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Fast near-field HRTF measurements using reciprocal method

Noriyuki MATSUNAGA, Tatsuya HIRAHARA

Faculty of engineering, Toyama Prefectural University, Imizu, Japan

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ABSTRACT

A fast head related transfer function (HRTF) measurement system based on the Helmholtz reciprocity principle was built, and near-field HRTFs were measured using two types of miniature speakers. The HRTF measuring system can measure 36-channel HRTFs at a time using five word clock analog-to-digital convertors, which are PreSonus multi-track recording equipment. HRTFs can be measured with good signal-to-noise ratios from 250 Hz to 13 kHz using a DTEC-30008 (Knowles Electronics); the miniature speaker has a high output level in the low and the mid frequency range. HRTFs can be measured with good signal-to-noise ratios from 2 to 20 kHz using an ED-29689 (Knowles Electronics); the miniature speaker has a high output level in the high frequency range. HRTFs cannot be measured accurately below 250 or 400 Hz with either speaker because the signal-to-noise ratio of the TSP signal responses is too low. Although the sound pressure level is higher at near-field (0.2-m distance) than at far-field (1-m distance), the signal-to-noise ratio below 400 Hz is not sufficient in either case. These results indicate that the reciprocal HRTF measuring system can measure HRTFs from 400 Hz to 20 kHz quickly and accurately; the frequency range, however, depends greatly on the frequency response of the miniature speaker placed in the outer ear canal.

INTRODUCTIO

The head-related transfer function (HRTF) is an acoustic transfer function, which varies depending on the shape of the head and ear, and sound source position. The HRTF is obtained by repeated measurements of impulse responses from a speaker, placed away from the subject's head, to a microphone placed at the entrance of the subject's ear and with the speaker changing positions. This traditional HRTF measuring method is called the direct method. As the position of the speaker has to be changed, HRTF measurements with this method take a long time. Thus, there is an increase in serious measurement errors, because subjects cannot keep their own heads still during such long measurements [1].

A fast HRTF method of measurement using the Helmholtz reciprocity principal proposed by Zotkin *et al.* can overcome this problem [2]. The reciprocal method is used to measure HRTFs by placing a speaker at the ear and placing microphones around the head. This method is not commonly used because there are few miniature speakers that can be inserted into the ear canal. The low-output sound pressure level of the speakers is another issue. We built a reciprocal HRTF measurement system. We then measured horizontal HRTFs that were 10 degrees apart at distance of 1 m. We tested and confirmed that the reciprocal method could measure HRTFs well in the frequency range where the earplug speaker produces enough sound pressure.

A number of measurements of HRTFs in the far-field have been done and some of the measured HRTF data sets are available. Very few measurements of HRTFs in the near-field, however, have been reported thus far. Loudspeakers used for measuring HRTFs in the far-field cannot be used as sound sources when measuring HRTFs in the near-field. This is because the speaker cannot be regarded as a point sound source as it is too large compared with the head. A special sound source such as a spark noise source or a very small dodecahedral loudspeaker is required to measure HRTFs in the near-field [3, 4].

Another way of measuring HRTFs in the near-field is to make use of the reciprocal method. As previously described, the reciprocal HRTF measurement system uses a small speaker at the ear position and small microphones around the head. Each of the microphones is sufficiently small, thus they do not disrupt the measurement of acoustical impulse responses. The very same measurement system can be used both in far- and near-field HRTFs. This paper describes the reciprocal HRTF measurement system we built and the near-field HRTFs we measured with the system.

MEASUREMENT SYSTEM

Reciprocal HRTF measurement system

The reciprocal HRTF measurement system consists of a microphone array with fixed microphone sockets 10 degrees apart and an earplug speaker inserted into a dummy-head's ear canal (Figure 1(a)). The microphone array consists of a circular piano wire (1.5-mm diameter) with a radius of 0.2 m and 36 microphones. The microphones were bound to the piano wire with vinyl covered wire, and arranged in a circle with a 0.2-m radius, as shown in Figure 1(b). A high-sensitivity small electret condenser microphone (Primo, EM133) was used as the system's microphone. Miniature speaker (Knowles Electronics, DTEC-30008 or ED-29689) was used as the earplug speaker. The speaker was embedded in a silicon impression material, as shown in Figure 1(c). The dummy-head was an epoxy-based resin made in the shape of a human's with a rapid prototyping system and filled with an acoustic absorbent [5].

