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Measurement of spatial information in sound fields by closely located four point microphone method

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When we estimate a sound field in a room, it is important to grasp the spatial information, especially of the early reflection periods. In this paper we'll discuss a way to grasp the spatial infornation of sound fields from impulse responses measured at closely located four points, the origin and three points of the same distance (3•`5cm•jfrom the origin on the rectangular coordinate axes. From these four impulse responses the coordinates and powers of virtual image sources are calculated by correlation technique or intensity technique. Concert halls, opera 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.

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1. INTRODUCTlON

•@Reverberation times and sound pressure levels are very important parameters to evaluate sound fields. But we often get a quite different acoustic impression in the sound fields which have about the same reverberation time and sound pressure level. This kind of difference might come from the diffrence 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 introduce a microphone which has very sharp directivity.

Here, we'll discuss a way to grasp spatial information of sound fields from impulse responses measured at clsely located four points; the origin, and three points of the same distance (3•`5cm) from the origin on the rectangular coordinate axes. From small differences of these four impulse respomses, we try to estimate the positions and powers of direct and reflected sound sources by correlation technique or intensity techniquc. It might be called three dimensional triangular surveying.

2. IMPULSE RESPONSE OF SOUNDFIELDS

An impulse response of a sound field consists of the direct sound, discretely reflected sounds and degenerated number of reflections and represents the transmission characteristics from a certain source point to an observation point. We can calculate output signals for any input signals by the convolution with the impulse responses, if the sound field is considered to be a linear and time invariant system.

If we measure and keep only one impulse response of a room, we can calculate afterward not only room parameters, reverberation time and so on, but also the waveform of a music played in the room by convolving the impuse response with waveform of dry music, where dry music means a music played in an anechoic chamber. The four point method is developed to keep three more impulse responses to get the spatial information of a sound field.

Usually we measure impulse responses as follows. A loudspeaker, the sound source, is driven by a unit sample pulse whose width is $5\mu s$ and amplitude

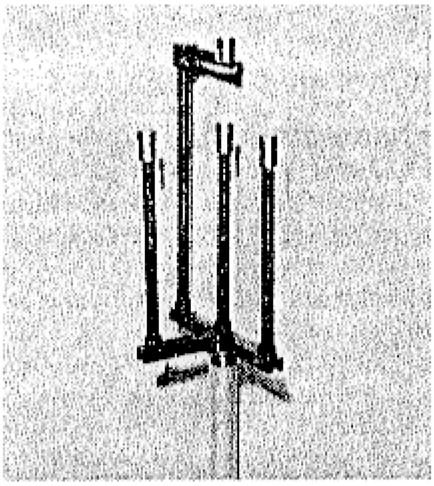


Fig.1 Foour point microphone system.

is 100 V. The output signal of each microphone is digitized with a 16 bit AD converter whose sampling frequency is 44.1 kHz or 48 kHz. The digitized signals are averaged 32 to 256 times by a personal computer to improve the signal to noise ratio. The number of averaging is selected 32 to 256 times 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.

In some casesm when we hace not enough time to measure or the background noise level is very high, we use preudo random noise or rapidly swept sinusoidal wave[1] instead of the unit sample pulses and they are directly recorded to a digital tape recorder.

3. MICROPHONE ARRANGEMENT

Usually we use a four point microphone system shown in Fig.1. 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. Theoretically four microphones should not be placed on the same plane and the distances of microphones should be sufficiently shorter than the wacelength of the sound.

Though the shorter the distances of microhones 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.

4. CALCULATION OF COORDINATES OF VIRTUAL IMAGE SOURCES

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

Figure 2 shows the simple ecperiment in anechoic chamber with hard (iron) and soft (iron covered by urethane foam) walls. The local peaks in the impluse responses represent the traveling distance of the reflected wave as shown in Fig.2(b). The sound source corresponding to each local peak should be on a spherical surface of radius r_{in} whose chenter is at the observation point as shown in Fig.3, 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 estimate only the source points corresponding to the direct sound and a few reflections. As shown in the later part, estimated source points corresponding to the reflections are considered to be of the degenerated equivalent reflections. So we call them as virtual image sources.

