Modeling of external ear acoustics for insert headphone usage

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ABSTRACT

Although acoustics of the external ear has been studied extensively for auralization and hearing aids, the acoustic behavior with insert headphones is not as well known. Our research focused on the effects of outer ear physical dimensions, particularly to sound pressure at the eardrum. The main parameter was the length of the canal, but eardrum’s damping of resonances was also studied. Two ear canal simulators and one dummy head were constructed. Measurements were also performed from 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 earphones with in-ear microphones were constructed for this purpose. Physics-based computational models were finally used to validate the approach.

1. INTRODUCTION

It is well known that the outer ear contributes to the spectral shaping of sounds we hear in everyday life [1]. People have different ears and different ear canals, hence the sound pressure responses at people’s eardrums 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. The unblocked ear canal acts like a quarter-wave resonator and hence amplifies the resonance frequencies. The locations of these resonance frequencies in the frequency domain 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 from listening to loudspeakers or acoustically open headphones. The sound wave travels through the ear canal only, 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 shape of the frequency response at the eardrum [2]. Furthermore, the pressure chamber effect and the occlusion effect (emphasis of own voice) are important factors regarding insert earphones.

1.1. Goal of the study

Physical simulators, such as ear canal simulators and dummy heads, have been used widely as substitutes of human test subjects. (An overview of ear simulators is presented in Subsection 1.2.) The accuracy to 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. The goal of our research was to learn what kinds of effects the differences in physical parameters of the outer ear has to its frequency response, both for open and occluded canal. We aimed at constructing a physical dummy head with adjustable ear canal features and having as accurate human-like acoustical behavior as possible. Furthermore, we aimed at putting up physics-based computational models for mathematical understanding of the problem.

Simple tube-like adjustable ear canal simulators were found useful in determining the effect of the ear canal length (details in Section 3). The frequencies of the ear canal resonances and antiresonance notches found in measurements were the same as those calculated with physics-based formulas. The acoustic 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 the human peripheral hearing (details in Section 3). We were hence able, with good accuracy, to study the effect of the differences in human ear canal lengths and eardrum impedances.

Physics-based computational modeling with lumped and distributed elements was also applied to open and closed ear canal simulation (details in Section 4). For a simplified open ear canal such 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 from the physical simulators and real human ear canal up to 10-15 kHz. These modeling efforts help us to understand better how the insert earphones work for individual listeners.

1.2. Overview of ear simulators

Originally ear simulators were primarily targeted for hearing aid and audiometry headphone calibration. All calibrators were designed to mimic the acoustic load of real ears, or at least provide a load in the same range as that of a real ear. Nowadays, ear simulators are increasingly used for headphone and mobile handset calibration as well. Ear simulators should be separated in three different categories: couplers, ear simulators, and head and torso simulators (HATS).

Couplers are normally small volumes offering a reasonable load for hearing aid and insert type of headphone measurements. The sound pressure developed by an earphone is not, in general, the same as in a person’s ear. However, these kind of coupler measurements offer a practical and simple way to compare different kinds of earphones. Most of the couplers do not simulate the ear canal and the measurements do not show the resonance behavior of a real ear. This limits the usable upper frequency for the coupler measurements for some applications. One common problem with couplers, for insert headphone usage, is that the coupling is assumed and designed to be very tight, with no leaks. For insert headphones in real usage this is rarely the case, and therefore coupler measurements tend to exaggerate low frequencies.

Ear simulators for insert type of headphones and hearing aids offer a more realistic representation of a human ear. Ear simulators are designed to have standing wave patterns similar to that of a real ear. The impedance is also designed to mimic the real ear impedance. Occluded ear simulators (commonly based on the ANSI S3.25 [4] and IEC60711 [5] standards), define the acoustic transfer impedance at the eardrum. The standards are defined in the frequency range of 100 Hz - 10 kHz, thus the corresponding commercial simulators are calibrated in this frequency range as well. The simulators offer a fairly realistic representation of a human ear characteristic but one of the main problems with these simulators is the lack of a realistic ear canal entrance.

ITU-T has published a recommendation (ITU-T P.57 [6]) that extents the IEC60711 standard by combining different types of pinnae with the simulator. The ear canals
recommended in the 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 exaggerated bass response. There are also recommendations for leakage in the headset coupling but due to the recommended construction, the leakage simulators are only suitable for supra-concha or larger headphones.

