Modeling the attenuation of a loosely-fit insert headphone for augmented reality audio

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ABSTRACT

In Augmented Reality Audio (ARA) headsets a small microphone is integrated with an earphone. In a normal listening situation the microphone signals are directly connected to the earphones, thus the sound wave passes the headset electrically from the microphone to the earphone. However, headsets do not seal the ear canal completely, and a portion of impinging sound wave is transmitted to the ear canal as leakage around and through the headset. The characteristics of these leakage paths must be known in order to make the ARA-headset acoustically transparent. In this paper a model for leakage in loosely-fit insert headphones is introduced. The model is compared to measurement results performed with an artificial head and ear simulator. The results show that the model is capable of predicting the acoustics behavior of leakage with different types of loosely-fit insert headphones in the frequency range up to 6-7 kHz.

1. INTRODUCTION

In augmented reality audio (ARA) the user’s natural (real) acoustic environment is enriched with virtual audio objects. These sound objects can have fixed positions in the environment, i.e., they do not move even though the user is moving. The virtual audio events are played to the user through his or her own special headset, which also has embedded microphones [1]. These microphones allow binaural capturing of surrounding sound, and also the user’s own voice. However, as the headsets are either inserted in the ear-canal or placed at the entrance of the ear-canal, they interfere listening to surrounding sounds. One way to overcome this problem is to feed the microphone signals directly to the earphones (similar to hearing aids), and thus reproducing a pseudo-acoustic version of the surrounding sounds to the user. However, depending on the headset design, some portion of the sound always leaks around or through the headset.

The electrically transmitted sound and the leaked sound are summed inside the ear-canal. This results in a colored sound signal, thus deteriorating the usability of an ARA headset. Naturally, the goal of an ARA-headset is to produce the same sound signal inside the ear-canal as it would exist without the headset, i.e., the headset would be acoustically transparent.

Fig. 1: A typical earphone used with portable sound devices.

Knowing the acoustic behavior of a headset placed in the ear enables creating realistic and natural sounding virtual sound events. This can be done, e.g., by using the user’s own HRTFs [2, 3]. If the leakage paths around and through the headset are known, the sound going electrically through the headset can be modified to compensate the effect of the leakage sound, thus producing an unaltered sound signal at the eardrum. However, different types of headsets have very different types of leakage behavior. Some insert-type headsets seal the ear-canal effectively resulting in very little leakage around the headset, whereas some earbuds fit loosely on the entrance of the ear-canal and most of the sound leaks around the
headset.

Design-wise, some insert-type headsets are very similar to certain types of earplugs for hearing protection, and thus the acoustic characteristics [4, 5] should be somewhat similar and applicable to insert headphones, as well. In hearing aid research, a lot of effort has been put in earmold acoustics and modeling different aspects of a hearing aid (see, e.g. [6, 7, 8, 9, 10, 11]). However, these studies mainly concentrate on very tight fitting earmolds or earplugs, whereas common portable headphones fit fairly loosely in the ear. There is also quite extensive amount of literature related to circum- and supra-aural headphones (see, e.g., [12, 13, 14, 15, 16]), but other than the works of Poldy [17], there is very little literature on loosely-fit type of insert headphones. Fig. 1 illustrates an example of this type. This is a very popular design, most often included with portable audio devices. The simple and practical design also lends itself to an ARA usage. By embedding a pair of microphones in the headphones, this type of a headphone could be used as a practical headset for Augmented Reality Audio.

This paper studies the acoustic characteristics of a loosely-fit insert headphone fitted in an ear (from this on term ‘insert headphone’ will be used to mean a loosely-fit insert headphone, unless otherwise stated). The electro-acoustic aspect of insert headphones will not be considered, only the acoustic behavior due to the headphone’s mechanical design. In the paper, a model for acoustic loading of the ear canal due to an insert headphone, is introduced. Later on, this information is used when designing the filtering needed to compensate the effect of the leakage sound, thus making the headset acoustically transparent. The paper is structured as follows. Chapter 2 first introduces the main acoustic components related to this kind of insert headphones. In Chapter 3 a lumped element model of the headset is introduced, and in Chapter 4 the model is compared with measurements performed with an ear simulator. Finally, Chapter 5 discusses the results.

