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# Acoustic survey of auditoriums in Europe and Japan

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The authors are now making cooperative work to investigate room acoustic characteristics of various types of auditoriums. Up to this time, we have made surveys of concert halls and opera theaters in several European countries and Japan. In this article, the outlines of the acoustic measuring methods applied in these surveys are introduced and some examples of the measured results are illustrated.

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## 1. INTRODUCTION

From September to October 1986, the Osaka Philharmony Orchestra performed a series of concerts in European countries. We took this opportunity to organize a cooperative research group, which traveled with the orchestra to make an acoustic survey of a variety of concert halls. In this first survey trip in Europe, acoustic measurements of seven concert halls in four countries were made.[1),2)] A second survey trip in Europe was conducted in August 1988, in which the measurements of eight auditoriums (three concert halls, four opera theaters, and one multipurpose hall) were made in three countries. In addition, acoustic measurements on several representative concert halls in Japan have been performed in the same way.

The main aim of these acoustic surveys was to obtain various kinds of objective room acoustic data of various types of auditoriums by a uniform measuring method. At the same time, it was also aimed to obtain basic data for the subjective comparison tests of acoustics in different room conditions. In this article the measuring methods adopted in these acoustic surveys and some examples of the measured results are presented.

## 2. THE AUDITORIUMS SURVEYED

In the cooperative survey work, we are making efforts to obtain as much data of room acoustic characteristics as possible. The auditoriums which have been surveyed up to this time are shown in Table 1. The acoustic condition of an auditorium is not constant. Therefore, the date when the measurement was performed should be noted.

## 3. CONTENTS OF THE ACOUSTIC MEASUREMENT

Through the surveys, the following acoustic measurements were made.

(1) Ordinary measurements

To investigate basic acoustic characteristics of auditoriums, reverberation time, echo time pattern and sound pressure level distribution were measured as the ordinary measurements.

(2) Impulse response measurements

As the physical data include a lot of acoustic information, impulse responses with wide frequency

**Table 1** The auditoriums surveyed and their properties.

| No. | Auditorium | $V$(m³) | Seats | $RT_{500}$ empty/occup.(s) | Date of measurement |
|---|---|---|---|---|---|
| | (1st survey in Europe) | | | | |
| 1 | Bratislava, Philharmonie Hall | (9,000) | (700) | 2.0 | Oct. 6,1986 |
| 2 | Praha, Dovorak Hall | (10,000) | 1,037 | 3.0 | Oct. 9,1986 |
| 3 | Vienna, Grosser Musikvereinssaal | 15,000 | 1,680 | 2.9/2.0 | Oct. 8,1986 |
| 4 | Munchen, Philharmonie Halle | 30,000 | 2,500 | 2.1/1.9 | Oct. 14,1986 |
| 5 | Bonn, Beethoven Halle | 15,700 | (1,500) | 1.7/1.5 | Oct. 17,1986 |
| 6 | Amsterdam, Concertgebouw | 18,700 | 2,206 | 2.6/2.1 | Oct. 19,1986 |
| 7 | Rotterdam, De Doelen | 27,070 | 2,222 | 2.3/2.1 | Oct. 21,1986 |
| | (2nd survey in Europe) | | | | |
| 8 | London, Barbican Center | 18,850 | 2,000 | 1.8 | Aug. 15,1988 |
| 9 | London, Royal Albert Hall | 86,600 | 6,080 | 3.0 | Aug. 16,1988 |
| 10 | Manchester, Free Trade Hall | 15,400 | 2,569 | 1.8 | Aug. 17,1988 |
| 11 | Paris, UNESCO Convention Hall | 11,000 | 978 | 1.7 | Aug. 19,1988 |
| 12 | Paris, L'Opera | 9,960 | 2,131 | (1.3) | Aug. 19,1988 |
| 13 | West Berlin, Deutsche Oper Berlin | 10,800 | 1,900 | 1.5 | Aug. 26,1988 |
| 14 | East Berlin, DeutscheStaatsoper | 7,500 | - | 1.6 | Aug. 25,1988 |
| 15 | Dresden, Semperoper | - | - | 1.8 | Aug. 28,1988 |
| | (survey in Japan) | | | | |
| 16 | Osaka, The Symphony Hall | 17,000 | 1,702 | 2.2/1.9 | Oct. 6,1988 |
| 17 | Tokyo, Suntory Hall | 21,000 | 2,006 | 2.6/2.1 | May 13,1987 |
| 18 | Tokyo, Hitomi Memorial Hall | 19,400 | 2,378 | 1.8 | Aug. 4,1988 |
| 19 | Kawasaki, Maeda Memorial Hall | 14,700 | 1,176 | 2.2/2.0 | Sep. 29,1987 |
| 20 | Kumamoto, Prefectural Concert Hall | 19,410 | 1,808 | 2.1 | Oct. 2,1988 |

( ): not exact.

components were measured by monophonic, binaural, and 4-microphone receiving systems as mentioned below. From the impulse responses measured by the monophonic system, various acoustic quantities can be obtained. From impulse responses measured by the binaural system, arbitrary sounds such as music and speech performed in auditoriums can be synthesized by using the digital convolution technique.

(3) Three-dimensional impulse response measurement by 4-point microphone method

From theimpulse responses simultaneously measured at closely located four points which are not on the same plane, various spatial (three-dimensional) information can be derived. So, in all the measurements, the 4-point microphone technique[3] was applied.

(4) Binaural recording of dry music

For subjective tests, dry music was reproduced from an omnidirectional loudspeaker system mentioned below, and the sounds in audience area were recorded by using a dummy head system.

## 4. MEASURING METHOD

4.1 Sound Source System

In the first survey in Europe, a dodecahedral

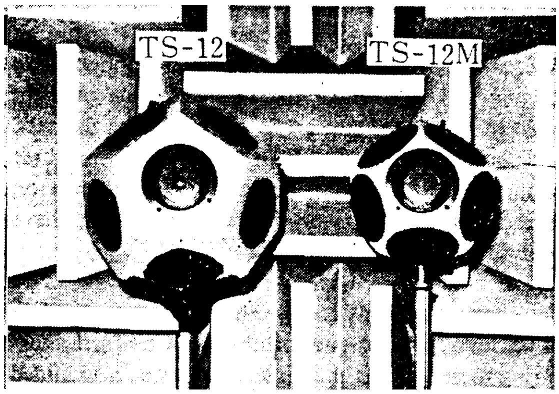



**Fig.1** Dodecahedrall foundspeaker Systems used in thesurveys.

loudspeaker system, named TS-12 shown in Fig. 1, was used for the ordinary measurements and for reproduction of dry music. This sound source system was made up of twelve regular pentagons of 14cm side length. A loudspeaker of 10cm diameter (FOSTEX UP-103) is installed at each surface (This system was designed as a standard sound source for room acoustic measurement, and is now being widely used in Japan). As shown in Fig. 2, this system has omnidirectionality up to 2kHz octave band, and can radiate relatively high sound power. So, almost all kinds of room acoustic measurements can be performed only by using this system.