In Fig.2(b), t_{on}, t_{xn}, t_{yn} and t_{zn} correspond to the distances between a certain source and each observation point. Then the distances are

$$\begin{aligned} r_{on} &= c \cdot t_{on}\,, & r_{xn} &= c \cdot t_{xn}\,, \\ r_{yn} &= c \cdot t_{yn}\,, & r_{zn} &= c \cdot t_{lx}\,, \end{aligned} \tag{1}$$

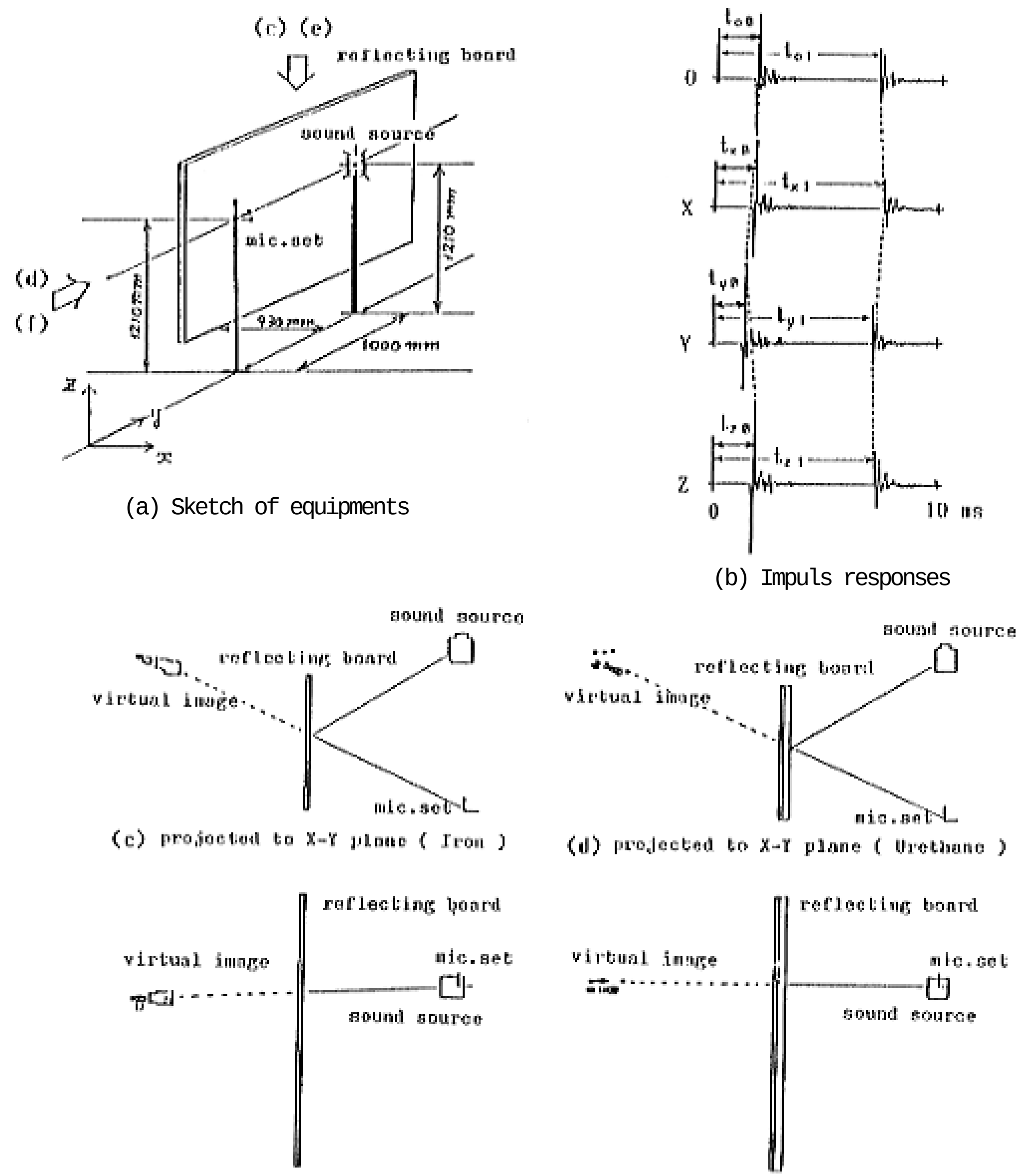
where c is the velocity of the sound.

