A five-microphone method to measure the reflection coefficients of headsets

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ABSTRACT

In binaural audio, particularly when using headphone for sound reproduction, the reflections from a headset to the ear canal can have a considerable compact on listeners' subjective perception. They may affect the electroacoustic transfer function from the electrical input of headsets to the sound pressure at the eardrum. In order to characterize such effects, it is needed to measure the reflection coefficients from headsets to ears. A widely used measurement method is the transfer function method, which is described in ISO-105340-2. However, the frequency range above 10 kHz may not be accurately measured with only a single pair of measurement sensors. In this paper, a five-microphone method is proposed for measuring the reflection coefficients using an impedance tube with a standard pinna simulator that the headsets coupled. Comparisons are made between the new method and the one microphone technique for the experimental results. It is showed that the measured results agree well and the accuracy of the proposed method can be up to 16 kHz. This method can be expected to have applications in model the acoustic transfer functions of external ears as well as to headphone sound reproduction.

Keywords: Headset, Reflection Coefficient, Microphone I-INCE Classification of Subjects Number(s):72.9

1. INTRODUCTION

Headsets are becoming more and more popular, especially in combination with mobile devices. The sound perception usually differs among people with varieties of headsets (including over-ear headphones, on-ear headphones, in-ear headphones, etc.) even if they are listening to the same sound because the differences in the wearing conditions produce different reflections around the head, ears and even within the ear canal. Simulations show that reflections from headsets to ears introduce unwanted resonances of the ear canal, which is distinctly different from the resonance of a natural open ear canal (1). Considering the acoustic load caused by the headsets, the measurement results vary with an "open-pinna" and different wearing conditions (2). This means that the sound signal reproduced at the human eardrum can be affected by the reflections from headsets to the ear canal and the electroacoustic transfer function from headsets to the sound pressure at the eardrum. A few experimental measurements on the human ears have been made in the literature (3-4) and some methods for estimating the sound pressure magnitude at the eardrum are proposed (5-7). Recently, a developed parametric model of the electroacoustic transfer function has been formulated in (1). To characterize the effect of the electroacoustic transfer function for a headset, its reflection coefficient to the ear canal needs to be measured through an impedance tube with a standard pinna simulator.

There are several methods for measuring the acoustic reflection coefficients of acoustic loads. The standing wave ratio method is a classical acoustic measurement method and has been standardized by ASTM C384-90a (8). It can be considered as reliable and accurate, but time consuming. A widely used method is the "transfer function method", sometimes called the two-microphone method, which is described in ISO-105340-2 (9). By using two microphones with a distance, the reflection coefficient of the acoustic load can be determined over a wide frequency range and the measurement can be much faster than the SWR method. However, it is not possible to find an appropriate microphone spacing which can cover the whole frequency range of interest satisfying the desired accuracy range. The least square method is a developed measurement method

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in which the results are processed by least-squares fitting (10). It can be employed by using multiple measurement positions and the number of microphones is usually more than three. It is noted that the least square method reduces to the transfer function method when the number of microphones is only two.

In this paper, a five-microphone method has been proposed for measuring the reflection coefficients of headsets, and analyzing the measuring accuracy and effective frequency spans caused by the microphone spacing which may cause the singularity problem. This paper is organized as follows. In section II, the least square method is reviewed. A general procedure to estimate the incident and reflected wave components using the least-squares fitting is outlined followed by a discussion of the number of microphones and the optimal sensor position. Section III presents the experiment setup, and the measuring results between the proposed method and the traditional one-microphone method. Section IV contains the conclusions.