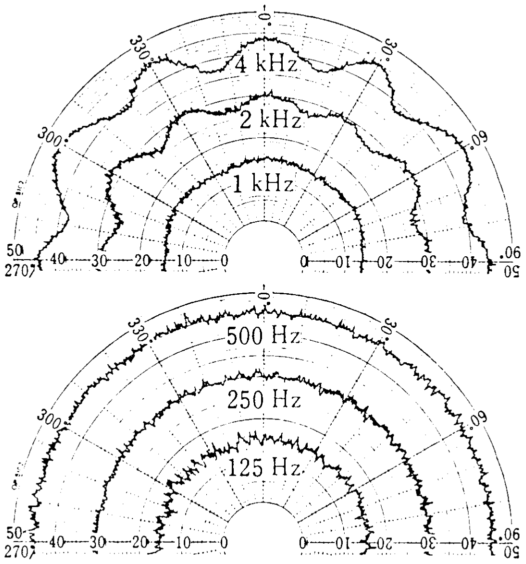



**Fig. 2** Directivity characteristics of the loudspeaker system TS-12.

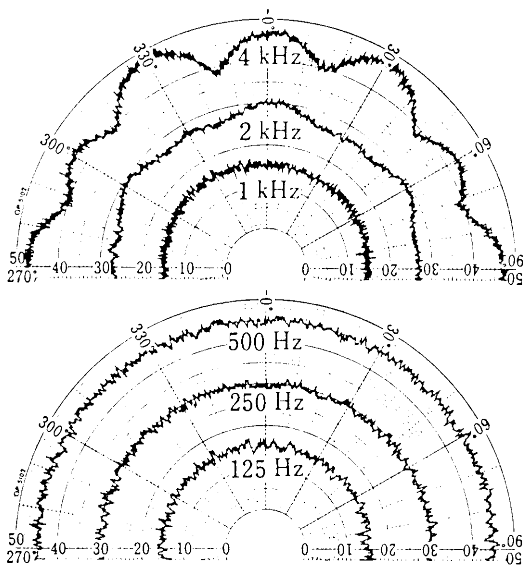



Fig. 3 Directivity characteristics of the loudspeaker system TS-12M.

Another dodecahedral loudspeaker system, TS-12M shownin Fig. 1, was newly designed for the second survey in Europe. This sound source, made up of twelve regular pentagons of 10cm side length and loudspeakers of 10cm diameter (FOSTEX FE-103), is a bit smaller and lighter than the former one. The directivity characteristics of this system is shown in Fig. 3.

Figure 4 shows the sound power spectrum characteristics in 1/3 octave bands of these two loudspeaker systems when applied a white noise of 1 watt electric input power. The spectral characteristic of the system TS-12M is rather uneven, and therefore it was corrected by using a spectral equalizer when used in the measurements mentioned below.

For the measurement by the 4-point microphone method, a couple of loudspeakers of 20cm diameter in facing configuration were used as an approximate pulsating point source in the first survey in Europe. In the second survey in Europe and some surveys in Japan, TS-12M was used as the common sound source for all measurements.

In the measurements in auditoriums, each sound source was placed on the center of stage at a height of 1.5m, about 3m from the stage front.

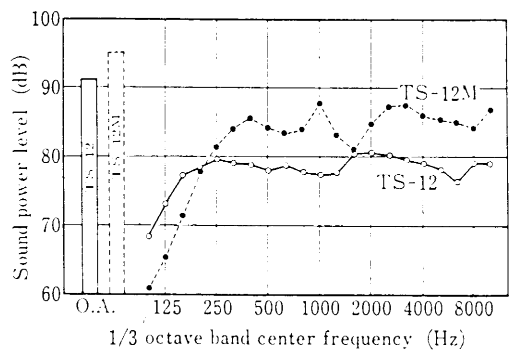


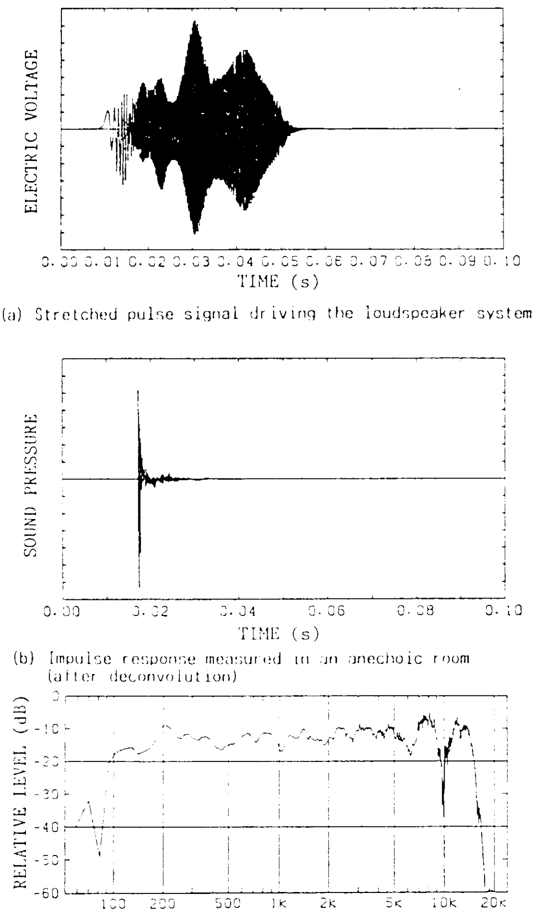

Fig. 4 Sound power spectrum characteristics of the loudspeaker systems TS-12 and TS-12M (input signal: white noise, 1W).

