Towards Non-Invasive Diagnosis System for Middle-Ear Dysfunctions Based on Principles of Impulse Response Measurement

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***Abstract*—Sweep frequency impedance (SFI) meter can be used to diagnose the middle-ear dysfunctions. However, the performance of the previous SFI meter has easily been degraded by noise inside the ear canal. This paper proposed a method for stably measuring middle-ear dynamic characteristics with applying the principles of impulse response measurement. Noise robustness for the proposed method was evaluated using a 2-cc cavity, showing that the proposed method had almost the same performance even under -6-dB signal-to-noise ratio condition compared to that under clean condition. Additionally, the SFI measurement was conducted for human ears with normal middle-ear conditions and with ossicular-chain dysfunctions, showing that our improved SFI meter successfully monitor the middle-ear dynamic characteristics with more robustness of noise.**

***Index Terms*—middle ear, dynamic characteristics, sweep frequency impedance, impulse response**

I. Introduction

Accurate diagnosis and cure of hearing loss are one of the important issues in otorhinolaryngological field. There are two types of hearing loss: conductive and sensorineural hearing loss. Since the conductive hearing loss is caused by the lesions in the middle ear (i.e., the conductive system in the ear), such as the separation and fixation of the ossicular chain, and the otitis media.

Tympanometry is known as a popular measure to diagnose the conductive hearing loss due to such lesions, especially the otitis media. This measure still has poor performance to diagnose the separation and fixation of the ossicular chain due to similar results between those different types of dysfunctions.

An alternative impedance measure based on sweep frequency impedance (SFI) has been proposed for diagnosing the ossicular chain dysfunctions [1], [2]. SFI has shown to be available for such dysfunctions even only with a sound pressure stimulus without static pressure [3], [4].

However, our previous SFI meter still has poor performance due to noise inside the ear canal or body movement [5]. This paper aims to propose a method for stably measuring middle-ear dynamic characteristics with applying the principles of impulse response measurement using swept-sine signals.

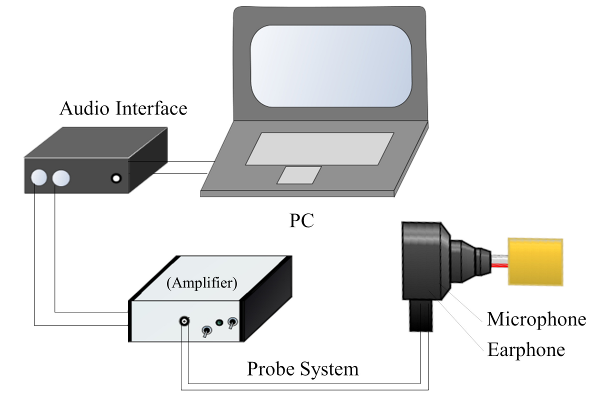

Fig. 1. Overview of SFI meter for measures of middle-ear dynamic characteristics.

II. Method

A. Principles

1) Apparatus: Figure 1 illustrates an overview of the SFI meter. The SFI meter consists of a personal computer, an audio interface (RME, Babyface Pro FS) and a probe system (Etymotic Research, ER-10C).

2) Calibration: Before mesurements, the probe is inserted into a 2-cc cavity (i.e., a syringe) to present a sweep signal at a 75-dB sound pressure level (SPL) and record the observed signal here. The 2-cc volume of the cavity is determined so that the ear canal volume for adults is approximately 2 cc. At that time, the theoretical sound pressure level at the microphone P_{theo} can be approximated by the one-dementional acoustic-tube theory as follows [6]:

$$P_{\text{theo}} = \Delta V \frac{\omega \rho_a u_a}{S} \frac{\cos(l\omega/u_a)}{\sin(l\omega/u_a)}, \quad (1)$$

where ΔV denote the volume displacement at the probe loudspeaker, ω the angular frequency, ρ_a the air dencity, u_a the sound velocity, S the cross-section of the ear canal, and l the ear canal length. Here, l is set to 3.50×10^{-2} m and the ear canal radius r is set to 4.25×10^{-3} m (i.e., $S = \pi r^2$) so that