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

$$\begin{aligned} X_n &= (d^2 + r_{on}^2 - r_{xn}^2)/2d, \\ Y_n &= (d^2 + r_{on}^2 - r_{yn}^2)/2d, \\ Z_n &= (d^2 + r_{on}^2 - r_{zn}^2)/2d. \end{aligned} \tag{2}$$

where d is the distance of microphones.

Figures 2(c)~(f) show the distributions of virtual image sources prejected to $X - Y$ and $X - Z$ plane. The center of the squares represents the calculated coordinates of the virtual image source, and the area



(a) Sketch of equipments

(b) Impuls responses

(c) projected to X-Z plane (Iron)   (f) projected to X-Z plane (Urethane)

Fig.2 Principle of four point measurement.

of each square represents tile power of the corre-sponding sourcce. The direct sound is displayed almost same but the reflections are observed clearly different. That is, the refleted image sources of sort wall are much weaker and distributed widely because of the dinfference or reflectlion character-istics.

4.1 Correlation Technique

Here we'll explain the process to calculate the coordinate of the virtual image sources by correla-tion technique:

1) Four impulse responses are interpolated 256 times to keep high accuracy in the following process.

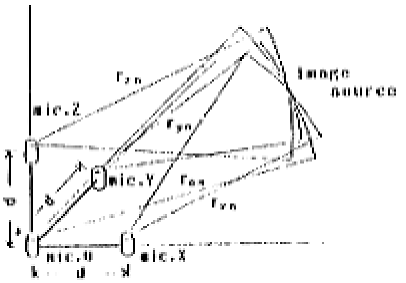


Fig.3 Calculation of reflection.

2) The corresponding reflections are selected by use of the cross-correlation function.
3) The distance between a virtual image source and each observation point is decided from 1).
4) The coordinate of the virtual image source is calculated by Eq.(2).

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 compulers. The personalcomputer system has not 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 are exist. And the adaptive processingis also introduced as follows:

1) The six short time correlation coefficients from t_a to $t_a+\Delta$, $S_{ox}, S_{oy}, S_{oz}, S_{xy}, S_{yz}, S_{xz}$, between the four impulse responses, $h_0(t), h_x(t), h_y(t), h_z(t)$, are calculaled by the following equation

$$S_{ij}(\tau)=\int_{t_a}^{t_a+\Delta}\frac{h_i(t)\cdot h_j(t+\tau)}{(h_i^2(t)\cdot h_i^2(t))^{1/2}}dt, \qquad (3)$$

where $i=o, x, y, z$ and $j=x, y, z$
2) The τ which gives local peak of each correlation coefficient is searched, and the length of Δ which gives correlation coefficient more than a threshold value (we usually use 0.8) is determined. Let the τ which gives local peaks of correlation ccefficient be $\tau_{ox}, \tau_{oy}, \tau_{oz}, \tau_{xy}, \tau_{yz}, \tau_{xz}$, and Δ be Δ_{ox}, $\Delta_{oy}, \cdots, \Delta_{xz}$.
3) The minimum duration $\Delta_{\min}$ of $\Delta_{ox}, \Delta_{oy}, \cdots$, Δ_{xz} is searched.
4) Duration $\Delta_{\min}$ is interpolated 16 times, to determine $\tau_{ox}, \tau_{oy}, \cdots, \tau_{xz}$ precisely.
5) The averaged certain reflection waveform of four impulse responses is calculated and subtracted from original inmpulse responses.
6) Subsequently the process from 1) to 5) is repeated.