2. IMPROVED METHOD

2.1 Theoretical Background

In this section, the least square method according to Ref. (11) is reviewed. Figure 1 presents the apparatus of the reflection coefficient measurement. This setup consists of a straight tube which is the measurement acoustic wave guide. One end of the tube is connected to an acoustic source and a linear passive termination on the other end. The sound field for a plane wave propagating in the duct can be expressed as

$$P(x,f) = P_i(f)e^{jkx} + P_r(f)e^{-jkx}, \tag{1}$$

where $P(x,f)$ is the frequency spectrum of the measured acoustic pressure at a position x, P_i and P_r are the Fourier transform of the incident and reflected wave pressures respectively, k is the wave number of the sound. In general, if tube attenuation is considered, the wave number can be determined as (9)

$$k = 2\pi f/c - j0.0194\sqrt{f}/Dc, \tag{2}$$

where D is the diameter of the tube, c is the sound speed, and f is the frequency of the sound. Then the sound pressure signals at positions x_1, x_2, …, x_N can be obtained as

$$\begin{bmatrix} e^{jkx_1} & e^{-jkx_1} \\ e^{jkx_2} & e^{-jkx_2} \\ \vdots & \vdots \\ e^{jkx_N} & e^{-jkx_N} \end{bmatrix} \begin{bmatrix} P_i \\ P_r \end{bmatrix} = \begin{bmatrix} P_1 \\ P_2 \\ \vdots \\ P_N \end{bmatrix}, \tag{3}$$

This over-determined linear matrix equation also can be expressed as

$$Ax = b, \tag{4}$$

It is noted that the chosen measurement positions need to avoid the singularity problem and make matrix A full rank over the frequency range of interest. Consequently, the following least-squares solution of Eq. (4) can be obtained via pseudo-inversion

$$x = A^{+}b = (A^H A)^{-1} A^H b, \tag{5}$$

Here, A^H denotes the Hermitian matrix of A. Given $P_i(f)$ and $P_r(f)$, then the frequency response of the reflection coefficient can be determined

$$r_o(f) = P_r(f)/P_i(f). \tag{6}$$

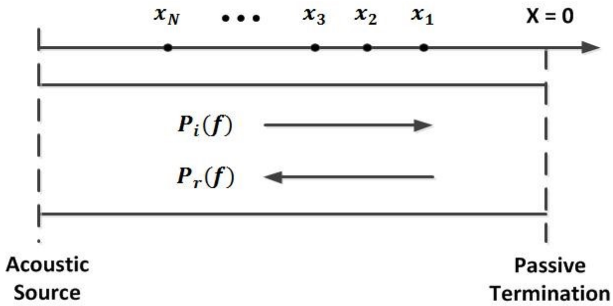

Figure 1 – Basic measurement configuration of the least square method.

2.2 Selection of the Number of Microphones and Optimal Positions

To obtain the same degree of accuracy for all frequencies of the overall bandwidth, using only a single pair of microphones is not attainable. It is reported that the least square method gives more accurate results than the transfer function method if the measurement is performed with multiple microphones (11). A natural question arises. If multiple microphones should be arranged, what the number of microphones is suited for measurement? To account for this problem, we should calculate the estimating error which is denoted as the singularity factor (11) to determine the reasonable multiple-sensor set. In this paper, we should rewrite the singularity factor to characterize the estimating error over the whole bandwidth below the cutoff frequency of the tube,

$$SF = \sum_f \sqrt{\sum_j \Lambda_j^{-2}}, \tag{7}$$

where Λ^{-1} is the singular value of the Moor-Penrose generalized inverse matrix A^{+}. This new object function can present the sensitivity of the least square method to estimating errors over the measurement bandwidth instead of that vary with frequency bins. Different estimating errors are plotted in Figure 2 by varying microphones configuration with uniform and arbitrary spacing, where the estimating error is normalized by the maximum of the singularity factor. One can find that the estimating errors reduce efficiently as the number of measuring point increases. Figure 3 shows the effective frequency spans with various number of uniform and arbitrary spacing measuring points, where the singularity factor within the frequency range is usually set as less than 1.7. It is noted that the frequency range is normalized by the critical number, which is defined in Ref. (11). Comparisons are also made between uniform and arbitrary spacing microphone configuration, it is found that the arbitrary spacing configuration has higher accuracy and wider frequency spans. Although the estimating errors can be reduced and the frequency range can be widen as the number of measuring point increases, the effect of microphone configuration seems to become marginal when the number of measuring microphones is greater than 5.

