From concha to eardrum - extended abstract

Acoustics of the exterior ear and the influence of hearing protection / earbuds

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Short abstract

In order to protect the eardrum from unwanted contact, it is placed inside of the head. Between the concha and the eardrum is a small channel, called the ear canal. This channel introduces a frequency dependent amplification / attenuation of the sound. These days it is common to put some device inside of the ear canal. Examples are hearing protection and wireless earphones. The consequence of, this at least partly, occlusion of the ear canal is that the frequency response is altered. At the least the typical quarter wavelength resonance of the ear canal is altered.

In a well designed in-ear acoustic product, this change of the ear canal frequency response is tuned to create a desired response, to alleviate part of the change introduced.

In the presentation and extended abstract we will elaborate on simulation and measurement methods for the ear canal transfer function. Shown applications are the design of in-ear hearing protection and earphones.

Contents

1 Introduction and definitions

As the eardrum is a sensitive piece of mechanics, nature took care to properly protect it from the outside world. Between the eardrum and the auricle, a canal runs inwards into the head, which is logically called the ear canal. Fig. 1 shows a schematic of the ear canal.

Fig. 1 also shows three red points of importance. The first is the eardrum reference point (DRP), located at the position of the eardrum. The eardrum is a small and thin membrane that separates the ear canal from the middle ear cavity. The middle ear cavity has a vent to the outside world (Eustachian tube), that is only open at subsonic frequencies, with the main function of static pressure relief. The eardrum picks up the acoustic pressure at this DRP for further processing.

The second point is the ear entrance point (EEP), located at the entrance of the ear canal. This point is located in such a way, that all effects of the head on the acoustic field are already accounted for. The presence of the ear canal locally affects the acoustic field, which results in a relatively strong difference in the acoustic pressure between the entrance of the ear canal and somewhere else at the concha. The concha is the inner plane in the auricle that is the closest to the ear canal. The last point is the ear reference point. It is located sufficiently far from the EEP, to give a measure of the acoustic pressure field *as if the ear canal was not present*, but close enough to be a good measure of the acoustic pressure at the outside of the ear.

Note that the acoustic pressure at these three points only varies significantly above 1 kHz, as will be shown further on. Below, say, 200 Hz all these acoustic pressures effectively coincide.

In blue, a reference plane is depicted. This plane is typically used as the separation plane between the unaffected part of the ear canal, called the residual ear canal, and the affected part. The afffected part is filled when a person inserts a device in the ear canal, see Fig. 1, right side.

In modeling and measuring in-ear effects, we assume that the ERP acoustic pressure gives an independent measure for the acoustic field outside of the ear. The ERP pressure is assumed to be independent on what one inserts in the ear canal. Note that this is not necessarily valid, especially for larger earpieces.

The topic of this masterclass is how the DRP pressure is related to the ERP pressure, when affected by changes to the ear canal. A nomenclature of all used symbols is given on page 13.

2 Acoustic aspects of the ear canal

No ear is the same, which is challenging from a design and measurement point of view. In an attempt to enable reproducible measurements, research efforts have been put in developing ear simulators, which are supposed to be an acoustic equivalent of the average human ear,. In this section we will elaborate on the common denominator of how all human ear canals behave.

As the eardrum and side walls of the ear canal have a finite acoustic impedance, a mechanical shape with the same geometry would not have the same acoustic behavior as a real ear. However, some acoustic features can be derived from its dimensions. Fig. 2 shows some cross sectional shapes of the ear canal for different persons. A typical length of the ear canal is ~ 3 cm. The diameter can be set around ~ 7.5 mm. These are rough values.

Now, if we assume that these dimensions are correct, and we also assume the ear canal is a prismatic duct with hard walls, a simple acoustic model can give some first clues of the acoustic features of the ear canal. Because the diameter is only 7.5 mm, the cut-on frequency for for non-planar modes[1, p. 329 and around] is $f_c = c_0/1.7D \approx 27$ kHz. Hence, we safely assume plane "plane" wave propagation in the whole audible range. Note that plane is between apostro-

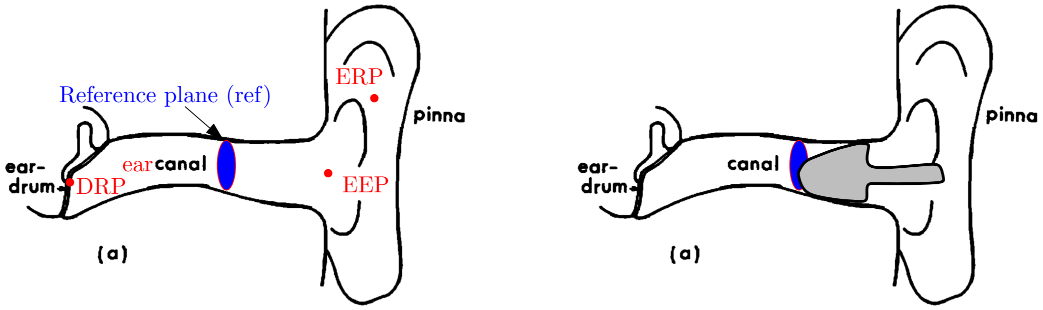

Figure 1 – Left: schematic of the ear canal. Picture from [9], red and blue annotations by this author. Right: schematic of ear canal filled with earplug.