4.2 Short Time Intensity Technique

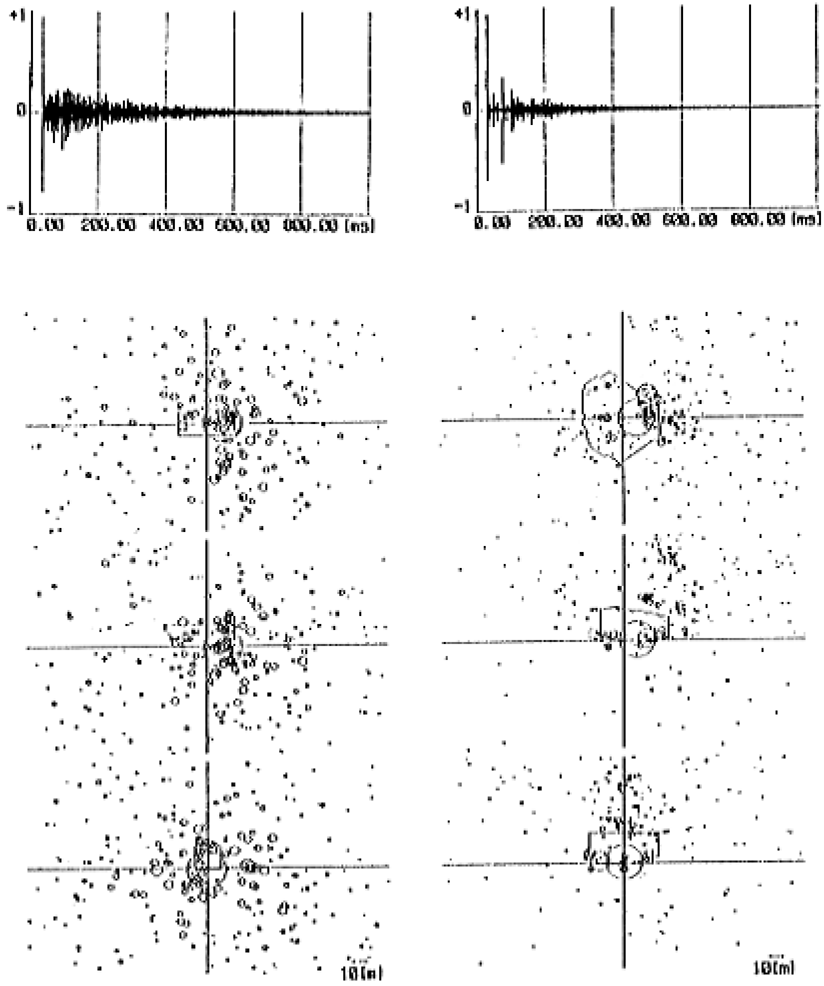
We explained the calculation of virtual image sources by correlation technique. Four microphones are arranged on the rectangular axes. So we can calculate intensity vector for three orthogonal directions. From short time intensiey we can decide the direction, the distance and the power or a virtual image sources by polar coordinate. Strictly speaking this is not a image source, but the equivalent center of gravity or 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 frequecy bands. The process is as follows:
1) The impulse response is filtered through a band-pass filter.
2) A part of the impulse response is cut out by a short time window or certain duration. We usually use 10 ms rectangular windows.
3) The short time intensity vectors are calculated with the outputs of three pairs (OX, OY, OZ) of microphones, using the imaginary part of cross spectrum.
4) The coordinate of a virtual image source is determined by short time intensity vector.
5) The window is shifted to the next priod.
6) The process from 2) to 5) is subsequently repeated.

5. DEVELOPMENT OF VIRTUAL IMAGE SOURCES

5.1 Distribution of Virtual Image Sources

Figure 4(a) shows impulse responses of Musikvereinssaal and Munchen Philharmonie Hall, Fig.4 (b) shows distributions of the virtual image sources projected to three planes calculated by the correlation technique. The center of the circle represents the estimated 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, and the distance between the progonal sound source and the obsercation point is 12m. The outlines of the concert hall are also shown.



(a) Musikvereinssaal, Wien (b) Munchen Philharmonie

Fig.4 Impulse responses and distribution of virtual image sources (Musikvereinssaal and Munchen Philharmonie.)

5.2 Time Divided Distribution

Time divided distributions of virtual image sources can be also displayed. Figure 5(a) shows the image sources in the first 50ms from the direct sound, (b) shows those between 50ms and 100ms, (c) shows those after 100ms.

5.3 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 10ms above from the observation point. FIgure 6 shows the virtual image sources projected to $X-Y$ (floor) plane of above 10m (a), from -10m to +10m (b) and below -10m (c).