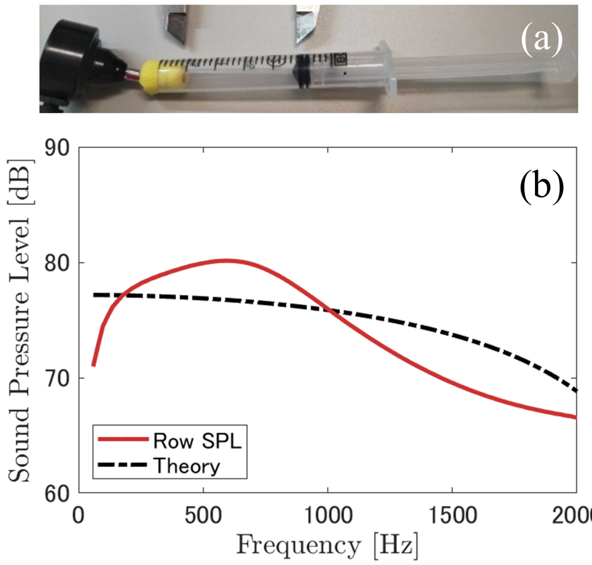

Fig. 2. SPL calibration using 2-cc cavity: (a) calibration setup and (b) row (i.e., observed) and theoretical SPL

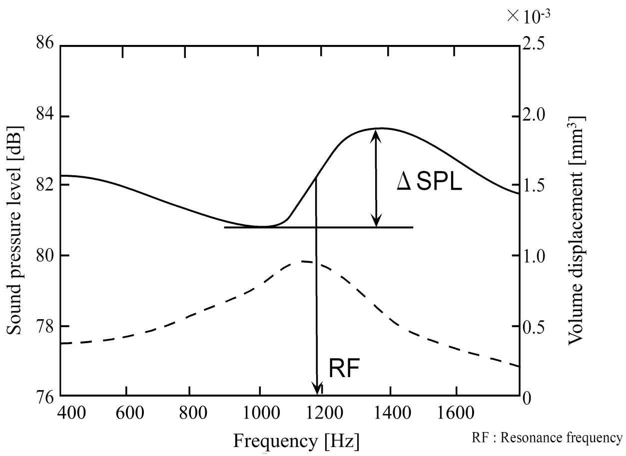

Fig. 3. Relationship between ear canal sound pressure and eardrum volume displacement.

the ear canal volume Sl is approximately 2 cc. Figure 2 shows (a) the calibration setup and (b) the row and theoretical SPL. The SPL in the ear canal is compensated for the difference between the row and theoretical SPL.

3) Common procedure: The probe is inserted into the ear canal to present the sweep signal at a 75-dB SPL and record the observed signal. Here, the observed ear canal SPL is affected by the eardrum volume displacement as a function of frequencies. Figure 3 shows the relationship between the ear canal SPL and the eardrum volume displacement. The SPL curve observed in human ears have a sharp trough (i.e., local minimum) and a sharp peak (i.e., local maximum) in the lower and the higher frequency range, respectively. Theoretically, the resonance frequency (RF) of the middle ear is obtained as the following equation:

$$\mathrm{RF} = \frac{f_{\mathrm{L}} + f_{\mathrm{H}}}{2}, \tag{2}$$

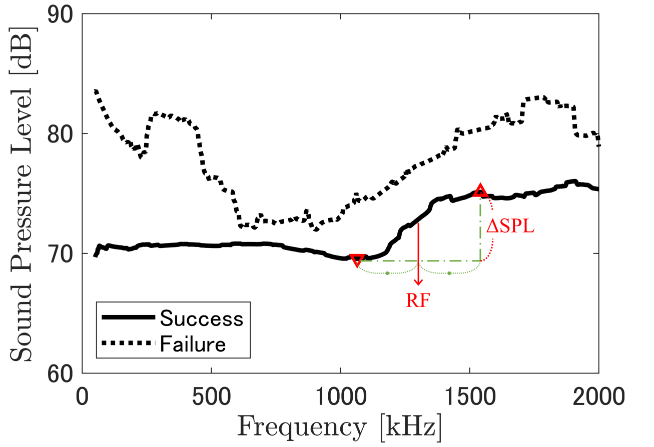

Fig. 4. SPL curves for a normal ear obtained in our previous measurement [5]. Triangular marks correspond to local minimum and maximum SPLs, respectively.