2. ADJUSTABLE SIMULATORS

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 manufactured for these purposes are presented in this paper.

2.1 Ear canal simulators

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 skin on the canal walls has little or no effect on the acoustics of the canal. Hence, a straight rigid wall tube acts as a good starting point when building physical ear canal simulators.

For better understanding of the acoustic behavior of the ear canal we needed to study the frequency responses of a large variety of different sizes of artificial ear canals. For that reason, we built a new device, the ADjustable Ear Canal Simulator (ADECS), which is depicted in Fig. 1. The ‘ear canal’ is made of a hard plastic tube with a diameter of 8.5 mm and a total length of 49 mm. The canal entrance is simply an open round hole. The ‘eardrum’ is made of a movable plastic piston so that the simulator canal length can be adjusted from 0 mm to 39 mm. A millimeter scale is attached to the side of the canal for easier control of the canal length. In the center of the piston is a round hole, where a miniature microphone is fitted. The position of the eardrum microphone is adjustable by hand. It can be located at the eardrum piston level or pushed out as far as 57 mm into the canal towards (and outside of) the canal entrance. The exact position of the microphone is supervised with a millimeter scale at the back end of the simulator.

A simulator with a stiff eardrum has a frequency response that is slightly different from that of a human ear. Resonance frequency peaks and antiresonance notches are sharp when measured with rigid wall simulator, whereas with real ears they are smoother. For achieving a better analogy with the human ear a new artificial eardrum was manufactured. The piston used in ADECS was replaced with a piston made of aluminum and consisting of the microphone and an adjustable Helmholtz resonator. An opening for the resonator’s neck was drilled on the piston and the resonator’s cavity was mounted behind it. A diagram of the eardrum (and simulator) is depicted in Figure 2. The position of the eardrum piston is adjustable from 0 mm to approximately 40 mm. In addition, the volume of the resonator’s cavity can be changed by sliding the back wall of the cavity. The Helmholtz resonator acts as a damper at the eardrum as some of the sound energy inside the ear canal is dissipated in the resonator. Its resonance frequency was initially set to approximately 2 kHz. In order to spread the damping effect to a wider frequency range, absorbing material was added inside the resonator’s cavity.
2.2 Dummy head with adjustable ear canals

An ear canal simulator without pinna and head is suitable only for occluded ear measurements. For measurements in free field and a listening room the next step in our research was to build a complete dummy head. A manikin head was modified by replacing its ears with acoustically realistic artificial pinnae and fabricating a torso with dimensions of an adult human as depicted in Figure 3. The pinnae were mounted so that they were exchangeable and ear canal simulators (ADECS) were attached in the same manner. The total length of DADEC’s ear canal is the length of the simulator’s canal added with approximately 6 mm (blocked canal) to 12 mm (open canal) since the concha of the artificial ears extends the ear canal significantly. The dummy head was later used in various free field and listening room measurements.

3. MEASUREMENTS ON THE ACOUSTIC PROPERTIES OF THE OUTER EAR

The acoustic behavior of the outer ear and the ear canal were studied through extensive measurements with ear canal simulators, the dummy head, and human test subjects. The goal was to learn how the outer ear behaves with and without insert earphones.

For measuring 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 Figure 4. When the acoustic 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. Impulse response measurements were made with log sine sweep technique [7].
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Measured using the movable eardrum microphone of the simulator.

Transfer functions from loudspeaker to the ADECS ear canal entrance are depicted in Figure 6. Two different canal lengths (18 and 23 mm) were used. The two first peaks of the resonant frequencies of the quarter-wave resonators are at approximately 3.1 and 9.5 kHz with the 23 mm canal, when the response is measured at the canal entrance (Fig. 6). In the frequency domain, directly after the peaks follow the anti-resonance notches. 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, as in 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. The ADECS was 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 with 1 mm steps from 0 to 30 mm while the pressure frequency responses were measured with the eardrum microphone. Some examples of these responses are depicted in Figure 7.

The eardrum is not a rigid straight wall at the end of the ear canal. It participates in the shaping of the pressure frequency response of the ear canal in a complex way. The damped eardrum for ADECS was manufactured as we wanted to obtain frequency responses that are close to those measured with human subjects.

