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SIMULATING EXTERNAL-EAR TRANSFER FUNCTIONS

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It is known that current standard ear simulators as used in standard dummy heads (or used separately) can only simulate acoustical responses of typical human ears below 10 kHz due to difficulties in constructing accurate acoustic simulators of eardrum impedance at higher frequencies. Those ear simulators are not satisfactory when it is desired to simulate realistic sound pressure responses over the full range of audible frequencies at the eardrums of average ears, or those of non-typical ears. Considering that digital acoustic signals have been widely used in the analysis of acoustic systems, without constructing various acoustic ear simulators, this paper presents a new method of constructing an analytical digital filter to simulate the acoustic transfer function of external ears given the radiation impedance of the pinna, the eardrum impedance and the ear canal cross-sectional area function. The filter is needed to synthesize the sound pressure response at the eardrum of a listener given the sound pressure signal obtained at the entrance to the ear canal. It is also needed to simulate the transfer functions of external ears wearing a device (such as an earphone, insert, headphone or hearing aids) to help understand the combined effect of the device and the ear canal and improve the design of the audio systems. The accuracy of the simulation is evaluated by comparing it with the transfer function measured on a standard ear simulator, and it is found that they agree with each other very well.

1. Introduction

Ear simulators are used in many applications. Some are used to simulate the acoustic load to device such as telephones, hearing aids, headphones, earphones, inserts, or ear buds; while some are installed in dummy heads to simulate the sound pressure signals received at human eardrums in sound fields. A standard ear simulator consists of a main cavity, a microphone and acoustic networks (cavities and slits) to simulate the average ear canal and eardrum acoustic impedance. Unfortunately however, current standard ear simulators cannot simulate average human ears above 10 kHz as indicated in [1]. Moreover, current ear simulators use invariable acoustic networks to simulate average ear canals and eardrums [2], and cannot accurately produce the sound pressure response of human ears with individual differences in ear-canal length and shape and the eardrum acoustical impedance.

The individual differences in ear canals and eardrums are excluded in some dummy heads (e.g., B&K4100) in which two microphones are at the two entrances to the blocked ear canals. Such dummy heads are often used to record binaural spatial sounds. Recording sound pressure signals at the entrances to blocked ear canals can also be done using human subjects, which is more convenient than directly recording sounds at eardrums. It is ultimately however desired to obtain high-fidelity sound signals inside the ear canal for various listeners in virtual reality applications. Without constructing various physical ear simulators, this paper proposes to construct a digital filter to simulate the transfer function of the external ears, which can then be used to derive individual eardrum sound signals from the sound signals obtained at the entrances to blocked ear canals. The present paper formulates the transfer function of external ear (TFoEE) from the sound pressure at the entrance to the blocked ear canal to the sound pressure at the eardrum based on an acoustic model taking into account the ear canal cross-sectional area function, eardrum impedance and the radiation impedance of the pinna. The TFoEE can be individualized to estimate the sound pressure signal at the individual eardrums given the sound pressure signals at the entrances to blocked ear canals.

The transformation characteristics of external ears with or without headphones have been investigated by many researchers. The transfer function of the ear canal and the eardrum impedance are measured assuming that an ear canal is a tube of constant cross section [3]. The eardrum impedance is measured without that assumption, and the eardrum impedance is defined as the complex ratio of the sound pressure to the volume velocity at a reference plane at a distance of 2-3 mm from the eardrum, at which distance the effective acoustic termination of the ear canal can be reproduced by an ear simulator and plane wave propagation can be ensured with reasonably accuracy [4]. The transfer function from the sound pressure at the entrance to the blocked ear canal to the sound pressure at the eardrum without headphones has been measured on several human subjects [5]. The transfer function from the input of a headphone to the sound pressure at the eardrum, and the effect of ear canal shape on it have been investigated [6]. Simulations of the sound pressure responses of a realistic eardrum impedance and various ear canals connected with headphone Beyer DT-48 have shown that for most frequencies above 2 kHz, the response levels are below that of the IEC 711 ear simulator connected with the same headphone, and the errors of the ear simulator caused by the effect of individual ear canal shapes can reach 15 dB around 3-4 kHz [6]. Obviously, current invariable ear simulators are not satisfactory in some applications that aim to obtain high-fidelity sound signals at human eardrums over the range of audible frequencies. It is found that the individual features affecting the eardrum pressure are mainly the length and the shape of the ear canal. In general, the cross sectional area is an ear canal is not constant but variant along the axis of the canal, and the individual difference in ear canal shape can lead to large differences between ear canal transfer functions above 8 kHz [7].

