Modeling of External Ear Acoustics for Insert Headphone Usage*

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Although the acoustics of the external ear has been studied extensively for auralization and hearing aids, the acoustical behavior of insert headphones is not equally well known. It is laborious to measure the sound pressure at the eardrum for individual insert headphone users. The present research focused on the effects of the outer ear on sound pressure at the eardrum during insert headphone listening. The main factors of interest were the length of the canal and the impedance of the eardrum. Ear canal simulators and a dummy head were constructed, and measurements were also performed with human ear canals. The study was carried out both with unblocked ear canals and when the canal entrance was blocked with an insert earphone. Special insert headphones with in-ear microphones were constructed for this purpose. Physics-based computational models were finally used to validate the approach. The different methods used to investigate the pressure inside the ear canal gave similar and accurate results. Hence the modeling techniques proved to be useful in estimating the pressure frequency responses at the eardrums of individual insert headphone users.

0 INTRODUCTION

0.1 Background and Previous Research

It is well known that the outer ear contributes to the spectral shaping of the sounds we hear in everyday life [1]. Humans have different ears and different ear canals, hence the sound pressure responses at the eardrums of human test subjects are not similarly distributed. In part therefore, people perceive sounds differently.

In normal listening situations the whole outer ear contributes to the spectral shaping of sounds before they reach the eardrum. An unblocked ear canal acts like a quarter-wave resonator and hence amplifies the resonance frequencies. The locations of these resonance frequencies depend mainly on the effective length of the ear canal. The shape and size of the pinna and the curvature of the ear canal also have an effect on the pressure frequency response at the eardrum.

Insert-type earphones are increasingly popular when listening to music and together with mobile phones, yet their behavior has not been studied thoroughly. The sound transmission path from the insert earphone to the eardrum is different than when listening to loudspeakers or acoustically open headphones. The sound wave travels only, through the ear canal, an ear canal that is suggestive of a half-wave resonator. The half-wave resonance frequencies are pronounced at the eardrum, and the locations of these frequencies depend once again on the length of the ear canal. In addition the overall structure of the ear canal has an effect on the frequency response at the eardrum [2], [3]. Furthermore the pressure chamber effect, the occlusion effect, and leakage are important factors with regard to insert earphones and low-frequency reproduction. In this study, however, the emphasis is on the frequency range of 1 to 15 kHz.

Several methods have been developed to measure the ear canal or eardrum impedance of real ears [2], [4]–[17]. The coupling of headphones to the ear has been studied by [18] among others, who concluded that there are significant differences in the frequency responses generated in the ears of different individuals. Important results related to the transfer characteristics of headphones in human ears have been published [19], [20]. In the present work additional results related to the coupling of an insert earphone to the ear canal are presented. The presented computational model and measurement methods are useful in the design of insert earphones.
0.2 Goal of Study

The goal of our research was to learn what kinds of effects the differences in the physical parameters of the outer ears have on their frequency responses, both for open and occluded canals. We aimed at constructing a physical dummy head with adjustable ear canal features and having as accurate a humanlike acoustical behavior as possible. Furthermore we aimed at presenting physics-based computational models for a mathematical understanding of the problem.

Simple tubelike adjustable ear canal simulators were found useful in determining the effect of the ear canal length (for details see Section 3). The frequencies of the ear canal resonances and antiresonance notches found through measurements were the same as those calculated with physics-based formulas. The acoustical behavior of a simulator equipped with a damped eardrum was much like that of the human ear canal. In addition, a custom-designed dummy head used in our measurements proved to be a fairly accurate model of human peripheral hearing (details are given in Section 3).

We were hence able, with good accuracy, to study the effects of the individual differences in the outer ear parameters.

Physics-based computational modeling with lumped and distributed elements was also applied to open and closed ear canal simulation (see Section 2). For a simplified open ear canal such a model is very accurate. In the case of an insert earphone feeding the canal the main problem is to estimate a good acoustic Thévenin equivalent for the earphone driver. With different model calibration techniques we managed to get close to the behavior measured with physical simulators up to 20 kHz. These modeling efforts help us to understand better how the insert earphones work for individual listeners.

