DEVELOPMENT OF MICRO-DODECAHEDRAL LOUDSPEAKER FOR MEASURING HEAD-RELATED TRANSFER FUNCTIONS IN THE PROXIMAL REGION

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ABSTRACT

This paper describes new equipment for measuring head-related transfer functions (HRTFs) near a listener's head. 3D sounds in headphones are generated by the convolution of sound signals and an HRTF, which is defined as the acoustical transfer function between a point sound source and the entrance to the ear canal. A loudspeaker is usually used for HRTF measurements, and a distance of more than 1 m separates the loudspeaker and the subject. The region within 1 m of the head is called the 'proximal region,' where a small loudspeaker is needed for accurately measuring HRTF, that is, a conventional loudspeaker cannot be used. In our study, a micro-dodecahedral loudspeaker with twelve piezoelectric ceramic devices is used for HRTF measurements at a diameter is 38 mm. Our experiments examined the characteristics of this loudspeaker. From the results, our developed loudspeaker provides similar performance to a point source, and it is very effective for measuring the HRTFs in the proximal region.

1. INTRODUCTION

Spatial audio technology has been applied to such sound systems as virtual reality systems, computer games, and mobile phones. Spatial audio systems are provided in two ways: with plural loudspeakers and with headphones. In both methods, the head related transfer function (HRTF) is very important. HRTF contains reflections and refractions of sound waves at the ears and head, and the HRTF characteristics are different at every sound source location. In our study, HRTF is defined as the acoustical transfer function between the sound source and the entrance to the ear canal. We can perceive greater presence than stereo sound by convolving arbitrary signals with HRTFs, which are measured with a loudspeaker as the sound source and a microphone located at the entrance to the ear canal. To use HRTFs, it is usually necessary to take measurements at every sound source location. In acoustic measurements, a point source is desirable because the transfer function is defined between two points in the space. Under far field conditions, a loudspeaker is considered the point source. However, in the field near a head, a conventional loudspeaker cannot be used as the point source. If the HRTF near a head is measured with a loudspeaker, the reproduced sound does not have clear sound localization.

A few HRTF methods for taking measurements in the sound field near the head have been examined. In one approach, a point source was realized by using a probe [1]. In other research, an electrical discharge was used [2]. The probe method has a problem in dealing with other sound sources to improve features at low frequencies, and the electrical discharge method poses dangers to human subjects. Therefore, a safe sound device that does not rely on such devices is needed.

In recent years, the piezoelectric loudspeaker has been developed and installed in various products, such as mobile phones and laptop computers. This piezoelectric device is small, secure, and stable. In our study, a dodecahedral loudspeaker was developed based on a piezoelectric device[3], and its characteristics were evaluated precisely. Furthermore, we performed HRTF measurements near the head with a head and torso simulator.

2. DODECAHEDRAL LOUDSPEAKER

A dodecahedral loudspeaker is usually used to measure the acoustics in a room, a hall, and so on. If the measurement space is large, the dodecahedral loudspeaker is considered the point source. Accordingly, if a small dodecahedral loudspeaker was developed, it could serve as the sound source for measuring the acoustics near the head. A piezoelectric device creates mechanical deformation by providing the potential difference. Such mechanical deformation gives us a sound signal. Piezoelectric devices are robust against temperature and provide good electric performance. A piezoelectric loudspeaker can produce high frequency sounds exceeding 100 kHz. Since it does not need a magnet, which is installed in conventional loudspeakers, a sound device using a piezoelectric device can be downsized [4]. In this work, the piezoelectric device's diameter is 18 mm and its thickness is 1 mm (NIHON CERATEC MR-18). A dodecahedral loudspeaker is developed with twelve devices, as shown in Fig. 1. This loudspeaker's diameter is 38 mm, and its interior is filled with polyurethane. Silicone covers the surface of the loudspeaker. The twelve piezoelectric devices are connected in parallel.

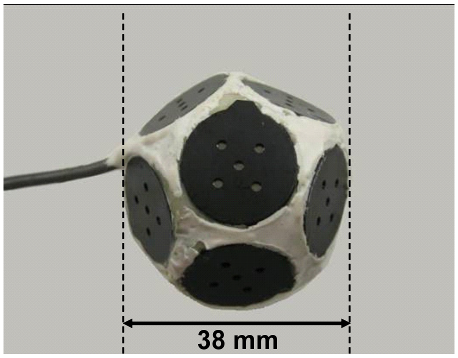

Fig. 1. Dodecahedral loudspeaker.

