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ACOUSTIC OUTPUT IMPEDANCE AS A MEASURE FOR INDEPENDENCY OF INDIVIDUAL ACOUSTIC EAR CONDITIONS

T. Zurbrügg
toz GmbH
8500 Frauenfeld
Switzerland
info@toz.ch

A.M. Hölzl, S. Köhler
Sonova AG
8712 Stäfa
Switzerland

S. Harsch
Phonak Communications AG
3280 Murten
Switzerland

ABSTRACT

The performance of electroacoustic actuators for in-ear applications strongly depends on the individual acoustic load conditions. On the one hand, this fact leads to intra-individual variances, i.e. differences after removal and reinsertion of an earpiece due to different coupling to the ear with different leakage. On the other hand, this fact gives rise to inter-individual variances, i.e. differences in the resulting frequency responses between different users (e.g. due to differences in residual volumes, middle ear compliances etc.). While both types of variances might be acceptable in conventional earphone applications to some degree, they cause a major concern in the context of closed-loop active noise control (ANC) where they critically influence performance and stability conditions. This paper discusses the relevance of the acoustic output impedance of the earpiece relative to the spread of acoustic load impedances as an objective measure for the independency of the performance from individual acoustic factors.

1. INTRODUCTION

The goal of sound reproduction is the provision of a certain amount of *sound pressure* at a specific spatial location. In order to achieve this goal, a various amount of *volume velocity* is required, depending on individual characteristics.

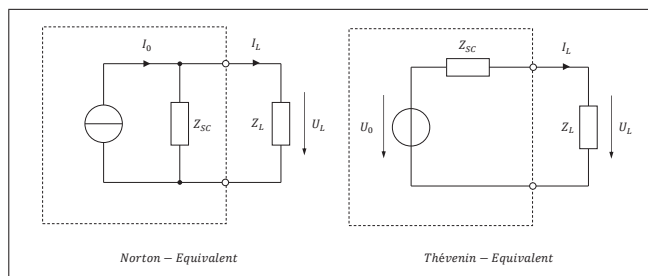


Figure 1. Norton equivalent (left) and Thévenin equivalent (right).

In electrical engineering, it is common practice to represent networks containing any type of sources as either an ideal current source i_0 along with a parallel source impedance Z_{sc} (Norton equivalent) or, alternatively and

fully equivalently, as an ideal voltage source u_0 along with the same serial source impedance Z_{sc} [1–4]. Considering the fact that an ideal current source represents infinite source impedance and an ideal voltage source represents a zero source impedance (Eqn. (1)), it is apparent that both representations yield an identical source impedance.

$$Z_{sc} || Z_{Z_{i,ideal}=\infty} = Z_{sc} + Z_{Z_{u,ideal}=0} = Z_{sc} \quad (1)$$

According to well-known analogies, the acoustic sound pressure is equivalent to an electrical voltage and the acoustic volume velocity is equivalent to an electrical current [5]. Consequently, the acoustic output impedance of an earpiece relative to the electrical input impedance of the ear canal (both measured in $\text{Pa} \cdot \text{s} \cdot \text{m}^{-3}$) can be used to characterize the source type.

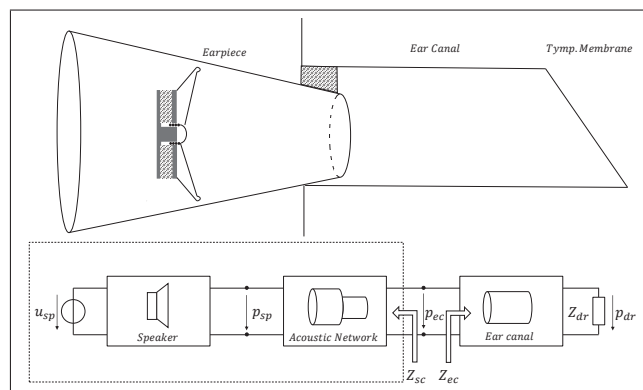


Figure 2. Schematic representation of physical implementation of earpiece (top) and corresponding acoustic two-port network (bottom).