0.3 Overview of Simulators

Physical simulators, such as ear canal simulators and dummy heads, have been used widely as substitutes of human test subjects. The accuracy with which physical simulators can imitate the behavior of the outer ear and the ear canal depends on how well different physical details have been taken into account.

Originally ear simulators were primarily targeted for hearing-aid and audiometry headphone calibration. All calibrators were designed to mimic the acoustical load of real ears, or at least provide a load in the same range as a real ear. Nowadays ear simulators are increasingly used for headphone and mobile handset calibration as well. Ear canal simulators for insert-type headphones and hearing aids aim to offer a realistic representation of a human ear. Ear canal simulators are designed to have standing wave patterns similar to those of a real ear. The impedance is also designed to mimic the real ear impedance. Occluded ear simulators (commonly based on ANSI S3.25 [21] and IEC 60711 [22]) define the acoustic transfer impedance at the eardrum. The standards are defined in the frequency range of 100 Hz to 10 kHz, thus the corresponding commercial simulators are calibrated in this frequency range as well. ITU-T has published a recommendation (ITU-T P.57 [23]) that extends the IEC60711 standard by combining different types of pinnae with the simulator. The ear canals recommended in ITU-T P.57 are comprised of a 10-mm-long uniform tube, and as they are designed for tight coupling of hearing aids, measurement results for insert headphones yield an exaggerated bass response.

The exact time a manikin or artificial head for acoustic research was presented for the first time cannot be determined exactly. The period from 1880 to 1930 can be considered the initial phase of development of binaural recording devices, with the inventions of Goehner, Jones, Firestone, and Fletcher [24]. According to Firestone [25], the first time a manikin was used as a recording device was around 1928 to 1930. Firestone describes the use of a manikin that imitated a human head made of wax and a wooden torso. The microphones were Baldwin receivers, placed where the ears would be. The dummy head was used to investigate phase and intensity differences at the microphones. During the years of 1960 to 1970 the development was rapid, with advances such as the head-related transfer function (HRTF) and significant new knowledge gained about the function of the pinnae [24].

1 MEASUREMENTS

The acoustic behavior of the outer ear and the ear canal were studied through extensive measurements with ear canal simulators, a dummy head, and human test subjects. The goal was to learn how the outer ear behaves with and without insert earphones. In order to measure the effects of the differences in physical parameters of the outer ear a variety of different ear canal simulators, different kinds of artificial pinnae, and a dummy head were constructed. The main focus of this study was on the effect of the length of the ear canal and the effect of the eardrum impedance. Therefore only the simulators constructed for these purposes are presented in this paper.

1.1 Earphone with Fitted In-Ear Microphone (EFIM)

To measure the frequency responses of a blocked ear canal, a special earphone was constructed. A Knowles FG-23329 miniature microphone was fitted in front of the transducer port of a Philips SHN2500 earphone, as depicted in Fig. 1. When the acoustical behavior of a blocked ear canal or ear canal simulator was studied, this earphone with fitted in-ear microphone (EFIM) was placed at the canal entrance, as depicted in Fig. 2. Impulse

Fig. 1. Pair of earphones with fitted in-ear microphones (EFIM).
response measurements were made using the exponential sine sweep technique [26].

The transfer functions from the transducer to the in-ear microphone in different situations (attached to a small cavity, attached to a long acoustically terminated tube with 9-mm diameter, and in free field) are depicted in Fig. 3. The strong peak in the frequency response at 6 kHz is the earphone’s self-resonant frequency peak.

1.2 Adjustable Ear Canal Simulator (ADECS)

The main reason why ear canals are often modeled as straight rigid wall tubes is related to the wavelength of audible sound waves. The diameter of the ear canal is smaller than the wavelength of the highest audible frequencies. The compliance of the stiff canal walls of adults is negligible with respect to the middle-ear compliance [10]. Hence a straight rigid wall tube acts as a good starting point when building physical ear canal simulators.

