The Impact of Ear Canal Geometry on In-Ear Headphone Testing

In this Whitepaper, we examine another important factor besides frequency response when testing in-ear headphones

GRAS Sound & Vibration
WHITEPAPER // By Brian Johansen, Per Rasmussen, and Morten H. Pedersen

Introduction

As expectations for in-ear headphone sound quality continue to rise, the development of advanced solutions has accelerated, necessitating the use of increasingly sophisticated measurement equipment.

To address these needs, a range of ear simulators has been introduced by various vendors, designed to cover the entire human audible frequency spectrum. Among these are the 60318-4 IEC standard Ear Simulator (100 Hz – 10 kHz), the GRAS “711” High-Frequency Ear Simulator (100 Hz – 20 kHz), and the ITU-T recommended Type 4.3 Ear Simulator (20 Hz – 20 kHz). There is growing interest in the high-frequency spectrum within the human ear canal, as well as an emerging focus on factors like leakage and placement, which are crucial for both device performance and accurate measurement.

While efforts have been made to design a “one size fits all” ear simulator, which essentially reflects an “average ear” geometry, there is an often-overlooked dimension at play. Research indicates that the success of headphones, particularly in-ear models, is not solely determined by assessing the frequency response between the in-ear transducer and the ear simulator. Instead, the listening experience is significantly shaped by how the pressure field develops within the semi- or fully enclosed ear simulator, making factors such as leakage and insertion position critical.

As a result, addressing immediate issues can lead to new challenges, complicating efforts to ensure consistency and repeatability when characterizing in-ear devices. To evaluate the impact of various ear canal geometries, Pressure Acoustics frequency domain simulations are performed using the COMSOL Type 4.3 Ear Simulator. The simulations begin with the specific geometry outlined in ITU-T Rec. P.57 Type 4.3, assuming the in-ear headphone is placed inside the ear canal, but not extending beyond the reference plane for practical reasons.

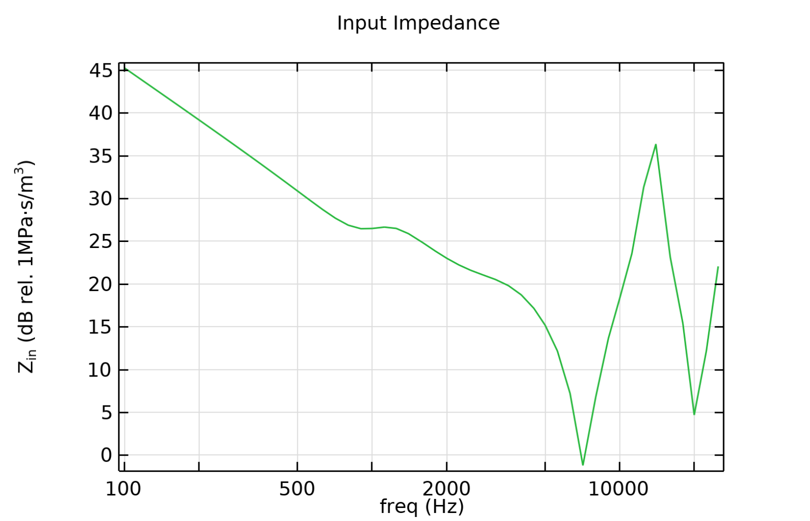
TRANSFER IMPEDANCE AND THE SOUND SOURCE

The key defining parameter for an ear simulator is its transfer impedance, which is often measured using a measurement microphone as the sound source. For this type of source, the diaphragm's deflection is directly proportional to the input signal, making the source behave as a constant deflection source. Consequently, the diaphragm's velocity increases in proportion to the frequency.

Transfer impedance is defined as the sound pressure generated at the eardrum position divided by the volume velocity at the input plane. To account for the frequency proportionality and accurately determine the transfer impedance, the measured signal should be divided by the frequency. This approach simulates how the measurement would be conducted if a constant volume velocity source, rather than a constant displacement source, were used.

FIGURE 1.

The curve shows the transfer impedance of the traditional 60318-4 IEC ("711") ear simulator



While a capacitive-type transducer, like a measurement microphone, functions as a constant displacement source, a typical earphone speaker operates more as a constant pressure source. In a dynamic transducer with a coil in a magnetic field, the force generated is proportional to the current in the coil, which creates a consistent pressure on the diaphragm, regardless of the load.

This means that the input to the ear simulator is not a constant velocity signal, but rather a constant pressure source, or possibly something in between. Therefore, it is more relevant to focus on the pressure transmission from the input area to the eardrum region.