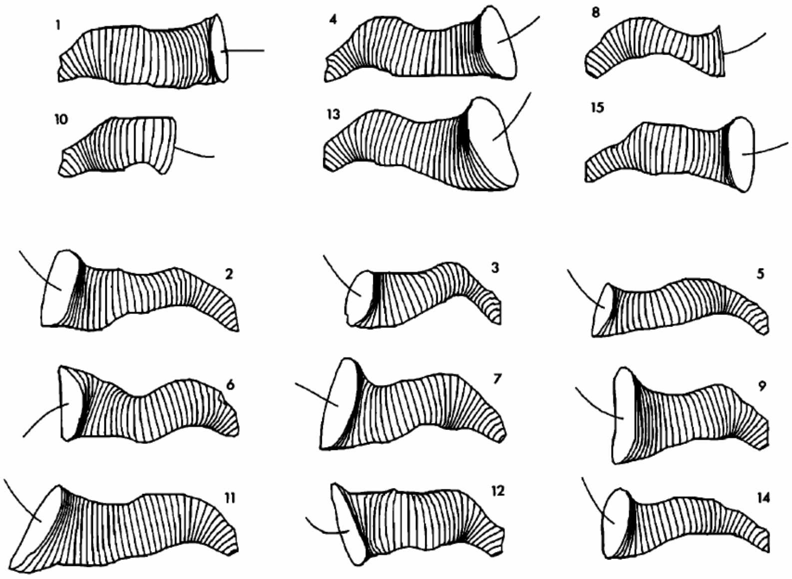

FIG. 9. Comparison of the 15 ear canal molds studied. For each canal, the cross-sectional slices determined from the analysis procedure are shown. Canals from the left ear (1, 4, 8, 10, 13, 15) and from the right ear (2, 3, 5, 6, 7, 9, 11, 12, 14) are grouped separately and shown with approximately the same orientation (posterior view). The scale is identical for all canals.

Figure 2 – Figure taken from Stinson et al.[9]

phes, as the actual ear canal is far from a prismatic cylinder.

If we neglect the damping and end-effects for now, this means the frequency domain pressure at the eardrum can be described by:[1]

$$p_{\mathrm{DRP}} = \frac{p_{\mathrm{ERP}}}{\cos(kL)}, \tag{1}$$

where $k = \omega/c_0$, and L is the length of the prismatic cylinder from EEP to the DRP. Clearly, p_{DRP} is singular when $kL = \pi/2 + n\pi$; $n \in \mathbb{N}$. Hence when the frequency equals f_n, where

$$f_n = \frac{c_0\left(\frac{1}{4} + \frac{1}{2}n\right)}{L}, \qquad n = 0, 1, 2.. \tag{2}$$

we have a resonance. f_0 is called the quarter wavelength resonance. Based on the length of 30 mm, we find $f_0 \approx 2.8$ kHz. Fig. 3 shows some measurements of this frequency response. As can be observed, there is a peak around 3 kHz. This matches pretty well with f_0. This is the reason that we call this the quarter wavelength resonance of the ear canal. The first harmonic is at f_1 ≈8.6 kHz. In the figure we can also see that the level increases again around that frequency, so this first harmonic also fits well.

2.1 Ear simulator

The goal of an ear simulator is to create an acoustic representation of the ear canal. An ear simulator uses a microphone to pick up the signal at DRP and a coupling volume (“coupler”), which represents the load represented by a typical ear canal. As human ears are all different, this is done for an “average ear”. In the past, research and development has been performed in creating a geometry that is able to represent this acoustic equivalent [3, 4].

From here on, we will assume that this average ear is a good representation. However, for actual products this always needs to be verified. With some exceptions, we have experienced that an improved result on the ear simulator most often also results in a subjective improvement.

Fig. 4 shows a device that is capable of representing the acoustic equivalent of the ear canal. Referring to Fig. 1, the coupler part represents the ear canal from the reference plane to the eardrum.

2.2 Acoustic modeling

As discussed, the ear canal cross section is much smaller than the wavelength. Due to this fact, the acoustics in the ear canal is essentially (quasi)-1D. It can therefore be modeled effectively with lumped elements. This is also true for the ear simulator. We will focus here again on an average ear. The residual ear volume is the part of the ear canal that is unaffected when a device is inserted in the ear canal. The transfer impedance is defined as the acoustic pressure at the ear drum divided by the volume flow at the reference plane:

$$Z_t = \frac{p_{\mathrm{DRP}}}{U_{\mathrm{ref}}}. \tag{3}$$

This impedance is important to predict the acoustic pressure at the eardrum for low output impedance in-ear speakers. The amount of “back-force” a speaker feels for a certain volume flow output, is called the input impedance of the residual ear canal:

$$Z_i = \frac{p_{\mathrm{ref}}}{U_{\mathrm{ref}}}. \tag{4}$$

Given a model of an earphone speaker, or earbud, and when data is available of these two impedances, the SPL of an in-ear speaker can be predicted. The transfer impedance of the average ear is standardized in IEC 60318-4:2010 [3]. Fig. 5 shows the input and transfer impedance curves as provided by a model of the occluded ear simulator. These curves are the result of the lumped network as given in Fig. 6.

As visible in Fig. 5, below 800 Hz the input and transfer impedance magnitude fall on top of each other, indicating that for this frequency range the acoustic pressure is the same at the reference plane and at the eardrum. The green line shows the impedance curve of a simple acoustic volume, with a capacitance of $C = V/\gamma p_0$, where we have set $V = 1.2\ \mathrm{cm}^3$. Above 800 Hz, the input and transfer impedance start to deviate from the simple volume model.