To study the effect of the ear canal length an ear canal simulator with adjustable canal length (ADECS) was constructed (see Fig. 4). The “ear canal” is made of a hard plastic tube with a diameter of 8.5 mm, which is slightly larger than the average canal diameter of an adult male. The cross-sectional area of the human ear canal varies along the canal length, being approximately 35 mm² (female) or 50 mm² (male) [27].

The “eardrum” is a movable plastic piston, which makes it possible to adjust the canal length from 0 to 39 mm. Fig. 5 shows a diagram of the ADECS. The structure of the human eardrum as well as its conical shape and inclination all affect the pressure frequency response in the ear canal, especially at frequencies above 10 kHz [28]. Inclined and conical versions of the artificial eardrum were also tested during this study, but only the results for the perpendicular version are presented here.

A miniature microphone was fitted in the center of the piston. The position of the microphone along the canal is manually adjustable. It can be located at the eardrum piston level or pushed out as far as 57 mm into the canal toward (and outside of) the canal entrance.

An important characteristic of the human eardrum is that it dampens the resonance peaks and antiresonance notches caused by the ear canal. These notches and peaks are sharp in a rigidly terminated tube, whereas they are smoother in real ears. The human eardrum normally softens the mentioned notches and peaks by damping the sound wave that reflects from the drum. The impedance of the eardrum determines the magnitude of the reflecting wave at different frequencies. To achieve a better analogy with the human ear, a damped artificial eardrum was also fabricated. The movable plastic eardrum piston used in the undamped ADECS was replaced with a movable piston made of aluminum and consisting of the microphone and an adjustable Helmholtz resonator. The resonator acts as a damper at the eardrum as some of the sound energy inside the ear canal is dissipated in the resonator. The volume of the resonator cavity can be changed by sliding the back wall of the cavity. Absorbing material was added inside the cavity to spread the damping effect to a wider frequency range. A diagram of the eardrum and the ear canal is shown in Fig. 5.

The goal was to achieve a behavior similar to the human ear canal, especially when the simulator is used with insert earphones. The best similarity with human ear canals for frequencies between 1 and 10 kHz was achieved when the...
resonator resonance frequency was set to approximately 2 kHz, which is close to the first antiresonance notch with the blocked canal (as depicted in Fig. 19). The amount of absorbing material was also selected with care. An almost similar approach was used in [29]. The damped eardrum worked well as a practical solution, but further studies on modeling the eardrum are nevertheless of great interest.

1.2.1 Unblocked ADECS Measurements

When studying the pressure frequency responses of the ADECS, the simulator was mounted on a microphone stand (as shown in Fig. 4) in an anechoic chamber and pointed toward a loudspeaker at a distance of 2 m. The responses at different points along the ear canal were measured using the movable eardrum microphone of the simulator. The ADECS was also used to study the behavior of the resonant frequency peaks as the length of the “ear canal” changes. The length of the ADECS canal was adjusted from 0 to 30 mm in 1-mm steps while the pressure frequency responses were measured with the eardrum microphone. Both the undamped and the damped eardrums were used consecutively. The results are presented in Section 3.1.

1.2.2 Blocked ADECS Measurements

Compared to normal listening conditions with an unblocked ear canal, the acoustic behavior of the ear canal is very different when it is blocked with an insert earphone. When the signal is played with a loudspeaker all the outer parts of the auditory system act together to form the total transfer function. In a listening room, with the ear canal left open, the acoustics of the room is also shaping the frequency response of the system, that is, the transfer function from loudspeaker to eardrum. When using an insert earphone the effects of the head, shoulders, pinna, and concha are absent and only the acoustic properties of the ear canal are of significance. Nevertheless the outer parts of the outer ear have a major role in shaping the way we are used to hear external sound sources, which is important, especially in directional hearing. These outer parts should therefore not be completely forgotten when contemplating the acoustics of the occluded ear canal.