The following electroacoustic equipment was used in the measurement system (Figure 2). The time-stretched pulse (TSP) signal was digital-to-analog converted with a USB-audio interface (EDIROL, UA-101), then fed to the earplug speaker through a headphone amplifier (audio-technica, AT-HA20). The TSP response signals received by the microphones were amplified by 33 dB (audio-technica, AT-MA2), then fed to the analog-to-digital converters (PreSonus, DIGIMAX FS) connected to a FireWire-audio interface (PreSonus, FireStudio Lightpipe). The command to start recording was sent from PC1 to PC2 and 3 using TCP/IP. A reference signal was put into the analog-to-digital convertors 3 and 4 to adjust the time of recording. A word clock was used to synchronize the analog-to-digital convertors and the FireWire-audio interfaces.

The sampling frequency of the analog-to-digital and the digital-to-analog converters was 48 kHz. The TSP signal was a 65,536-sample-long optimized Aoshima's time-stretched pulse (OATSP) [6]. The measurement room was a sound-proof room (3.24×3.54×2.30 m). The A-weighting level of background noise was 16.5 dB. As one measurement session consisted of the TSP signal repeated 20 times, the total measurement time was about 30 s.

Earplug speakers

The miniature speakers, DTEC-30008 and ED-29689, were balanced-armature electro-acoustics transducers. The transducers were originally designed for the driver-units of insert-type earphones. Thus, they did not generate large sound pressure levels in open-air space. The DTEC-30008 was 7.87×4.09×5.61 mm and the input impedance was 39 Ω at 1 kHz. The ED-29689 was 6.32×4.31×2.99 mm and the input impedance was 10.2 Ω at 1 kHz.

Figure 3 shows the frontal frequency responses of the two speakers and noise-floor spectrum level. The red and blue thick lines plot the responses of the DTEC-30008 and ED-29689 measured with a microphone placed at a distance 0.2 m from the front. The dotted lines are those measured at a distance 1 m from the front. The sound pressure level produced by the speakers was about 12 dB more at the distance of 0.2 m than that at 1 m. Both speakers produced larger sound pressures than the noise-floor level except for the low frequency range. The signal-to-noise (SNR) of the DTEC-30008 was over 20 dB above 250 Hz for the 0.2-m distance and above 500 Hz for the 1-m distance. It produced sufficient sound pressure in the higher-frequency range for both distances. The SNR of the ED-29689 was over 20 dB above 400 Hz for the 0.2-m distance and 700 Hz for the 1-m distance. It produced a higher sound pressure than the DTEC-30008 in the higher-frequency range for both distances. The DTEC-30008 had a preference for low frequencies and the ED-29689 had a preference for high frequencies.

Figure 4 shows variations in frequency responses for 12 horizontal directions that are 30-degree apart. Both speakers were omnidirectional below 8 kHz but not omnidirectional above 8 kHz. They radiated more intense sound from their front than their rear. The DTEC-30008 had several deep notches in the frequency responses at certain angles. A deep notch appeared at 13 kHz in a rear position response. A deep notch also appeared around 16 to 17 kHz in several frontal position responses. This directivity of radiation by speakers could adversely affect HRTF measurements.

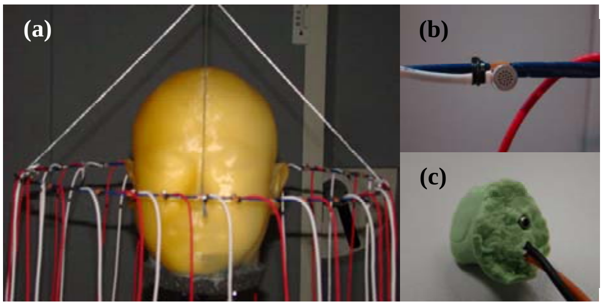

Figure 1: Reciprocal system for HRTF measurement (a) Overview of system, (b) Close up of microphone, and (c) earplug speaker.

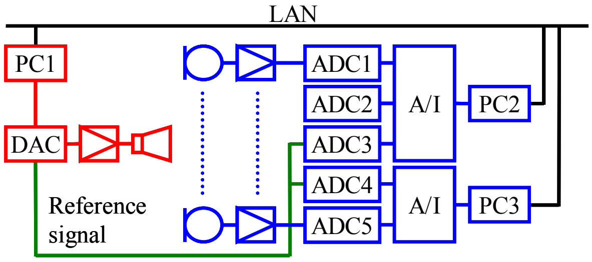

Figure 2: Block diagram of electroacoustic equipment.