### 4.2 Source Signals

For the ordinary measurements, four kinds of source signals were used: (A) stationary white noise of 30s duration time, (B) two-octave band noise bursts (2s on and 3s off) of 125～250Hz, 500Hz～1kHz, and 2～4kHz, (C) two-octave band pulses of 500Hz～1kHz and 2～4kHz which are the impulse responses of two-octave band pass filters, and (D) dry music of a violin, a flute and a snare drum recorded in an anechoic room. These source signals were previously recorded on a PCM taperecorder or a digital audio taperecorder (DAT), and they were reproduced from the dodecahedral loudspeaker system successively. The acoustic output from the source system was kept constant throughout all measurements, by monitoring the input voltage to the loudspeaker system.

For the measurement by the 4-point microphone method in the first survey in Europe, a rectangular impulse of 10$\mu$s duration time was radiated 32 or 64 times from the coupled loudspeakers.

In the second survey in Europe, the sweep pulse method (signal compression method)[4),5)] was applied for the impulse response measurement. Figure 5 (a) shows the waveform of the stretched pulse signal driving the loudspeaker system. This signal was made by a computer and the spectral characteristic was modified through a spectrum equalizer to roughly correct the frequency characteristic of the loudspeaker system TS－12M. Figure 5 (b) and (c) show the waveform and energy spectrum of the impulse response measured in an anechoic room by using the stretched pulse source and by deconvolution processing. In actual measurements in auditoriums, this source pulse was radiated 35 times for each measurement to improve S/N ratio by the synchronous averaging technique. As the duration time of the stretched pulse is very short (40ms), we can check the acoustic conditions, such as presence of harmful echoes, by hearing.




(a) Stretched pulse signal driving the loudspeaker system

(b) Impulse response measured in an anechoic room (after deconvolution)

(c) Energy spectrum characteristic of the impulse shown in (b)

**Fig. 5** Sweep pulse method. (a) Stretched pulse signal driving the loudspeaker system, (b) Impulse response measured in an anechoic room (after deconvolution), (c) Energy spectrum characteristic of the impulse shown in (b).

### 4.3 Receiving Systems

In all surveys, measurements were made in the following three ways: (1) monophonic receiving with sound level meters (RION NL－02) for the ordinary measurements, (2) binaural receiving with a dummy head made by Ruhr University[6)] to obtain the materials for subjective hearing tests, and (3) 4—point receiving with a closely located fou rmicrophone system for three-dimensional impulse response measurement.

The microphone output signals were recorded on ordinary and PCM taperecorders in the first survey in Europe. After that, digital audio taperecorders (DAT) came into the market in 1988, and they were used for signal recordings in the surveys after that time.

In the measurement of each auditorium, a position 12 m from the sound source was chosen as the standard measuring position. The remaining measuring positions were distributed as uniformly as possible in the audience area. The number of the measuring positions varied in each measurement, mainly according to the time allowed for the measurement. The height of the measuring point was set at 1.2 m above the floor.

## 5. MEASURED RESULTS

The essential phase of auditoriums is when they are occupied, but it is almost impossible to make detailed acoustic measurements under such conditions. Consequently, almost all measurements in our surveys were conducted in the unoccupied condition. Regarding opera theaters, it should be noted that the measurements were made in the absence of reflective stage settings.

Since the amount of data obtained in our surveys are enormous, some examples are shown here.

### 5.1 Results of Ordinary Measurements and Impulse Response Measurements

(1) Reverberation time

From the measurement using two-octave band noise bursts, reverberation times in 1/3 octave bands from 100 Hz to 5 kHz were obtained according to the ordinary method. The results measured in seven concert halls and three opera theaters are shown in Fig. 6. In these figures, the dotted line shows the reverberation times in octave bands under

