

Sound collection effect of a pinna of an artificial head

Kiyoshi Sugiyama*

Faculty of Engineering, Tokyo Institute of Polytechnics,
Iiyama 1583, Atsugi, 243-0297 Japan

(Received 24 December 2002, Accepted for publication 27 February 2003)

Keywords: HRTF, Artificial head, Pinna, Sound collection effect, Diffraction coefficient

PACS number: 43.20.EI [DOI: 10.1250/ast.24.311]

1. Introduction

It is considered essential that the indoor acoustic field and characteristics of the acoustic field at the point of hearing should be understood before designing a high-quality voice teleconference system.

Head related transfer function (HRTF) expresses acoustic characteristics corresponding the sound source position. HRTF is defined as the ratio of the sound pressure in the eardrum to that of the free field at the center of the head [1]. There are many reports of the measurement of HRTF using human subjects [2,3], but it is considered very difficult to measure the sound pressure in the eardrum. Many artificial heads are proposed, and HRTFs of the artificial heads are compared with HRTFs of human subjects.

If the HRTF is shown as a function of the effect of the

pinna, the ear canal and the body including head and torso, each effect on HRTF can be discussed separately. If the pinna of an artificial head is removed and/or if the ear canal is blocked, HRTFs can be divided into three parts corresponding to the pinna, the ear canal and the body [4].

This report discusses the effect of pinna as a part of HRTF. The sound collection effect of the pinna is defined as the ratio of the sound pressure in the eardrum of an artificial head before removing the pinna to that after removing the pinna. This effect was calculated and is discussed as a function of the direction of sound incidence, in this paper.

2. Sound collection effect of pinna

HRTF is defined by the following equation in this paper.

$$\begin{aligned} \text{HRTF} &= \frac{\text{sound pressure in the eardrum}}{\text{free field sound pressure at the center of the head}}, \\ &= \frac{\text{source} \times \text{speaker} \times \text{space propagation} \times \text{pinna} \times \text{ear canal} \times \text{mic}}{\text{source} \times \text{speaker} \times \text{free field} \times \text{mic}}, \\ &= \frac{\text{space propagation} \times \text{pinna} \times \text{ear canal}}{\text{free field}}. \end{aligned} \quad (1)$$

The “space propagation” in Eq. (1) means the component corresponding to the sound propagation from the speaker to the entrance of ear canal of artificial head with pinna. Eq. (1) can be written as Eq. (2) to explicitly show the conditions of the measurement procedure.

$$\begin{aligned} \text{HRTF} &= \frac{\text{space propagation} \times \text{pinna} \times \text{ear canal}}{\text{free field}}, \\ &= \frac{\text{artificial head with pinna}}{\text{artificial head without pinna}} \times \frac{\text{artificial head without pinna}}{\text{artificial head blocked ear canal}}, \\ &\quad \times \frac{\text{artificial head blocked ear canal}}{\text{free field}}. \end{aligned} \quad (2)$$

The first term denotes the sound collection effect of pinna under the condition of existence of pinna. The second term denotes the transmission ratio of the sound pressure in the eardrum of an artificial head without pinna to that of the entrance of a blocked ear canal [5]. The third term denotes the diffraction coefficients at the entrance of a blocked ear canal of an artificial head without pinna. Measured values of these coefficients are in good agreement with calculated values of a

2-sphere model in which the head and torso are approximated by spheres [6,7].

3. Measurements

HATS (Head And Torso Simulator, B&K Co. Type 4128) was used as the artificial head. Figure 1 shows the side view of HATS before and after removing its pinna. The distance from the front of the speaker to the center of the head of HATS is 1.5 m. The axis of rotation of HATS is the z axis, the incidence is given by the angle between the z axis and the

*e-mail: sugiyama@image.t-kougei.ac.jp

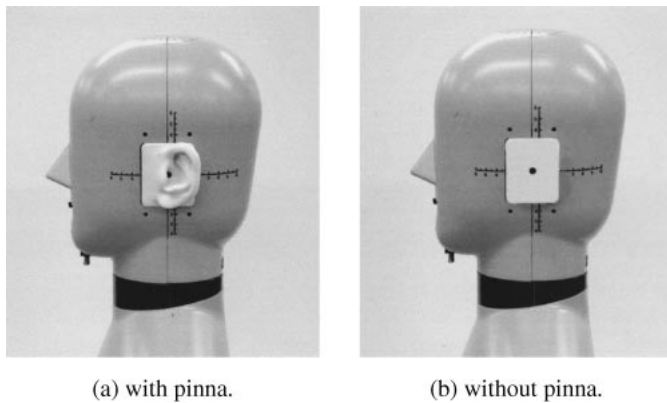


Fig. 1 Side view of HATS.