To investigate responses at the eardrum of the dummy head (DADEC) with the damped and undamped eardrum simulators (ADECS) a set of measurements was performed. The DADEC was placed directly facing (azimuth = 0°) a loudspeaker at a distance of 180 cm in a listening room. Each eardrum was tested with DADEC consecutively. Comparison between the frequency responses of the two different eardrums, in similar listening room environments, is shown in Figure 8. There is a significant difference in the responses measured with each of the eardrum microphones. The effect of the damping is clear at the resonant frequencies of the ear canal, where the eardrum attenuates the peak of the resonant frequency by 6 to 10 dB. Additional measurements with the damped eardrum were made with different ear canal lengths. The pressure frequency responses at the eardrum are depicted in Figure 9. Compared to previous measurements with the undamped eardrum, the quarter-wave resonant frequency peaks are significantly softer.

Three different fabricated pinnae were attached to DADEC with the undamped ADECS as ear canal in sim-
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Fig. 9: Responses with various ear canal lengths measured at the eardrum of DADEC (with damped ADECS) in the listening room.

Fig. 10: The effect of the size and shape of the pinna. Three different fabricated pinnae attached to DADEC with ADECS as ear canal. Responses measured from the eardrum.

Fig. 11: DADEC eardrum responses in a listening room (azimuth 0°) and in an anechoic chamber (azimuth 30°). The ear canal is 18 mm long damped ADECS.

ear canal, the acoustic behavior of the ear canal is very different when it is blocked with e.g. an insert earphone. All of the outer parts of the auditory system act together to form the total transfer function when the signal is played with a loudspeaker. In a listening room, with the ear canal left open, also the acoustics of the room is shaping the frequency response of the system, that is, shaping the transfer function from loudspeaker to eardrum. When listening e.g. to music with 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 hearing 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.

The behavior of the blocked ear canal was studied through extensive measurements both with simulators and human test subjects. One of the most important characteristics of the ear canal is its length, the effect of which was in the center of our research. In addition, the effect of the impedance of the eardrum was studied with simulators and a human test subject.

During the research, several measurements were performed with EFIM mounted to an ear canal simulator as depicted in Figure 12. A log sine sweep was reproduced with EFIM and recorded with EFIM’s in-ear microphone and the eardrum microphone of 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 with 1 mm steps from 5 mm (minimum) to 40 mm. In Figure 13 the responses from ADECS with a 20 mm ear

3.2. Frequency responses of blocked ear canals

Compared to normal listening conditions with unblocked ear canal, the acoustic behavior of the ear canal is very different when it is blocked with e.g. an insert earphone. All of the outer parts of the auditory system act together to form the total transfer function when the signal is played with a loudspeaker. In a listening room, with the ear canal left open, also the acoustics of the room is shaping the frequency response of the system, that is, shaping the transfer function from loudspeaker to eardrum. When listening e.g. to music with 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 hearing 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.

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Fig. 12: Diagram of measurement setup where EFIM is fitted to ADECS and the length of the canal is adjusted by moving the eardrum piston.

Fig. 13: Pressure frequency responses of undamped ADECS (Adjustable Ear Canal Simulator) with canal length of 20 mm measured with the eardrum microphone (drum) and with the in-ear microphone of EFIM (entr).

canal are depicted. The graph shows the antiresonance notch at approximately 1.6 kHz at the earphone microphone (canal entrance). The first half-wave resonance is approximately at 10 kHz.

A similar set of measurements was performed with the damped eardrum. The length of the simulator’s canal was adjusted as frequency responses were measured using the eardrum microphone and the in-ear microphone. The damped eardrum smoothens the antiresonance notch around 2 kHz, as can be seen from Fig. 14. In Fig. 15 responses at the eardrum were measured using different canal lengths. The half-wave resonance peaks move in the frequency domain in unison with the varying canal length.

With the EFIM it was easy to measure the pressure frequency responses also from real 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 participated in these measurements, both ears of whom were measured. The differences between individuals were significant, and in addition, the differences between right and left ears were interestingly outstanding with some of the subjects. The

Fig. 14: Pressure frequency responses of damped ADECS with canal length of 20 mm measured with the eardrum microphone (drum) and with the in-ear microphone of EFIM (entr).

responses from measurements with Subject 5 are depicted in Figure 16. The lengths of the canals seem to be different, since the first half-wave resonance peaks are located at 7.3 kHz (right) and 8.3 kHz (left).