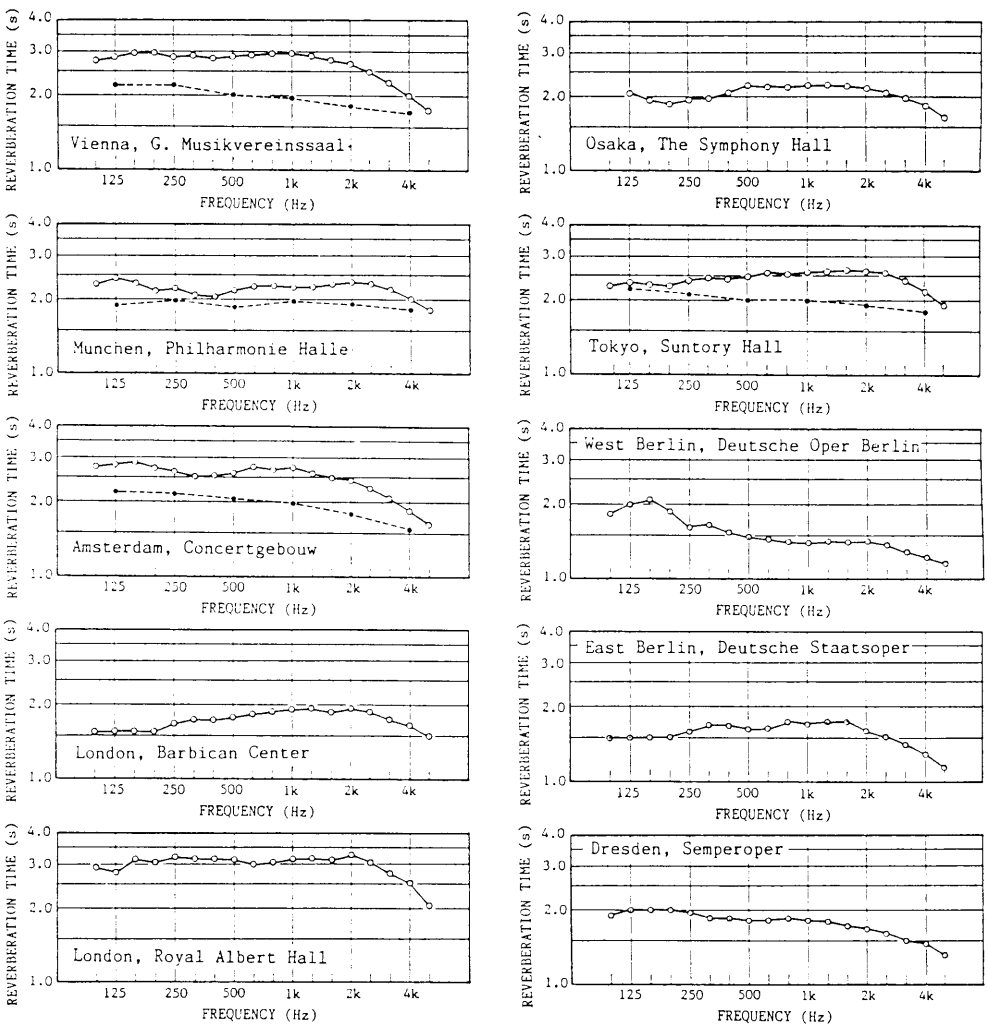



**Fig. 6** Examples of measured results of reverberation time.

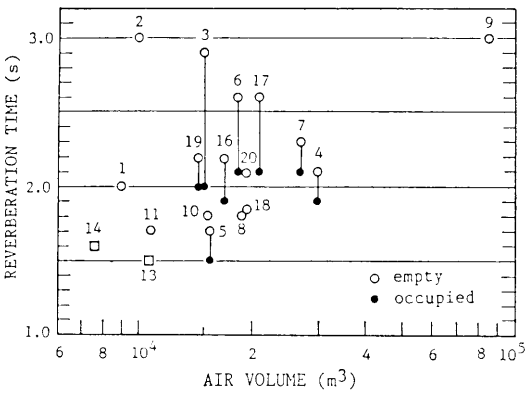



**Fig. 7** Comparison of reverberation time in 500 Hz octave band.

the occupied condition. These data were obtained by recording the performance of orchestra music, and by analyzing the reverberation decay at the end of the music. These measurementd were made at only one or two positions in audience area and the measuring condition was not sufficient. Therefore, these data are shown here only for reference. As the representative value of reverberation time of each auditorium, the value in 500 Hz octave band (the average of the values in 400 Hz, 500 Hz and 630 Hz in 1/3 octave band) is shown in Table 1 and Fig. 7.

(2) Echo time pattern

From the measurement using two-octave band pulse, echo time patterns in octave bands of 500 Hz, 1 kHz and 2 kHz were analyzed. In the case of the second survey in Europe and some measurements in Japan, they were derived from the impulse responses measured by the sweep pulse method and by digltal filtering technique. Among them, the patterns of 1 kHz octave band measured in seven auditoriums are shownin Fig. 8. They were the results measured at the standard measuring position (12 m from the sound source) in each auditorium, while some variances in amplitude of the direct sound are seen. This may be caused by the inaccuracy of setting the measuring positions and the differences of boundary conditions such as stage, floor and seats. In Fig. 8, the values of Deutlichkeit ($D$), Klarheitmass ($K$) and Schwerpunktzeit ($T_s$) are shown for reference.

(3) Impulse response and quantities obtained from it

Figure 9 (a) shows an impulse response measured

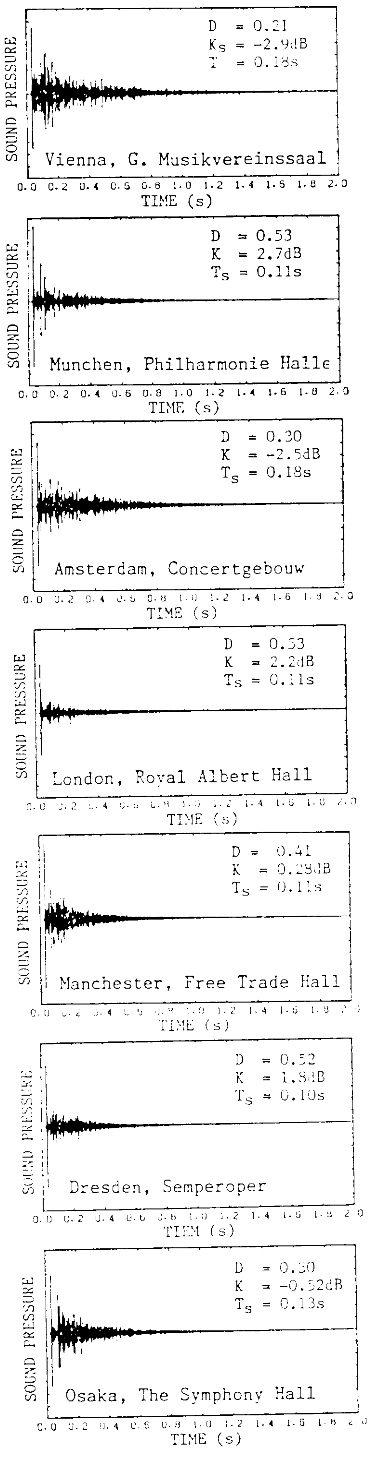



**Fig. 8** Examples of measured results of echo time pattern in 1 kHz octave band.

in the Free Trade Hall in Manchester by the sweep pulse method. In this case, synchronous averaging over 35 tests was performed to reduce the effect of background noise as previously mentioned. From this result, various quantities can be derived by digital signal processing.

For example, Fig. 9 (b) is the echo time pattern of 500 Hz octave band, and Fig. 9 (c) is the reverberation decay obtained from it according to the Schroeder's method. Figure 10 shows the Wigner distribution in 1/3 octave bands calculated from the impulse response shown in Fig. 9 (a). From this presentation, the transient characteristics both in time domain and in frequency domain can be directly observed in visual form.

(4) Sound pressure level distribution and mean sound pressure level

From the measurement using stationary white noise source, sound pressure levels in octave bands from 125 Hz to 4 kHz at each measuring position were analyzed. In the measurement in each auditorium, the sound level meter was calibrated by