Fig. 7 shows an open ear and an ear filled with an earplug. Now suppose we want to know p_{DRP}. The open part of the ear canal can be described by a frequency dependent transfer matrix. A transfer matrix couples the pressures and volume flow on one side of the segment to the other side as:

$$\begin{aligned} \left\{ \begin{matrix} p \\ U \end{matrix} \right\}_{\mathrm{right}} &= \boldsymbol{T} \cdot \left\{ \begin{matrix} p \\ U \end{matrix} \right\}_{\mathrm{left}} \\ &= \begin{bmatrix} T_{11} & T_{12} \\ T_{21} & T_{22} \end{bmatrix} \cdot \left\{ \begin{matrix} p \\ U \end{matrix} \right\}_{\mathrm{left}} \end{aligned} \tag{5}$$

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[1] We use the $\exp(+i\omega t)$ convention for phasors, where $i = \sqrt{-1}$

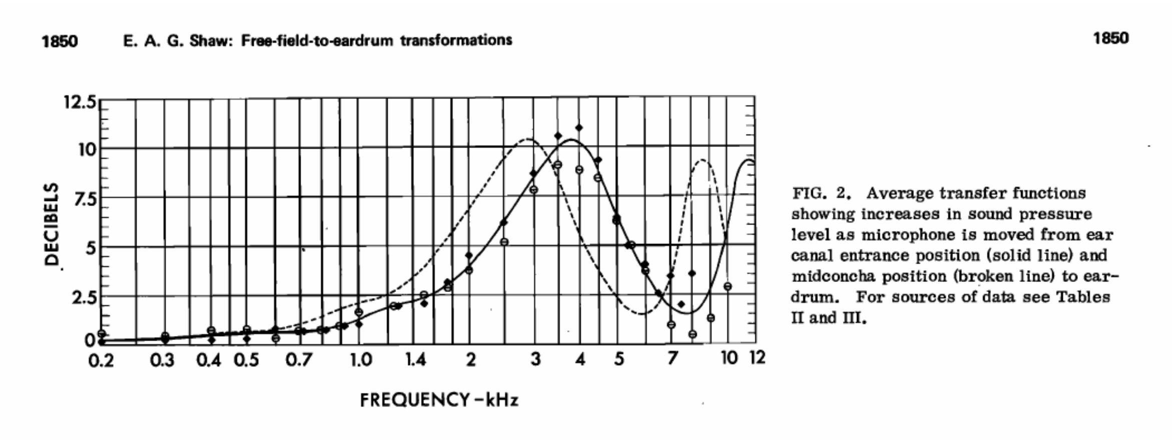

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FIG. 2. Average transfer functions showing increases in sound pressure level as microphone is moved from ear canal entrance position (solid line) and midconcha position (broken line) to eardrum. For sources of data see Tables II and III.

Figure 3 – Picture taken from [8]. Dashed line: transfer function from outside (ERP) to eardrum (DRP) (dashed line).

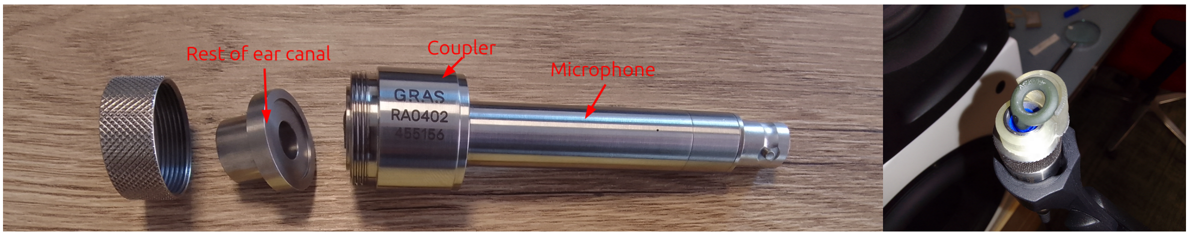

Figure 4 – Left: photo of a coupler device. Right: photo of device under test (a proto of the Loop Experience 2) placed in "rest of ear canal", in front of speaker.

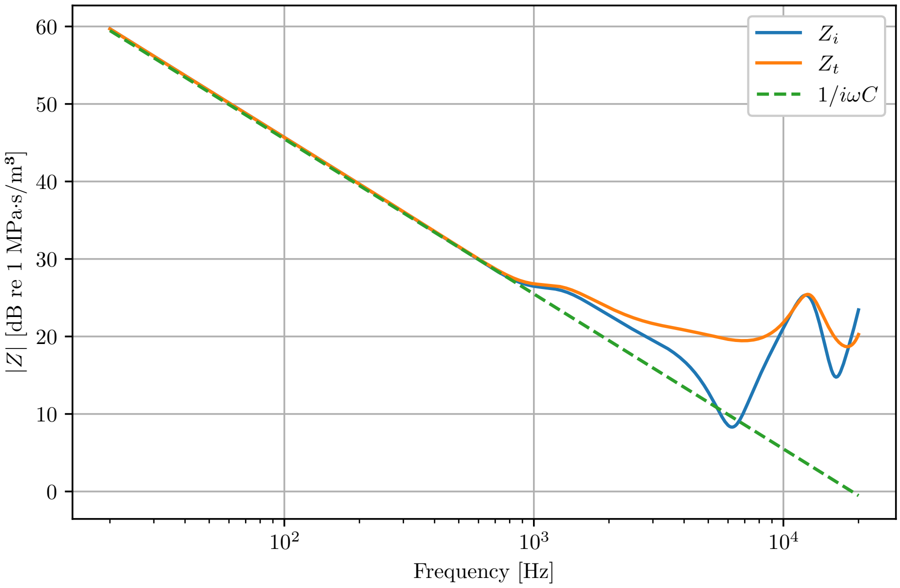

Figure 5 – Input and transfer impedance magnitude of the occluded ear simulator from a lumped element simulation model.