The present paper models the acoustic transfer function of external ears, and provides a digital filter to simulate the transfer function in the discrete-time domain, which is needed in digital binaural signal processing and synthesis, as well as in design of earphone audio systems. Section II presents the acoustic model used for deriving the discrete-time domain transfer function of external ears. Section III presents the simulation results based on our derived digital filters. Section IV contains the experimental results measured on a standard ear simulator to validate the model and simulation. Section V contains conclusions.

2. Acoustic model of external ears

The TFoEE is defined here as the transfer function from the sound pressure at the entrance to the blocked ear canal to the sound pressure at the eardrum, which is also called as the transfer function from the source to the drum [8]. The frequency response of TFoEE for various ear canal area functions are shown in Fig.17 of [7]. The radiation impedance Z_0 and reflection coefficient at the entrance of the ear canal have been measured and shown in Fig. 1 of [9].

Given a sound field, let P_0 be the sound pressure at the entrance to the blocked ear canal, P_1 be the sound pressure at the entrance to the open ear canal, P_{ed} be the sound pressure at the eardrum, U_{ed} be the total volume velocity at the eardrum, Z_{ed} be the eardrum acoustic impedance, and Z_0 be the radiation impedance looking from the entrance of the ear canal into the space. Thevenin equivalent circuit can be used to represent P_0 and Z_0 and the relationship between P_0 and P_{ed} as shown in Fig. 1.

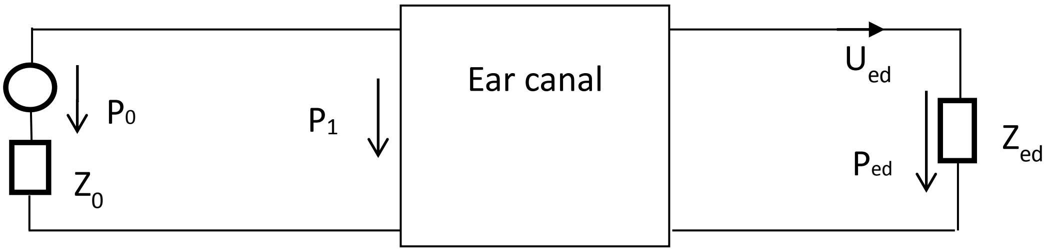

Fig. 1 The model of the transfer function of the external ear with a Thevenin equivalent source

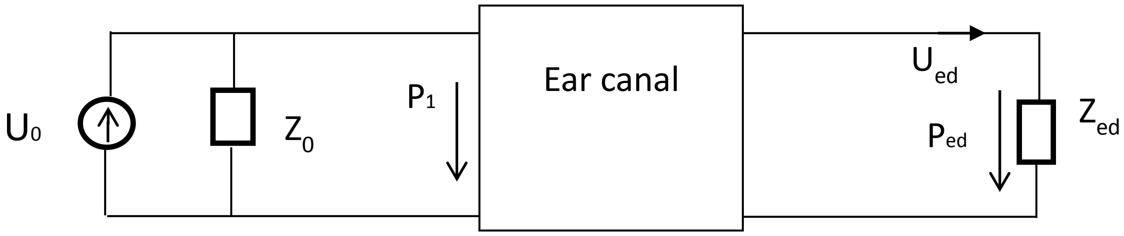

Fig. 2 The model of the transfer function of the external ear with a Norton equivalent source

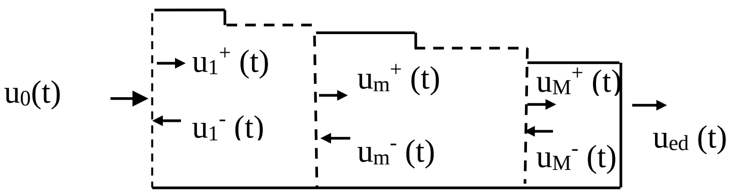

Fig. 3 The tube model of the ear canal with the Mth section ending at the eardrum.