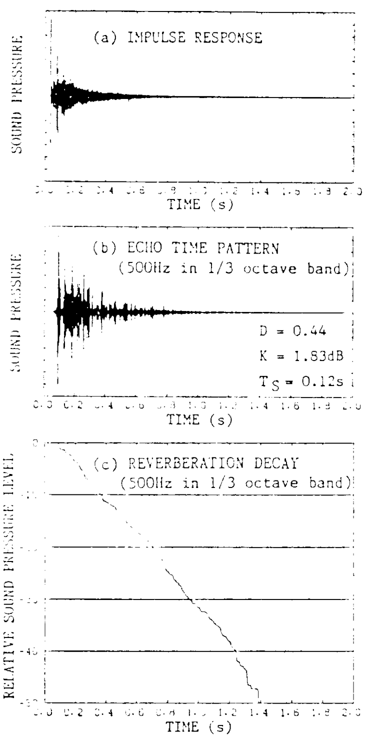



**Fig. 9** An example of the impulse response measurement by the sweep pulse method (Manchester, Free Trade Hall).

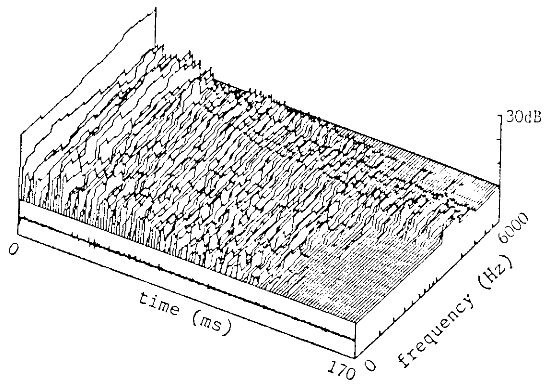



**Fig. 10** Wigner distribution calculated from the impulse response shown in Fig.9 (a) (1/3 octave band analysis).

using a calibrator (B&K 4230), and the calibration signal was recorded on the taperecorders. The sound power levels in each octave band of the sound source system were previously measured according to the diffuse field method (ISO 3741), and it can be considered that these sound powers were almost exactly reproduced in each measurement. Therefore, the measured results of sound pressure level distribution can be observed absolutely, and we can compare them mutually among diffrent auditoriums.

Ten examples of sound pressure level distribution in 500 Hz octave band are shown in Fig. 11. In these figures, the value of sound pressure level is indicated nominally by assuming that the octave band sound power level is 100 dB. The curves in the figures regarding concert halls are theoretical values calculated by the following equation. In this calculation, the equivalent sound absorption area $A$ was calculated from the nominal air voiume and the measured reverberation time by using Sabine's equation.

$$L_{\mathrm{p}} = L_{\mathrm{w}} + 10\log\left(\frac{1}{4\pi r^2} + \frac{4}{A}\right)$$

where, $L_{\mathrm{p}}$ : sound pressure level (dB)
$L_{\mathrm{w}}$ : sound power level of the sound source (100 dB, re $10^{-12}$W)
$r$ : distance from the sound source (m)
$A$ : equivalent sound absorption area ($\mathrm{m}^2$)

In Fig. 11, it can be seen that the measured sound pressure levels and the theoretical values are ap-

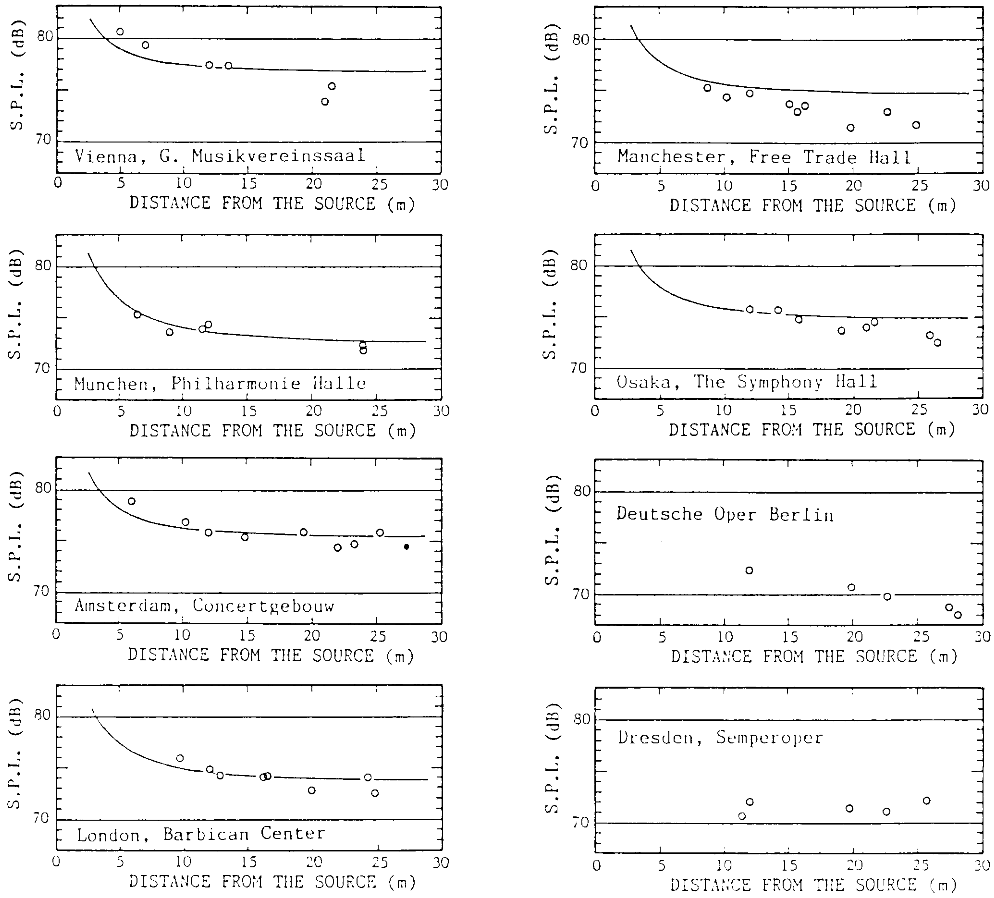



**Fig. 11** Examples of measured results of sound pressure level distribution in 500 Hz octave band (Octave band sound power level of the source: 100 dB).

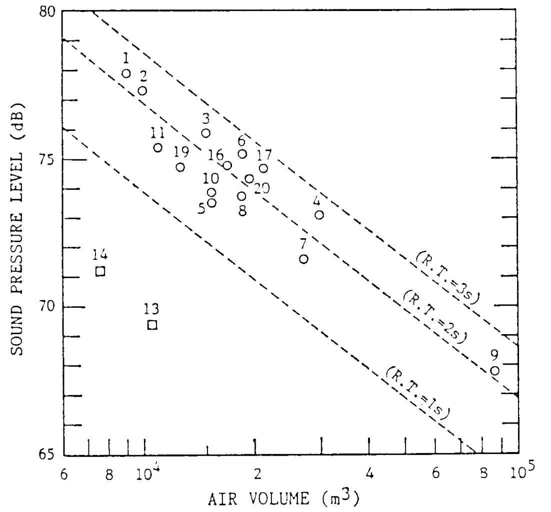



**Fig. 12** Comparison of mean sound pressure level in 500 Hz octave band (Octave band sound power level of the source: 100 dB).

proximately in good agreement. In lower and higher frequency bands, however, such a tendency was observed that the measured values are lower than the theoretical values according to the above equation.

