ACOUSTICAL LETTER

Transmission characteristics of ear canal of artificial head

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1. Introduction

The head related transfer function (HRTF) expresses how the acoustical characteristics change with the sound source position. HRTF is defined as the ratio of the sound pressure at the eardrum to that of the free field at the center of the head [1].

If the HRTF is shown as a function on the effect of the pinna, the ear canal, and the body including head and torso, each effect 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 [2].

In this paper, we discuss the impact of the ear canal and how it changes with the sound incidence direction. Measured values are compared with values calculated for a 2-sphere model in which the head and torso are approximated by spheres.

2. Transmission characteristics of ear canal

HRTF is defined by the following equation in this paper [2].

$$\begin{aligned} HRTF &= \frac{\textit{sound pressure in the eardrum}}{\textit{free field sound pressure at the center of the head}}, \\ &= \frac{\textit{artificial head with pinna}}{\textit{artificial head without pinna}}, \\ &\quad \times \frac{\textit{artificial head without pinna}}{\textit{artificial head blocked ear canal}}, \\ &\quad \times \frac{\textit{artificial head blocked ear canal}}{\textit{free field}}. \end{aligned} \tag{1}$$

The first term denotes the sound collection effect of the pinna [2]. The second term denotes the transmission ratio of the sound pressure in the eardrum without pinna to that of the entrance of a blocked ear canal without pinna. The third term denotes the diffraction coefficients at the entrance of a blocked ear canal of an artificial head without pinna [3].

3. Measurements

HATS (Head And Torso Simulator, B&K Co. Type 4128) was used as the artificial head. Figure 1(a) shows the side view of HATS after removing its pinna. Figure 1(b) shows sound pick up at the entrance of a blocked ear canal of HATS. 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 direction of sound incidence as a function of the zenith angle (θ) and azimuth angle (ψ). Note that the 0 degree azimuth angle is the direction of the 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 FFT. Moreover, in AD and DA conversions, low-pass filters with the cut-off frequency of 12 kHz were used as the anti-alias filters.

4. Results of measurements

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

In Fig. 2, the measured values of the right ear of HATS without pinna and diffraction coefficients are shown by the line with open circles and that with crosses, respectively, for the case of $\theta = 90$ [deg.] and $\psi = 0$ [deg.]. Also the difference between those are shown by the solid line in the same figure. This difference denotes the transmission characteristics of the ear canal of the artificial head. The peaks at the frequency of about 3 kHz and 9 kHz indicate the resonance of the length of the ear canal.

Figures 3(a)–(c) show the cases of azimuth angles (ψ) of 0, 90, and 180 degrees, respectively. In these figures, the measured values of the transmission characteristics of right ear of HATS are shown by the line with open circles, crosses and triangles for the zenith angles (θ) of 60, 90, and 120 [deg.], respectively.

5. Calculation of transmission characteristics

Figure 4 shows the artificial head model in which the head and torso are approximated by spheres.

If a solid body which vibrates a piston at one area is put in the sound field, boundary conditions are given by the next equation [4],

$$\frac{\partial \phi_i}{\partial n} + \frac{\partial \phi_{1s}}{\partial n} = \begin{cases} -V\cos\Theta & \text{[on the surface } S] \\ 0 & \text{[on the surface } S_0 \text{ except } S] \end{cases} \tag{2}$$

where ϕ_i, ϕ_{1s} mean the velocity potential of incident wave and that of scattering wave from the body, respectively, n means the normal component from the surface of the body, V means the amplitude of the velocity of a piston, Θ means the angle between n and the direction of V, S_0 means the surface of the solid body, and S means the area of the piston vibration. The velocity potential of scattering wave ϕ_{1s} is given by the sum of two velocity potentials. One is the velocity potential of scattering wave ϕ_{2s} when the body is placed in the free field of

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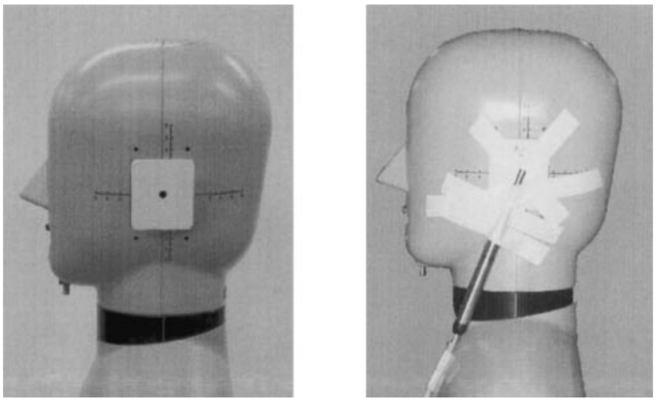


(a) without pinna. (b) blocked ear canal.