In deriving the transfer function from P_0 to P_{ed}, a Norton equivalent circuit is more convenient as shown in Fig. 2, where the volume velocity source is:

$$U_0=P_0/Z_0 \tag{1}$$

In the discrete-time domain, the ear canal transmission line can be modeled using an M-sectional tube as shown in Fig. 3, where $u_m^+(t)$ and $u_m^-(t)$ are the going-in and going-out volume velocities at the beginning of the mth tube section, respectively. Let each section have the same length, similar to the model of vocal tract transfer function in the discrete-time speech signal processing [10,11]. Denote the cross-sectional area of the ear canal as [S_1, S_2, ……, S_M], with S_1 starting from the entrance of the ear canal and S_M ending at the reference plane for measuring the eardrum impedance.

Denote ρ as the air density and c as the sound speed in the air. Then, according to the continuity of volume velocity and the signal flow model in Fig. 2, at the beginning of the first tube section, the following equation holds:

$$u_1^+(t) + u_1^-(t) = u_0(t) - p_1(t)/Z_0 = u_0(t) - [u_1^+(t) - u_1^-(t)]\rho c / Z_0 S_1 \tag{1}$$

Define the reflection coefficient as:

$$r_0 = \frac{Z_0 - \rho c / S_1}{Z_0 + \rho c / S_1} \tag{2}$$

Then, from Eqs. (1) and (2), we get:

$$u_1^+(t) = 0.5(1+r_0)u_0(t) - r_0 u_1^-(t) \tag{3}$$

At the boundaries of each tube section, the continuity of volume velocity and of sound pressure exists. Let D be the time delay of the sound waves in each section. Then, the following two equations hold:

$$u_m^+(t-D)+u_m^-(t+D)=u_{m+1}^+(t)+u_{m+1}^-(t) \tag{4}$$

$$[u_m^+(t-D)-u_m^-(t+D)]\rho c/S_m=[u_{m+1}^+(t)-u_{m+1}^-(t)]\rho c/S_{m+1} \tag{5}$$

Define the reflection coefficient at the left side of the boundary of the mth and m+1th sections as:

$$r_m=\frac{S_{m+1}-S_m}{S_{m+1}+S_m} \tag{6}$$

From Eqs. (4-6), we get:

$$u_{m+1}^+(t)=(1+r_m)u_m^+(t-D)-r_m u_{m+1}^-(t) \tag{7}$$

and

$$u_m^-(t+D)=r_m u_m^+(t-D)+(1-r_m)u_{m+1}^-(t) \tag{8}$$

At the end of Mth section is the reference plane of the eardrum impedance, and the continuity of sound pressure leads to:

$$[u_M^+(t-D)-u_M^-(t+D)]\rho c/S_M=Z_{ed}u_{ed}(t) \tag{9}$$

while the continuity of volume velocity leads to:

$$u_M^+(t-D)+u_M^-(t+D)=u_{ed}(t) \tag{10}$$

Define the eardrum reflection coefficient as:

$$r_{ed}=\frac{\rho c/S_M-Z_{ed}}{\rho c/S_M+Z_{ed}} \tag{11}$$

From Eqs. (9-11), we get:

$$u_{ed}(t)=(1+r_{ed})u_M^+(t-D) \tag{12}$$

and

$$u_M^-(t+D)=r_{ed}u_M^+(t-D) \tag{13}$$

The relationship between the volume velocities in each tube section can be summarized in the signal flow diagram shown in Fig. 4.

If the length of each tube section L/M is determined as

$$L/M=c/2F_s \tag{14}$$

where L is the total length of the ear canal and Fs is the sampling frequency of the sound signal, then in the Z domain the time delay D of each tube section is represented by $z^{-1/2}$, and Fig. 4 is transformed to Fig. 5. The transfer function from $U_0(z)$ to $U_{ed}(z)$ can be derived as:

$$\frac{U_{ed}(z)}{U_0(z)}=\frac{z^{-M/2}0.5(1+r_0(z))(1+r_{ed}(z))\prod_{m=1}^{M-1}(1+r_m)}{\left[1,\ r_0(z)\right]\left\{\prod_{m=1}^{M-1}\begin{bmatrix}1 & r_m\\ r_m z^{-1} & z^{-1}\end{bmatrix}\right\}\begin{bmatrix}1\\ r_{ed}(z)z^{-1}\end{bmatrix}} \tag{15}$$