2. ACOUSTICS OF A LOOSELY-FIT INSERT HEADPHONE

The insert earphone type, under study in this paper, is loosely placed at the entrance of an ear canal. The coupling of the headphone to an ear canal is fairly loose and commonly the leakage path between the headphone and the skin is quite open. In addition, there are other leakage paths, as well, as depicted in Fig. 2. Some sound is always transmitted as bone and tissue conduction, although this sound is attenuated tens of decibels [18]. Also, some sound will travel through the headphones. Almost every insert headphone design has some openings at the back of the casing that enable sound transmission through the headphones. Furthermore, the elasticity of the skin allows the headphone to vibrate and the sound wave transmits to the ear canal by means of headphone vibration, as well. The leakage is a reciprocal phenomenon, and information studied in the paper may also be used to inspect the acoustic load due to leakage seen by the headphone.

2.1. Leakage between the skin and the casing

Fig. 3 shows a close-up view of an insert headphone placed on an artificial ear. The opening of the ear canal is visible through the headphone. The figure nicely illustrates the characteristics of an insert headphone fitting. Firstly the headphone is not centered around the ear canal, thus the path length from inside the ear canal to outside the headset varies along the circumference of the headphone. Secondly, at some parts, the headphone fits tightly to the skin and at some parts there is a clear opening to the ear canal underneath the headphone. Acoustically, this leakage path can be considered as a one wide and thin slit around the headphone, or as a number of narrower slits in parallel, opening from the ear canal entrance outside the headphone [15].
As long as the wavelength is long compared to the dimensions of the leakage path, the leakage can be modeled with a simple lumped element circuits shown in Fig. 4. On top, the leak is modeled with a single branch of a resistance and inductance in series. On bottom, the leak is modeled with a number of thinner leaks in parallel. Inductance corresponds to the mass of the air that fits inside the slit and uniformly vibrates according to the sound pressure differences at either side of the slit. Resistance is due to viscous forces at the boundaries of the slit. At higher frequencies, when the wavelength approaches the slit dimensions, a lossy transmission line would be more applicable model for the slit. One of the drawbacks in this kind of a leakage path is that it’s acoustic qualities, both acoustic inductance and resistance, depend on the geometry of the ear, which varies between individuals. As a result the acoustic characteristics of the headphone vary between different users, as well.

For this work, the leak was considered as a one wide leak around the headset. The diameter of an insert headphone is commonly in the range of 14-18 mm, so the perimeter of the headphone face (width of the slit) is around 5 cm. The depth of the slit is hard to define due to irregular shape of individual ear canal entrances and conchas. As a rough estimate the slit depth and height were first set to 5 mm and 0.5 mm, respectively. This was used as an initial value, and the final model component values were hand tuned to match the measurement results. The final component values for the model are shown together with the complete model in the following chapter. For derivation of the model component values, please see [12].

### 2.2. Clothing around the headphone

Some insert headphones are available with a foam-like porous cloth covering the headphone casing. The cloth has two main effects on the acoustics of a headset. First, the leakage paths between the skin and the headphone are filled with foam-like porous material, i.e., effectively the one open slit is now comprised of a number of small holes. As a result, as the holes in the cloth are so small, the leakage path becomes almost purely resistive. Sec-
ondly, the acoustic qualities of the slit become less sensitive to fitting of the headphone, and to differences in the ear geometries. These both issues increase the predictability of the headphone’s acoustics behavior in an ear between different users.

2.3 Vibrating headphone

The insert headphone is designed to fit inside the concha, as seen in Fig. 3. However, the elasticity of the skin allows the headphone to vibrate. The vibration of the headphone depends on the mass of the headphone, and the elasticity and the damping of the skin. Fig. 5 shows a lumped element model of the headphone vibration. Inductance corresponds to the mass of the headphone, and capacitance and resistance correspond to the elasticity and damping of the skin, respectively.

2.4 Sound transmission through the headphone

Most insert headphones have some sort of openings at some parts of the casing. These can be, e.g., simple holes, covered with clothing inside the enclosure, or bass tubes. Every opening allows sound waves to enter the back chamber of the headphone. Depending on the transducer design there are some openings from the back of the transducer to the back of the membrane and the voice coil cavity. Furthermore, in front of the membrane there is often a grille with holes to protect the membrane and then, maybe another finer grille, letting the sound go outside the headphone. Fig. 6 shows a simplified view of an insert headphone, and the sound transmission paths through the headphone. The detailed design of the sound transmission paths vary between different headphone models. However, these components are practically always present in one form or another.