Numerous actuator principles for in-ear applications are known. Within a hearing instrument context, the predominant actuators are miniature, encapsulated “balanced armature” receivers. The acoustic output impedance of these drivers is considerably higher than the input impedance of an average human ear canal. This transducer type can thus be seen as volume velocity source, the resulting sound pressure being directly proportional to the load impedance. Within a consumer electronics context, predominant actuators are so-called “moving coil” speakers with considerably larger membrane areas. The acoustic

output impedance of these drivers can be designed to exhibit considerably lower values than the input impedance of an average human ear canal. In some frequency ranges, this transducer type can thus be seen as sound pressure source, the resulting sound pressure being widely independent of the load impedance.

2. IMPEDANCE VALUES

In the following, representative values of the (generally complex-valued, frequency-dependent) acoustic impedance are studied. As a reference, Fig. 2 shows a schematic representation of physical implementation of an earpiece (top) and the corresponding acoustic two-port network (bottom). In the latter, a distinction between the output impedance of the earpiece (source impedance Z_{sc}) and the load impedance (ear canal impedance Z_{ec}) is made. The plane where this distinction is made is motivated by the fact that Z_{sc} represents all the factors which can be influenced by the design of the ear piece, while Z_{ec} summarizes individual factors not manipulable by the earpiece designer. Depending on the specific application, other distinguishing planes can make sense, namely the stability determining intersection between the speaker and the canal microphone in closed-loop ANC (also known as active feedback noise control [6, 7]) setup.

2.1 Load impedance

2.1.1 Eardrum impedance

The eardrum impedance Z_{dr} can be approximated by a 4th-order lumped-parameter equivalent circuit model [8, 9]. The electrical circuit depicted in Fig. 3 is parametrized with values given in Tab. 1. The resulting impedance magnitudes are given in Fig. 4 (top).

It is reasonable to assume a spread between the lowest and the highest middle ear compliance of roughly a factor of four, corresponding to equivalent volumes of $0.3 \text{ cm}^3 \leq V \leq 1.3 \text{ cm}^3$ (values derived from [8]). This explains the low-frequency spread up to roughly 1 kHz. The spread between the lowest and the highest assumed masses of the middle ear ossicles is roughly a factor of three, corresponding to masses of $5 \text{ mg} \leq m \leq 15 \text{ mg}$. This explains the spread towards high frequencies.

Quantity	μ	σ	Unit
R_1	56	18	M Ω
L_1	3.6	2.1	kH
C_1	3.5	1.6	pF
L_2	3.5	1.4	kH
C_2	1.4	0.7	pF

Table 1. Parameters for eardrum impedance model, Fig. 3.

2.1.2 Ear canal input impedance

The acoustic characteristics of the human ear canal can well be approximated by a rigid tube terminated by

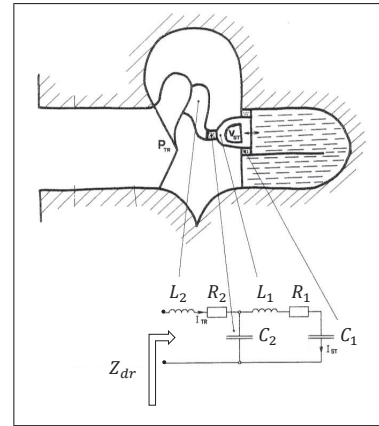


Figure 3. Middle ear model (derived from [8]).

some complex-valued eardrum impedance in the frequency range of interest. While the distal part (roughly two third) of the ear canal consists of cartilaginous tissues, the proximal part (roughly one third) consists of bony texture [10]. It is worth noticing that the so-called “bone-conducted” vibrational portion of the own voice and other body sounds leading to the perception of an “Occlusion Effect” is primarily entering the ear canal through the cartilaginous part [11].

From an acoustic point of view, the minimization of the residual ear canal volume would be desirable. On the one hand, a given volume velocity would yield maximum sound pressure, and on the other hand, the occlusion effect would be resolved [12]. From an anatomic point of view, however, an object which is touching the bony portion of the ear canal and which is removed and re-inserted on a daily basis usually leads to discomfort. Hence, a considerable amount of residual ear canal volume has typically to be accounted for.

The middle subplot of Fig. 4 shows the input impedance of a perfectly sealed residual ear canal volume of exemplary length $l_{ec} = 20 \text{ mm}$ and diameter $d_{ec} = 7.5 \text{ mm}$, terminated by the reference eardrum impedances discussed in Sec. 2.1.1. The typical notch above 4 kHz is due the quarter-wavelength resonance associated with a pipe which is acoustically hard terminated unilaterally.

$$l_{ec} = 20 \text{ mm} \leftrightarrow f_{res} = \frac{c_0}{4 \cdot l_{ec}} = 4.3 \text{ kHz}, \quad (2)$$

with $c_0 = 343 \text{ ms}^{-1}$ being speed of air.