5.4 Directivity Patterns (Hedgehog Patterns)

We can calculate directivity patterns by observing three dimensional distributions of virtual image sources through the supposed microphone with vertical open angle ± 45 degrees as shown in Fig.7. Figure 8 shows directivity patterns, the total power of virtual image sources with horizontal open angle 1, 10 and 30 degrees, vertical open angle 45 degrees,

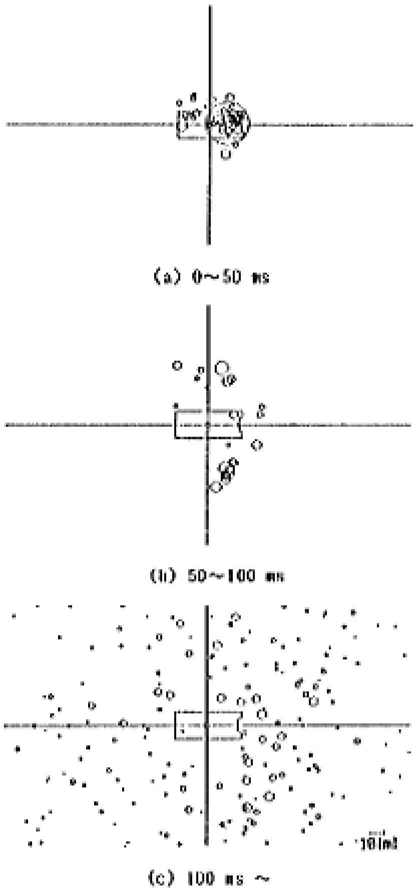


Fig.5 TIme divided distribution (Musikvereinsssaal). (a) from 0 to 50ms, (b) from 50 to 100ms, (c) after 100ms.

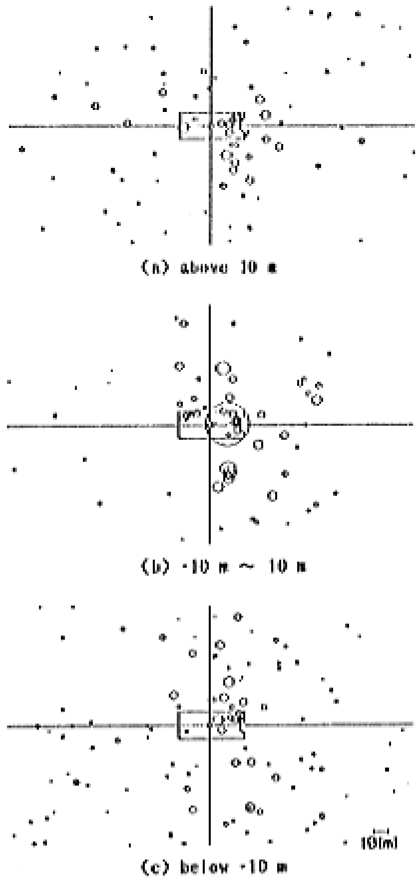


Fig.6 Distribution of Limited space (Musikvereinssaal). (a) above 10m, (b) from -10m to 10m, (c) below -10m.

and 1 division represents 10 dB.

5.5 Frequency Band Limited Distribution

Figure 9 shows distribution of frequency band limited virtual image sources of Musikvereinssaal and Munchen Philharmonie calculated by the intensity technique.

5.6 Reconstruction of Impulse Responses

Figure 10 shows impulse responses of Musikvereinssaal, upper one is original and lower one is reconstructed from calculated virtual image sources. Reconstructed one is thinner than the original one, but it represents well the characteristics of original

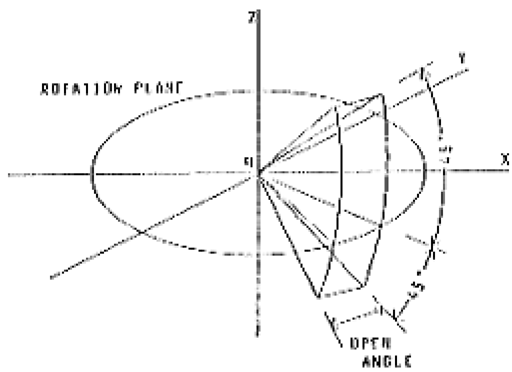


Fig.7 Supposed microphone for calculation of directivity pattern.