3. EVALUATION OF DODECAHEDRAL LOUDSPEAKER

The characteristics of the developed dodecahedral loudspeaker were examined. First, the sound pressure level was measured with a sound-level meter. Directivity, stability, and distance characteristics were examined by measuring impulse responses between the dodecahedral loudspeaker and the microphone. In the case of measuring impulse response, the swept sine signal [5] whose duration was 1.365 sec was used. The sampling frequency was 48 kHz. Other measurement conditions are shown in Table 1.

Every experiment was performed in a reverberant room whose reverberation time was 150 msec.

3.1. Sound Pressure Level

According to the specifications, the piezoelectric device has several resonance frequencies. In particular, the resonance at about 8 kHz influences to measurement of the HRTF, because an individuality of the HRTF appears at these frequencies.

The sound pressure levels were measured with a sound-level meter (ONO SOKKI LA-5120) to evaluate their suitability for measuring the HRTF. The frequency was changed from 0.1 to 15.0 kHz at intervals of 0.1 kHz. Since measurements at frequencies above 12.5 kHz don't be guaranteed by the specifications, the results above 12.5 kHz are just for reference. The distance between the sound-level meter and the dodecahedral loudspeaker was 1 m, and the reference sound pressure level was 65.0 dB at 10.0 kHz. The other conditions are shown in Table 2.

Fig. 2 shows the sound pressure level. From the results, there is a small dip from 7.3 to 7.5 kHz. However, when the sound pressure levels were measured precisely from 7.3 to 7.5 kHz at intervals of 10 Hz, no dip or peak appears. This indicates that the inverse filter of the loudspeaker characteristics can be designed and that the measured HRTF is compensated by it.

Table 1. Measurement conditions

Background noise level	14.0 dB(A)
Room temperature	24.5 °C
Sound pressure level	65.7 dB(A) (1 m)

Table 2. Experimental conditions of measuring sound pressure level

Background noise level	28.6 dB
Room temperature	19.8 °C
Sound pressure level (10.0 kHz)	65.0 dB (1 m)

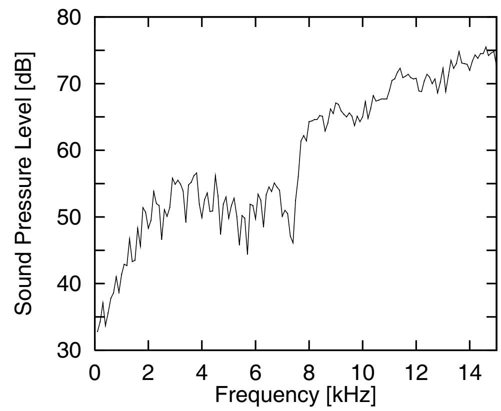

Fig. 2. Sound pressure level.

On the other hand, a lower sound pressure level was obtained below 2 kHz. In particular, the sound pressure level below 0.2 kHz was same as the background noise level. It is thus necessary to take care in compensating the loudspeaker's characteristics.

3.2. Directivity

The dodecahedral loudspeaker was positioned on a turntable (NITTOBO Acoustic Engineering) whose movement could be controlled within 0.3° accuracy. Since the turntable moved at intervals of 1°, 360 impulse responses were measured. Duration of measured impulse response is 512 points (10.7 ms). The distance between the dodecahedral loudspeaker and the microphone was 1 m. The measured impulse responses were examined by octave-band spectral analysis (Fig. 3). Our dodecahedral loudspeaker has no directivity from 1 to 8 kHz; however, it has directivity at other frequencies. These results are allowed in our measurements. The characteristics below 1 kHz are not good, in agreement with the results of measuring the sound pressure level. These results suggests that it is difficult to transduce low frequencies with a piezoelectric device in our experiments. To improve characteristics above 8 kHz, we must control the phase and deformation with high precision.