Fig. 1 Side view of HATS.

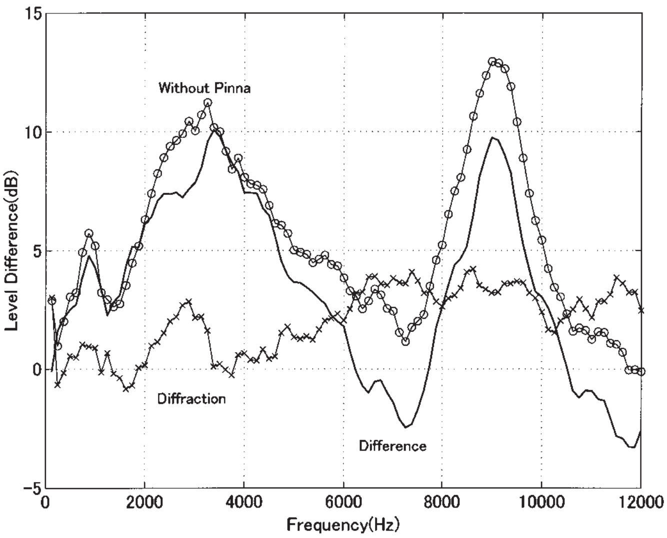


Fig. 2 Transmission characteristics of ear canal (Right ear, incident angle; zenith angle $\theta = 90$ [deg.], azimuth angle $\psi = 0$ [deg.]).

sound. In this case, the normal component of the velocity on the body surface equals to zero because it does not move. Thus the boundary condition can be written

$$\frac{\partial\phi_{\mathrm{i}}}{\partial n} + \frac{\partial\phi_{2\mathrm{s}}}{\partial n} = 0 \quad \text{[on the surface } S_0\text{]}. \tag{3}$$

Diffraction coefficient at the point on the surface S_0 is given by

$$D = \frac{\phi_{\mathrm{i}} + \phi_{2\mathrm{s}}}{\phi_{\mathrm{i}}}. \tag{4}$$

The force on the surface S is given by the next equation,

$$F_0 = i\omega\rho \int_S (\phi_{\mathrm{i}} + \phi_{2\mathrm{s}}) \cos\Theta dS \tag{5}$$

where ω is the angular frequency, and ρ means the density of the air. Another velocity potential of the scattering wave is given by the velocity potential $\phi_{3\mathrm{s}}$ when the solid body which vibrates a piston at one area is placed in the sound field without incident wave. In this case, the boundary condition is given by the next equation,

$$\frac{\partial\phi_{3\mathrm{s}}}{\partial n} = \begin{cases} -V\cos\Theta & \text{[on the surface } S\text{]} \\ 0 & \text{[on the surface } S_0 \text{ except } S\text{]} \end{cases}. \tag{6}$$

The force on the surface S is given by the next equation,

$$F_1 = i\omega\rho \int_S \phi_{3\mathrm{s}} \cos\Theta dS. \tag{7}$$

The radiation impedance of the piston (Z_{r}) is obtained by the ratio of the force on the surface S and the velocity of the piston,

$$Z_{\mathrm{r}} = \frac{F_1}{V} = \frac{i\omega\rho}{V} \int_S \phi_{3\mathrm{s}} \cos\Theta dS. \tag{8}$$