Fig. 7 shows a lumped element model for sound transmission through the headset. The model is slightly simplified from the actual headphone design. The openings at the back of the casing are modeled with a single branch of series inductance and resistance. Also, there is no bass tube in the model, as there was none in the headphones measured for this study. The cavities behind the membrane (and between the voice coil) are modeled with a single capacitance, though the actual geometry is always more complex. However, the purpose was to keep the model more applicable to various headphone models. When finding the component values for the model, the physical parameters of the headphone parts were first measured, if possible. Then the model was fine tuned in parts where exact measurements were hard to perform.

2.5 Bone and tissue conduction

Bone and tissue conduction is always present in all listening situations. However, tissue-conducted sound is attenuated tens of decibels [18]. With insert headphones the leakage around and through the headphone is so prominent that bone and tissue conduction can be safely omitted from the model. With tightly fitting insert headphones, where the attenuation of surrounding sounds is considerably higher, the bone and tissue conduction must be taken into account. Therefore, bone and tissue conduction will not be considered in this model.

3. MODEL FOR INSERT HEADPHONE LEAKAGE

By combining all the components introduced in the previous section, a model for the leakage of an insert headphone can be composed. Fig. 8 shows a complete model for the leakage. Physical values of the headphone parts, used in the example model, are listed in Table 1 and the corresponding model element values are given in the model. Membrane weight, compliance and vacuum resonance frequency are estimates, based on [17]. Also, usually openings in the headphone casing, and at the back of the transducer are covered with porous clothing. The values for such openings were estimated from similar openings without clothing. The correction was performed by increasing the resistance and decreasing the inductance accordingly. Furthermore, the leakage path between the skin and the headphone is hard to measure, and therefore the geometry of the leakage slit was also estimated based.
on visual inspection of the fitting. In the middle of the model, the SUB1 is a sub-circuit containing a model for the openings at the back of the transducer. There was fifteen holes around the transducer, so the sub-circuit has 15 models for a hole connected in parallel. The sub-circuit was used for clarity.

Two different ear models were used when evaluating the model. One, and a simpler ear model, was comprised of a lossless 20 mm long transmission line terminated by a series RCL-circuit to model the ear drum impedance\(^1\). The other, and a more realistic model, was based on an IEC711 ear simulator.

A sound wave approaching the headphone can be modeled by a voltage source with a certain internal impedance. Due to reciprocity, the internal impedance is the same as the radiation impedance of the leak component, as if it would be radiation sound. Radiation impedance of the leakage path openings was divided in two different branches. Vibrating headphone and the leakage between the skin and the headphone was assumed to be one uniform piston radiating on an infinite plane. The surface of the headphone was considered as the radiator (piston). The small opening at the back of the headphone are so small, that they were assumed to radiate separate from the to other parts, thus having a radiation impedance of their own.

Fig. 9 shows the attenuation of an example insert headphone, by using both ear simulator models. The plots

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\(^1\)\(R = 40 \, \text{M}\Omega, L = 100 \, \text{H}, \text{and} \, 6.5 \, \text{pF}\).
Fig. 9: Transfer function estimated by the model in Fig. 8. Top plots are modeled with a simple RCL ear drum impedance, and the lower plots are simulated with an IEC711 ear simulator model. Solid line: Headphone without a wool-like cloth. Dashed line: Headphone with a wool-like cloth covering the headset.

on the top are computed with the simple RCL ear canal model, and the plots below are obtained by using the IEC711 ear simulator model. For both ear simulators, the attenuation was simulated with and without porous clothing covering the headphone. The clothing was modeled by adding a series resistance in all of the leakage branches in the model. A cloth placed over the headphone affects all leakage branches. The slit between the headphone and the skin is filled with cloth, front grille is covered with the cloth, and the fitting is also affected by the cloth.

The attenuation was computed by comparing the simulated ear drum pressures with the headset model to a model where the pressure source with radiation impedance was directly connected to an ear simulator.

One thing should noted about the model and the estimated attenuation responses. The model does not take the effect of the pinna into account. The headphone fills the concha partially, and for this reason the concha resonance is not present, or is at least affected, when the headphone is fitted. This effect is not counted in the model.

4. MEASUREMENT SETUP

A group of insert headphones, shown in Fig. 11, were measured to verify the introduced model. The measurements were performed with a Brüel&Kjær Head And Torso Simulator (HATS Type 4128) in an anechoic chamber. The HATS is a manikin with realistic pinnae and IEC711 middle ear simulators (Type 4158).