Unfortunately, the geometry of the residual ear canal is subject to considerable variations. Besides different lengths and diameters leading to different residual volumes between individuals, the assumption of a perfect seal is not valid in reality. Consequently, the lower subplot of Fig. 4 shows the magnitude of ear canal input impedances considering not only different total volumes (visible in the increased spread in the frequency range between 100 Hz and 1 kHz), but also different residual ear canal lengths (visible in the variation of the notches in the frequency range of 4 kHz up to 6 kHz) as well as different leakages (namely equivalent to narrow tubes of length $l_{leakage} = 10 \text{ mm}$

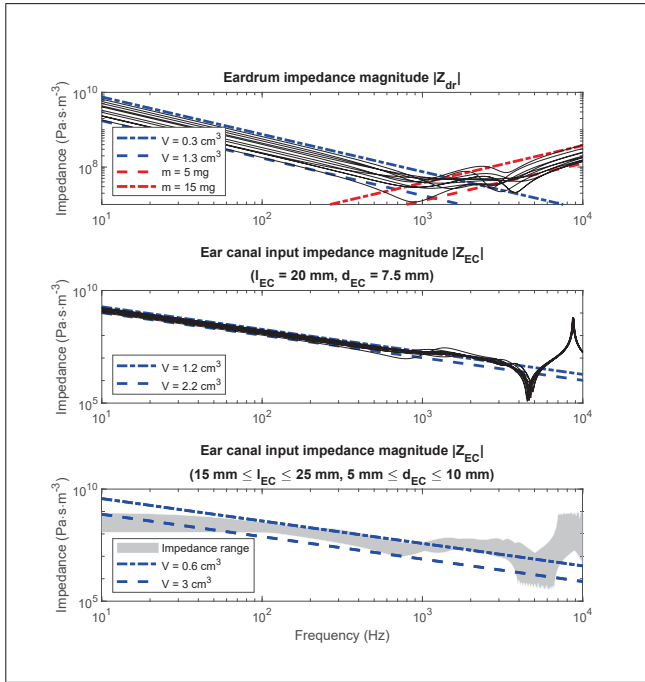


Figure 4. Acoustic impedance magnitudes: $|Z_{dr}|$ (top); $|Z_{ec}|$ assuming one standard geometry of the residual ear canal (middle); $|Z_{ec}|$ assuming a spread in the geometry of the residual ear canal (bottom).

and diameters $0.3 \text{ mm} \leq d_{leakage} \leq 0.5 \text{ mm}$, visible in a flattening of the curves below 100 Hz).

2.2 Source impedance

2.2.1 Speaker source impedance

Fig. 5 shows speaker source impedance magnitudes of an exemplary balanced armature (BA) speaker usually employed in hearing aids (blue curve) as well as of an exemplary moving coil (MC) speaker (red curve). Both impedance simulations are based on the same lumped parameter model shown in Fig. 6, parametrized with values given in Tab. 2. In this model, R_e and L_e are the electrical resistance and inductance, respectively, Bl is the electro-mechanical conversion factor, known as force factor, R_{ms} , M_{ms} and C_{ms} are the mechanical friction, mass and compliance, respectively, and S_d is the mechano-acoustical conversion factor, which is the effective membrane area (piston equivalent). Along with these acoustic impedance curves, the expected spread of ear canal input impedance magnitudes according to the discussion in Sec. 2.1 is shown in light gray.

Both output impedance magnitudes basically represent a mass-spring series oscillator consisting of the mechanical mass M_{ms} and the mechanical compliance C_{ms} of the speaker. Accordingly, the resonance frequency is given by

$$f_{res} = \frac{1}{2\pi\sqrt{M_{ms}C_{ms}}}, \quad (3)$$

corresponding to 1.6 kHz and 160 Hz for the balanced armature and the moving coil driver, respectively. This difference in resonance frequency by a factor of 10 is due to