where the f_{L} and f_{H} denote the frequency at the trough and the peak, respectively. Additionally, here we define ΔSPL as the following equation:

$$\Delta\mathrm{SPL} = \mathrm{SPL}_{\mathrm{H}} - \mathrm{SPL}_{\mathrm{L}}, \tag{3}$$

where the $\mathrm{SPL}_{\mathrm{L}}$ and $\mathrm{SPL}_{\mathrm{H}}$ denote the trough and peak SPL, respectively. RF and ΔSPL correspond to the middle-ear stiffness and mobility, respectively. For the ears with ossicular-chain separation, lower RF and higher ΔSPL have found to be observed. On the other hand, for the ears with ossicular chain fixation, completely the opposite trends have found to be observed [1], [2].

B. Additional Processing for Noise Robustness

In our previous study [5], the SPL curve was obtained from the root-mean-squared amplitude in a sliding window with 1024 samples, based on the time-frequency correspondence of a 2-sec linear sweep signal, with 10000-Hz sampling frequency and 24-bit quantization. Figure 4 shows an example of the SPL curve for a normal ear obtained in the previous measurement. The sharp trough and peak, shown as the triangular marks on the solid line, are expected to be detected. Here, as shown in the dotted line, the observed SPL curve was easily affected by the instantaneous sound pressure fluctuation especially due to intermittent noise, making it difficult to determine the RF and ΔSPL.

For measuring SFI with robustness of noise, our proposed method applied the principles of the acoustical impulse response measurement to the SPL curve observation. A 2-sec logarithmic sweep signal with the frequency range between 50 and 3000 Hz, where the amplitude was constant between 100 and 2000 Hz, was used as the input. Figure 5 shows a block diagram of the SPL curve observation in our proposed

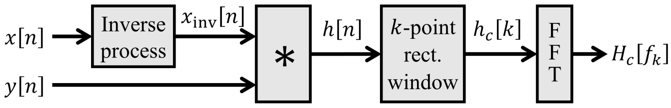

Fig. 5. Block diagram of SPL curve observation in our proposed method. $x[n]$ and $y[n]$ denote input and observed signal, respectively. $x_{\mathrm{inv}}[n]$ denotes signal with inverse frequency characteristics of $x[n]$. "*" denotes operation of convolution.

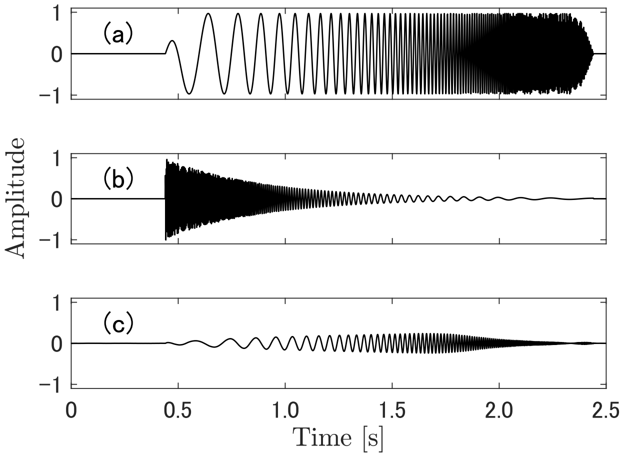

Fig. 6. Example of (a) input signal $x[n]$, (b) time-mirrored and amplitude-modified input signal $x_{\mathrm{inv}}[n]$, and (c) observed signal $y[n]$ used for impulse response calculation.

method. Here, $x[n]$ and $y[n]$ ($1 \leq n \leq N$) denote the input signal and the observed signal in the ear canal, with the signal length of $N = 20000$. The impulse response of the outer and middle ear ($h[n]$) was calculated as follows:

$$h[n] = y[n] * x_{\mathrm{inv}}[n] \tag{4}$$

where $x_{\mathrm{inv}}[n]$ is a time-mirrored and amplitude-modified signal of $x[n]$ [7]. "*" denotes the operation of the convolution. Figure 6 shows an example of the signals $x[n]$, $x_{\mathrm{inv}}[n]$, and $y[n]$. Figure 7 shows an example of the impulse response $h[n]$ obtained in Eq. (4). The rectangular windowing with the length of $K = 128$ was performed to obtain $h_c[k]$ ($1 \leq k \leq K$), so that the center of the window corresponds to the peak of $h[n]$. The desired SPL curve $H_c[f_k]$ was obtained by the fast Fourier transform of $h_c[k]$, where f_k is the frequency sequence. $H_c[f_k]$ corresponds to the acoustical transfer functions between the input and the observed signals.