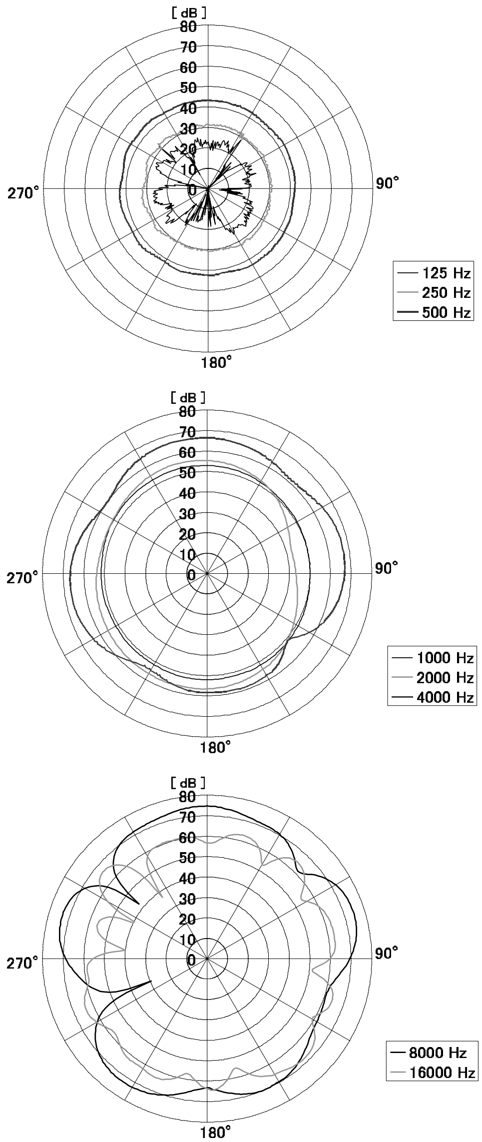

Fig. 3. Directivity of dodecahedral loudspeaker.

3.3. Sound attenuation of distances

The microphone faced the dodecahedral loudspeaker, and it was attached to the positioning equipment (NITTOBO Acoustics Engineering) and moved with this equipment. The distance between the dodecahedral loudspeaker and the microphone was from 10 to 100 cm at intervals of 10 cm. Ten impulse responses were measured at each distance, and these were used to evaluate stability. Duration of measured impulse response is 512 points (10.7 ms). An conventional loudspeaker (BOSE ACOUSTIMASS, 63 mm diameter) was used for the comparison. Measured impulse responses were evalu-

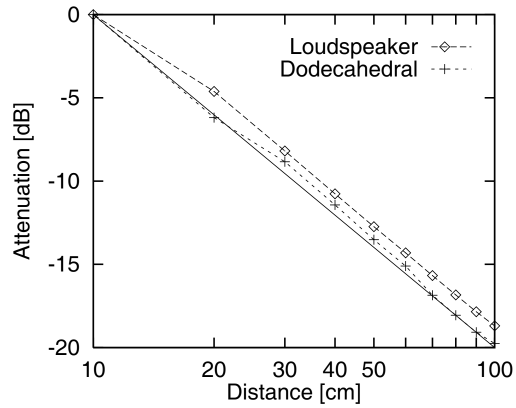

Fig. 4. Distance characteristics (Solid line represents ideal sound attenuation).

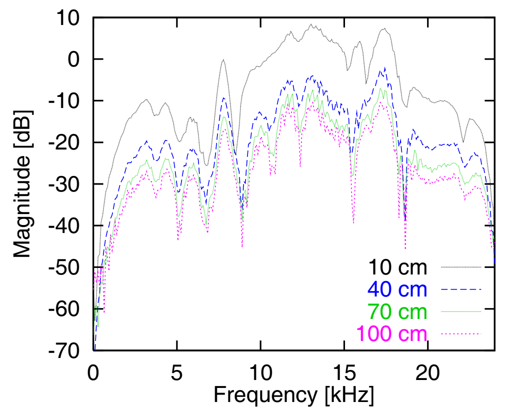

Fig. 5. Magnitude response of the impulse response at four distances (10, 40, 70 and 100 cm).

ated by calculating their power given by:

$$\text{Power} = 20 \log_{10} \left(\sqrt{\frac{1}{512} \sum_{n=0}^{511} h(n)^2} \right) \quad \text{[dB]}, \qquad (1)$$

where $h(n)$ is an impulse response. The resultant sound attenuation is shown in Fig. 4. The results show that the characteristics of the dodecahedral loudspeaker are similar to the ideal, however, this is not the case for a conventional loudspeaker when the distance between the dodecahedral loudspeaker and microphone is short. This result indicates that our dodecahedral loudspeaker can be considered a suitable point source. Fig. 5 shows the magnitude responses at several distances, suggesting that sound attenuation by distance occurred equally at all frequencies within 1 m.