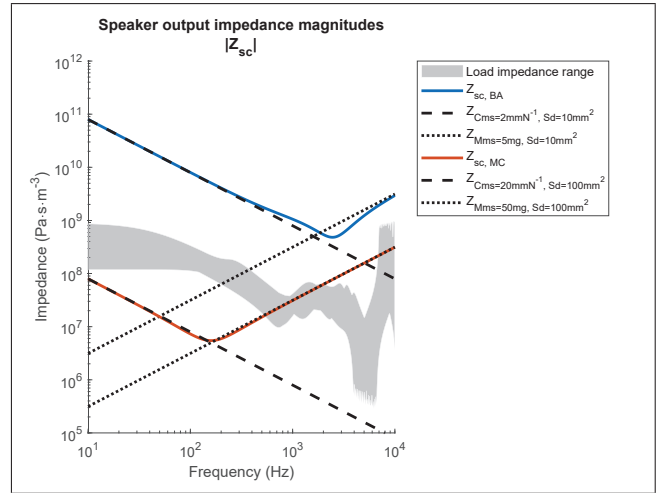


Figure 5. Exemplary speaker output impedance magnitudes for exemplary balanced armature (BA) receiver and moving coil (MC) speaker.

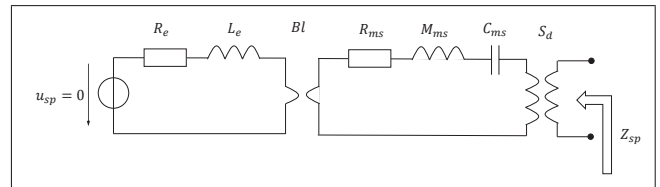


Figure 6. Lumped parameter equivalent electrical model of electroacoustic speaker.

the fact that the moving coil speaker does have both a moving mass and a mechanical compliance which is 10 times greater than in the balanced armature receiver. Apart from that, another obvious difference is an effective speaker membrane area which, again, is greater by a factor of 10 in the moving coil speaker. As a result, the balanced armature receiver acts as almost ideal volume velocity source over the whole frequency range considered, while the moving coil speaker beneficially acts as a sound pressure source up to some hundred Hertz.

2.2.2 Earpiece source impedance

The design of an acoustic network around the speaker unit involves the definition of front- and back volumes, front and/or back openings and a potential front-to-back connection, as well as the connection of the front volume with the ear canal. One goal in the design is achieving a low spread within a vast variety of different load impedances. This goal, as pointed out above, can be achieved by considering the minimization of the acoustic output impedance relative to the spread of assumed load impedances, as one of the design goals. This is especially beneficial in the case where active feedback noise control is employed, where independency of the load conditions increases the stability margin, resulting in robustness.

2.2.3 Combined source and load impedances

Fig. 7 shows simulated voltage-to-sound-pressure frequency responses (denoted “frequency responses” for short

Quantity	BA	MC	Units
R_e	60	30	Ω
L_e	5	0.1	mH
Bl	2	1	T · m
R_{ms}	10	10	mN · s · m ⁻¹
M_{ms}	5	50	mg
C_{ms}	2	20	mm · N ⁻¹
S_d	10	100	mm ³

Table 2. Parameters for speaker model, Fig. 6.

hereafter) of both BA (top) and MC (bottom) transducer types with identical load impedances. As it is expected from the discussion in Sec. 2.2.1, the BA receiver indeed acts as a *volume velocity source* over the whole frequency range, with the resulting sound pressures p_{ec} being directly proportional to the corresponding load impedance. Consequently, the spread of the load impedance (roughly a factor 10 at low frequencies) directly corresponds to sound pressure variations in the range of roughly 20 dB. In contrast, the MC speaker indeed proves - in good approximation - to act as a sound pressure source in the frequency range where its acoustic source impedance is well below the acoustic load impedance (i.e. up to frequencies of 500 Hz to 600 Hz). Consequently, the resulting sound pressure is widely independent of individual load impedance variances, including leakage.

Especially in active feedback noise control applications where a stability-limiting high-frequency overshoot is typically located in the 1 kHz to 2 kHz frequency range [13], one considerable concern is a relatively high source impedance in this frequency range, leading to considerable variations in the plant frequency response in this critical range. As a consequence, a robust compensator filter needs to take these variations into account, generally leading to a decreased attenuation performance. This should be carefully considered when designing the acoustic network of an earpiece for ANC applications.