direction of sound incidence as a function of the zenith angle (θ) and azimuth angle (ψ). However the 0 degree azimuth angle is the direction of nose of HATS. A 14-th order MLS with the sampling frequency of 32 kHz was used as the source signal. This signal and the received signals were transformed to frequency spectra by use of FFT. Moreover, for the AD and DA conversions, low-pass filters with the cut-off frequency of 12 kHz were used as the anti-alias filters [6].

4. Results of measurements

In the measurements, the direction of the azimuth angle was adjusted by rotating the HATS counterclockwise.

In Fig. 2, the measured values of the left ear of HATS with and without pinna are shown by the line with open circles and that with crosses, respectively, for the case of $\theta = 90$ [deg.] and $\psi = 270$ [deg.]. Also the difference between with and without pinna shown by the solid line in the same figure denotes the sound collection effect of pinna. In the low frequency range up to 3 kHz, the sound collection effect is small and about 0 dB. In the range from 3 to 4 kHz, a negative collecting effect is observed and in the range from 4

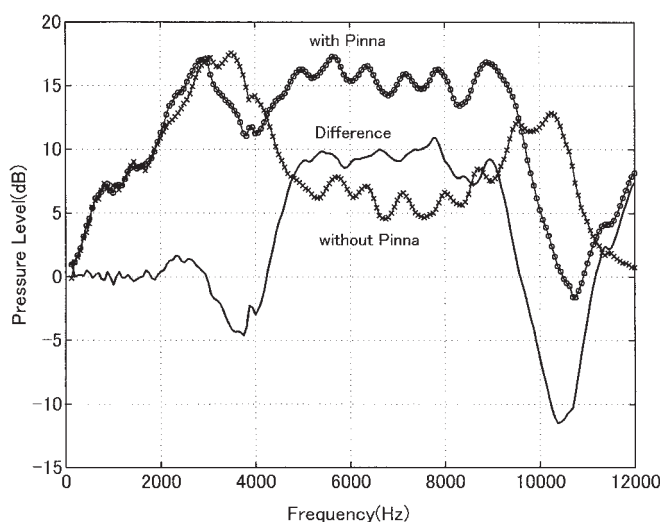


Fig. 2 Sound collection characteristics of pinna (Left ear, incident angle; zenith angle $\theta = 90$ [deg.], azimuth angle $\psi = 270$ [deg.]).

to 9 kHz, a positive effect is observed. In particular, in the range from 5 to 9 kHz, this effect reaches about 10 dB. In the range from 9 to 11 kHz, negative values are again observed.

Figures 3(a)–(c) show the sound collection effect of the pinna. Each panel of this figure corresponds to a certain azimuth angle. The solid lines and dashed lines show the values with a distance of 1.5 m and that of 1 m, respectively when $\theta = 90$ [deg.]. The plots with crosses, open circles and triangles are for $\theta = 30, 60$ and 120 [deg.], respectively. As the difference between solid and dashed lines is small, it is considered that the distance between the speaker and HATS does not contribute much to the sound collection effect.

In the case of Fig. 3(a) and (b), the sound collection effect is large when ψ is small. In particular, in the case of $\psi = 180$ [deg.] and $\psi = 120$ [deg.], the gain of the sound collection effect is not observed.

In Fig. 3(c), when $\psi = 270$ [deg.] and $\theta = 90$ [deg.], the sound collection effect is the largest and is almost constant at about 10 dB in the range from 4 to 9 kHz. When the zenith angle of the direction of sound incidence is greater or smaller than $\theta = 90$ [deg.], the gain is smaller than that at $\theta = 90$ [deg.].

5. Estimation of HRTF

It is considered that the product of the first term and the third term of Eq. (2) means a blocked ear canal HRTF. In the case of binaural reproduction by use of HATS, we listen to through the ear canal of HATS and that of the listener. Accordingly, the second term of Eq. (2) is doubly counted. Therefore, the product of the first term and the third term of Eq. (2) without the second term is suitable for a practical use and is thus considered here.

