4pEAa1. Individual in-situ calibration of insert headphones

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An important procedure in binaural reproduction is the calibration of headphones, which is commonly achieved by first measuring the headphone transfer functions (HpTFs). The commonly used methods of measuring the HpTF are not applicable for insert headphones, since the inserts block the ear canal entrance and since the transducer ports of the inserts are inside the ear canals. Recently, an alternative technique of obtaining HpTFs of inserts using measurements with in-ear microphones, computational modeling, and electro-acoustic Norton-type source models of the inserts has been proposed. In this study, the technique is evaluated using measurements at the eardrums of six human subjects and computational modeling with normal human ear canal parameters. In addition, different methods of obtaining the electro-acoustic source model parameters are compared. It is shown that the most reliable method of obtaining the Norton source parameters of insert headphones is through measurements with a miniature-sized pressure-velocity sensor and several tubes with different cross-sectional diameters as acoustic loads. The evaluations show that the proposed technique of obtaining the HpTFs of insert headphones is accurate and reliable at least up to 10 kHz, which bolsters the applicability of the technique for individual in-situ calibration in binaural reproduction.
INTRODUCTION

Even though insert headphones are becoming more and more popular, they have not been commonly used in binaural reproduction, where circumaural headphones are more popular instead. The acoustics of the occluded ear canal has been studied mostly from a hearing aid point of view [1, 2], albeit not all hearing aids occlude the ear canal completely. The goal there is to calibrate the hearing aid individually to achieve best possible correction for the hearing impaired. In the design of insert headphones the goal is often to produce the best possible overall perceptual quality of sound. Hence, knowing the acoustic behavior of the occluded ear canal is very beneficial in the design of inserts as well as in binaural reproduction with inserts.

In order to achieve high perceptual plausibility, the headphones used in binaural reproduction must be calibrated, i.e., equalized individually [3, 4, 5]. With appropriate individual HpTFs available, the headphones are equalized using the HpTFs as filters to produce a flat frequency response at the eardrum. Consequently, an audio signal having a flat spectrum will produce a flat frequency response at the eardrum after the HpTF filtering and playback through the headphones in question.

If blocked ear canal HRTFs and HpTFs are used, the ear canal responses are not included, but their filtering effects are naturally added in sound reproduction through headphones, assuming the headphones used have Free-air equivalent coupling to the ear. Hence, with blocked HRTFs and HpTFs the headphones are equalized with the blocked ear canal entrance as the point of reference instead of the eardrum. The blocked ear canal HRTFs and HpTFs, however, are not directly applicable to be used in binaural reproduction with insert headphones. For insert headphones, the HRTFs and the HpTFs used should have the eardrum as point of reference instead.

METHODS

The insert headphones used in the research were Nokia HS-86 headphones. Knowles FB-series miniature microphones were added in front of the transducer gates of the inserts as depicted in Fig. 1. Pressure frequency responses inside the ear canal of simulators and human test subjects were measured with the in-ear microphones.

Figure 1: Nokia HS-86 insert headphones used in the research.

Obtaining Thévenin and Norton parameters

The Thévenin electroacoustic source model terms $P_S$ and $Z_S$ of the headphones were estimated by measuring the pressure signals evoked by the headphone inside five tubes with various diameters from 5 to 10 mm and solving the source parameters using

$$
\begin{bmatrix}
Z_1 & -P_1 \\
Z_2 & -P_2 \\
\vdots & \vdots \\
Z_M & -P_M \\
\end{bmatrix}
\begin{bmatrix}
P_S \\
Z_S \\
\end{bmatrix}
=
\begin{bmatrix}
P_1Z_1 \\
P_2Z_2 \\
\vdots \\
P_MZ_M \\
\end{bmatrix}.
$$

(1)
where \( Z_M \) are the wave impedances, \( Z_w = \rho c/A \), and \( P_M \) are the measured pressures inside the tubes. \( A \) is the cross-sectional areas of the tubes, \( \rho \) is air density, and \( c \) is speed of sound. The pressures were measured with a separate probe microphone. In addition, the Norton equivalent velocity source parameters were solved by first measuring the acoustic particle velocities evoked by the headphones inside the above-mentioned tubes and then solving the source parameters using

\[
\begin{bmatrix}
1/Q_1 & -Z_1 \\
1/Q_2 & -Z_2 \\
\vdots & \vdots \\
1/Q_M & -Z_M
\end{bmatrix}
\begin{bmatrix}
Q_S \\
1/Z_S \\
\vdots \\
1
\end{bmatrix}
= \begin{bmatrix}
1 \\
1 \\
\vdots \\
1
\end{bmatrix},
\]

(2)

where \( Z_M \) are the wave impedances, \( Z_w = \rho c/A \), and \( Q_M \) are the measured volume velocities inside the tubes. A new miniature-sized acoustic pressure-velocity (PU) sensor presented in [6] was used in the measurements.