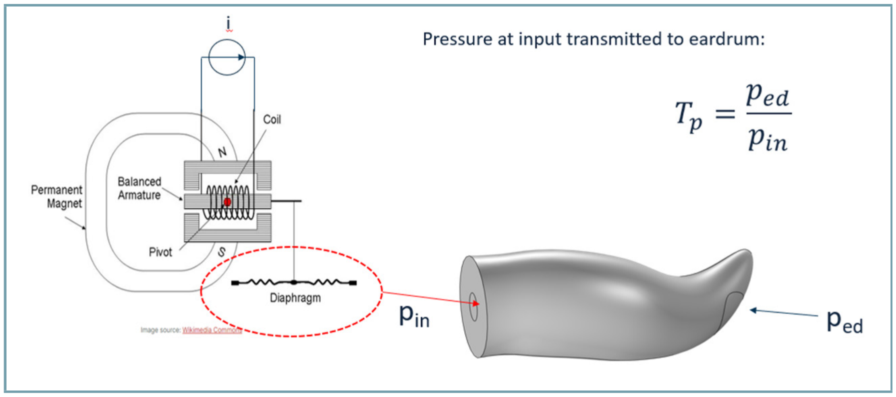


FIGURE 2.
The transmission of pressure from a Balanced Armature Receiver to the eardrum is determined by the pressure transfer coefficient (T_p)

It is therefore important to know the input impedance of the ear simulator, as this defines the relationship between the pressure at the input area and the particle velocity in the same plane

$$Z_{in} = \frac{p_{in}}{v_{in}}$$

By having both the Transfer Impedance Z_{tr} and the Input Impedance Z_{in}, the Pressure Transfer T_p can be obtained:

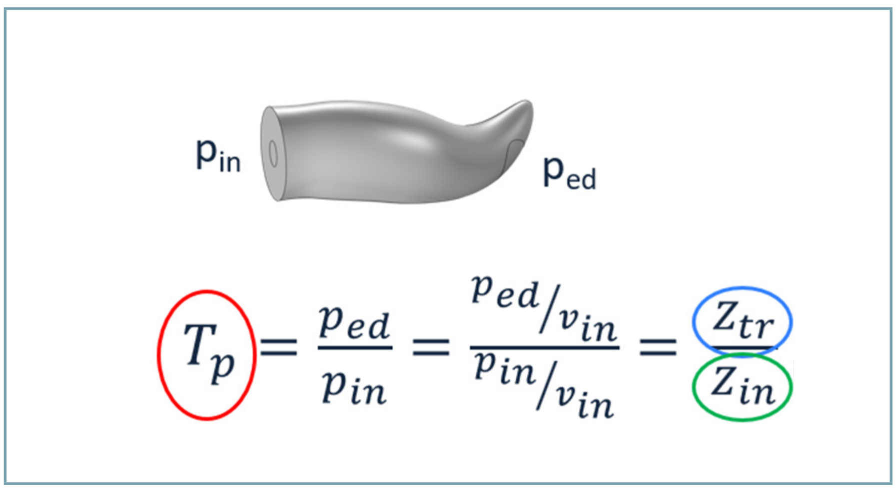
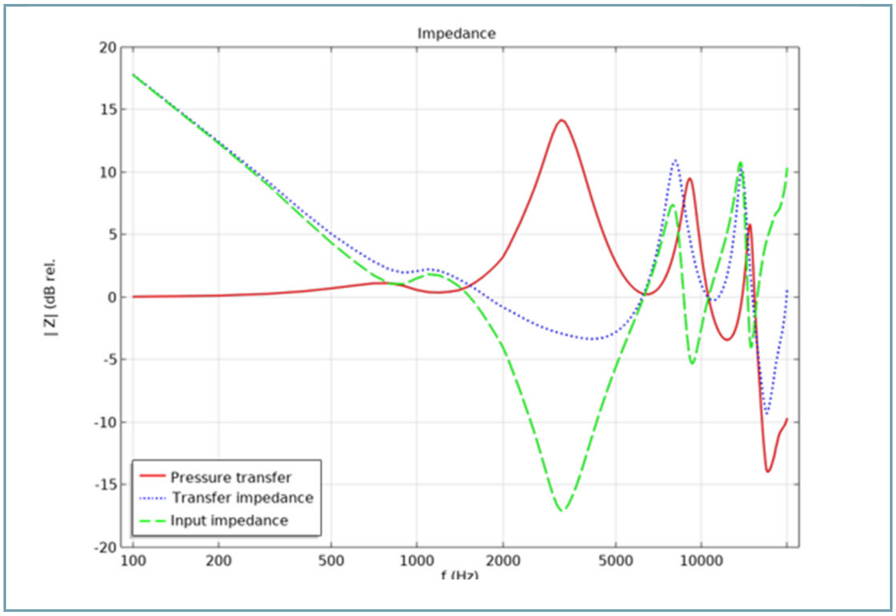


FIGURE 3.
The pressure transfer is the ratio between the transfer and input impedance.

The pressure transfer curve can be used to calculate p_{ed} (pressure at the eardrum) from p_{in} (input pressure) illustrated by the red curve in Figure 4. It is noteworthy that the dip in the input impedance (green) significantly impacts the pressure transfer, leading to a peak somewhere between 2-5 kHz, influenced in this case by the ¼ wavelength resonance in the ear canal.

FIGURE 4.
Transfer and input impedance and resulting pressure transfer for the ITU Type 4.3 ear simulator.