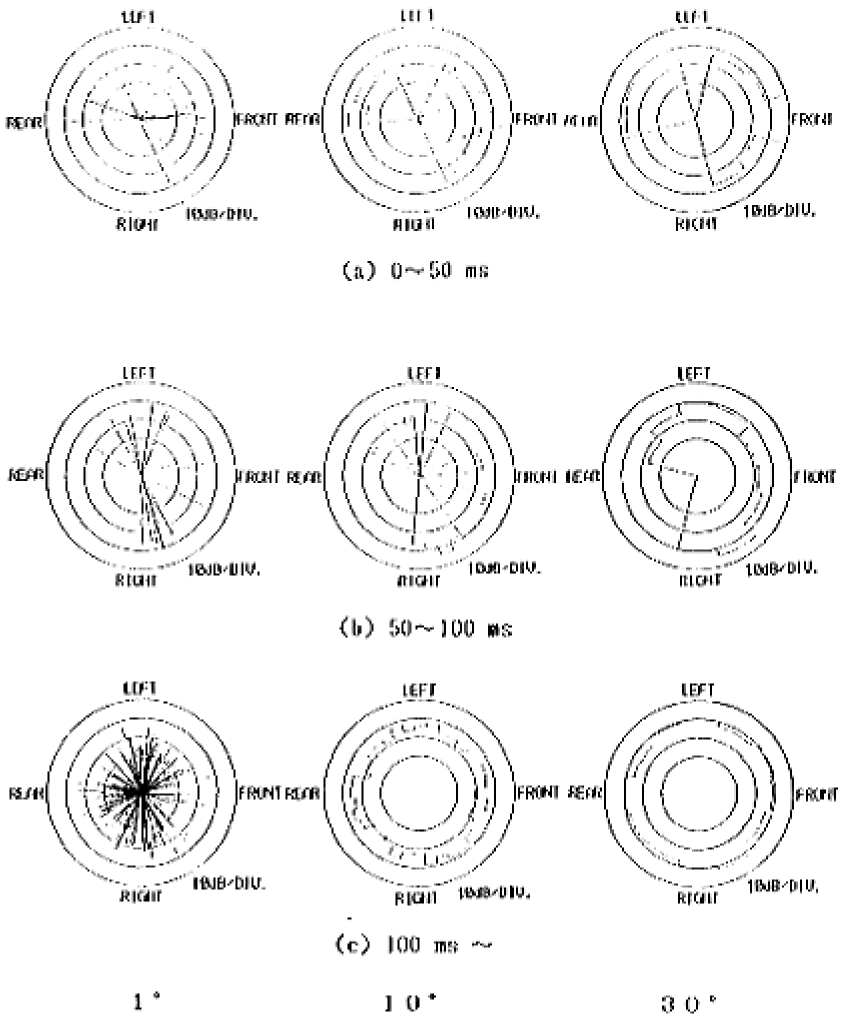


Fig.8 Directivity patterns (Musikvereinssaal).

one especially in early period. So this method can be used for our first aim, to frasp spatial information of sound fields in early reflection period.

From virtual image sources, we can reconstruct not only the impulse resoinse of the observation point, but also the impulse respoinses of the point near the observation point. The impulse responses from special direction can also be calculated.

6. CONCLUSION

In this paper we discuss the way to grasp the spatial information in a sound field by a four point microphone method.

FIrst, the principle of this method and the simple ecperiment in anechoic chamber are shown. Then the some measurements in actual sound fields are shown, and the development of virtual image sources are discussed.

Figure 11 shoes the distribution of virtual image sources projected to $X-Y$ (floor) plane of three different kinds of sound fields, a living room, a concert hall (Boston Symohony Hall) and a cathedral