The blocked ear canal HRTFs calculated as the product of the first and third terms are shown in Fig. 4 with solid lines. In the Figure, the first and the third terms are also shown with dashed lines (Pinna) and dash-dot lines (Body), respectively. Each panel corresponds to different azimuth angles ψ of 0 (front), 180 (rear) and 270 (contralateral) [deg.]. In the case of $\psi = 0$ [deg.] as shown in Fig. 4(a), the blocked ear canal HRTF is nearly 0 dB up to 1 kHz, is positive up to 7.5 kHz, is negative in the range from 7.5 to 10 kHz and is positive again in the range from 10 to 12 kHz.

In the case of $\psi = 180$ [deg.] as shown in Fig. 4(b), the blocked ear canal HRTF is generally smaller than that for frontal direction (Fig. 4(a)). The difference between $\theta = 0$ and 180 [deg.] shows a directional dependence of HRTFs. The third term (shown by the dash-dot line) of $\psi = 180$ [deg.] is similar to that of 0 [deg.], but the first term (shown by dashed line) of $\psi = 180$ [deg.] is smaller than that of 0 [deg.]. This means that the sound collection effect of pinna may contribute to the front-back judgement of the direction of sound incidence.

In the case of the contralateral direction, i.e. when the direction of sound incidence is opposite to the ear of the HATS ($\psi = 270$ [deg.]), the blocked ear canal HRTF has a gain of about from 2 to 7 dB in the low frequency range up to 4 kHz as shown in Fig. 4(c). This gain shows the third term of the diffraction coefficients of HATS without pinna. Therefore, this result shows that the sound collection effect of pinna is