The next relation is obtained from Eqs. (2), (3) and (6),

$$\phi_{1\mathrm{s}} = \phi_{2\mathrm{s}} + \phi_{3\mathrm{s}}. \tag{9}$$

The velocity of a piston vibration is given by

$$V = -\frac{i\omega\rho}{Z_{\mathrm{a}}} \int_S (\phi_{\mathrm{i}} + \phi_{2\mathrm{s}} + \phi_{3\mathrm{s}}) \cos\Theta dS \tag{10}$$

where Z_{a} means the mechanical impedance of the piston. From Eqs. (5) and (8), the velocity V is given by the next equations,

$$V = \frac{F_0}{Z_{\mathrm{r}} + Z_{\mathrm{a}}} \tag{11}$$

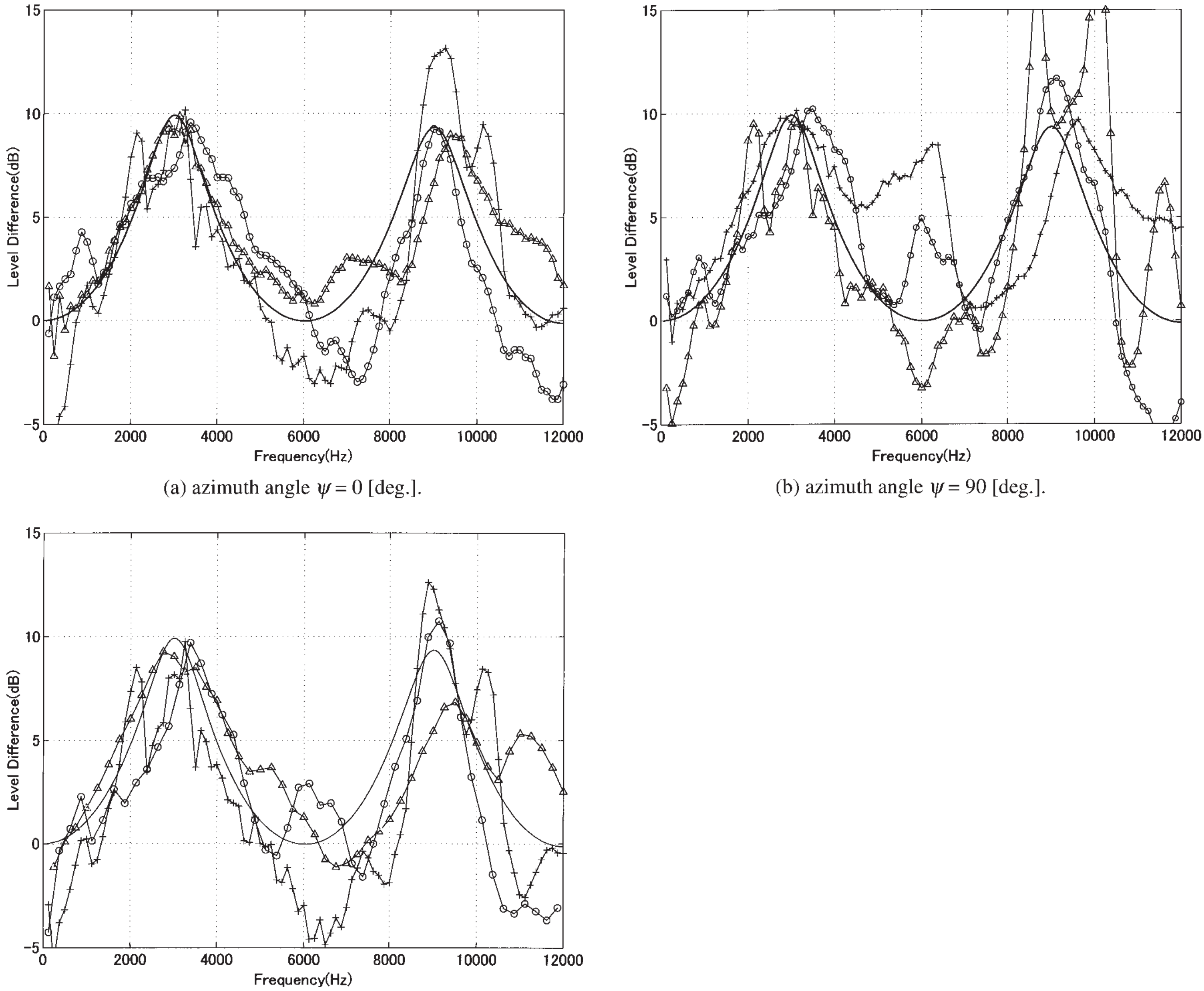
Figure 5 shows the equivalent circuit of ear canal of the artificial head obtained from Eq. (11), where Z_{a} means the acoustic impedance of a ear canal (sound pressure/volume velocity), which replaces the mechanical impedance of the piston (force/velocity). In this case, the ear canal is equivalent to an acoustical pipe terminated with an acoustical resistance R, which consists of waste threads in front of the microphone in order to damp the resonance of the pipe,