The estimation of the Thévenin and Norton source parameters of the insert headphones is accomplished by using 3-meter long open-end pneumatic tubes with diameters of 5, 6, 7, 8, and 10 mm. The inserts are rigidly connected to these tubes by gluing the interchangeable rubber caps of different sizes to the front ends of the tubes. The inner diameter of the interchangeable rubber caps, i.e., the tube that connects the transducer port and the load tubes, is 6 mm in all cases. The earphones are then put to place for the measurements by connecting them to the rubber caps and sealing possible leaks between the rubber caps and the earphones with blu-tack. Hence, the impedance towards the source, as seen at the connection point, remains constant with each of the tubes, which would not necessarily be the case if a compressed flexible seal were used in the connection point. In the study by, e.g., Huang et al. [7] such a flexible seal was used, which changed the impedance at the connection point when using tubes with different diameters because: “the seal is less compressed because it fills a larger diameter”.

Another significant difference to be noted is that the method commonly found in literature includes short closed-end tubes with rigid terminations. In the method that uses long tubes with varying cross-sectional diameter, the back reflection from the open end of the tubes is removed by temporal windowing of the impulse response obtained with the miniature microphone (or the PU sensor as in [8] and [9]). Hence, the windowing removes the effects of standing waves in the tubes. The point of measurement is 7 mm away from the insert headphone in order to avoid near-field effects as depicted in Fig. 2. At this distance a forward traveling plane wave has already been formed. Having the point of measurement not exactly at the transducer port does not mean...
that the short part of the tube between the point of measurement and the headphone should be considered to be a part of the source impedance $Z_S$. The measured impulse response $P_E'$ (in Fig. 2) represents perfectly the impulse response $P_E$ at the connection point in the theoretical situation that all near-field effects were removed. The only difference is that a small delay has been added to $P_E'$. This delay is removed by using minimum phase representations of the obtained impulse responses in the calculations of the source parameters. Hence, in the estimation of the Thévenin or Norton source parameters the impedance of the load is in each case $Z_W = \rho c/A$ and the impedance of the source $Z_S$ remains constant.

Hence, the impulse responses at the entrances of the tubes were measured both with a miniature-sized pressure microphone and a miniature-sized particle velocity sensor in order to compare the applicability of the methods for estimation of the source parameters. The accuracy of the Thévenin and the Norton parameters were verified, by using short closed-end tubes (ear canal simulators) with known theoretical load impedance.

The source parameters ($P_S$, $Z_S$, and $Q_S$) can also be estimated directly by measuring simultaneously both the pressure and the volume velocity in front of the insert headphone when the headphone is attached to a long tube with known wave impedance.

Another completely different method for the estimation of the source parameters was also studied. The method includes measuring the pressure at the entrance of, e.g., two short closed-back tubes with constant cross-sectional area, varying length, and known theoretical load impedance. In this case the source impedance is solved by:

$$Z_S = \frac{P_{E1} - P_{E2}}{\frac{P_{E1}}{Z_{L1}} - \frac{P_{E2}}{Z_{L2}}}$$

(3)

where $P_E$ stands for the measured pressure in front of the headphone and $Z_L$ stands for the known theoretical impedance of the load. However, the experiment was not performed through real measurements, but in a matlab-simulation instead. The simple procedure was to test whether the original source parameters that were used in the simulation could be obtained by using the method under investigation. The same kind of test was performed to the main method, which includes long tubes with varying cross-sectional diameters.

**Model of the ear canal and estimating pressure at the eardrum**

Individual computational models of the ear canals of human test subjects were constructed for the study. The parameters needed for the modeling were the length and shape of the ear canal and the eardrum impedance ($Z_D$). The eardrum impedance used in the study is based on pressure and velocity measurements in human ear canals and ear canals simulators. The ear canal was modeled as a transmission line with variable cross-sectional diameter. The pressure and velocity responses along the ear canal model were obtained either using 1) measured pressures at the ear canal entrances or by 2) pure modeling using the ear canal model and source parameters $P_S$ and $Z_S$.