During the research several measurements were performed with the EFIM mounted to an ear canal simulator, as depicted in Fig. 2. An exponential sine sweep was reproduced with the EFIM and recorded with its in-ear microphone and the eardrum microphone of the ADECS. Similar to the measurements with the open ear canal, the effect of the canal length was studied, making good use of the adjustable simulator. The length of the canal was adjusted from 5 mm (minimum) to 40 mm in 1-mm steps.

A similar set of measurements was performed with the damped eardrum. The canal length of the simulator was adjusted as frequency responses were measured using the eardrum microphone and the in-ear microphone. The damped eardrum smoothens the antiresonance notch at around 2 kHz (as can be seen from Fig. 20).

1.3 Dummy Head with Adjustable Ear Canals (DADEC)

An ear canal simulator without pinna and head is only suitable for occluded ear measurements. For measurements in the free field and a listening room, the next step in our research was to build a complete dummy head. A torso with the dimensions of an adult male human was added to a manikin head. Acoustically realistic artificial pinnae with different sizes and shapes were fabricated and used with the dummy head. The ADECS with undamped and damped eardrums was used as the ear canal. Both the pinnae and the ear canals were interchangeable. The dummy head with adjustable ear canals (DADEC) is depicted in Fig. 6. In the present research the total length...
of the ear canal of the DADEC is defined as the length of the ear canal of the ear canal simulator plus a few millimeters since the artificial ear extends the ear canal, as depicted in Fig. 7. The defined length of the open canal is greater than that of the blocked canal.

To investigate responses at the eardrum of the dummy head (DADEC) with the damped ear canal simulator (ADECS) a set of measurements were performed. The DADEC was placed at a distance of 1.8 m with an azimuth angle of 30° in an anechoic chamber. The length of the ear canal was adjusted in steps of 1 mm while the pressure frequency responses were measured with the eardrum microphone of the ADECS.

To study the effect of the pinna three different fabricated pinnae were attached to the DADEC with the undamped ADECS as the ear canal in listening room conditions. In addition to the “normal” pinna used in most measurements (see, for example, Fig. 17), two larger pinnae (“big” and “cuplike”) were used (see [30] for details).

1.4 Human Test Subjects

The pressure frequency responses of the blocked ear canal were also measured with real human ears. The test subjects were asked to place the EFIM in their ears, and the responses were then captured using the earphone and its in-ear microphone. Eight test subjects (seven male and one female) participated in these measurements, with both ears being measured. The test subjects were between 25 and 35 years of age, and they had normal ears and normal hearing.

2 EAR CANAL MODELING

Computational modeling was applied to open and closed ear canal cases in order to test our comprehension of the phenomena involved in ear canal and earphone acoustics. This was accomplished by comparing modeling results against measured data from the physical simulators.

2.1 Unblocked Ear Canal Modeling

An open ear canal, closed at the other end by the eardrum, acts as a quarter-wavelength resonator. The resonance frequencies of a cylindrical tube open at one end, such as the ear canal, are [31]

$$f_n = \frac{nc}{4(L + \frac{8r}{3\pi})}$$

where $n$ is an odd number (1, 3, 5, ...), $L$ is the length of the tube, $r$ is the radius of the tube, and $c$ is the speed of sound. The resonator produces only odd multiples of the fundamental resonance frequency, which is an octave lower than in a tube that is open at both ends.

An open ear canal simulator without a dummy head is simply a terminated tube. It can be modeled as a system composed of approximate eardrum impedance, a practically lossless ear canal as an acoustic transmission line, and an external pressure sound source with internal acoustic impedance, equivalent to the radiation impedance of the tube opening [32, ch. 5] due to the reciprocity principle [33, ch. 7]. The equivalent circuit applied is shown in Fig. 8.