The responses obtained from real ears showed similarities with those measured from ADECS. As one example of this, Fig. 17 shows the responses measured with
Fig. 17: Ear canal frequency response measured at the left ear canal entrance of Subject 3 compared with similar measurement from DADEC.

Fig. 18: Circuit model for the open ear canal.

DADEC (with damped ADECS as ear canal) and the left ear of Subject 3. In this example, the ear canal was set to 22 mm, upon which the concha adds a few millimeters. Hence, the total ear canal length of DADEC, in this case, was approximately 28 mm (see Section 2).

4. COMPUTATIONAL MODELING

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

4.1. Open ear canal modeling

An open ear canal without a dummy head is simply a terminated tube. It can be modeled as a system composed of approximate eardrum impedance, 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 [8, Ch. 5] due to the reciprocity principle [9, Ch. 7]. The equivalent circuit applied is shown in Fig. 18.

Figures 19 and 20 show a comparison between the measured and modeled responses at the canal entrance and the eardrum, respectively, for a 23 mm long ADECS ear canal simulator with diameter of 8.5 mm. The eardrum impedance used in the computational model was an acoustic resistance and the radiation impedance was as shown in Fig. 18. As can be seen, the measured and modeled responses agree well.

4.2. Acoustic Thévenin Equivalent of the Earphone

To enable computational modeling of 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 electro-mechanic-acoustic equivalent circuit, it is enough to estimate a Thévenin type of source model with voltage-to-pressure source term $P_S$ and acoustic source impedance $Z_S$, as illustrated in Fig. 21. For a given acoustic load $Z_L$, the pressure response $P_L$ delivered by the source is

$$P_L = \frac{Z_L}{Z_S + Z_L} P_S \tag{2}$$

For headphone modeling in general, see [10] and [11].
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 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 of the mentioned conditions 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, 12–24]. 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 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 [25].

A commonly used method of calibrating the impedance probe is to load it by several hard-walled closed tubes or cavities, for which there exists an analytically computable impedance expression [14, 16, 19]. 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 [14, 16].

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 air density, and $c$ is speed of sound. A tube length of about 2-3 meters is long enough when the back-reflection from the open end is removed by temporal windowing of the reflection function.

With $M = 5$ calibration loads $Z_i$ of diameters from 5 to 10 mm and measuring related pressures $P_i$, the source terms $P_S$ and $Z_S$ for the earphone driver were solved in least squares sense from the overdetermined set of equations

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

(3)

using pseudo-inverse (function `pinv` in Matlab). Figure 22 shows the magnitude responses of the measured pressures $P_1$ and Figs. 23-24 plot the magnitude behaviors of the source pressure $P_S$ and the impedance $Z_S$, respec-
Fig. 25: Magnitude response at 7 mm from the earphone in 26 mm long ADECS simulator: (blue) from modeling and (red) from measured data.

Fig. 26: Magnitude response at eardrum position in 26 mm long ADECS simulator: (blue) from modeling and (red) from measured data.

4.3 Interaction of driver and ear canal

Having estimated the Thévenin source model, acoustic responses to any point in the ear canal model can be computed and compared to measured data. Figure 25 depicts the modeled vs. measured response at 7 mm from the earphone and Fig. 26 shows the corresponding responses at the eardrum. Measurements are made with the ADECS simulator with canal length of 26 mm. The resemblance between the modeled and measured data is good so that the model is applicable in exploring the behavior of the insert earphone connected to different kinds of ear canals.

5. SUMMARY AND CONCLUSIONS

The aim of this study was to explore the acoustic behavior of the external ear together with insert type of earphones. Understanding the individual features of listeners and how they reflect to earphone-reproduced sound helps in 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 parts need to be taken into account carefully in detailed auralization, but in music reproduction their individual variation is not as prominent, as can be concluded from Fig. 10.

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 of 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 in 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. According to our experiments, the variation in eardrum impedance can have even a larger impact than the canal length.

Other physical parameters, such as the shape of the ear canal and other parts of the outer ear were studied also [3], although they are not reported in this paper. It was found that differences in the shape of the outer ear are a factor to be considered when modeling the outer ear. However, in comparison to the eardrum impedance and varying ear canal length, other differences were found to be of less importance.

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7. REFERENCES