$$\begin{bmatrix} Df_0 \\ V \end{bmatrix} = \begin{bmatrix} 1 & Z_{\mathrm{r}} \\ 0 & 1 \end{bmatrix} \begin{bmatrix} S & 0 \\ 0 & 1/S \end{bmatrix} \begin{bmatrix} \cos kl & iZ_0 \sin kl \\ i/Z_0 \sin kl & \cos kl \end{bmatrix} \begin{bmatrix} p_{\mathrm{out}} \\ U_{\mathrm{out}} \end{bmatrix}, \tag{12}$$

where D given by Eq. (4) means the diffraction coefficient on the entrance of blocked ear canal of the artificial head without a pinna, f_0 means the force of the incident wave, l is the length of the ear canal, Z_0 ($= \rho c/S$) is the characteristics resistance, p_{out}, U_{out} indicate the sound pressure and volume velocity, respectively. Then, the second part of Eq. (1) is

$$\begin{aligned} HRTF(2) &= 20\log_{10}\frac{p_{\mathrm{out}}/p_0}{D} \\ &= -20\log_{10}\left\{\left[1 + \frac{Z_{\mathrm{r}}'}{R_{\mathrm{T}}}\right]\cos kl + i\left[Z_{\mathrm{r}}' + \frac{1}{R_{\mathrm{T}}}\right]\sin kl\right\}(\mathrm{dB}), \end{aligned} \tag{13}$$

where $p_0 = i\omega\rho\phi_{\mathrm{i}}$, $R_{\mathrm{T}} = SR/\rho c$, $Z_{\mathrm{r}}' = Z_{\mathrm{r}}/\rho cS$. The calculated values are obtained, using a_1 (radius of the sphere 1) = 8.85 cm, a_2 (radius of the sphere 2) = 15 cm, a_{12} (distance between the center of sphere 1 and 2) = 28.85 cm, d (diameter of the acoustical pipe) = 7 mm, l (length of the acoustical pipe) = 2.8 cm, and $R_{\mathrm{T}} = \sqrt{10}$. However, Z_{r} is the



(a) azimuth angle $\psi = 0$ [deg.].

(b) azimuth angle $\psi = 90$ [deg.].

(c) azimuth angle $\psi = 180$ [deg.].

Fig. 3 Comparison of the transmission characteristics with zenith angle. $+$: $\theta = 60$ [deg.], ○: $\theta = 90$ [deg.], △: $\theta = 120$ [deg.]. Solid line means the calculated values.

radiation impedance of sphere 1 only [4].

At the first, the diffraction coefficients D and the radiation impedance Z_r are calculated from Eqs. (4) and (8), and the force F_0 by the incident wave on the entrance of the acoustic pipe is calculated from Eq. (5). Next, the velocity V is calculated from Eq. (11). Then, p_{out} is calculated from Eq. (12).

In Fig. 6, the calculated values of Eq. (13) are shown by the line with open circles and that with crosses, respectively, for the case of p_{out}/p_0 and D. Then, the difference between p_{out}/p_0 and D is shown by the solid line.

6. Disscussion

In Figs. 3, a solid line shows the calculated values of Eq. (13) for the case of $\psi = 0$, 90 and 180 [deg]. The solid line coincides with the measured values for 10 dB at the frequency of about 3 kHz which shows the peak values.

The peak values of measured values at the frequencies of about 3 kHz and 9 kHz agree with calculated line, but the dip values of measured values at the frequency of about 6 kHz do not agree with the calculated line. These mismatches are considered by the directional characteristics of a microphone used the measurement of the diffraction coefficients shown in Fig. 1(b).