2.2 Blocked Ear Canal Modeling

To enable computational modeling of the interaction between the earphone and the ear canal, a model of the earpiece as an electroacoustic source is needed. Instead of trying to derive an electromechanic-acoustic equivalent circuit, [1] it is enough to estimate by measurements a Thévenin type source model with voltage-to-pressure source term $P_S$ and acoustic source impedance $Z_S$, as illustrated in Fig. 9. For a given acoustic load $Z_L$, the pressure response $P_L$ delivered by the source is

$$P_L = \frac{Z_L}{Z_S + Z_L} P_S.$$  \hfill (2)

In principle the easiest way to obtain the two unknowns is to measure the open-circuited ($Z_L = \infty$) pressure, equal to $P_S$, and the short-circuited ($Z_L = 0$) volume velocity $Q_L = P_S/Z_S$, from which $Z_S$ is solved. In contrast to electric circuits, a problem in acoustics is that both conditions mentioned are difficult to obtain, and therefore other more ideal loading conditions need to be applied.

There are a number of published methods to measure and estimate the Thévenin source parameters. Many of the methods have been developed for probes used to measure the ear canal or eardrum impedance for audiology purposes [2], [4]–[17]. The impedance probes in audiology typically include a sound source driver fed through a thin vent and a microphone through a probe tube, sensing pressure at

\[\text{For headphone modeling in general, see [34] and [35].}\]

\[\text{Fig. 8. Circuit model for open ear canal. } R_S—\text{source resistance; } L_S—\text{source inductance; } P_S—\text{pressure source; } Z_W—\text{canal wave impedance; } Z_e—\text{eardrum impedance.}\]

\[\text{Fig. 9. Acoustic Thévenin equivalent circuit for earphone.}\]
a short distance from the source radiation point. Responses measured very close to the radiation source are not directly applicable due to near-field effects [36].

A commonly used method of calibrating the impedance probe is to load it with several hard-walled closed tubes or cavities, for which there exists an analytically computable impedance expression [6], [8], [11]. Using, for example, five different lengths of tube loads, there will be five equations to solve for two variables. This means an overdetermined set of equations, leading to least-squares optimization of both the source pressure term and the acoustic impedance [6], [8].

We tried many different methods to estimate a Thévenin source model for the Philips earphone. The best results were obtained when using several approximately resistive loads, made of long tubes with different diameters, for which the wave impedance is \( Z_w = \rho c/A \), where \( A \) is the cross-sectional area of the tube, \( \rho \) is the air density, and \( c \) is the speed of sound. A tube length of about 2–3 m is long enough when the back reflection from the open end is removed by temporal windowing of the reflection function.

Five \(( M = 5 )\) different calibration loads \( Z_i \) with diameters of 5, 6, 7, 8, and 10 mm were used to measure the in-ear microphone pressure frequency responses \( P_i \). The source terms \( P_S \) and \( Z_S \) for the earphone driver were solved in the least-squares sense from the overdetermined set of equations

\[
\begin{bmatrix}
Z_1 & -P_1 \\
Z_2 & -P_2 \\
\vdots & \vdots \\
Z_M & -P_M \\
\end{bmatrix}
\begin{bmatrix}
P_S \\
Z_S \\
\vdots \\
P_M Z_M \\
\end{bmatrix} =
\begin{bmatrix}
P_1 Z_1 \\
P_2 Z_2 \\
\vdots \\
P_M Z_M \\
\end{bmatrix}
\]

(3)

using the pseudoinverse function \( \text{pinv} \) in MATLAB.

Fig. 10 shows the magnitude responses of the measured pressures \( P_i \), and Figs. 11 and 12 plot the magnitude behaviors of the source pressure \( P_S \) and the impedance \( Z_S \), respectively. Due to the near-field effects of the sound source we could not use the in-ear microphone of the earphone (EFIM), but applied a separate probe microphone 7 mm from the earphone outlet to measure the pressures \( P_i \).
In the blocked ear canal model the acoustic load $Z_L$ was composed of the eardrum impedance and a lossless ear canal as an acoustic transmission line, similar to the unblocked model.