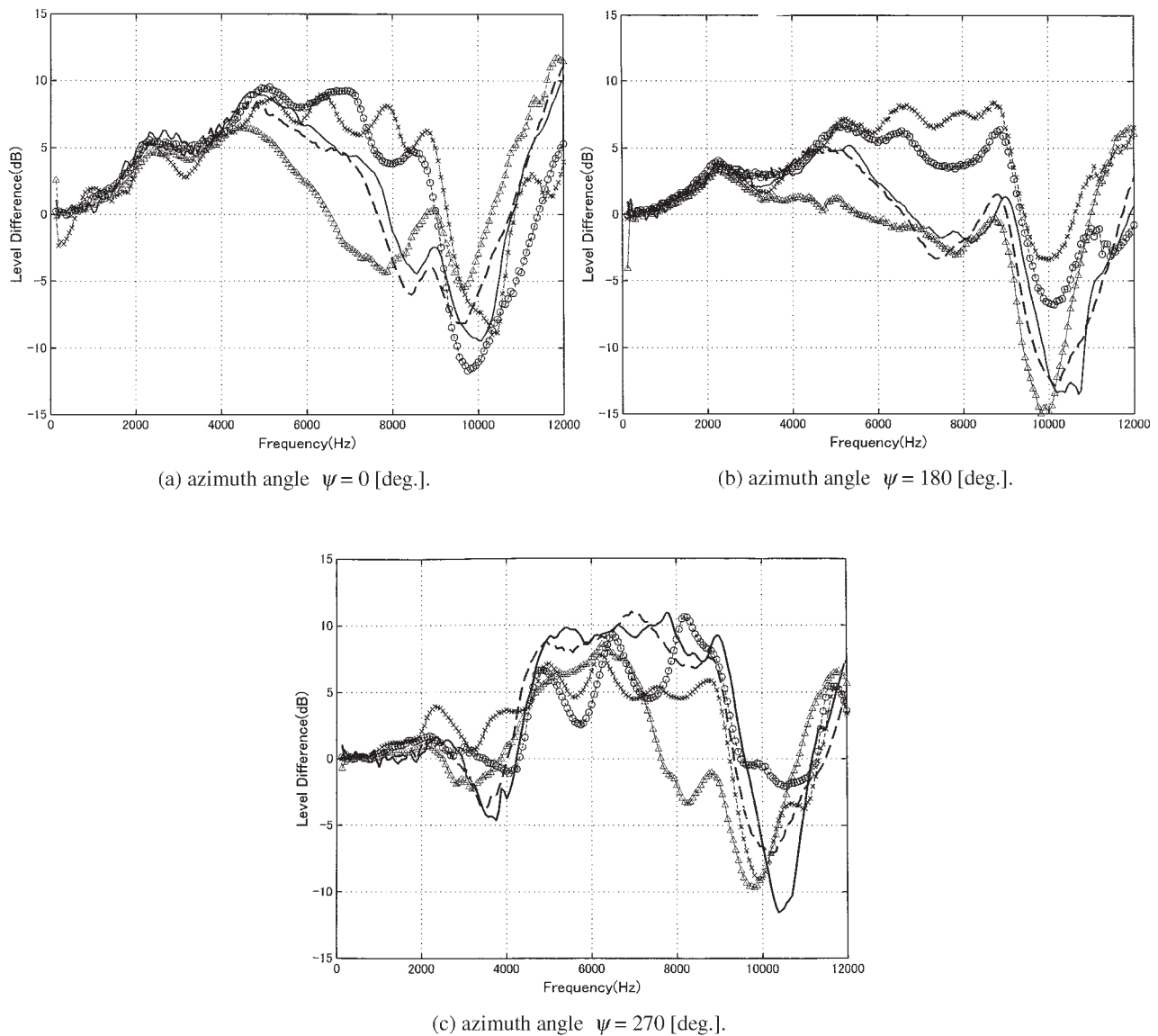


Fig. 3 Comparison of the sound collection effect with zenith angle. \times : $\theta = 30$ [deg.] \circ : $\theta = 60$ [deg.] Δ : $\theta = 120$ [deg.]. Solid line means a distance of 1.5 m and dashed line means a distance of 1 m in the case of $\theta = 90$ [deg.].

dominant above 4 kHz.

The product of the first and third term of Eq. (2) shows comparative agreement with the blocked ear canal HRTF measured in 40 human subjects by Møller [3].

6. Conclusion

To aim at expressing HRTF as a product of parts of HRTF, we tested whether the HRTF is given by the product of the sound collection effect of pinna, the transmission ratio of ear canal without pinna and the diffraction coefficients of artificial head without pinna as shown in Eq. (2). The second and third terms of Eq. (2) can be used to calculate a 2-sphere model in which the head and torso are approximated by spheres.

The first term, which is called the sound collection effect of pinna, is discussed by measurements of HATS as a function of dependence on the direction of sound incidence. The sound collection effect is negative (= loss) over the entire frequency band at 12 kHz in the range of a zenith angle (θ) from 30 to

120 [deg.]. When the speaker is placed in the horizontal plane and opposite to HATS, the sound collection effect is largest at about 10 dB, but it is 0 dB in the range under 3 kHz and is negative in the range from 3 to 4 kHz. Compared with the front and the back incidence, gain of the front incidence is larger than the back incidence, especially, the difference is large in the case of $\theta = 120$ [deg.].

In the case of binaural reproduction, the blocked ear canal HRTF which consists of the product of the first and third terms of Eq. (2) is useful. Compared with the blocked ear canal HRTF measured by HATS and in 40 human subjects [3], comparative agreement is very good. In the case of the front incidence, the sound collection effect is more dominant than the diffraction coefficients in the component of the blocked ear canal HRTF. But in the case of HATS opposite to the speaker, the diffraction coefficients is dominant under 4 kHz, and the sound collection effect is dominant in the range from 4 to 9 kHz.