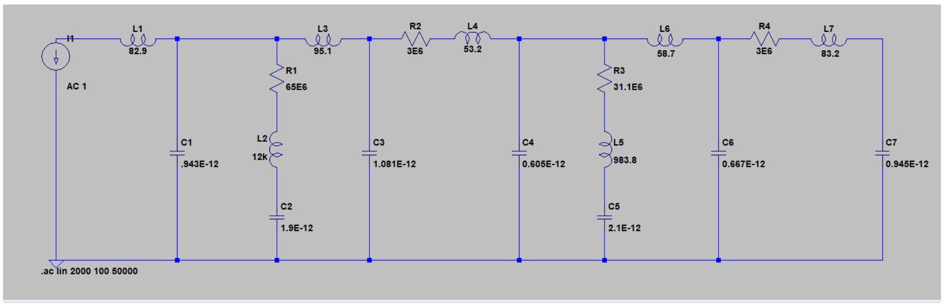

Figure 6 – Lumped model schematic of the GRAS RA0402 simulator. Provided to ASCEE by GRAS. This is an electric equivalent (impedance analogy). To use it in acoustic simulations we make the that 1 V corresponds to 1 Pa, and 1 A corresponds to 1 m$^3\cdot$s^{-1}.

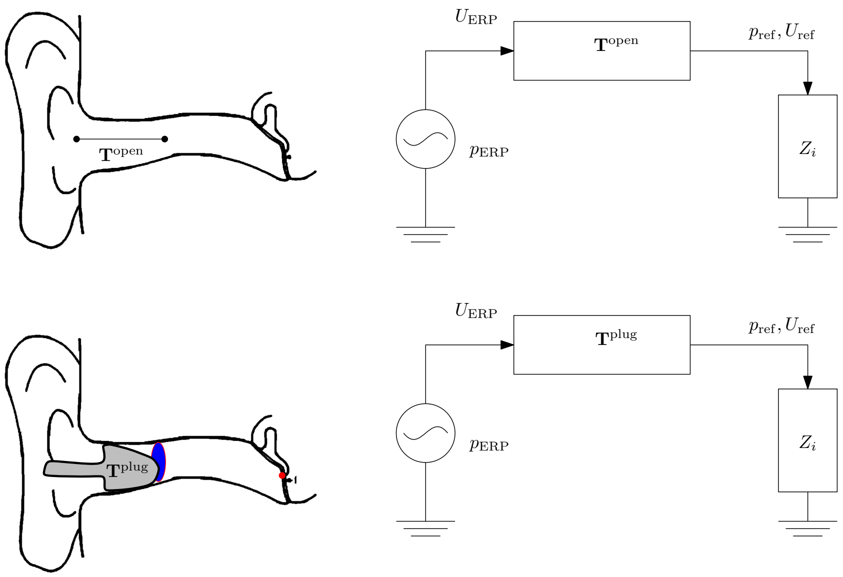

Figure 7 – Acoustic lumped element topology for usage of estimating the acoustic pressure at the eardrum. This only includes the first step, of which the output is U_{ref}. As post processing step, p_{DRP} is determined from $Z_i U_{\text{ref}}$ (Eq. 3). In our simulations we take p_{DRP} directly from the plugged in network of the ear simulator (Fig. 6).

Referring to Fig. 7, the convention used is that U is positive when the volume flow is from left to right. As an example, the transfer matrix of a piece of prismatic duct of length L and cross-sectional area S is:

$$\boldsymbol{T}_{\text{duct}} = \begin{bmatrix} \cos\left(kL\right) & -i\frac{z_0}{S}\sin\left(kL\right) \\ -i\frac{S}{z_0}\sin\left(kL\right) & \cos\left(kL\right) \end{bmatrix}. \quad (6)$$

To compute p_{DRP}, we first need to know U_{ref}, once we know U_{ref}, we compute p_{DRP} with Eq. 3. Including the transfer impedance we find the following general expression that couples the pressure at DRP to ERP:

$$p_{\text{DRP}} = Z_t \times \frac{T_{21} - \frac{T_{11}T_{22}}{T_{12}}}{1 - \frac{T_{22}Z_i}{T_{12}}} p_{\text{ERP}}. \quad (7)$$

This is a rather complicated expression that does not give a us a lot of physical insight. We therefore never use this in practice. It also shows us that, for example to reach a certain target for p_{DRP}, it requires a close interplay between the residual ear canal and the object in the ear canal represented by $\boldsymbol{T}$. If we model the lateral part of the ear canal using a prismatic and a conical duct, the transfer impedance $p_{\text{DRP}}/p_{\text{ERP}}$ for the open ear can be computed. Fig. 8 shows the result of this transfer impedance. This curve can directly be compared to measurements shown in Fig. 3.