Figure 12 shows a comparison of the average sound pressure level in 500 Hz octave band in the audience area of each auditorium. In this case, the average sound pressure level means the arithmetic mean value of the sound pressure levels at the measuring positions between 12 m and 25 m from the sound source in each auditorium, excluding both the area near the sound source, where the direct sound is dominant, and the area that is too far from the sound source. Here, it should be noted that the data obtained from the results measured at only several measuring points are included.

Concerning the opera theaters, the sound pressure levels are relatively low. This is a matter of course, because the acoustic condition on the stage is much different from that of concert halls, and the measurements were made without stage settings.

For this kind of measurement, precise measurement of sound power level of the sound source, strict monitoring of the output of the source, and accurate measurement of sound pressure level are needed.

### 5.2 Three-Dimensional Distribution of Virtual Image Sources

In the 4-point microphone method, four micro-

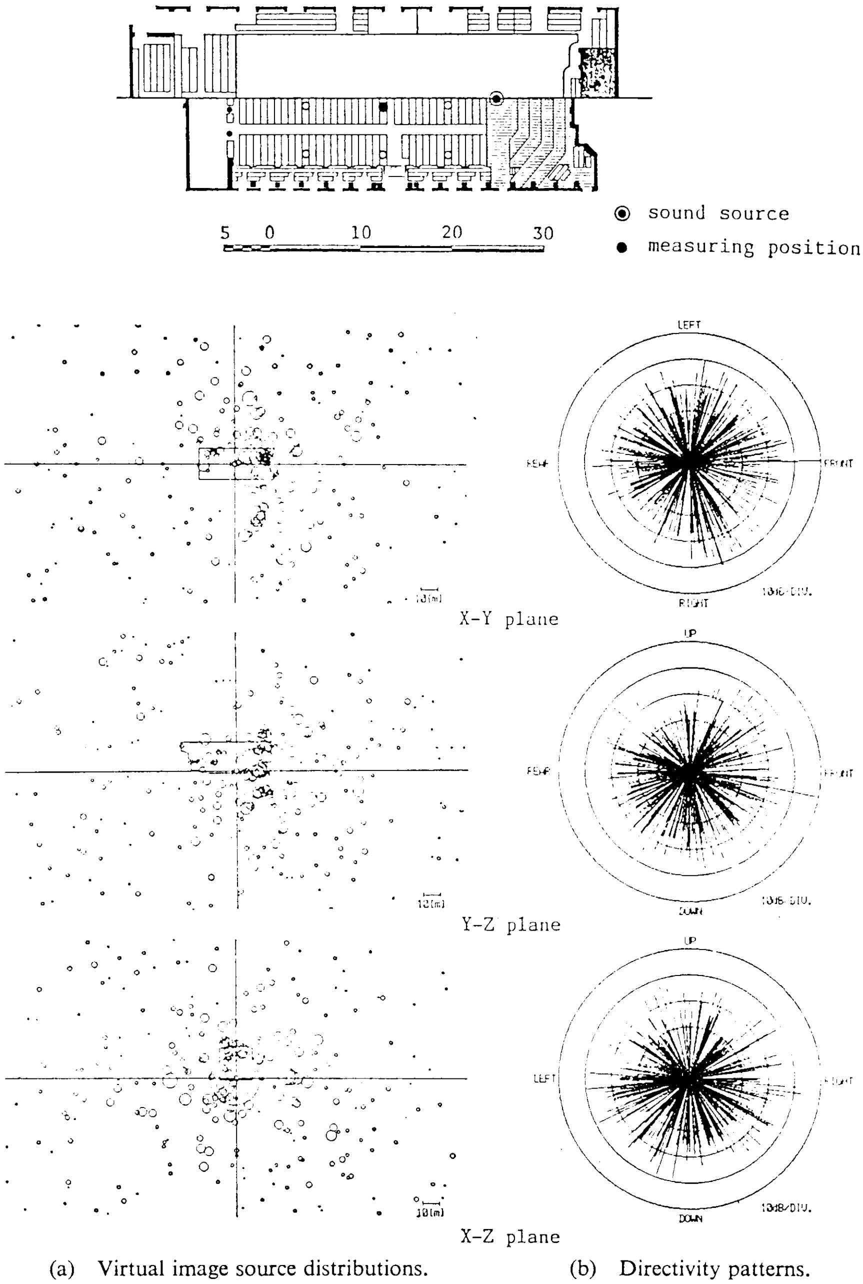
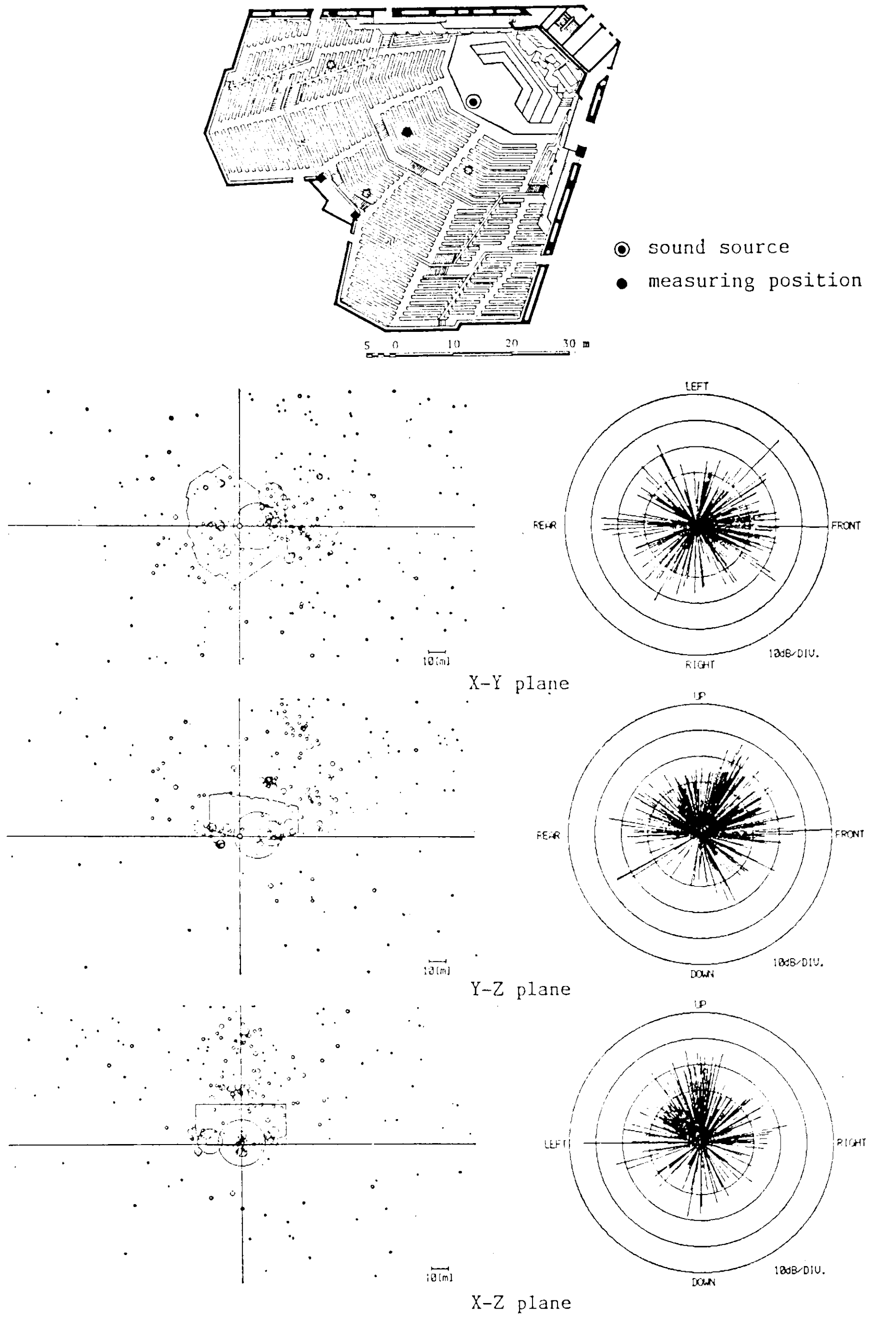