The pressures at the ear canal entrances of human test subjects were measured with the in-ear microphones of the inserts. The pressures at the eardrums of the human test subjects were estimated using a recently presented energy-based estimation method. A detailed presentation of the energy-based estimation method discussed here can be found in [6]. In addition to the energy-based estimation technique, transmission line equations were used in the computation.

When the particle or volume velocity in front of an insert headphone is estimated using pressure measurements with in-ear microphones of the inserts, an individual estimation of the cross-sectional area of the ear canal is needed. The wave impedances ($Z_w = \rho c/A$) of the individual ear canals were computed individually by using estimates of the cross-sectional areas ($A$) of the ear canals close to the ear canal entrance.
RESULTS

Comparison between methods

The applicability of the source parameter estimation methods including 1) pressure measurements in long tubes, 2) volume velocity measurements in long tubes, and 3) a combination of these were tested. The third method includes estimating first the pressure source parameters $P_S$ using pressure measurements as well as the volume velocity source parameters $Q_S$ using volume velocity measurements and then computing the source impedance directly:

$$Z_S = \frac{P_S}{Q_S}. \quad (4)$$

The impedances obtained with the three different methods are presented in Fig. 3. The results are very similar in all cases except for very high frequencies. However, based on this test only it is impossible to determine which one of the methods actually produces the most accurate model of the source impedance.

All the source parameters ($P_S$, $Z_S$, and $Q_S$) can be obtained using either pressure or velocity measurements in long tubes. If pressure measurement is used to obtain the Thévenin pressure source, the Norton velocity source can be solved through direct transformation with Equation 4. To study the similarity of the methods, the pressure source models $P_S$ obtained by three different methods are depicted in Fig. 4. Except for very high frequencies, the different methods yield similar estimations of the Thévenin pressure source.
Figure 5: Source impedance ($Z_S$) obtained using simulation of two different methods: 1) Estimated through $P$ measurements and 2 m long tubes with variable diameter, 2) Estimated through $P$ measurements using short tubes with variable length and constant diameter.

In the final comparison between different methods of obtaining the source parameters, the method including short closed-back tubes was compared to the one(s) using long open-back tubes. The purpose of the simulated “measurements” was to study if the original source parameters could be obtained using the methods under investigation. Hence, if the method is valid, the estimation method should produce exactly the same parameters that were used in the simulation. Unfortunately, the method using short closed tubes failed completely in the test, where source impedance was estimated as depicted in Fig. 5. Hence, based on these initial results, it would seem that using long tubes and windowing out the back reflection yields the most accurate source parameters.

Results from computational model

Using the individual model of the ear canal, source parameters, and purely computational modeling it was possible to simulate accurately the situation where an insert headphone is being used by an individual test subject. The energy-based estimation method yields the correct frequency response at the eardrum of the model as depicted in Fig. 6. The volume velocity at the eardrum is significantly smaller than the corresponding pressure, which is congruent with the idea presented first in [10].

Figure 6: Computational model of an insert headphone connected to an ear canal with individual human ear canal parameters. The energy-based estimation method gives the same response at the eardrum as the transmission line model.
Estimation vs. measurements

Estimating the pressure at the eardrum evoked by an insert headphone, i.e., the HpTFs of the insert headphones, is more complicated with human subjects than with a simulator due to the unknown length and cross-sectional area of the ear canal. Nevertheless, the estimation was successful by using the energy-based estimation technique presented first in [10]. The validation of the results were made by comparing the estimated frequency responses to those measured with a probe microphone at the eardrums of the test subjects. The results from measurements and estimations of eardrum pressure with five additional test subjects of [8], which were not included in the original paper, are presented here. The first graph (upper left) shows the results previously reported in [8]. The results shown here do not differ notably from the results shown in [8], which bolsters the applicability of the method with different individuals.

CONCLUSIONS

The results presented here are useful in the design of insert headphones and hearing aids. In addition, the results presented here validates the recently presented methods that enable individual in-situ equalization of inserts for binaural reproduction. The methods can also be used to study the noise exposure in music playback over insert headphones [11]. When all the ear canal parameters and the source parameters are modeled accurately, the computational model obtained can be used to study the behavior of the pressure and velocity components at difference
positions in the ear canal. Most importantly, it was shown that the most accurate method of obtaining the Norton or Thévenin source parameters of insert headphones is through measurements with several tubes with different cross-sectional diameters as acoustic loads. Additional confirmation to the accuracy of the parameters can be obtained by measuring both pressure and particle velocity measurements, e.g., with a miniature-sized pressure-velocity sensor.

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REFERENCES