The insertion loss L_i is an important quantity when considering the amount of isolation against environmental noise. It is defined as the frequency dependent ratio in acoustic power between the open ear p_{DRP} and the occluded one[2]:

$$L_i = 10\log_{10}\left(\frac{\left|p_{\text{DRP, open}}\right|^2}{\left|p_{\text{DRP, occluded}}\right|^2}\right) \quad [\text{dB}]. \quad (8)$$

In computing this ratio, the input signal and the transfer impedance cancel out, leaving only dependence on the input impedance, and the open vs occluded transfer matrix components.

2.3 Series impedance element as a simple hearing protection plug

Suppose we have a simple earplug that can be described by the standard open ear canal, plus a series impedance Z_s, as shown schematically in Fig. 9.. Then only the T_{12} component of the matrix will be different, and we work out Eq. 7-8 to obtain the following simple relation for the insertion loss:

$$\text{IL} = 10\log_{10}\left(\frac{1+\frac{Z_i}{Z_s}}{\frac{Z_i}{Z_s}}\right). \quad (9)$$

We can verify some features of Eq. 9 with our physical insight:

1. For $|Z_s| \to 0$, we find IL $\to 0$, i.e. when the series impedance is small, the insertion loss is 0.
2. For $|Z_s| \to \infty$, we find IL $\to \infty$, i.e. high series impedances give high insertion losses.
3. If we wish have a flat frequency insertion loss, Z_i/Z_s should be independent of the frequency.

For statement 2, there are practical limits though, as for high insertion losses the ignored bone conduction paths that bypass the ear canal will become significant, effectively topping off the maximum practically achievable insertion loss of an earplug [2]. In terms of a single noise rating, this limit is somewhere between 35 and 45 dB. In general, this limit is frequency dependent, as the bone conduction path has an attenuation that increases with frequency.

2.4 Music earplugs

A flat insertion loss is a desired feature for music applications, where the level needs to be reduced, but the tonal balance be kept the same. To obtain a frequency independent insertion loss, the series impedance Z_s should be equal to κZ_i, where κ is a constant. For the low frequency range, the input impedance Z_i corresponds to a compliance, hence Z_s needs to be compliant as well. An acoustic element that acts as a series compliance is called a membrane.

A pure membrane responds as $\Delta p = p_{\text{right}} - p_{\text{left}} = U/\left(i\omega C\right)$, i.e. its pressure difference is proportional to $U/\left(i\omega\right)$. Pure membranes do not exist in reality. At some frequency, they start to resonate and beyond resonance there response becomes $\Delta p = i\omega LU$, i.e. "massy".

The blue line in Fig. 10 shows the insertion loss curve for a pure membrane that is tuned at an insertion loss of 30 dB. Due to the high frequency effects of Z_i, above 3 kHz the insertion loss drops significantly. Hence a simple membrane can deal well in following the compliance curve, but drops to values that are too low for the high frequencies.

The orange line shows a simulated insertion loss curve for a prototype of an actual product: the Loop Experience 2. Here, careful design with tuning of acoustic masses, a membrane with parasitic leakage, inlets and channeling through the product has been

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[2] For the same p_{ERP}, in order to have a fair comparison.

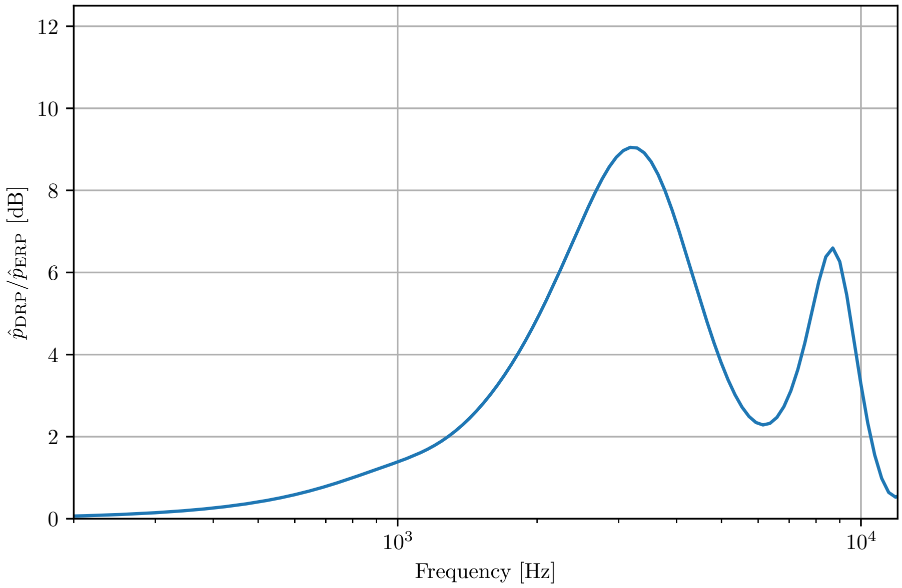

Figure 8 – Computed open ear ERP to DRP transfer impedance using a model of the ear simulator and prismatic + conical sections for the part of the ear canal on the left side of the reference plane in Fig. 7.