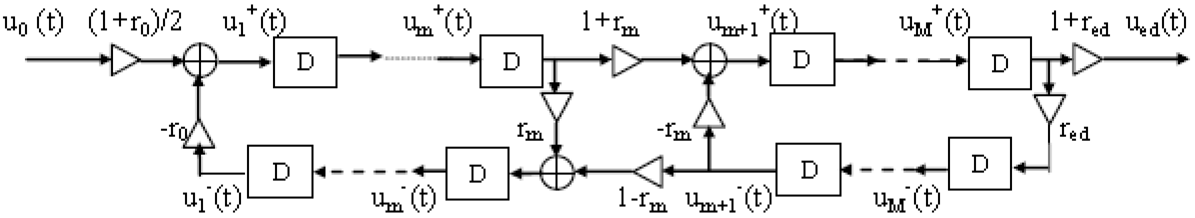

Fig.4. The volume velocity signal flow within the ear canal.

The transfer function from $P_0(z)$ to $P_{ed}(z)$ is

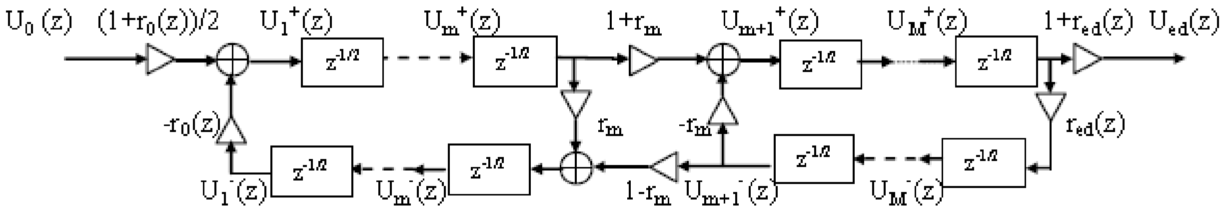

Fig. 5 The discrete-time volume velocity signal flow within the ear canal

$$\frac{P_{ed}(z)}{P_0(z)} = \frac{Z_{ed}(z)}{Z_0(z)} \frac{z^{-M/2} 0.5(1 + r_0(z))(1 + r_{ed}(z)) \prod_{m=1}^{M-1}(1 + r_m)}{[1, r_0(z)] \left\{ \prod_{m=1}^{M-1} \begin{bmatrix} 1 & r_m \\ r_m z^{-1} & z^{-1} \end{bmatrix} \right\} \begin{bmatrix} 1 \\ r_{ed}(z) z^{-1} \end{bmatrix}} \tag{16}$$

As indicated in the above equation, the sound pressure transfer function from the entrance to an ear canal to the eardrum is independent on sound source directions, but dependent on the pinna radiation impedance, the canal shape and length and the eardrum impedance.

3. Simulation

The ear canal is modeled using an M-sectional tube with each section being the same length. The radius function of the ear canal at the distance from the entrance of the ear canal is interpolated from the radius function of the "model ear canal" specified in [9] as shown by the red dotted line in the upper panel of Fig. 6. The "model ear canal" is 27 mm long, and is modeled using a 9-sectional tube with each section being 3 mm long and the last section ending in front of the eardrum. The radii of the *M* sections are shown using the blue lines in the upper panel of Fig. 6. The sampling rate in the simulation is then determined according to Eq. (14) as $Fs=cM/(2L)=340\times9/(2\times0.027)=58333$ Hz.

To determine the discrete-time transfer function from U_0(z) to U_{ed}(z), we need to know r_0(z), the discrete-time model of the reflection coefficient at the entrance of the ear canal, and r_{ed}(z), the discrete-time model of the reflection coefficient of the eardrum. It is known that the radiation impedance of a tube opening on a baffle is zero at very low frequencies and approximates to the tube wave impedance at very high frequency. Therefore, in this paper r_0 is modelled as a low-pass filter. According to the measurement results shown in Fig. 1 of [9], the reflection from the entrance of the ear canal is fully reflective at low frequencies; but it decreases considerably beyond 2 kHz, which is attributed to the effect of the concha. In the following simulation, r_0(z) is modelled using a 1st-order IIR filter:

$$r_0(z) = \mu \frac{(1+\beta z^{-1})}{(1+\alpha z^{-1})} \tag{17}$$

The parameters of r_0(z) can be determined as follows. $\mu = -(1+\alpha)/(1+\beta)$, because $r_0 = -1$ at zero frequency, i.e., $r_0(z=1) = -1$. Also, it is reasonable to assume that $r_0(f=Fs/2) = 0$, i.e., $r_0(z=-1) = 0$, and hence $\beta=1$, and $\mu = -(1+\alpha)/2$. From the measurement result given in Fig. 1 of [9], the absolute value of the reflectance at the entrance of the ear canal is about 0.6 at 5000 Hz. This leads to the following equation:

$$\left| 0.5(1+\alpha) \frac{1+e^{-j5000*2\pi/Fs}}{1+\alpha e^{-j5000*2\pi/Fs}} \right| = 0.6 \tag{18}$$

Solving the above non-linear equation, we get $\alpha = -0.657$. The frequency response of $r_0(z)$ is shown by the blue dash curve in the lower panel of Fig. 6. Given $r_0(z)$, $Z_0(z)$ can then be derived from Eq.(2):

$$Z_0(z) = \frac{1 + r_0(z)}{1 - r_0(z)} \frac{\rho c}{S_1} = \frac{1 + \mu + (\alpha + \mu\beta)z^{-1}}{1 - \mu + (\alpha - \mu\beta)z^{-1}} \frac{\rho c}{S_1} \tag{19}$$

The frequency response of $Z_0(z)$ normalized to $\rho c/S_1$ is shown using the red curve in Fig. 6(2). According to the measurement results in [3], the reflection coefficient at the reference plane in front of the eardrum is about 0.5-0.7 for most frequencies [4]. It is noted that the r_{ed} definition in Eq. (11) is negation of that in [3]. Therefore, $r_{ed}(z)$ is modeled as $r_{ed}(z) = -0.65$ in this paper. Given $r_{ed}(z)$, then according to Eq. (11), we model $Z_{ed}(z)$ as

$$Z_{ed}(z) = \frac{1 - r_{ed}(z)}{1 + r_{ed}(z)} \frac{\rho c}{S_M} \tag{20}$$

It is noted that if more accurate data of the eardrum impedance is available, $r_{ed}(z)$ and $Z_{ed}(z)$ can be modeled more accurately.

The frequency response of the transfer function from P_0 to P_{ed} can be calculated by inserting the above $r_0(z)$, $r_{ed}(z)$, r_m, $Z_{ed}(z)$ and $Z_0(z)$ into Eq. (16). Given the length of the ear canal L=27, the frequency responses of $P_{ed}(f)/P_0(f)$ are simulated for an ear canal with a constant cross sectional area, and for the “model ear canal” with the stepped radius function shown by the blue lines in the top panel of Fig. 6, respectively. In the top panel of Fig. 7, the blue solid line and the red dash line show the $P_{ed}(f)/P_0(f)$ frequency response of the “model ear canal” and that of the uniform ear canal, respectively. As can be seen, given the same canal length, the resonance frequencies of the uniform canal are obviously lower than those of the “model ear canal”. The frequency response of the “model ear canal” (blue solid line in the top panel of Fig. 7) is compared with the transfer function from the source pressure to the eardrum pressure shown in Fig. 17 of [8], and found that they are similar, although simplified eardrum reflectance and eardrum impedance are used in the present simulation.

The ear canal transfer function model shown in Fig. 2 can also be used to simulate the transfer function from the electrical input of an earphone to the sound pressure at the eardrum, where U_0 is the volume velocity source produced by the device, Z_0 is the source impedance looking through the device from the ear canal entrance into the open space, which is usually greater than the canal wave impedance. It is reasonable to assume that the reflectance from an insert to the ear canal is greater than 0.6 especially at high frequencies. Given r_0=0.6, the frequency response of the volume velocity transfer function from U_0 to U_{ed} is calculated according to Eq. (15), and is shown using the blue solid line in the middle panel of Fig. 7. It can be seen that the resonance frequencies of the ear canal wearing a reflective earphone are much higher than those of the natural open ear canal (curves in the top panel of Fig. 7). This means that the sounds heard at the eardrum contain the resonance of the blocked ear canal, which is very different from the resonance of a natural open ear canal.