3 RESULTS FROM MEASUREMENTS AND MODELING

The measured and modeled pressure frequency responses are presented in this section. Measurement results are presented for the unblocked and blocked ADECS, the DADEC with unblocked ear canal, and human test subjects with blocked ear canals. Frequency responses from the canal entrance are presented for the ADECS and the human test subjects. Responses from the eardrum are presented for the ADECS and the DADEC.

Comparisons between measured and computationally modeled pressure frequency responses are presented for the unblocked and blocked ADECS with the undamped eardrum.

3.1 Frequency Responses of Unblocked Ear Canals

3.1.1 Frequency Responses of Unblocked ADECS

The free-field transfer functions at the ADECS ear canal entrance (with canal lengths of 20 and 25 mm) are depicted in Fig. 13. The first two peaks of the resonance frequencies of the quarter-wave resonators are at 3 and 9 kHz for the 25-mm canal. In the frequency domain the antiresonance notches follow directly after the peaks. The frequencies at which these notches are located correspond to the distance between the measurement point and the eardrum, from where the reflected sound wave arrives.

When a sound wave enters a tube that is closed at the other end, the sound pressure has its maximum at the closed end. Antiresonance notches do not exist at the closed end, contrary to other parts of the tube. The pressure peaks of the resonant frequencies of the quarter-wave resonator tube are, however, pronounced at the closed end. Some examples of the measured responses with the two different eardrums are shown in Fig. 14. The effect of the damping is clear at the resonant frequencies of the ear canal, where the eardrum attenuates the peak of the resonance frequency by approximately 10 dB.

3.1.2 Measured versus Modeled Frequency Responses of Unblocked ADECS

Figs. 15 and 16 compare the measured and modeled pressure frequency responses at the canal entrance and the eardrum, respectively, for a 28-mm-long undamped ADECS ear canal simulator of 8.5-mm diameter. The eardrum impedance used in the computational model was a resistance $R = 200 \, \text{M} \Omega$. The radiation impedance was as shown in Fig. 8. As can be seen, the measured and modeled responses agree well.

3.1.3 Frequency Responses of Unblocked DADEC

The free-field pressure frequency responses at the eardrum of the dummy head (DADEC), with unblocked...
ear canals, are depicted in Fig. 17. The second resonance at around 10 kHz has been attenuated compared to Fig. 14. This damping is probably due to the improved impedance matching from the ear canal through the concha and the pinna to the environment. The concha and the pinna cause a hornlike expansion of the wavefront.

The effect of the three different pinnae used in the measurements (see Section 1.3), under listening-room conditions, is depicted in Fig. 18. The overall differences
in the obtained frequency response curves are not striking considering the exaggerated differences in the physical sizes and shapes of the pinnae.

3.2 Frequency Responses of Blocked Ear Canals

3.2.1 Frequency Responses of Blocked ADECS

The frequency responses measured with the eardrum microphone and with the in-ear microphone of the EFIM earphone from the undamped ADECS with a canal length of 25 mm are depicted in Fig. 19. The graph shows a sharp antiresonance notch at approximately 2.2 kHz at the earphone microphone (canal entrance). The first half-wave resonance, which is marked by an arrow, is approximately at 8 kHz. The peak at 6 kHz is caused by the self-resonance of the earphone.

The effect of the eardrum is clear when comparing Figs. 19 and 20. The damped eardrum attenuates the peaks and notches caused by the canal resonances, especially when measured at the canal entrance. The responses at the eardrum for different canal lengths are depicted in Fig. 21. The locations of the first half-wave resonance peaks, which are marked by arrows, are determined by the length of the canal. The impedance of the eardrum affects the response for a large frequency range, whereas the length of the canal determines the response at frequencies close to 10 kHz.