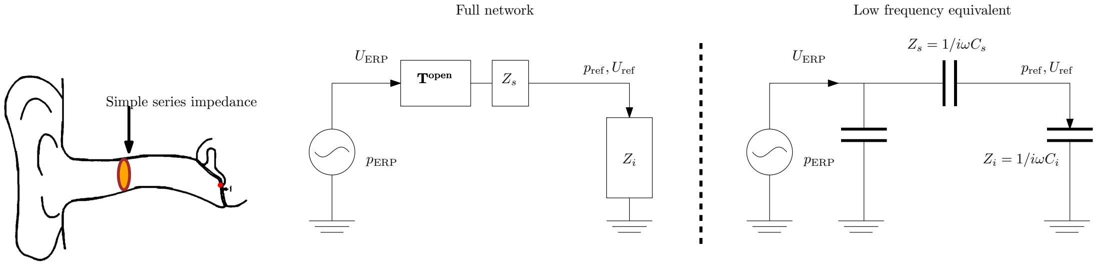

Figure 9 – Simplest description of an earplug: acoustic lumped element topology of a simple series impedance. Left: schematic. Middle: equivalent acoustic network. Right: low frequency equivalent (below 800 Hz), where we use a membrane as earplug.

included in the model. The membrane model for this curve is fitted with

$$\Delta p = U\left(R_l^{-1} + \left(\frac{1}{i\omega C} + R + i\omega L\right)^{-1}\right)^{-1} \tag{10}$$

to measurement data of an actual product. It is a mass-spring-damper that includes a (parallel) parasitic leakage path with resistance R_l. The design goal of the product was to get a flat insertion loss curve at a level of 28 dB. Within the restrictions of the design, this goal has been achieved pretty well.

2.5 In-ear speakers

In-ear speakers are another example where ear canal acoustics matter. In order to reproduce music that sounds "good", the audio signal needs to be adapted to match the open ear acoustics. E.g. the quarter wavelength resonance needs to be reconstructed. Research has been performed on listener's preferences in order to obtain what would be a preferred listener's curve [6, 7, 5]. Possibly already superseded (the author is not fully aware of all new developments), this has led to the so-called Harman IE 2017 target magnitude[3] curve, where IE abbreviates in-ear.

Fig. 11 shows the frequency response of this target curve. Note that it is a difficult task to get an objective in-ear target curve, as the variance in music preference is probably even higher than the variance in ear size. Among many others, the preferred curve is play level dependent, sex dependent, age dependent, hearing loss dependent and culture dependent.

The meaning of this target curve is as follows. If a combined effect of in-ear speaker response and equalizer (EQ) results in a frequency response on the coupler microphone that has a relative magnitude as given in Fig. 11, it would be preferred by a lot of listeners. Some interesting features of this curve can be explained, notably the peak at 3 kHz, which is our missing 3 kHz quarter wavelength resonance that would be present when people listen to music played back from normal stereo speakers. The second thing is the low bass boost. This is probably due to leakage of low frequency sound that is not present when the in-ear speaker is placed in an ear simulator [7]. So this target curve does have some objective aspects.

In case one is willing to generate this target curve, it would be just a matter of inventing a transforming filter that adjusts the given frequency response to the desired target curve. However, there are some problems with this. Firstly, if the speaker is not able to produce enough output, an EQ cannot invent extra output to meet the target curve. Hence to meet the target curve, the maximum output SPL at which it is able to reproduce without harmonic distortion might be too low. Secondly, too much filtering might result in an infeasible high computational cost, and filtering artifacts (weird sounds due to heavy filtering). Filtering artifacts are mainly the result of the finite precision available in digital computations. Therefore it is best if the "naked" frequency response of the speaker already looks a bit like the target curve.

Fig. 12 shows the schematics used as reference for a speaker model. The electro-acoustics of a speaker can be modeled with its measured / engineered electro-acoustic parameters:

- Active surface area: S_d in [m^2]
- Motor constant: $B\ell$ in [N/A]
- Coil resistance and inductance: R_e, L_e in [Ω and H]
- Mechanical mass, stiffness and damping: m_m, k_m, r_m in [kg, N/m and N·s/m]

The transfer matrix contains a sourcing, so has the form:

$$\left\{\begin{array}{c} p \\ U \end{array}\right\}_R = \boldsymbol{T} \cdot \left\{\begin{array}{c} p \\ U \end{array}\right\}_L + \boldsymbol{s}, \tag{11}$$

where

$$\boldsymbol{T} = \begin{bmatrix} 1 & -\frac{1}{S_d^2}\left(z_m + \frac{(B\ell)^2}{Z_{\text{el}}}\right) \\ 0 & 1 \end{bmatrix}, \tag{12}$$

$$\boldsymbol{s} = \left\{\begin{array}{c} \frac{B\ell}{Z_{\text{el}} S} V_{\text{in}} \\ 0 \end{array}\right\}, \tag{13}$$

in which:

$$z_m = i\omega m_m + r_m + \frac{k_m}{i\omega}, \tag{14}$$

$$Z_{\text{el}} = R_e + i\omega L_e. \tag{15}$$

Fig. 13 shows some curves of raw speakers responses, and the result of a tuning effort on the speaker response. The raw responses sound terrible. As visible in this figure, by tuning the major features of the Harman IE curve can be reasonably well reproduced. The result of such a tuning is that the raw response of the speaker already sounds proper without any additional EQ-ing.

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[3] The (relative) phase of a target curve is not of importance.