It is important to consider an ideal condition in which the acoustic impedance looking through an earphone from the entrance of the ear canal into the space matches the ear canal wave impedance. Under this condition, $Z_0 = \rho c/S_1$ and hence r_0=0, and the volume velocity transfer function calculated according to Eq. (16) for the 9-sectional “model ear canal” is quite flat as shown by the red dash curve in the middle panel of Fig 7. This suggests that the transfer function from the input of an earphone to the eardrum can be equalized by making the earphone reflection-less. In other words, a reflection-less earphone can reproduce its input signal nearly faithfully at the eardrum of an arbitrary listener without being much affected by the ear canal resonance. Thus, without direct recording eardrum sounds, it is possible to record P_0 at the entrance to blocked ear canals, synthesize the eardrum sound signal P_{ed} according to the length and the shape of the ear canal for different listener groups (e.g., large, median, small, etc.), and reproduce the synthesized P_{ed} at the eardrums for different listeners accordingly from reflection-less earphones.

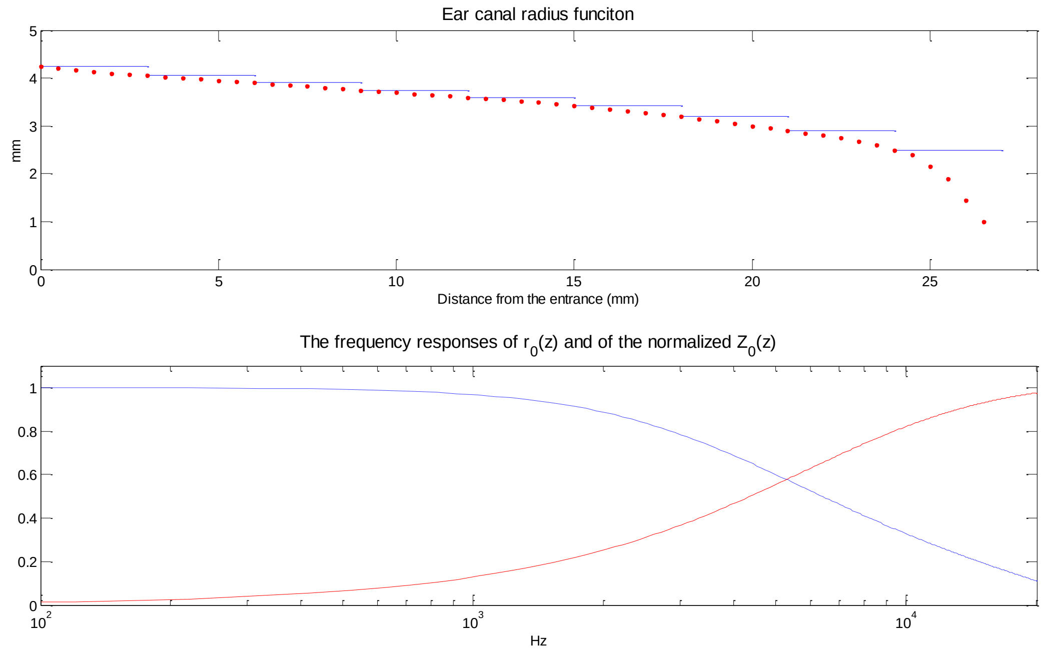

Fig. 6 Upper panel: the radius functions of the canal model (blue line) and the real canal (red line); lower panel: the frequency responses of $r_0(z)$ (blue line) and the normalized radiation impedance $Z_0(z)$ (red line).