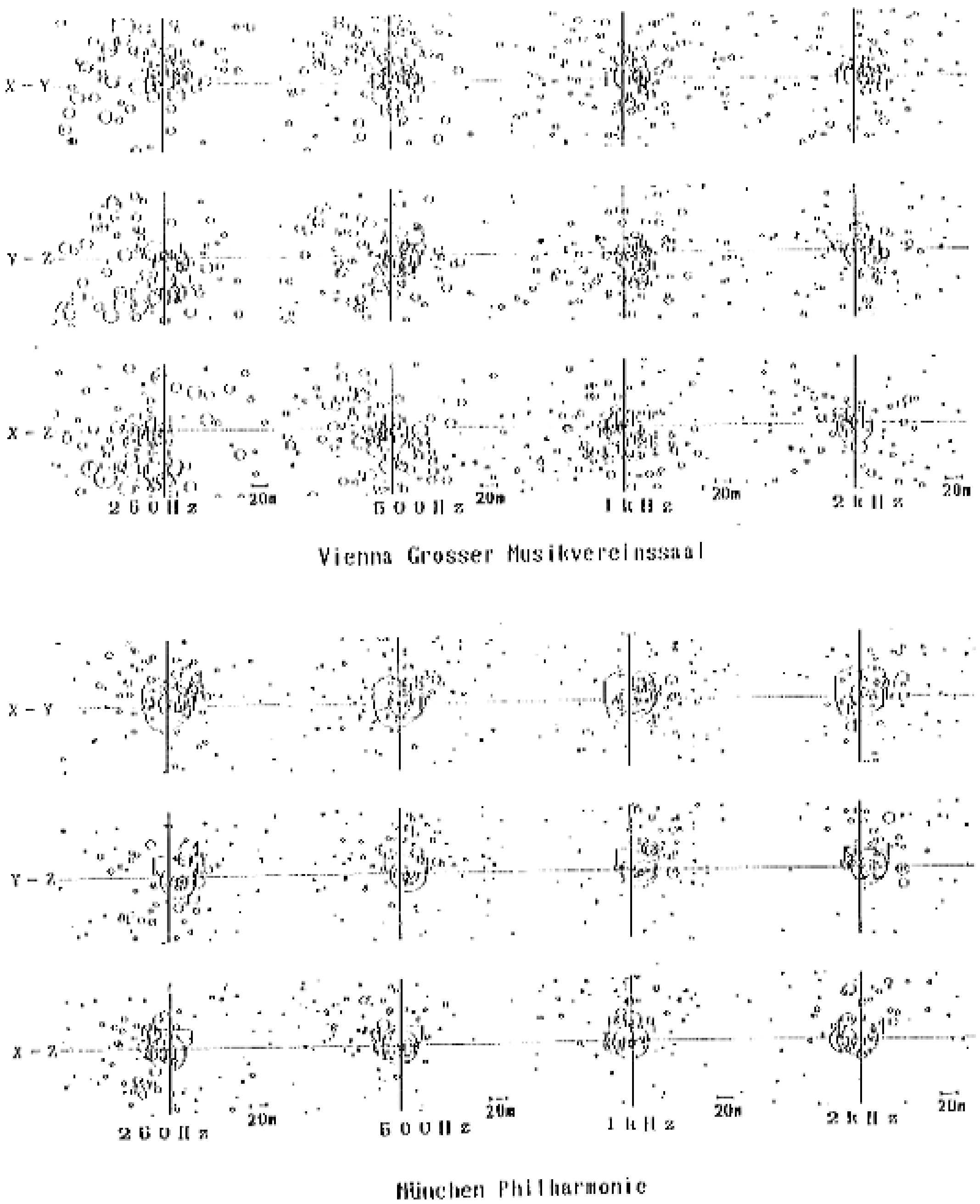


Fig.9 Distribution of band limited virtual image sources (Musikvereinssaal and Munchen Philharmonie).

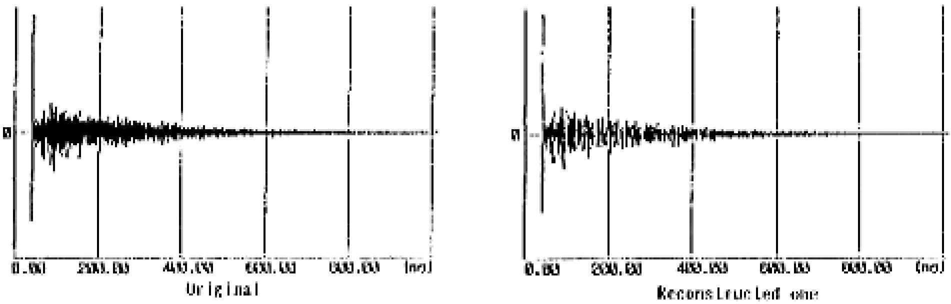


Fig.10 Original and re-constructed impulse responses.