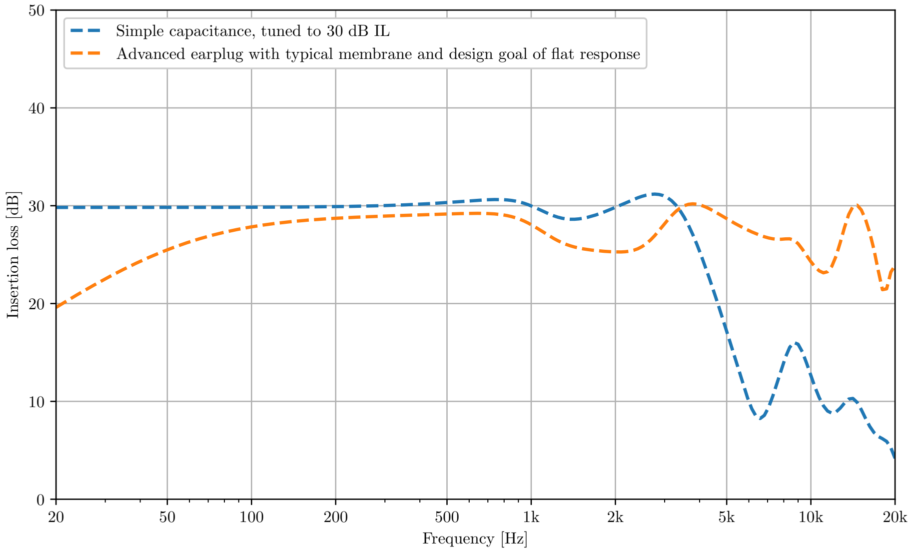

Figure 10 – Simulated insertion loss curves for two cases. The blue line is the insertion loss of an ideal membrane placed at the reference plane. The orange line shows the simulation of a music-tuned earplug, with a more accurate (leaking, resonating) membane model.

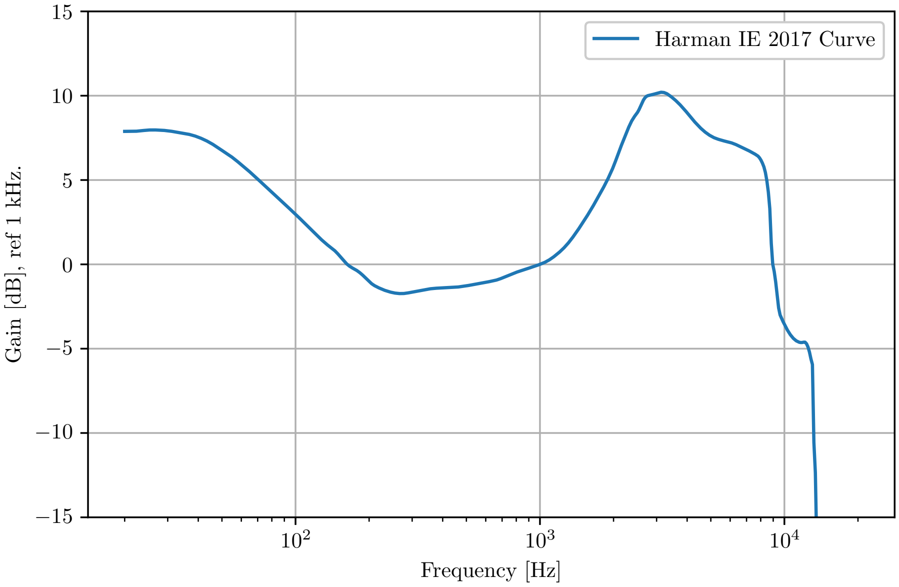

Figure 11 – In-ear target curve for the frequency response to be applied to recorded audio, in order to generate a preferred listening experience by a majority of listeners. From here on, called the Harman IE 2017 curve.

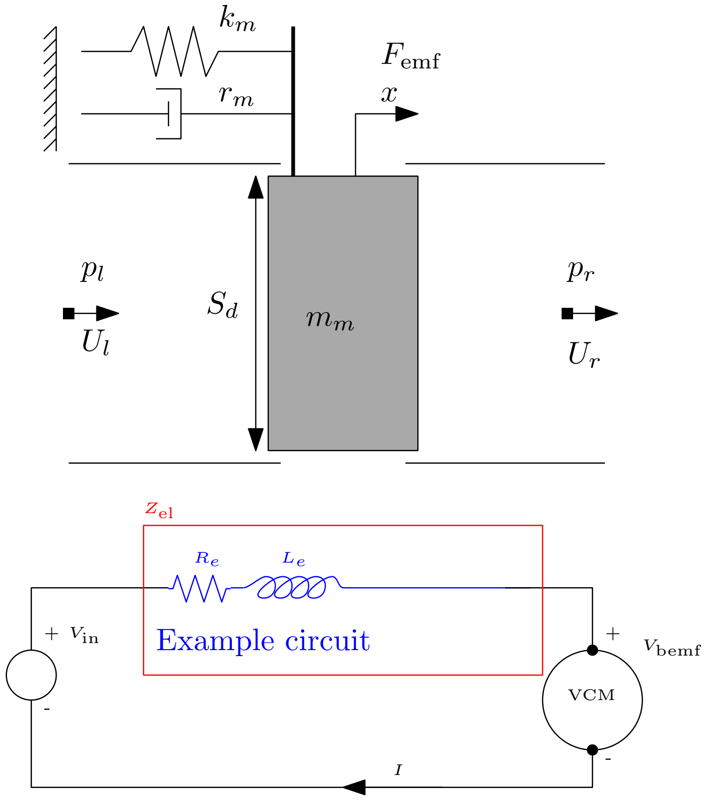

Figure 12 – Schematic of an in-duct speaker model. The top of the figure shows the mechanical diagram. The bottom is the electric part. $\frac{k_m}{i\omega}+r_m+i\omega m_m$ together form z_m. The coupling between electric and mechanical is in two directions. The electro-motive force is $F_{\text{emf}} = B\ell I$. In the other direction, the *back-emf* $V_{\text{bemf}} = B\ell\frac{\mathrm{d}x}{\mathrm{d}t}$.