Various acoustic modifications of the acoustic network in an earpiece design are known in the literature (e.g. [14]). The acoustic output impedance magnitude of the speaker has its minimum at the mechanical resonance frequency. The corresponding frequency range is typically well below 1 kHz for moving coil speakers (160 Hz in our example). Towards higher frequencies, the output impedance increases proportionally with frequency. In the critical 1 kHz to 2 kHz frequency range (denoted “overshoot range” hereafter), the output impedance has already exceeded the expected acoustic load impedance spread. This fact motivates an increase of the resonance frequency by roughly one decade. While a decrease of the mechanical mass is physically not feasible, a decrease of the mechanical compliance would have unresolvable disadvantages regarding low-frequency output. Decreasing the *acoustic* compliance can be achieved by an enclosed back volume. A back volume smaller than roughly 100 cm³ results in a stiffening of the mechano-acoustic system. Fig. 8 shows

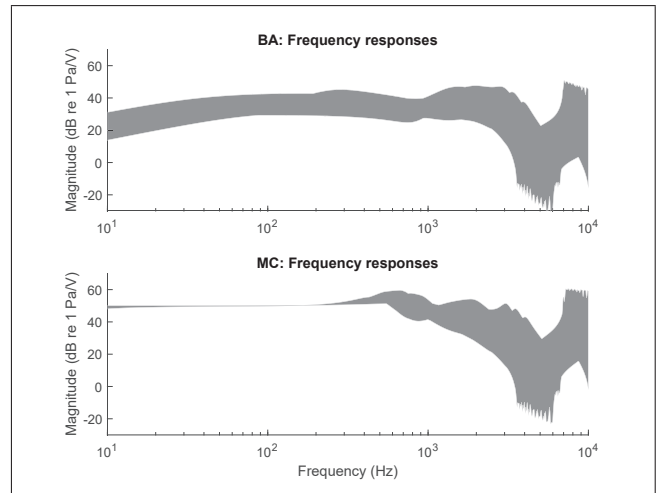


Figure 7. Frequency responses of BA receiver (top) and MC speaker (bottom) for identical spread of load impedances.

that an exemplary back volume of 0.5cm³ results in a decreased output impedance in the frequency range of interest. However, this improvement comes at the cost of an increased low-frequency source impedance of the earpiece.

One attempt to overcome this problem might be to incorporate a resistive opening of the back volume. As it is shown in Fig. 9, a sufficiently small back resistor is indeed capable of restoring the low acoustic source impedance at low frequencies. At the same time, however, the desirable output impedance notch above 1 kHz is also damped, merely leaving a small improvement over the original situation with the open back.

Resolving this issue can be achieved by opening up the back volume reactively, i.e. by means of a back vent. An adequately designed back vent can restore the low output impedance at low frequencies while maintaining the desired notch in the overshoot range. This leads to desirably low variances in the frequency response both at low frequencies and in the overshoot range. Note that the original mechanical resonance frequency is even lowered due to the acoustic mass loading. However, the undamped vent introduces a sharp peak in the output impedance along with an equally sharp notch in the frequency response between these frequency ranges, as shown in Fig. 10 (assuming different vent lengths while keeping the back vent diameter at constant $d_{backvent} = 1$ mm and the back volume at constant $V_{back} = 0.5$ cm³).

An obvious approach to damp the sharp notches is to introduce some serial acoustic resistance. As it is shown in Fig. 11, an adequately chosen acoustic resistance can reasonably damp the resonance while maintaining the desirably low output impedance both at low frequencies and in the overshoot range.

There is a large variety of additional acoustic modifications. All of these have in common that their influence on the variance of the resulting frequency responses and, consequently, on the robustness of a closed-loop ANC system can conveniently be analyzed by comparing the