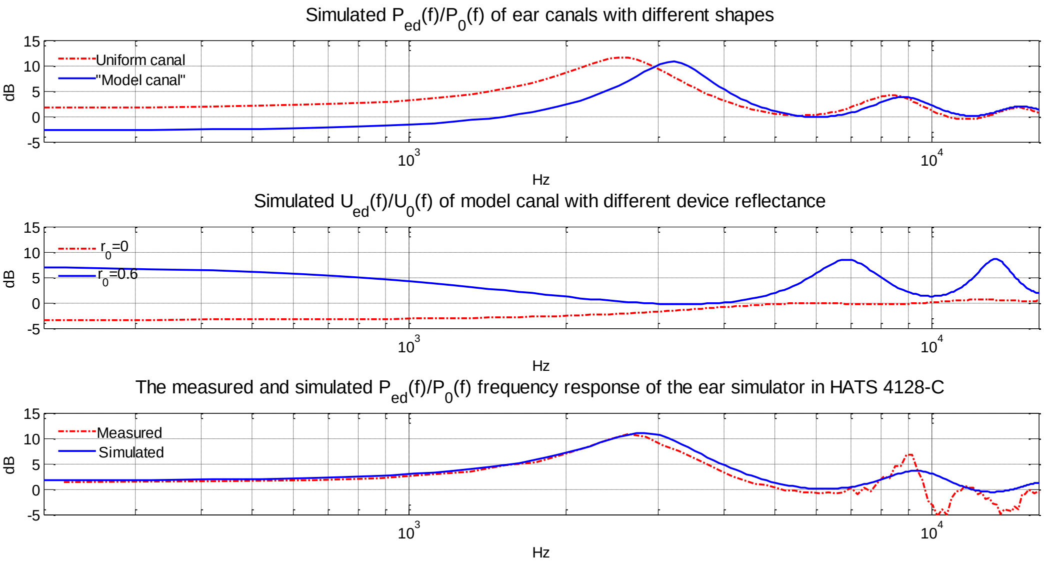

Fig. 7 Top: simulated $P_{ed}(f)/P_0(f)$ frequency responses of a uniform ear canal (red dash line) and the "model canal" (blue solid line); middle: simulated $U_{ed}(f)/U_0(f)$ of the "model canal" coupled with device with reflectance 0.6 (blue solid line) and 0 (red dash line); bottom: the measured (red dash line) and simulated (blue solid line) $P_{ed}(f)/P_0(f)$ of the right ear simulator of HATS 4128-C.

4. Experiments

To validate the derived transfer function $P_{ed}(z)/P_0(z)$, the P_0 and P_{ed} signals are measured on a B&K dummy head HATS Type 4128-C. It has two ear simulators and pinnae compiling with IEC 60318-4 and ITU_T Rec. P.57 Type 3.3. An exponential sweep tone signal from 20 Hz to 20 kHz is played back from a loudspeaker about 0.5 m away from the dummy head, and the right ear P_{ed} is recorded at a sampling rate of 65536 Hz using the built-in microphone of the dummy head. Next, keeping the positions of the dummy head and of the loudspeaker unchanged, position a miniature microphone (Sonion 8002) at the entrance to the right ear canal of the dummy head, and seal up the gap between the microphone and the canal. Then, play back the same sweep tone from the loudspeaker again, and record the signal P_0 from the miniature microphone. The frequency response of $P_{ed}(f)/P_0(f)$ is then obtained as shown by the red dash line in the bottom panel of Fig. 7. The frequency response of a typical Sonion 8002 microphone has a flat frequency response with -3 dB @ 50 Hz and +3.5 dB @ 10 kHz relative to 1 kHz value. The ear canal of the ear simulator is about 24 mm long, and is modeled as a tube with 8 sections each being 3-mm long and the same cross sectional area. The frequency response of $P_{ed}(f)/P_0(f)$ of the ear simulator is simulated according to Eq. (16), given M=8, r_m=0, $r_{ed} = -0.65$, and r_0(z) and Z_0(z) derived in Section 3, and is scaled as shown by the blue solid curve in the bottom panel of Fig. 7. It can be seen that the difference between the simulated frequency response of $P_{ed}(f)/P_0(f)$ and the measured one is less than 2 dB below 8 kHz. At 10 kHz, the measured $P_{ed}(f)/P_0(f)$ level is lower than the simulated level for about 7 dB. This is caused by the increased sensitivity of the Sonion 8002 microphone at 10 kHz [12].

5. Conclusions

In this paper, a method of simulating and deriving the discrete-time transfer function of external ears with or without wearing earphones has been developed, and the experimental verification through a standard ear simulator has confirmed the validity of the simulation at least up to 10 kHz (the specified frequency range of standard ear simulators). More accurate simulation can be obtained given more accurate eardrum impedance parameters. The method has potential applications in binaural signal processing and synthesis to faithfully reproduce sounds at the eardrums of listeners with individual difference in external ears given the sound signals at the entrances to blocked ear canals and external ear parameters. Moreover, the simulation of the transfer function from an earphone to the eardrum sound suggests that the effect of ear canal resonance in the reproduction of binaural sounds via earphones can be reduced by reducing the reflections from the earphones.

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