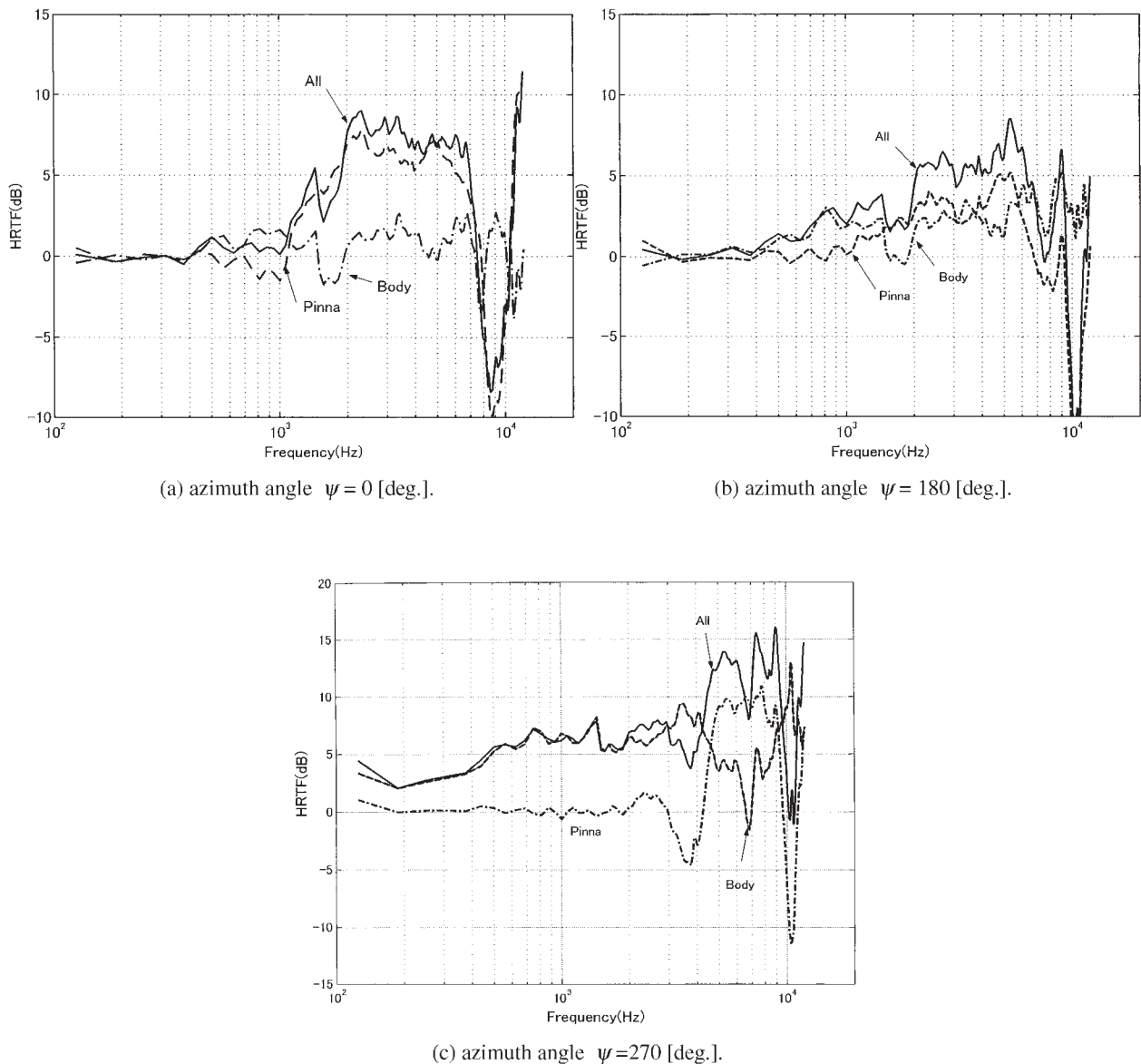


Fig. 4 Blocked ear canal HRTF of HATS.

Acknowledgement

I wish to thank members of the NTT cyberspace laboratory, especially, Dr. Masato Miyoshi of the NTT science laboratory for the use of the anechoic room and members of the image information processing laboratory of Tokyo Institute of Polytechnics for measurements.

References

- [1] J. Blauert, M. Morimoto and N. Gotoh, *Spatial Hearing* (Kajima Inst. Publishing Co., Tokyo, 1986), p. 18.
- [2] E. A. G. Shaw, "Transformation of sound pressure level from the free field to the ear-drum in the horizontal plane," *J. Acoust. Soc. Am.*, **56**, 1848–1861 (1974).
- [3] H. Møller, M. F. Sørensen, D. Hammershøi and C. B. Jensen, "Head-related transfer functions of human subjects," *J. Audio Eng. Soc.*, **43**, 300–321 (1995).
- [4] K. Sugiyama, "Influence of pinna and ear canal of the dummy head," *Tech. Rep. IEICE*, EA2000-119 (2001).
- [5] K. Sugiyama, "External ear canal of artificial head," *Tech. Rep. IEICE*, EA2001-69 (2001).
- [6] K. Sugiyama, "Sound diffraction coefficients of artificial head incident to horizontal plane," *J. Acoust. Soc. Jpn. (J)*, **58**, 745–752 (2002).
- [7] K. Sugiyama, "Diffraction coefficient of artificial head," *Tech. Rep. IEICE*, EA2002-49 (2002).