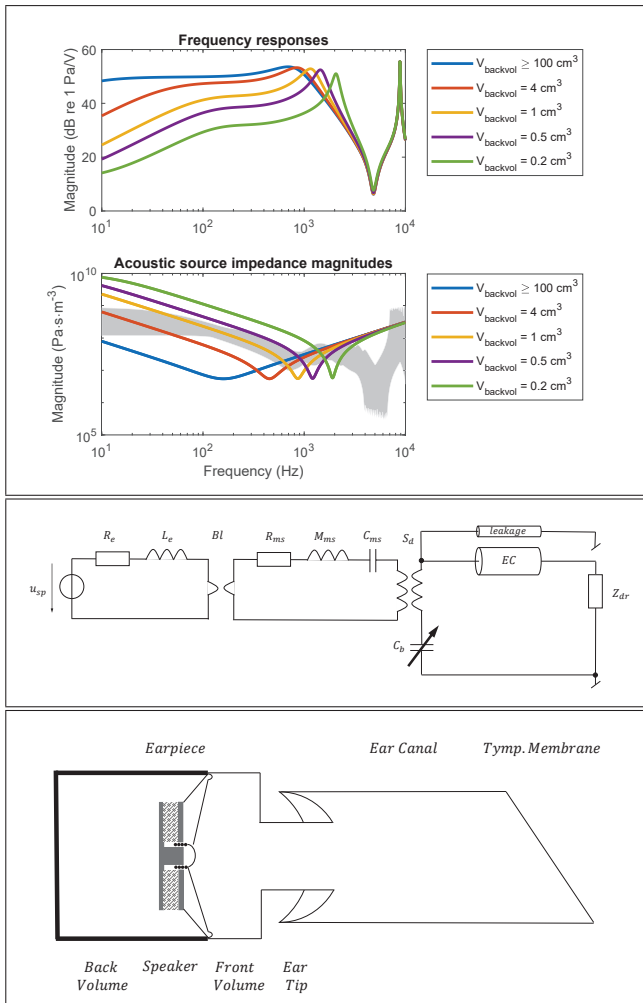


Figure 8. Influence of varying enclosed back volumes.

acoustic source impedance of the earpiece with the spread of expected input impedances of a leaky ear canal. The frequency regions of main interest typically include the overshoot regions, such as a typical frequency range between 1 kHz and 2 kHz. In these frequency regions, an output impedance considerably lower than the lowest expected input impedance represents a frequency response widely independent of the individual ear condition. As shown above, such modifications typically involve trade-offs, where improvements in one target dimension or in one frequency range must be carefully balanced with disimprovements in other target dimensions and/or frequency ranges.

3. CONCLUSION

In the design of an earpiece for in-ear applications, the use of the acoustic output impedance as a measure for independency of the load is suggested. In frequency ranges where the acoustic network can be adapted to exhibit an output impedance which is considerably lower than the expected spread of acoustic input impedances, the resulting sound pressure is considerably independent of the individual load impedance. This includes inter-individual variances of the eardrum impedance and of the residual ear canal geometry,

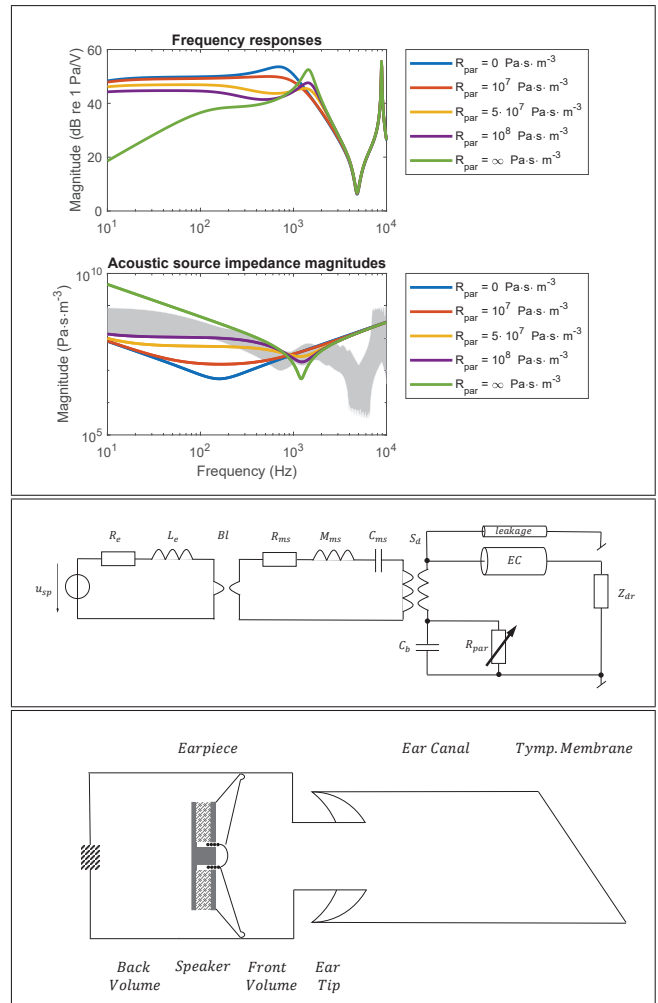


Figure 9. Influence of varying back resistors with given back volume.

as well as intra-individual variances such as differences in leakage after removal and re-insertion.