7. Conclusion

We checked whether the overall HRTF can be derived from the product of the sound collection effect of pinna, the transmission ratio of the ear canal without a pinna and the diffraction coefficients of an artificial head without pinna (see Eq. (1)). In this report, the second term, which is called the transmission characteristics, is assessed by HATS measurements and the calculation of 2-sphere model in which the head and torso are approximated by spheres as a function of the

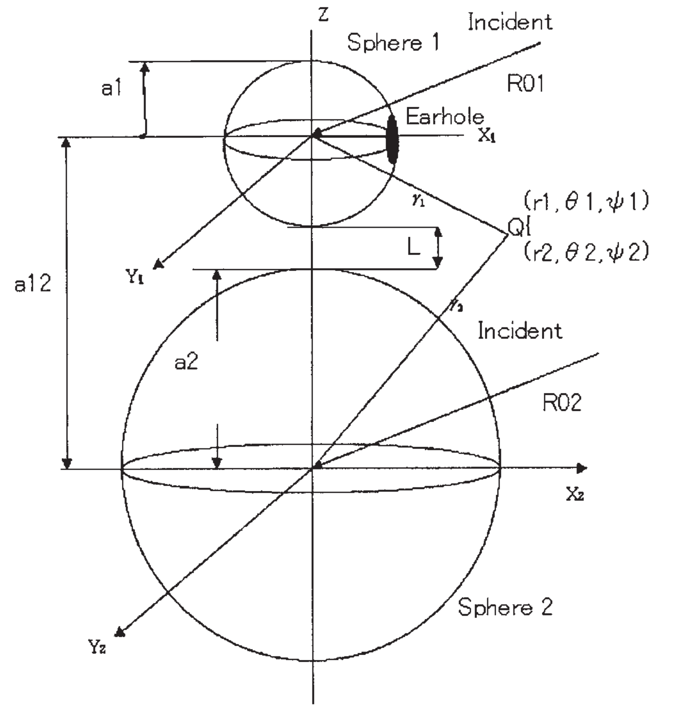


Fig. 4 2-sphere model.

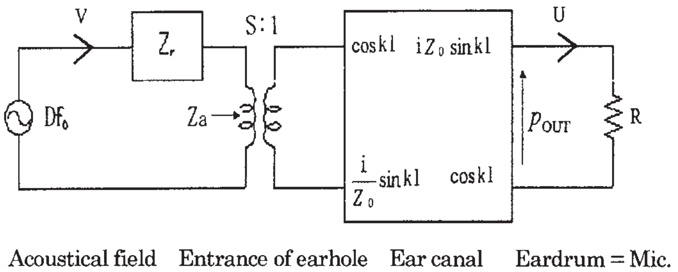


Fig. 5 Equivalent circuit of ear canal of artificial head.

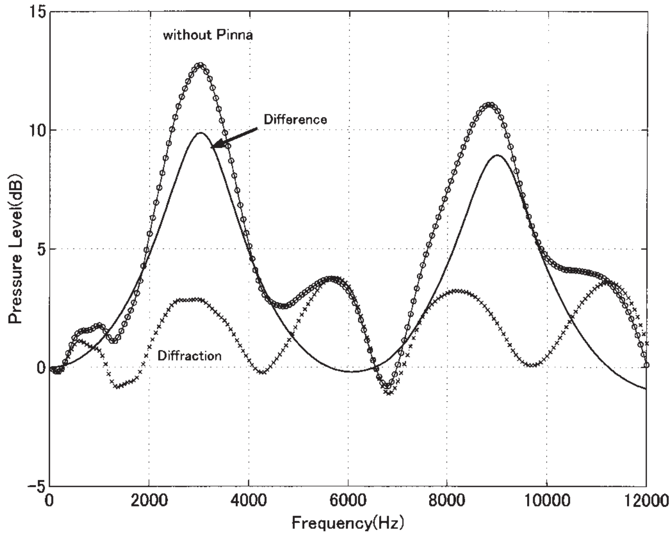


Fig. 6 Calculated values of the transmission characteristics of ear canal (Right ear, incident angle; zenith angle $\theta = 90$ [deg.], azimuth angle $\psi = 0$ [deg.]).

direction of sound incidence. As the radiation impedance (Z_r) does not include the part of the sound incidence direction in Eq. (13), we found that the transmission characteristics of the ear canal are not affected by the sound incidence direction [5].

In the case of binaural reproduction assessment using an artificial head, the sound perceived by the listener is determined consists of the transmission characteristics of the ear canal of the artificial head and that of listener. If the transmission characteristics of the ear canal of the artificial head are equal to that of the human subject, we can listen the characteristics subtracted from the transmission characteristics of the ear canal of the artificial head in the case of binaural reproduction.

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