3.4. Stability

The stability of the dodecahedral loudspeaker was evaluated with impulse responses measured in sound attenuation experiments. Ten impulse responses were measured at each distance. Stability was examined by spectral distortion (SD) and signal-to-deviation ratio (SDR). SD is given by:

$$\mathbf{SD}_{d,i} = \sqrt{\frac{1}{257}\sum_{k=1}^{257}\left(20\log_{10}\frac{|H_i(f_k)|}{|H_{ref}(f_k)|}\right)^2} \quad [\mathrm{dB}], \quad (2)$$

where $|H_{ref}(f_k)|$ is the magnitude response of the first measured impulse response, $|H_i(f_k)|$ is the magnitude response of the i-th measured impulse response $(i = 2, \cdots, 10)$,f_k is the frequency and d is the distance. The i-th measured impulse response is very similar to the first measured impulse response when a small SD is obtained. SDR is given by:

$$\mathbf{SDR}_{d,i} = 10\log\frac{\sum_{n=0}^{511}\{h_{ref}(n)\}^2}{\sum_{n=0}^{511}\{h_{ref}(n) - h_i(n)\}^2}[\mathrm{dB}], \quad (3)$$

where $h_{ref}(n)$ is the first measured impulse response, $h_i(n)$ is the i-th measured impulse response $(i = 2, \cdots, 10)$. The i-th measured impulse response is very similar to the first measured impulse response when a large SDR is obtained.

The total average of SD scores is 0.90 dB, and that of SDR is 25.1 dB. In the case of the conventional loudspeaker (BOSE ACOUSTIMASS), the average SD score is 0.61 dB and average SDR is 28.5 dB. The significant tests (T-test) were performed for those results. In the tests, the levels of significant α were 0.01 and 0.05. At both levels, there was no significant difference between the results of the dodecahedral loudspeaker and the conventional loudspeaker. This indicates that our dodecahedral loudspeaker has the same stability as a conventional loudspeaker.

4. HRTF MEASUREMENT

HRTFs near the head were measured with the developed dodecahedral loudspeaker in a reverberant room with a head-and-torso simulator (HATS, B&K 4128). HATS was positioned on the turntable and the dodecahedral loudspeaker was on an arched traverse. The turntable and the arched traverse could be moved at intervals of 1°, with an accuracy is 0.3°. The distance between the dodecahedral loudspeaker and the center of the bitragion changed from 20 to 100 cm. HRTFs were measured for 72 azimuths and 29 elevations at each distance. The total number of measurement points was 18,153 ((72×28+1)×9), and the sampling frequency was 48 kHz. The angles of azimuth corresponded to the following: the front was 0°, the negative angle was the left side, the positive angle was the right side, and the back was 180°. Negative elevation means that the sound source position was below the horizontal plane, and positive denotes it was above the horizontal plane. The horizontal plane was 0°. The other measurement conditions are shown in Table 3.

Table 3. Experimental conditions of measuring HRTFs

Background noise level	13.2 dB(A)
Room temperature	15.8 °C
Sound pressure level	60.2 dB(A) (1 m)
Azimuth	-175° – 180°, 5° intervals
Elevation	-50° – 90°, 5° intervals
Distance	20 – 100 cm, 10 cm intervals

In preliminary subjective experiments, the HRTFs measured with the dodecahedral loudspeaker were more effective than the HRTFs measured with the conventional loudspeaker.

5. CONCLUSIONS

In this paper, we described the development of a micro-dodecahedral loudspeaker based on a piezoelectric device for measuring HRTFs near the head. The characteristics of the dodecahedral loudspeaker were evaluated. As a result, the developed dodecahedral loudspeaker can be considered a point source that is suitable for measuring HRTFs near the head. These were measured by changing the distances from 20 to 100 cm between the sound source and the object. The total number of measurement points was 18,153, and the HRTF database reflecting the variability of direction and distance could be constructed. Future work includes improving the shape of the dodecahedral loudspeakers, measuring more HRTFs, and devising subjective tests for characteristics such as sound localization.

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6. REFERENCES

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