C. Noise Robustness Evaluation Using Cavity

Noise robustness for the proposed and previous SFI meter was confirmed using the 2-cc cavity. The SPL curves in the cavity were obtained under the clean (i.e., quiet) condition. Additionally, to simulate the observed signal under the noisy condition, the pink noise modulated by a 5-Hz cosine signal at modulation depth of 1 was added to the observed signals, with a −6-dB signal-to-noise ratio. We compared the changes of SPL curves for the clean and noise-added observed signals for the previous and proposed methods.

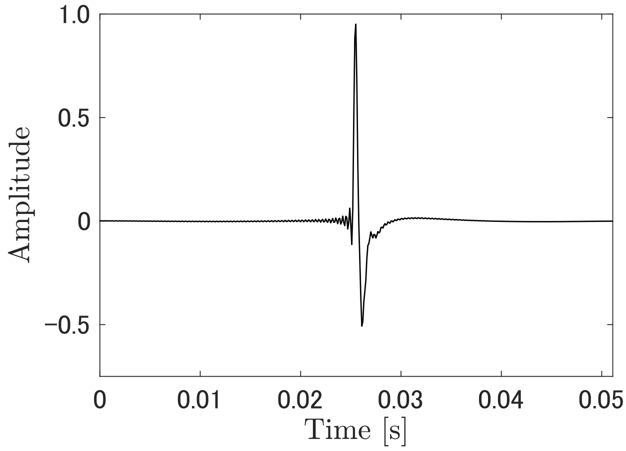

Fig. 7. Example of impulse response $h[n]$ obtained in Eq. (4) [5].

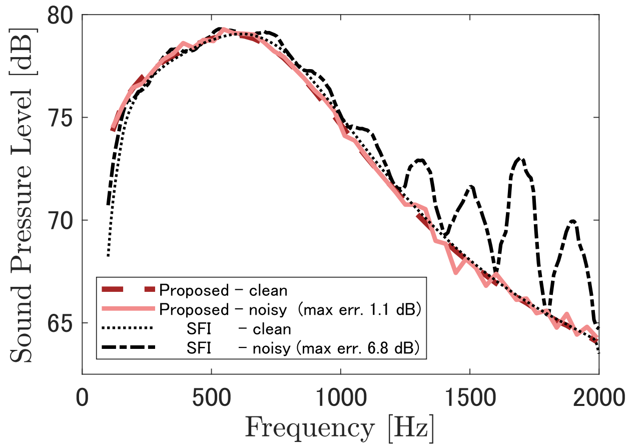

Fig. 8. SPL curves in 2-cc cavity under clean condition (with observed signal only) and noisy condition (with pink noise modulated by 5-Hz cosine signal added).

D. SFI measurement for human ears

SFI measurement was conducted for two ears of two participants with normal middle-ear condition, two ears of two patient with ossicular-chain separation, and two ears of two patients with ossicular-chain fixation. This measurement was conducted in accordance with the etical guidelines approved by the Medical Research Ethical Comittee of Kanazawa University and the Ethical Comittee of Toyama City Hospital.

III. Results

A. Noise Robustness Evaluation

Figure 8 shows the obtained SPL curves under each condition. For the previous method, the SPL curve under the noisy condition was found to be affected by the temporal fluctuation of the added noise. The maximum error between the SPL curve under the noisy condition and that under the clean condition was 6.8 dB. For the proposed method, on the other hand, the SPL curve under the noisy condition was found to be almost close to that under the clean condition. The maximum error