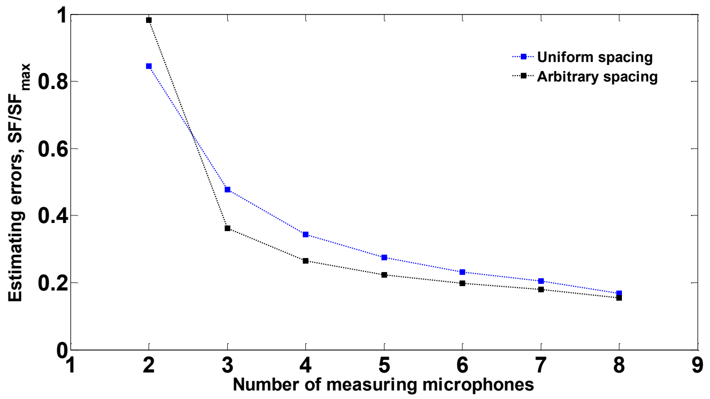

Figure 2 – The estimating errors over 100-20kHz vary with the number of measuring microphones by uniform and arbitrary spacing (x_{21}=1.7 cm, x_{32}=2.2 cm, x_{43}=1.3 cm, x_{54}=2.0 cm, x_{65}=1.8 cm, x_{76}=1.0 cm, x_{87}=2.5 cm)

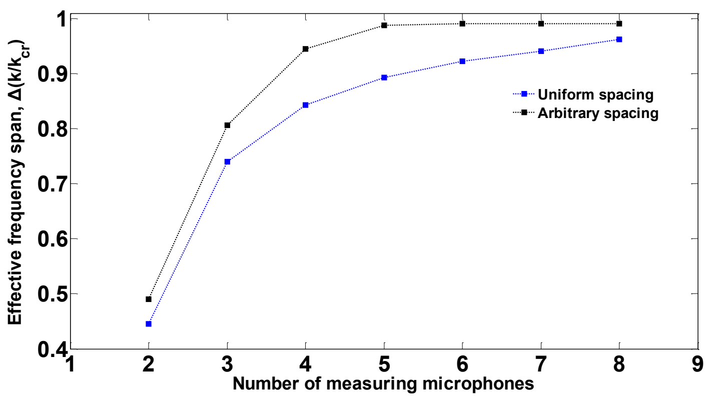

Figure 3 – Effective frequency spans vary with the number of measuring points by uniform and arbitrary spacing (x_{21}=1.7 cm, x_{32}=2.2 cm, x_{43}=1.3 cm, x_{54}=2.0 cm, x_{65}=1.8 cm, x_{76}=1.0 cm, x_{87}=2.5cm)

Knowing the absolute estimating errors as pointed out above may not be sufficient for the choice of the number of microphones. Next, the relative estimating errors will be defined to address this problem. From Eq. (4), the following relation can be written:

$$\tilde{b} = b - e = Ax - e = A\tilde{x} \tag{8}$$

Here, **e** denotes the measurement error in **b** and (~) represents the estimating value. Using $\|b\|_2 = \|Ax\|_2 \leq \|A\|_2 \|x\|_2$ with $x - \tilde{x} = A^{+}e$, then the relative estimating errors can be obtained

$$\frac{\|x-\tilde{x}\|_2}{\|x\|_2} = \frac{\|A^{+}e\|_2}{\|x\|_2} \leq \frac{\|A\|_2 \|A^{+}\|_2 \|e\|_2}{\|b\|_2} = \kappa \frac{\|e\|_2}{\|b\|_2} \tag{9}$$