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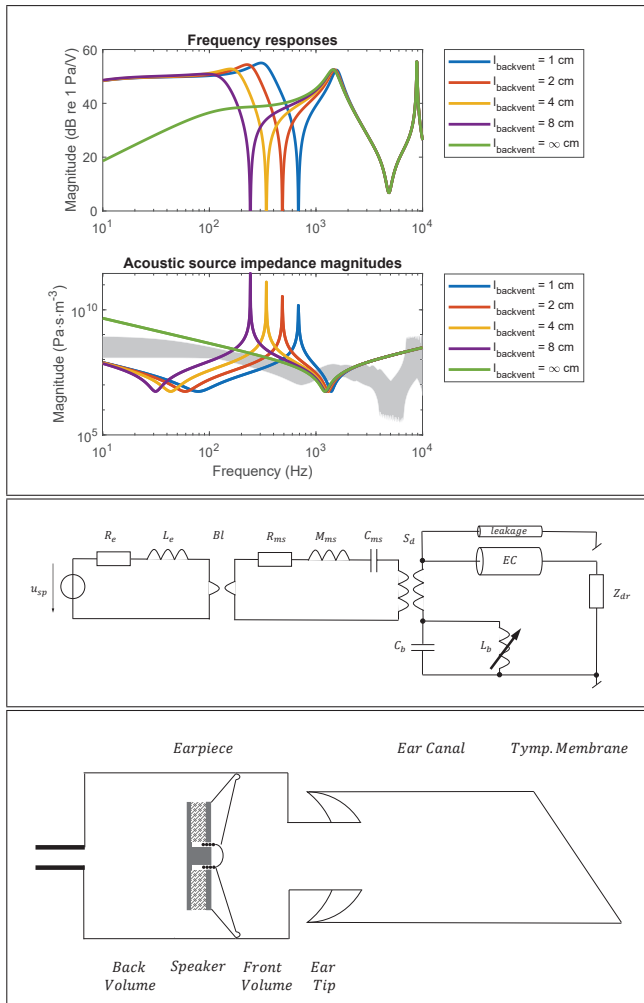


Figure 10. Influence of varying back vents with given back volume.

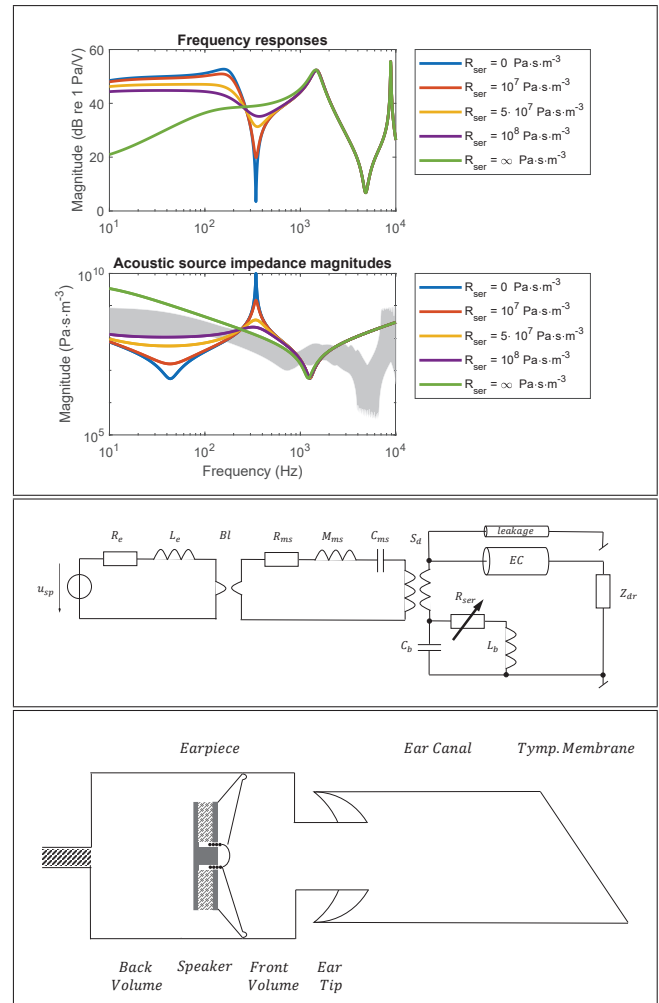


Figure 11. Influence of varying back vent serial resistors with given back vent and back volume.

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