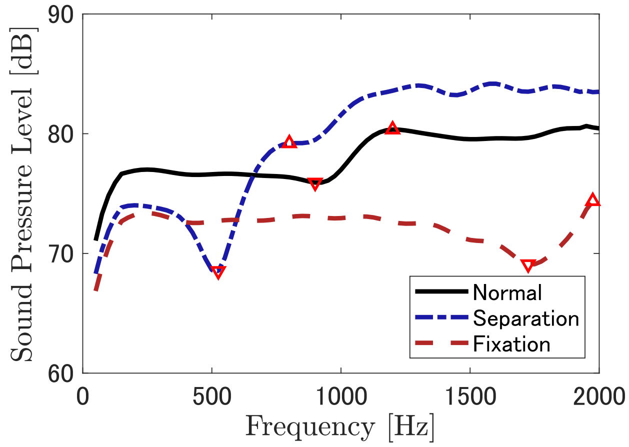

Fig. 9. SPL curves for a normal ear and those with ossicular-chain separation and fixation. Triangular marks correspond to local minimum and maximum SPLs, respectively.

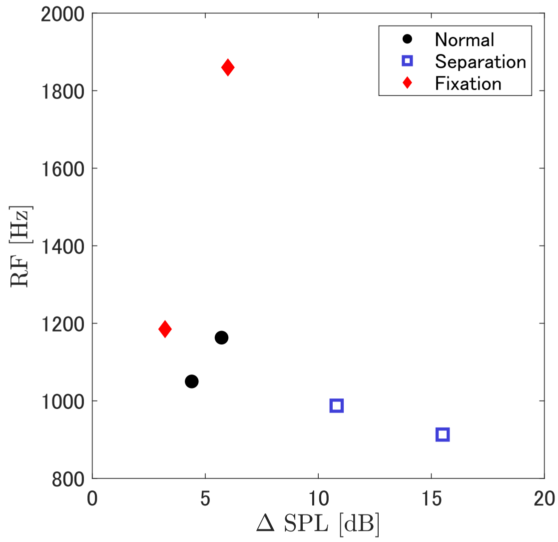

Fig. 10. Distribution of SFI data derived from measurements in human ears in RF-ΔSPL plane.

between the SPL curve under the noisy condition and that under the clean condition was 1.1 dB.

B. SFI measurement

Figure 9 shows the examples of the obtained SPL curves for three participant's ear. The proposed method was found to detect the local minimum and maximum SPLs due to the middle-ear dynamic characteristics (shown as the triangular marks on each line). Figure 10 shows the distribution of SFI measurement data in RF-ΔSPL plane. For the two normal ears, RFs were calculated as approximately 1100 Hz and ΔSPLs were calculated as approximately 4 to 6 dB. For the two ears with ossicular-chain separation, RFs were calculated as approximately 900 to 1000 Hz. ΔSPLs for two ears were calculated as 10.8 dB and 15.5 dB, respectively, which were twice as much as those for the normal ears. For the two ears with ossicular-chain fixation, RF for one was 1185 Hz but that for another was 1860 Hz, which was 1.7 times as high as those for the normal ears. ΔSPLs for two ears were calculated as 3.2 dB and 6.0 dB, respectively, which were almost as much as those for the normal ears.

IV. Discussion

The results of the evaluation using the 2-cc cavity (Fig. 8) indicated that the proposed method successfully reduces the influence of noise, enabling stable SFI measurements in various sound environment. Here, only the ammplitude-modulated pink noise was used for simulating noisy environment. Robustness of noise for real-measurement environment should further be tested.

The results of the SFI measurements for human ears (Fig. 9) indicated that the proposed method obtains the clean SPL curves compared to the previous method (Fig. 4). The differences of SFI distribution in the RF-ΔSPL plane among different middle ear conditions shown in Fig. 10 were assumed to highlight the middle-ear dynamic characteristics. The distribution obtained in this study was almost similar to that reported in the previous study [2].

For evaluating the practical diagnosability of SFI with the proposed method, we should further increase the participants to measure the SFI for multiple middle-ear conditions and investigate the distribution of the obtained SFI measurement data.

V. Conclusion

This paper proposed a method for stably measuring middle-ear dynamic characteristics. The results of the SPL curves obtained in the 2-cc cavity showed that the proposed method performed almost the same SPL curve observation even under −6 dB signal-to-noise ratio condition compared to that under clean condition. The results of the SFI measurement for human ears showed that our improved SFI meter successfully monitor the middle-ear dynamic characteristics with more robustness of noise.

Acknowledgment

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