where $\kappa = \|A\|_2 \|A^{+}\|_2$ is the condition number ($\kappa = \sigma_1/\sigma_N$ if the 2-norm $\| \|_2$ is used). This yields that the credibility of the accuracy to the $Ax = b$ in the face of uncertainties can be gauged by the relative estimating errors, which are in relation to the condition number and the ratio of measuring errors **e** and pressure signals **b**. It is noted that the relative estimating errors could be determined only by the condition number, because the ratio of measuring errors **e** and pressure signals **b** won't vary with the number of microphones in the same measurement environment. In other words, the condition number will be the reliable indicator of measuring accuracy for the least square method. Table I lists the average condition numbers over the whole frequency range varying with uniform and arbitrary spacing for each multiple-sensor set as discussed above. It is found that the decreasing trend of the average condition number is consistent with that of singular factors as the number of microphones increases. When the number of microphones is less than 4, the measurement accuracy could not reach the practical measurement requirement over the whole frequency range. Considering the measurement accuracy with effective frequency spans, it seems a viable choice to use five microphones for the reflection coefficients measurement in which unnecessary microphone redundancy also may be avoided by five microphones configuration.

Table 1 – The average condition numbers vary with the number of microphones

The number of MICs	2	3	4	5	6	7	8
Uniform spacing	5.01	3.19	2.47	2.08	1.84	1.68	1.57
Arbitrary spacing	5.90	2.31	1.79	1.62	1.52	1.46	1.41

Apart from the number of microphones, the measuring accuracy and effective frequency range can be influenced by the microphone arrangement. Analytical investigation has been given in Ref. (11) that recommends the use of uniform spacing configuration. However, this may suffer from the singularity problem when the microphone spacing is a multiple of half of the wavelength (12). If the non-uniform spacing should be considered instead of uniform spacing or arbitrary spacing as showed above, which microphone locations are suited for measurement? In Ref. (12), condition number of the propagation matrix A was introduced to determine the sensor location for a three-element array,

$$\kappa(f, d_{12}) = \sigma_1(f, d_{12})/\sigma_2(f, d_{12}). \tag{8}$$

where the $\sigma_1(f, d_{12})$ and $\sigma_2(f, d_{12})$ denote the first and the second singulars at the frequency f, and d_{12} is microphone spacing between the first and the second microphones. Then, the condition number over the measuring frequency range below the cutoff frequency of the impedance tube can be used as the objective function ($\bar{\kappa}$). Consequently, the spacing d_{12} that minimizes $\bar{\kappa}$ is the optimal solution. We can also utilize this solution as a guide for five microphones spacing configuration, where d_{12} will be considered to be the spacing of each sequence pair of measuring microphones. In the present work, the rational spacing for five microphones arrangement can be chosen: x_{21}=12.5 mm, x_{32}=64.5 mm, x_{43}=8 mm, x_{54}=25 mm. Each spacing choice seeks a local minimum (l_m=110mm in this situation) which is the optimal microphone location that displays in Figure 1 of Ref. (15). According to the standard ISO-105340-2, the distance between two measurement positions in the impedance tube determines its working frequency range, which is 0.05c/s < f < 0.45c/s. Combining all these positions can lead to the final measurement frequency range 155 Hz < f < 19 kHz, i.e., 0.05c/0.11 < f < 0.45c/0.008.

3. EXPERIMENTS

3.1 Experiment Setup

In this research, an acoustic impedance tube with a pinna simulator is constructed for the measurements as illustrated in Figure 4. The tube consists of a stainless steel tube with an inner diameter D_0=8 mm to simulate an average ear canal entrance diameter, an outer diameter 20mm, and a length 380 mm. The cut-off frequency of plane waves in the tube is $0.58c/D_0$, where c is the sound speed in the tube. One end of the tube is connected to a standard left pinna simulator removed from a dummy head GRAS 45 BM. The other end of the tube is terminated with a sound source, an insert headphone (the right piece of the Sennheiser IE60) to produce the excitation sound. A circular plate with a diameter 150mm and thickness 40mm is used to connect the pinna simulator to the tube and also to simulate the check and head area around a pinna. As suggested above, five measurement positions are chosen: x_1=52 mm, x_2=64.5 mm, x_3=129 mm, x_4=137 mm, x_5=162 mm. At these positions, five holes with a diameter 4mm are made through the wall of the tube to insert measurement microphones. When measuring the reflection coefficient of headsets, the headphone is connected to the tube via the pinna simulator.