![Fig. 19. Frequency responses from undamped ADECS with 25-mm canal length measured with eardrum microphone (drum) and with in-ear microphone of EFIM (entrance).](image1)

![Fig. 20. Frequency responses measured with eardrum microphone (drum) and with in-ear microphone of EFIM (entrance) from damped ADECS with 25-mm canal length.](image2)

![Fig. 21. Frequency responses measured with eardrum microphone of damped ADECS (blocked with EFIM) for different canal lengths.](image3)
3.2.2 Frequency Responses of Human Ears (Blocked)

The frequency responses of the left ears of eight test subjects measured with the in-ear microphone of the EFIM are depicted in Fig. 22. The differences between the in-ear frequency responses were significant. The responses below 2 kHz were strongly dependent on the fitting of the earphone. A loose fitting resulted in leakage and attenuated low frequencies. In addition the differences between right and left ears were interestingly large for some of the subjects. The responses from both ears of one subject (JV) are depicted in Fig. 23. The lengths of the left and right canals seem to be different, since the first half-wave resonance peaks are located at 7.3 kHz (right) and 8.3 kHz (left).

Fig. 22. In-ear frequency responses of left ears of eight test subjects measured with EFIM.

Fig. 23. Frequency responses at left and right blocked ear canal entrances of human test subject (JV).

The responses at the canal entrance obtained from real ears showed similarities with those measured from the ADECS and the DADEC. As one example of this, Fig. 24 shows the responses measured with the DADEC (with damped ADECS as ear canal) and the left ear of a human test subject (MH). The responses are similar up to 15 kHz. In this example the ear canal length of the ADECS was set to 17 mm, upon which the artificial ear adds a few millimeters, as described in Section 1.3 and Fig. 7.

3.2.3 Measured versus Modeled Frequency Responses of Blocked ADECS

Having estimated the Thévenin source model, acoustic responses to any point in the ear canal model can be
computed and compared to measured data. Figs. 25 and 26 show modeled and measured responses at 7 mm from the earphone (entrance) and at the eardrum (drum) for two different canal lengths. The resemblance between modeled and measured data is good, which shows that the model is applicable when exploring the behavior of the insert earphone connected to different kinds of ear canals.

4 SUMMARY AND CONCLUSIONS

The aim of this study was to explore the acoustic behavior of the external ear together with insert-type earphones. Understanding the individual features of listeners and how they affect the earphone-reproduced sound helps when designing earphones and using them in binaural reproduction and auralization. Insert earphones occlude the ear canal so that the effects of concha, pinna, head, and shoulders are excluded. These external parts need to be taken into account carefully in detailed auralization, but in music reproduction their individual variations are not as prominent.

In addition to the earphone driver itself, the tone color in insert earphone reproduction is dependent on the acoustic impedance of the eardrum, the size and form of the ear canal, and the leakage of the earphone fitting. The user must take great care to obtain tight fitting, because otherwise no full bass response is possible. From our measurement results we conclude that the length of the ear canal has a clear effect when determining the pressure frequency responses at the ear canal entrance and at the eardrum. In addition the eardrum impedance determines the sharpness of the resonance peaks and antiresonance notches. For a realistic model of a human ear canal, the impedance of the eardrum needs to be taken into account.

Other physical parameters, such as the shape of the ear canal and other parts of the outer ear were also studied [30], although they are not reported in this paper. Differences in shape of the outer ears are factors to be considered for accurate modeling of the outer ear. However, compared to the eardrum impedance and ear canal length, other differences were found to be of less importance.

The measurement methods and modeling techniques presented in this paper are applicable when exploring the behavior of insert earphones coupled to different kinds of ear canals. Future development of the physical simulators and the computational model presented include improved physical and computational models of the eardrum. Direct measurements of the eardrum pressure on human test subjects during in-ear headphone listening are also of great interest.

5 ACKNOWLEDGMENT

This work was supported by Nokia Corporation and project UI-ART at the Helsinki University of Technology. The authors wish to thank two anonymous reviewers for their comments.

6 REFERENCES


Fig. 25. Modeled and measured frequency responses at eardrum and at entrance of undamped ADECS with 26-mm ear canal.

Fig. 26. Modeled and measured frequency responses at eardrum and at entrance of undamped ADECS with 20-mm ear canal.


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