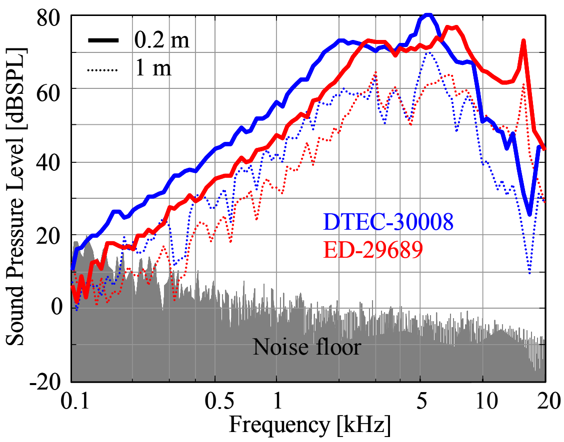

Figure 3: Frequency responses of earplug speaker in near-field.

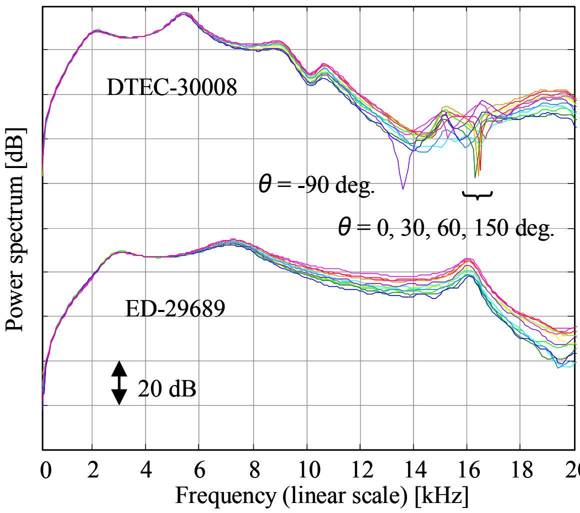

Figure 4: 12-direction (30-degrees apart) frequency responses of two miniature speakers in horizontal plane.

RESULT

Figure 5 has typical examples of near-field horizontal HRTF contour patterns measured with the reciprocal method using (a) DTEC-30008 and (b) ED-29689 miniature speakers. Figure 6 has typical examples of far-field horizontal HRTF contour patterns measured with the reciprocal method using (a) DTEC-30008 and (b) ED-29689 miniature speakers.

The near-field and far-field HRTF contour patterns measured with DTEC-30008 have a familiar horizontal HRTF contour pattern. The HRTF spectra have peaks on the ipsilateral side (left side) and notches on the contralateral side (right side). The notch frequencies vary according to the azimuthal angle. They are very similar to HRTFs measured with the conventional direct method or numerically computed HRTFs [7]. There are, however, several spurious spectral peaks and notches in the low frequency ranges.

HRTF spectra should be flat around 0 dB in the low frequency range, as the head has no effect due to the long wavelength compared to the size of the head. Thus, the spectral peaks and notches that appeared below 250 Hz in the near-field HRTF contour pattern (Figure 5(a)) and those that appeared below 500 Hz in the far-field HRTF contour pattern (Figure 6(a)) should be measurement errors. In the same way, the spectral peaks and notches that appeared below 400 Hz in the near-field HRTF contour pattern (Figure 5(b)) and below 700 Hz in the far-field HRTF contour pattern (Figure 6(b)) should be measurement errors.

In addition, spectral coloration can be seen in the mid frequency range, i.e. 400 Hz to 2 kHz, of the HRTF contour patterns measured with the ED-29689 miniature speaker (Figures 5(b) and 6(b)). Such spectral coloration is not seen in the HRTF contour pattern measured with the DTEC-30008 miniature speaker. Thus, there should have been some acoustical reflection that influenced the HRTF measurements with ED-29689.

Further, there are several spurious spectral peaks in the high frequency range around 13-17 kHz in the HRTF contour patterns measured with the DTEC-30008 miniature speaker (Figures 5(a) and 6(a)). The spectral peaks have anomalies in amplitude and appear at certain azimuthal angles. Such spectral peaks cannot be seen in the HRTF contour pattern measured with the ED-29689 miniature speaker. Thus, there should have been some acoustical anomalies that influenced the HRTF measurements with DTEC-3008.