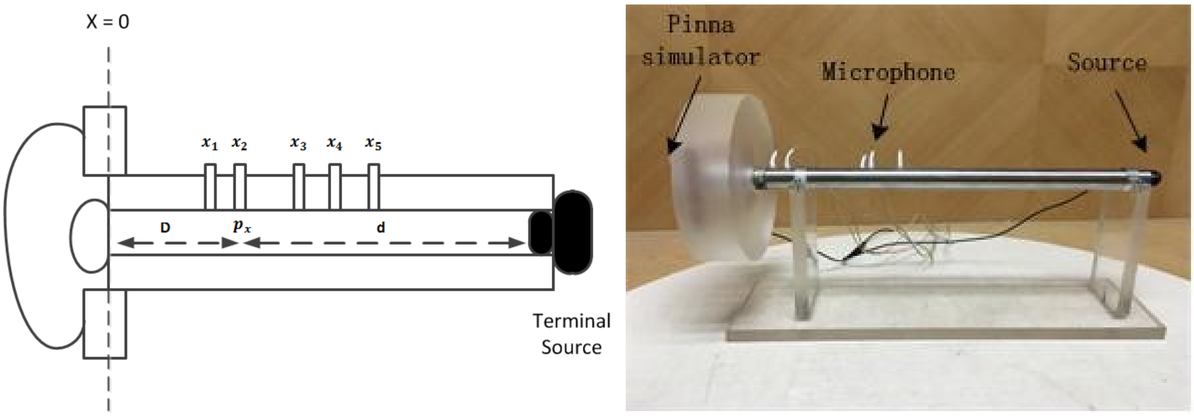

Figure 4 – The sketch (left) and device (right) of the acoustic impedance tube with pinna simulator.

The excitation signal for the measurement is a linear sweep tone from 22.05 Hz to 22.05 kHz via a B&K PULSE at a sampling rate 65536 Hz. The sound pressure signals at five positions in the tube are measured simultaneously with five miniature microphones Sonion 8002 (13) with a diameter of 2.6mm. Inevitably, the mismatch among the amplitude and phase of multiple microphones needs to be calibrated by introducing an extra calibration tube where five holes are made through the wall in the same plane. This has the implication that the pressure signals at the five holes are equal because of the plane wave generated in the calibration tube. In this situation, the calibration factor can be obtained by the ratio of two arbitrary microphone outputs. From the fact that Eq. (6) never changes by substituting $P_j(f)/P_{ref}(f)$ for $P_j(f)$, in which $P_{ref}(f)$ is considered as the reference signal that can be the sound pressure measured by a microphone at any fixed position. Then, the sound pressure transfer function $P_j(f)/P_{ref}(f)$ can be corrected by the microphone outputs with the calibration factor. As a consequence, the reflection coefficients of headsets will be obtained in calculating the ratio of the reflected pressure to the incident pressure in Eq. (6).

3.2 Results and Discussions

In this section, the reflection coefficients of the simulator pinna and headsets measured with one-microphone method, four-microphone method and the proposed five-microphone method are displayed. In general, the one-microphone method is regarded as the reference value to validate the accuracy and availability of the proposed method.

Figure 5 shows the amplitude and phase frequency response of the simulator pinna reflection coefficient without any headsets coupled. As frequency increases to about 7 kHz, the pinna reflection coefficient amplitude monotonically decreases from 1 to about 0.4. At higher frequencies, the pinna reflection coefficient amplitude exhibits the feature of peaks and valleys due to the resonance of the concha. Beyond that the result for the five-microphone method is quite accurate up to 16 kHz compared with one-microphone method. There is only a slight divergence in amplitude and phase frequency response above 10 kHz, but they can also agree well as a whole. Nevertheless, the results of the four-microphone method have distinct fluctuation below 2 kHz and larger divergence above 10 kHz compared with that of the five-microphone method. In figure 6, the amplitude and phase frequency response of the Sennheiser IE 60 insert headphone are displayed respectively. The measuring results for amplitude frequency response are once again accurate and no significant divergence can be found in the whole frequency range between the one-microphone method and the five-microphone method. However, the measurement results of the four-microphone method also have significant fluctuation over the whole frequency range compared with the five-microphone method. In addition, as can be seen from this figure, the differences in the phase frequency response are caused by the gap between the miniature microphone and the hole in the impedance tube where the diameter of the microphone is a little smaller than the hole.