**Fig. 13** The results measured by the 4-point microphone method (Vienna, Grosser Musikvereinssaal).

phones closely located at the origin and three points of the same distance (3cm～5cm) from the origin on the rectangular coordinate axes are used, and the short time cross-correlation technique or the sound intensity technique is applied to identiry each reflection.[3] According to this measuring method,

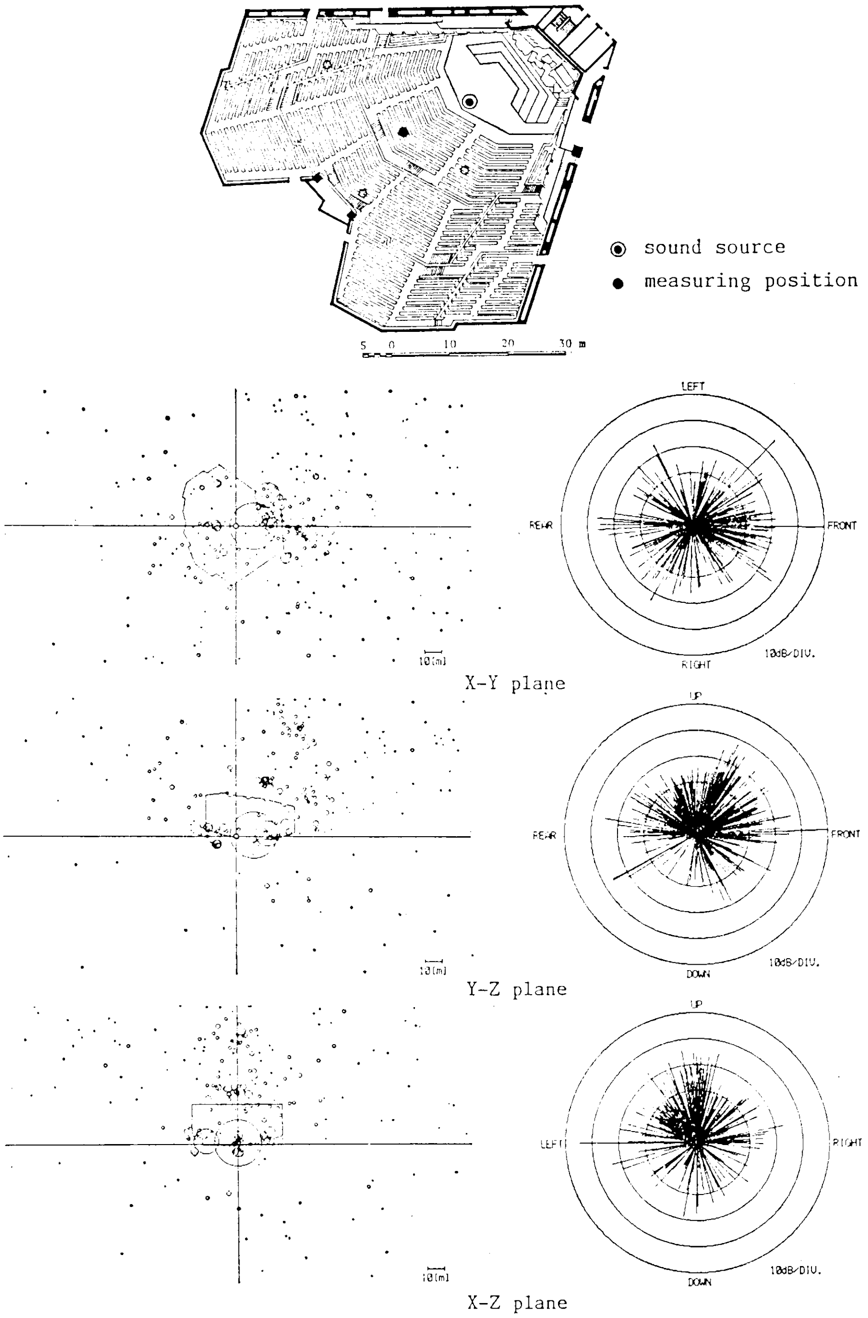



(a) Virtual image source distributions. (b) Directivity patterns.