To yield the frequency responses of the leakage from outside the headset into the ear canal, two different measurements are needed:

1. Transfer function $H_{\text{woh}}(f)$ from outside to inside the ear canal without a headset
2. Transfer function $H_{\text{wh}}(f)$ from outside to inside the ear canal with a headset

The leakage is then computed as a complex division in frequency domain, given as:

$$H_l(f) = \frac{H_{\text{wh}}(f)}{H_{\text{woh}}(f)}, \quad (1)$$

where $H_l(f)$ is the frequency response of the leakage, and $H_{\text{wh}}(f)$ and $H_{\text{woh}}(f)$ corresponds to measurements 1 and 2 in the above list, respectively.

A Genelec 1030A loudspeaker was placed 2.5 meters in front of the manikin. Fig. 10 illustrates the measurement setup. First, the measurement system was pre-calibrated so that the distance from the loudspeaker to the left and to the right ear simulators was the same. Then, frequency
responses to both ear simulator microphones were measured, and the difference of the responses was used to match both channels.

During the measurements, a headset was placed in the right ear of the manikin. By using a logarithmic sweep, impulse responses were simultaneously measured for both ears. As a result $H_{\text{wh}}(f)$ and $H_{\text{woh}}(f)$ were obtained. For each headset the measurement was repeated four times. Before every measurement, the headset was first removed and then refitted. This was done to see how refitting affects the results. When changing to the next headset type the calibration of the measurement system was always checked.

### 4.1. Frequency responses

Fig. 12 shows transfer functions of the measured insert headphones, as given in Eq. (1). Each headphone was measured four times, with and without the clothing placed over the casing. Except for the $hp09$ (without clothing), all the headphones were fairly insensitive to refitting. The variation in $hp09$ might be due to a shaped headphone face plate. The face plate was formed to improve the fitting of the headphone to the shape of a concha and the ear canal entrance, which can be seen as increased attenuation in some measurements. However, a
slight misplacement of the headphone affects the attenuation considerably. The clothing seems to make the headphone slightly more insensitive to fitting.

The mean of the measurements are presented in Fig. 13. The measurement data is plotted with a solid line, and a corresponding model is shown with a dashed line. The model component values for the models were measured from corresponding headphones. However, some of the model parameters had to be estimated as there was no way to measure them accurately. The simple RCL-ear model was used for the simulations.

Except for the hp09, the model was able to predict the measurement data up to about 5-6 kHz. For the hp09, the model was not able to track the measurement data. The main differences in this particular headphone, compared to other headphones, were that the fitting of the headphone was tighter compared to the others, and also there were no holes in the back of the transducer, thus the leakage through the headphone differed from the others, as well.

5. CONCLUSIONS AND DISCUSSION

This paper has introduced the basic leakage mechanisms related to insert headphones. The lumped element model is capable of predicting the leakage up to 6-7 kHz. The model also illustrates how different components in the headphone affect the leakage behavior of a headphone. In the following, some of the limits and drawbacks of the model are discussed.

The model does not take the effect of the pinna, and especially the effect of the concha, into account. When the headphone is placed in the ear the concha is almost fully filled by the headphone, and the acoustic characteristics of the concha are considerably altered. This might be one reason for poor modeling results in the frequencies above 7 kHz in Fig. 13.

The lumped element modeling assumes that the wavelength is always much longer than the dimensions of the components. A rule of thumb could be that the wavelength should be ten times the component dimension. The leakage paths between the skin and headphone, which is one of the longest acoustic components in an insert headphone, are in the range of 5 mm. By the 'tenth of a wavelength'-rule, this sets the high frequency limit of the model to 6.8 kHz.

The lumped element model for holes and slits are comprised of an inductance and a resistance in series. Above a certain cut-off frequency, based on the diameter of the opening, the resistance is frequency dependent by $\sqrt{f/f_0}$, where $f_0$ is the cut-off frequency. In the openings in an insert headphone the cut-off frequency is in the range of few hundred Hertz. The frequency dependence is not taken into account in the model and this causes some error in the higher frequencies.

Acoustic characteristics of some of the components in the model are hard to measure. Compliance of a membrane or skin are examples of such components. Therefore, some model components have to be estimated, either manually or, e.g., by curve fitting the model data to measurements.

6. ACKNOWLEDGMENT

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7. REFERENCES