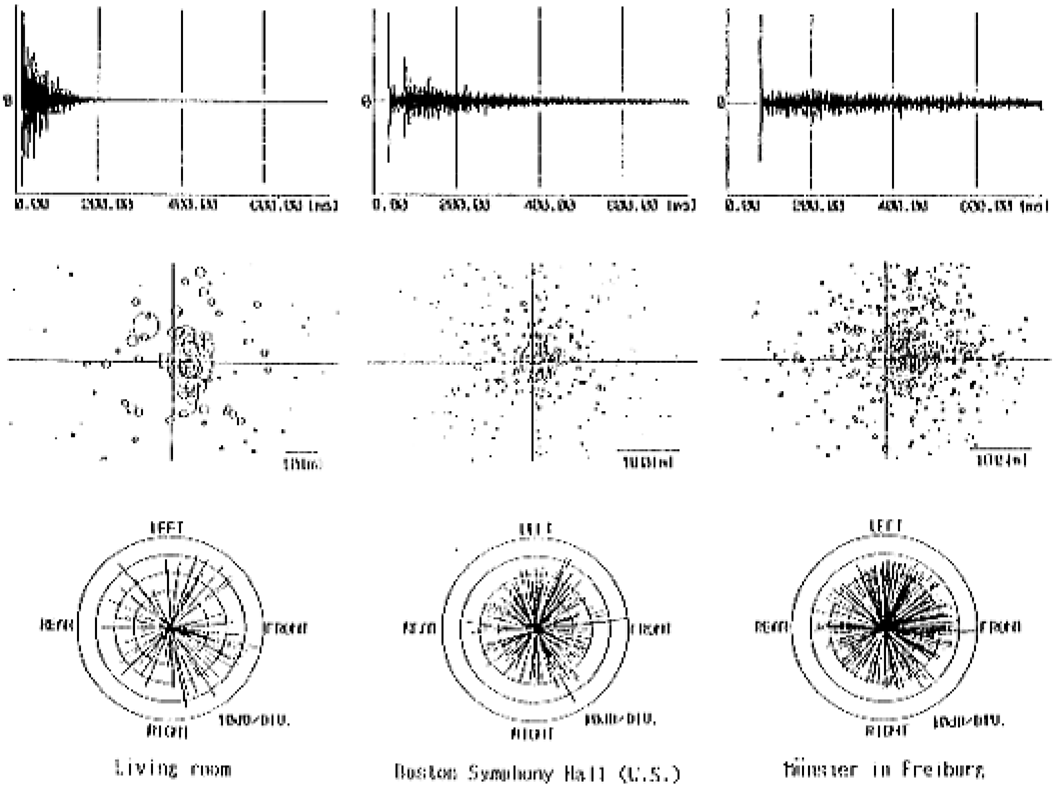


Fig.11 Impulse responses, distribution of virtual image sources and directivity patterns of three different kinds of sound fields.

(Munster in Freiberg). Impulse responses and the directivity patterns of floor plane with 1 degree open angle are also shown. From the projected virtual image sources shown in Figs.4 and 11, or directivity patterns shown in FIgs.8 and 11, we can easily grasp the spatial informations through eyes. Such as, Musikvereinssaal has very rich side reflections compared to Munchen Philharmonie. And the former has rich distributions from bottom, may be floor material of this hall is much harder.

We have measured many concert halls and opera theaters in Europe, the United States and Japan.[2–5]

Recently we introduce this technique to scale model measurements, too. We also use these data bases to estimate the sound fields or to feed them bact to the acoustic design.

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REFFERENCES

1) N.Aoshima, •gCOmputer-generated pulse signal applied for sound measurement,•hJ.Acoust.Soc. Am. 69, 1484-1488 (1981).

2) Y.Yamasaki, S.Yamasuda, H.Saito, K.Yasukawa, and T.Itow, •gAn application of digital techniques to obtain the spatial information of a room,•hRep. U.S.Jpn. Jt. Meet. BBB6 (1978).

3) K.Endoh, T.Horikoshi, Y.Yamasaki, and T. Itow, •gGrasp and estimation of spatial information method,•hProc. ICASSP 86, 909-912 (1986).

4) Y.Yamasaki, H.Tachibana, M.Morimoto, Y. Hirasawa, and Z.Maekawa, •gSurvey on the acoustics of concert halls in European countries (The 2nd Report)-Measured results by four-point microhopne method-,•hJ.Acoust.Soc.Jpn.(J) 43, 277-285 (1987) (in Japanese).

5) H.Tachibana, Y.Yamasaki, M.Morimoto, Y. Hirasawa, Z.Maekawa, and C.Posse;t, •gAcoustic survey of auditoriums in Europe and Japan,•hJ. Acoust.Soc.Jpn. (E), 10, 73-85 (1989).

6) H.Yanagawa, Y.Yamasaki, and T.Itow, •gEffect of transient signal length on cross-correlation functions in a room,•hJ.Acoust.Soc.Am. 84, 1728-1733 (1988).