**Fig. 14** The results measured by the 4-point microphone method (Munchen, Philarmonie).

various kinds of spatial informations can be obtained.

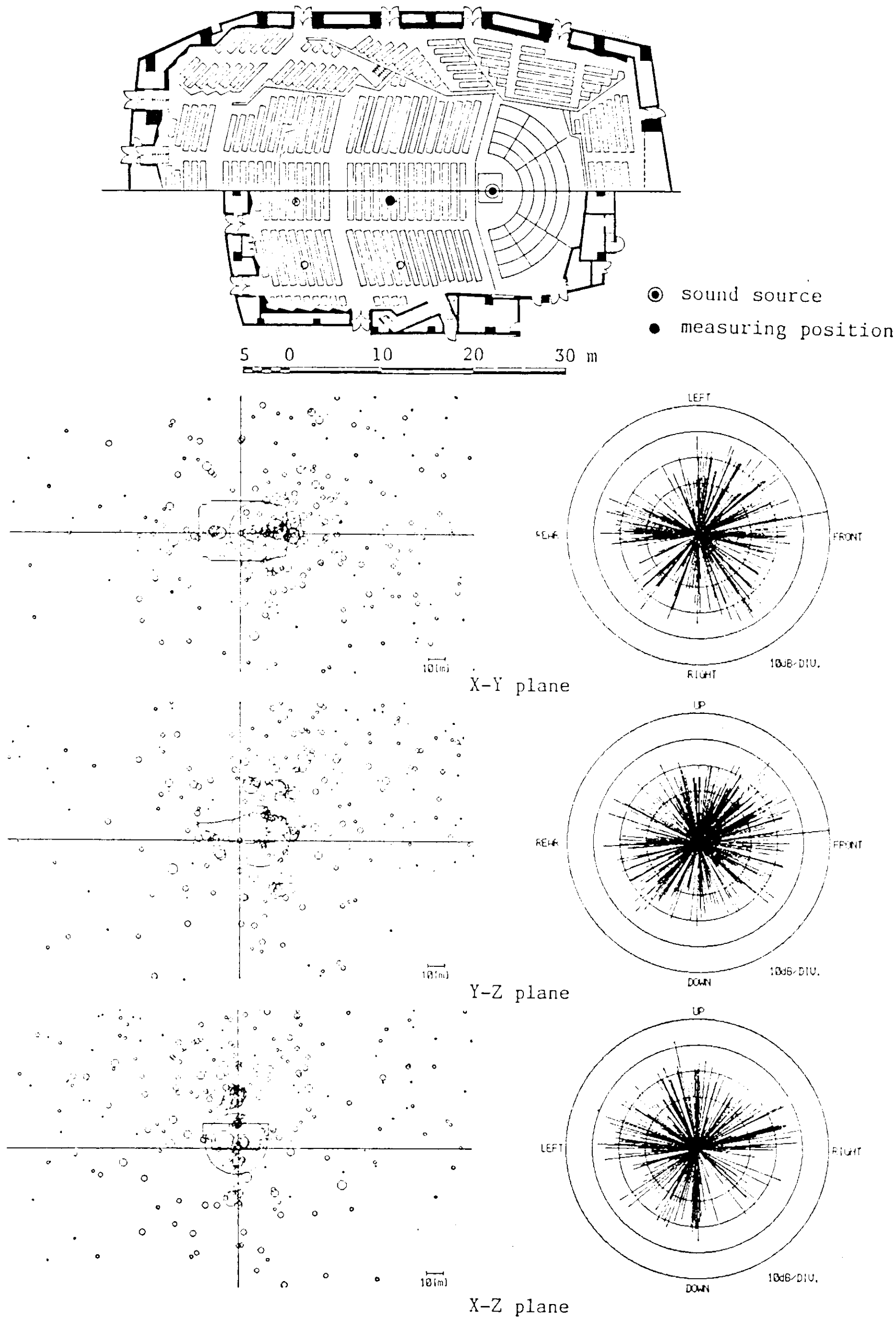
Among the results measured by this method using cross-correlation technique, the three-dimensional distribution of virtual image sources and the directivity patterns of four auditoriums are shown in




(a) Virtual image source distributions. (b) Directivity patterns.

**Fig. 15** The results measured by the 4-point microphone method (Osaka, The Symphony Hall).

Fig. 13 to 16. They were measured at the standard measuring position in each auditorium. In the figures of virtual image source distribution, the center of a circle indicates the position of a virtual image source and the area of the circle describes the magnitude of the image source. In the figures of the directivity pattern, a bar indicates the direction of a image source and its length indicates its mag-




(a) Virtual image source distributions. (b) Directivity patterns.

**Fig. 16** The results measured by the 4-point microphone method (Tokyo, Suntory Hall) nitude in dB. From these presentations, the acoustic characteristics, especially early reflections, of each auditorium can be clearly grasped. Beside these results, further information can be derived from the result of three-dimensional impulse response measurement.

## 6. SUBJECTIVE JUDGEMENT TESTS

In the first survey in Europe, binaural recordings of dry music were made through the dummy head in seven concert halls. By using these recordings, a preliminary preference test has been made.[7),8)] In this test, the test sounds were reproduced binaurally, and eighty-eight university students served as subjects. To summarize the test results, (1) there was no significance among preference scores for these halls when averaged over all subjects, and (2) subjects could be divided into several groups with respect to prererence, and in conclusion, (3) the acoustic quality of a concert hall could not be solely evaluated by the preference score.

In the second survey in Europe and that in Japan, the impulse responses through the dummy head system were measured by the sweep pulse method. These data are to be convolved with arbitrary dry music, and subjective hearing tests are to be made in the near future.

## 7. CONCLUSIONS

In this article, the methods for field measurement of room acoustic properties of auditoriums and some examples of the measured results obtained in the surveys in several European countries and Japan has been introduced.

The amount of data obtained in these acoustic surveys are enormous, and we are now making various investigations by using these data from physical and psychoacoustical viewpoints. The results of these researches will be reported in the near future. We have an intention to continue this kind of survey work on various types of auditoriums in many countries.

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At last, we are very sorry to inform that Dr. C. Posselt, one of the authors, suddenly died on 24 September 1988 in the middle of our cooperative work.

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