DISCUSSION

As seen in Figures 5 and 6, the near-field HRTFs could be measured better with the reciprocal method than the far-field HRTFs. The closer the distance between the speaker and the microphones, the more intense the sound pressure the TSP signal. However, the measured near-field HRTFs still had band-width problems. The effective band-width of the HRTFs was limited by that of the miniature speaker used in the measurements.

When the DTEC-30008 miniature speaker that had a preference for low frequencies was used as the earplug speaker, the near-field HRTF could be measured without error from 250 Hz to 13 kHz. Below 250 Hz, the low SNR of the received TSP signal affected the measurements of acoustical impulse responses. Above 13 kHz, the speaker response suffered from the directivity of radiation and deep notches appeared in the rear and frontal position responses. These notches turned out to be spectral peaks due to the normalizing procedure, where the spectrum of the TSP response received at the entrance of the ear was divided by that at the center position of the head. When the ED-29689 miniature speaker with the preference for high frequencies was used as the earplug speaker, the near-field HRTF can be measured without error from 2 kHz to 20 kHz. Below 400 Hz, the low SNR of the received TSP signal affected the measurements of acoustical impulse responses. From 400 Hz to 2 kHz, coloration by an unknown source modulated HRTFs. The microphone array may have

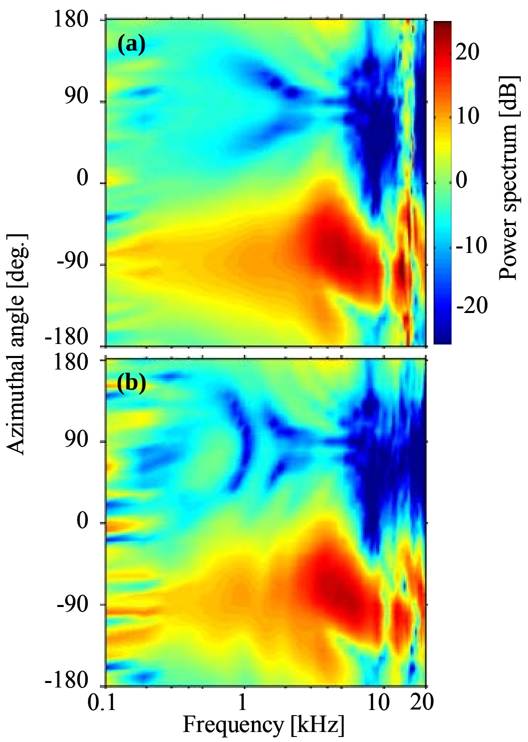

Figure 5: Near-field (0.2-m distance) HRTF contour patterns of left ear of dummy-head. (a) Using DTEC-30008 and (b) using ED-29689.

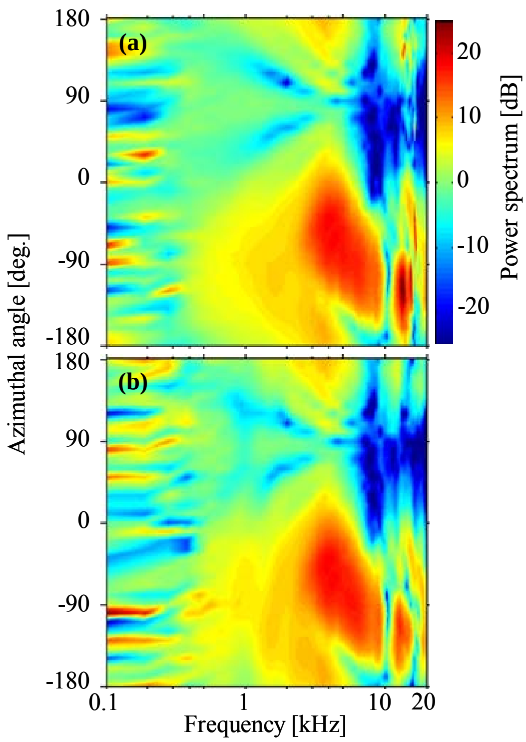

Figure 6: Far-field (1-m distance) HRTF contour patterns of left ear of dummy-head. (a) Using DTEC-30008 and (b) using ED-29689.