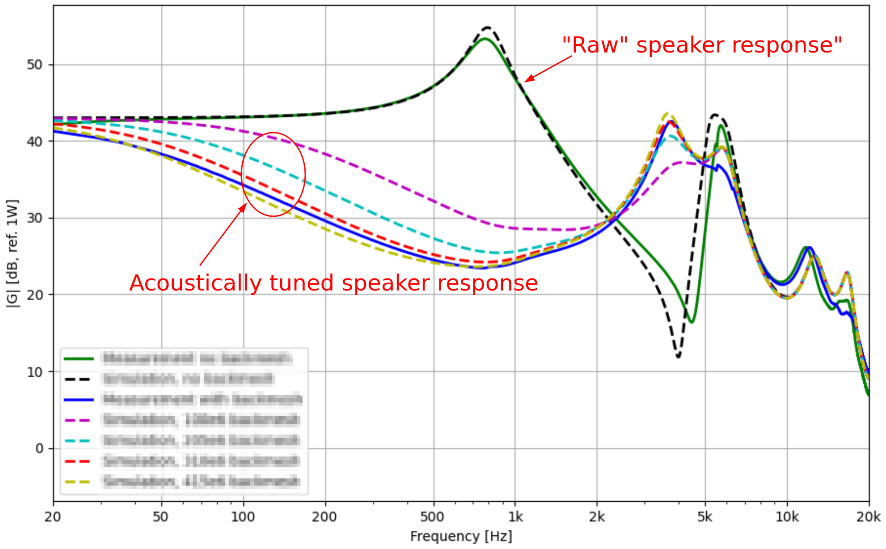

Figure 13 – Example of our work in speaker response tuning. The absolute scale is irrelevant. The green and black curves are "raw" responses. The others are attempts to tune the speaker response to the Harman IE 2017 curve. This works reasonably well, only the range of 6 kHz to 10 kHz misses output. This part of the frequency range can be filled up using an EQ.

3 Summary

In this extended abstract, some background information is provided concerning the acoustic modeling of the ear canal, including aspects that need to be taken into account when inserts are placed in the ear canal. We have shown that an ear simulator is able to reproduce the important features of the transfer function from outside the ear to the eardrum. Using simulation models, we are able to predict the effect of these inserts on the ear canal acoustics. This is demonstrated using the examples of designing for a target insertion loss curve for hearing protection, and the example of designing for a target in-ear speaker response.

4 Acknowledgments

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Nomenclature

Roman symbols

$B\ell$	Motor constant
C	Acoustic compliance in m^3/Pa
c_0	Speed of sound. Although the temperature in the ear canal is higher than 20 °C, calculation examples are done with 343 m/s.
D	Diameter
f	Frequency in Hz
f_c	Cut-on frequency
k	Wave number
k_m	Mechanical stiffness
L	Acoustic mass in Pa·s^2/m^3
L	Length (of ear canal)
L_{el}	Electrical coil inductance
m_m	Mechanical moving mass
p	Acoustic pressure, in either time domain or frequency domain depending on context.
p_0	Mean atmospheric pressure of air. In the calculation examples this value is set to 1 atm, or 101325 Pa
R	Acoustic resistance in Pa ·s/m^3
R_{el}	Electrical coil resistance
r_m	Mechanical viscous resistance
S_d	Active speaker surface area
U	Acoustic volume flow (phasor) in m^3/s
U_{ref}	Acoustic volume flow at the reference plane

V	Volume
z_0	Characteristic acoustic impedance: $z_0 = \rho_0 c_0$
Z_{el}	Electrical impedance
z_m	Mechanical impedance
EQ	Equalizer: digital audio filter that applies a (linear) filter to the audio. Mostly implemented using biquad sections.
SPL	Sound Pressure Level

Greek symbols

γ	Ratio of specific heats of air
ω	Radian frequency: $\omega = 2\pi f$

A Short abstract (Dutch)

Tussen de oorschelp en het trommelvlies zit het gehoorkanaal, zodat het trommelvlies niet aan de buitenkant van het hoofd geplaatst hoeft te worden. Dit kanaal zorgt voor een frequentie-afhankelijke versterking van het geluid (overdracht). Het is tegenwoordig populair om een product in dit gehoorkanaal te stoppen, zoals gehoorbescherming, en muziekoordopjes. Het gevolg hiervan is dat het geluid van buiten naar het trommelvlies een veranderde overdracht krijgt. Vaak is het zo dat tenminste de typische kwartgolfresonantie van het gehoorkanaal wegvalt.

In het geval een in-het-oor product een goed akoestisch ontwerp heeft, kan deze overdracht op een zinvolle manier beïnvloed worden, zodat de nieuwe overdracht een gewenste karakteristiek heeft.

In deze presentatie wordt ingegaan op reken- en meetmethodes t.b.v. deze oorkanaaloverdracht, met toepassing van gehoorbescherming, en geluid afgespeeld door muziekoordopjes. Als afsluiting laten we één of meer voorbeelden zien.