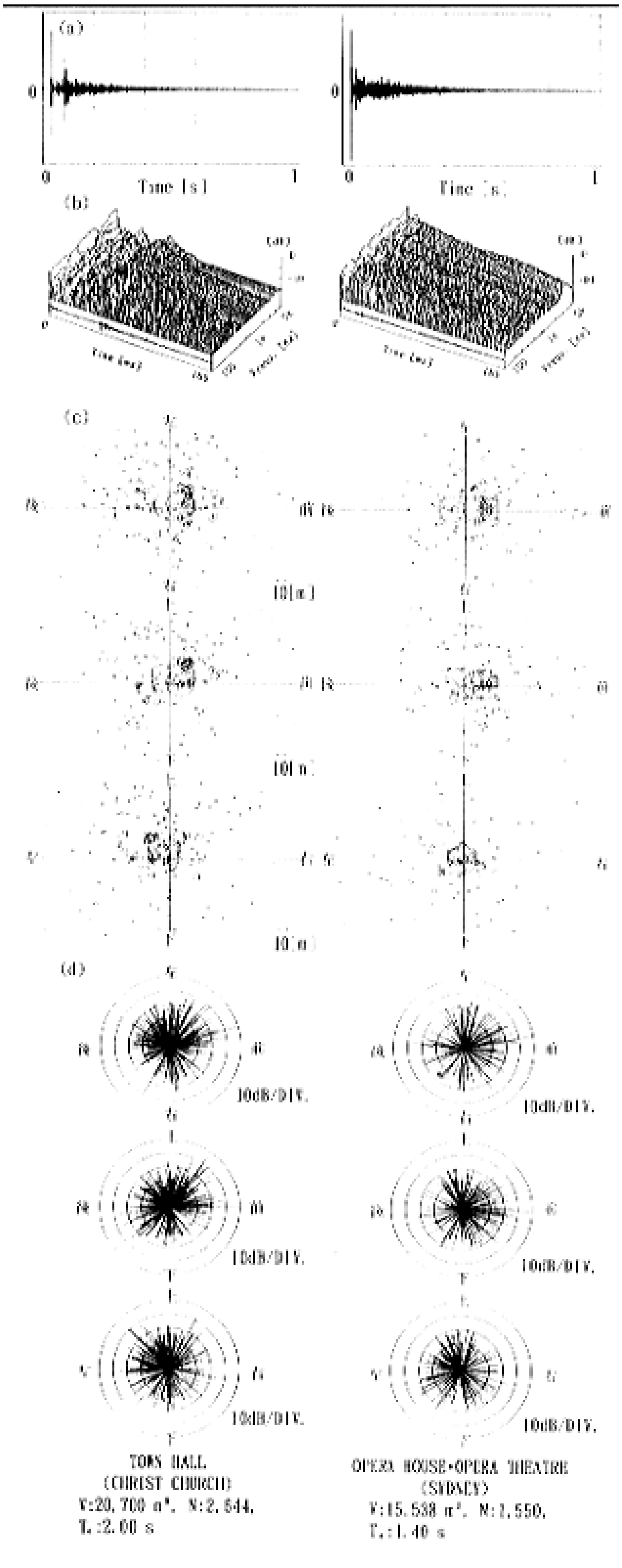

Fig.13 Measurement Results of Auditorium (3)

planes calculated by the correlation technique of auditoriums in Europe, America, Oceania and Japan. The outlines of the concert hall are also shown. In directivity patterns, the total power of virtual image sources with horizontal open angle 1 degree, vertical open angle 45 degrees, and 1 division represents 10 dB.

From the projected virtual image source shown in Fig.6 and 13, we can easily grasp the spatial informations through eyes. Musikvereinssaal has very rich side reflections compared to Munchen Philharmonie. And the former has rich distribution from bottom, maybe floor material of this hall is much harder.

AT THE END

We have measured many concert halls and opera theaters in Europe, the United States and Japan. Recently we introduce this technique to scale model measurements, too. We are trying to use these data bases to estimate the sound fields or to feed them back to the acoustic design.

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