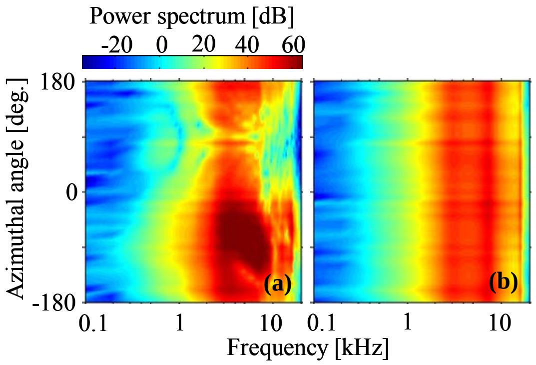

Figure 7: Near-field transfer function contour patterns of (a) H_{Ear} and (b) H_{Center} measured with ED-29689.

caused reflection. In Figure 7(a), we can see the impulse-response-spectrum contour pattern with the head, i.e., head-related impulse response spectra H_{Ear} and in (b) those without the head, i.e., head-center impulse response spectra H_{Center} at the 0.2-m distance. Figure 5 (b) was obtained by dividing Figure 7(a) by Figure 7(b) in the complex frequency domain, H_{Ear}/ H_{Center}. Although the same microphone array was used to measure both H_{Ear} and H_{Center}, coloration is only seen in H_{Ear} but not in H_{Center}. Consequently, the microphone array did not cause the reflection. The horizontal stripes in H_{Ear} and H_{Center} are due to differences in the microphone sensitivity and microphone amplifier gain for each channel. We need to search for the cause of coloration in future studies.

Usually, HRTFs have been measured over a wide frequency range from several hundred Hz to the Nyquist frequency, i.e., half the system sampling frequency. Even in the HRTF measurements with the direct method, accurate measurements of acoustical impulse responses in the high frequency range are not very easy as small geometrical differences affect the results. Subjects can hardly continue to hold their head position still during long HRTF measurement sessions [8]. Is such a wide frequency range necessary in practical use?

The physical acoustic indicated that the HRTF spectra should be flat around 0 dB at low frequency. There is no need to measure HRTF accurately below several hundred hertz. The psychophysical acoustics indicated that mid frequency spectral components are important to localize sound sources. Morimoto *et al.* reported that spectral components from 4.8 to 9.6 kHz are necessary to carry out sound localization in the median plane [9]. Morikawa *et al.* found that spectral components from 2 to 12 kHz are necessary to conduct sound localization in the horizontal plane [10]. There seems to be no need to measure HRTF accurately above a dozen kilohertz and below a few kilohertz.

The reciprocal system for HRTF measurements we built could measure 36 channel HRTFs in 30 s. The measuring time theoretically does not depend on the number of channels. The more microphones and analog-to-digital converters we have, the more channels of HRTF can be measured in 30 s. These very fast HRTF measurements can avoid the problems with conventional HRTF measurements systems using the direct method. We are now free of measurement error caused by subject head movements and changes in temperature and humidity during measurements. This is the greatest advantage of reciprocal HRTF measurements. The narrow-frequency range of the earplug speaker is the most serious issue with reciprocal HRTF measurements. We need to search for very small loudspeakers that can produce sufficient sound pressure over a wider frequency range in future work.

CONCLUSION

We measured near-field HRTFs with the reciprocal method using two types of miniature speakers. We obtained six main results.

1. The near-field HRTFs could be measured better with the reciprocal method than with far-field HRTFs.
2. HRTFs could be measured better with a good SNR from 250 Hz to 13 kHz using the DTEC-30008, which is a miniature speaker with a preference for low frequencies. The directivity of the DTEC-30008 was the cause of the spurious spectral peak that appears in HRTFs above 13 kHz.
3. HRTFs could be measured with a good SNR from 2 to 20 kHz using the ED-29689, which is a miniature speaker with a preference for high frequencies. The cause of coloration that appeared in the HRTFs from 400 Hz to 2 kHz remains unknown.
4. The reciprocal measured HRTF involved large measurement errors below 250 or 400 Hz in both speakers because of the low SNR of the TSP signal. The SNR of the TSP signal received by microphones should be 20 dB or more to measure HRTFs without errors.
5. The effective frequency range of the reciprocal HRTF measurements depended greatly on the frequency response of the miniature speaker used as the earplug speaker.
6. The effective frequency range of the reciprocally measured HRTFs was not very wide but it was sufficient to carry out sound localization in practice.

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