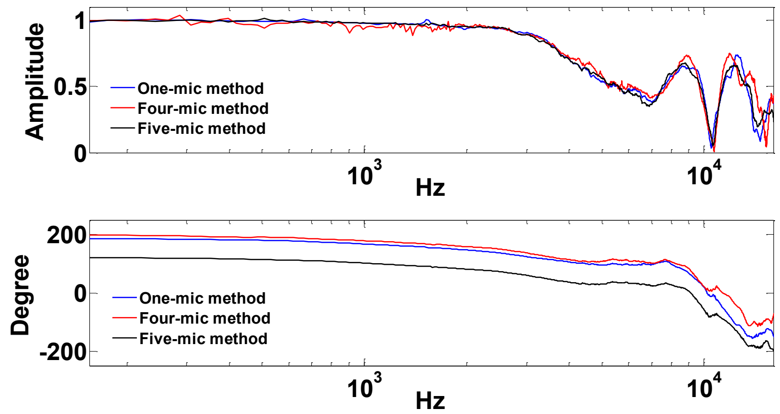

Figure 5 – Comparisons of the amplitudes and phases of the reflection coefficients of a simulator pinna without headsets.

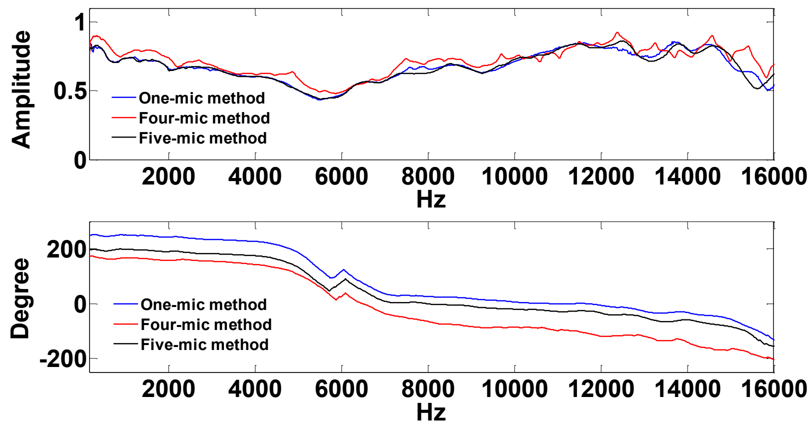

Figure 6 – Comparisons of the amplitudes and phases of the reflection coefficients of the Sennheiser IE 60 insert headphone.

To account for the availability of the proposed five-microphone method, comparisons are also made by introducing the four-microphone method in which the four measuring positions are chosen by excluding the first position of the five-sensor set as discussed in section 2.2. Table II lists the mean square error (MSE) between the four-microphone method and the proposed five-microphone method. As anticipated, the four-microphone method fails to yield more accurate measurement compared with the five-microphone method. This is also in good agreement with the previous discussion in section 2.2. Consequently, the proposed five-microphone method can attain fairly high measurement accuracy with effective frequency range up to 16 kHz.

Table II – MSEs between the four-microphone method and the five-microphone method.

MSE	four-MIC method	five-MIC method
pinna	7.94%	4.98%
headphone	11.86%	4.79%

4. CONCLUSIONS

The present research develops a five-microphone method of measuring the reflection coefficients of headsets with sufficient frequency range and effective accuracy up to 16 kHz. The estimating errors associated with the number of microphones and the effective frequency spans involved in the relative positions of microphones have been investigated by using the least square method. Based on the impedance tube with a standard pinna simulator, comparisons have been made for the reflection coefficients of the pinna simulator and headsets. The measured results show that the five-microphone method is in good agreement with the one-microphone method which can be regarded as the reference value. Possible future applications are relate to modeling external acoustic transfer function and binaural reproduction.

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