Ear simulators are typically specified in terms of dimensions—such as the length and volume of the ear canal segment—as well as transfer impedance, as outlined in various standards and literature (IEC, ITU-T, ANSI, etc.). The transfer impedance reflects the characteristics of both the physical structure of the ear canal and the ear drum simulator, where the simulator plane ideally accounts for the mechanical impedance of the eardrum and middle ear.

While the transfer impedance is influenced to some extent by the design of the device under test (DUT), the input impedance and pressure transmission from the DUT's active sound-generating plane are often more significantly affected by specific design elements of the earphone's sound outlet. This includes factors like the size of the opening and the length of the cavity in front of the active element. The length of the simulated ear canal, in particular, determines the high-frequency resonances. For transfer impedance, the first resonance corresponds to a half-wavelength. However, for input impedance and pressure transmission, the first resonance is determined by the quarter-wavelength, occurring at a lower frequency.

For example, if the first resonance for transfer impedance occurs at 12 kHz, the first input resonance will be at 6 kHz. Consequently, the effective ear canal length influences input impedance and pressure transfer at lower frequencies than it does for transfer impedance. This makes the positioning of the DUT within the ear canal even more critical than what an analysis based solely on transfer impedance might suggest.

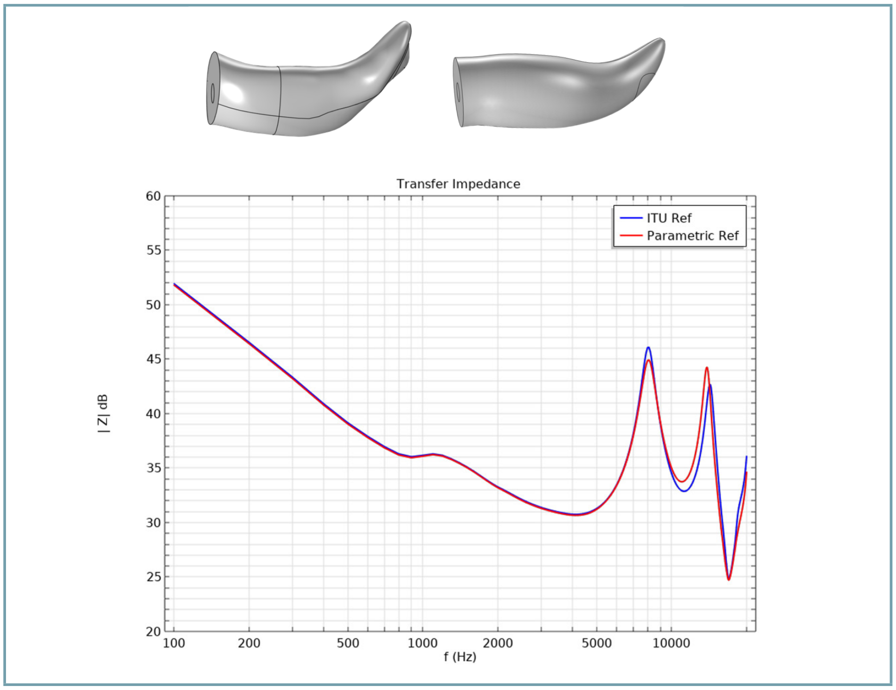
It is the input impedance of the ear simulator that loads the DUT. Because what we really want to ascertain using ear simulators is how robust our DUT is when subjected to the mechanical load of a human ear. That is the entire purpose and essence of Ear Simulator testing. The following simulations are conducted employing the COMSOL integrated 711 Ear Simulator and ear models.

THOUGHTS ON THE SHAPE OF THE EAR CANAL

The widely recognized IEC 60318-4 ear simulator features a straight cylindrical section of the ear canal, approximately 12 mm in length. In contrast, the more recently defined ITU-T Rec. P.57 Type 4.3 Ear Simulator incorporates a “human-like” ear canal with a length of about 17 mm to the reference plane. This longer canal places the reference plane farther from the eardrum simulator, potentially offering a more accurate reflection of the typical distance at which in-ear headphones are positioned. The canal is designed to resemble an “average human ear canal,” with its characteristic bends, rather than opting for a mechanically simpler, straight design.

Given these differences, it is worth investigating whether the transfer impedance varies with the geometric complexity of the ear canal. To be able to change the geometry during the simulations, the ITU-T geometry is approximated by a parametrized model, which can be described as a mathematically defined surface. The parametrized model can easily be changed in length, volume, and shape to investigate the effect of these parameters (Figure 5).

FIGURE 5.
The transfer impedances of the two models are similar for both models up to the 8 kHz ½-wavelength peak in the transfer impedance, where some small but negligible differences show.



If we then try to modify the shape of the ear canal, e.g., by making the cross-section oval instead of circular, we can see (Figure 6) that it does not change the transfer impedance much, except minor changes at the very high frequency around 20 kHz, and at these frequencies the typical specification ranges in the standards are +- 6 dB or more.

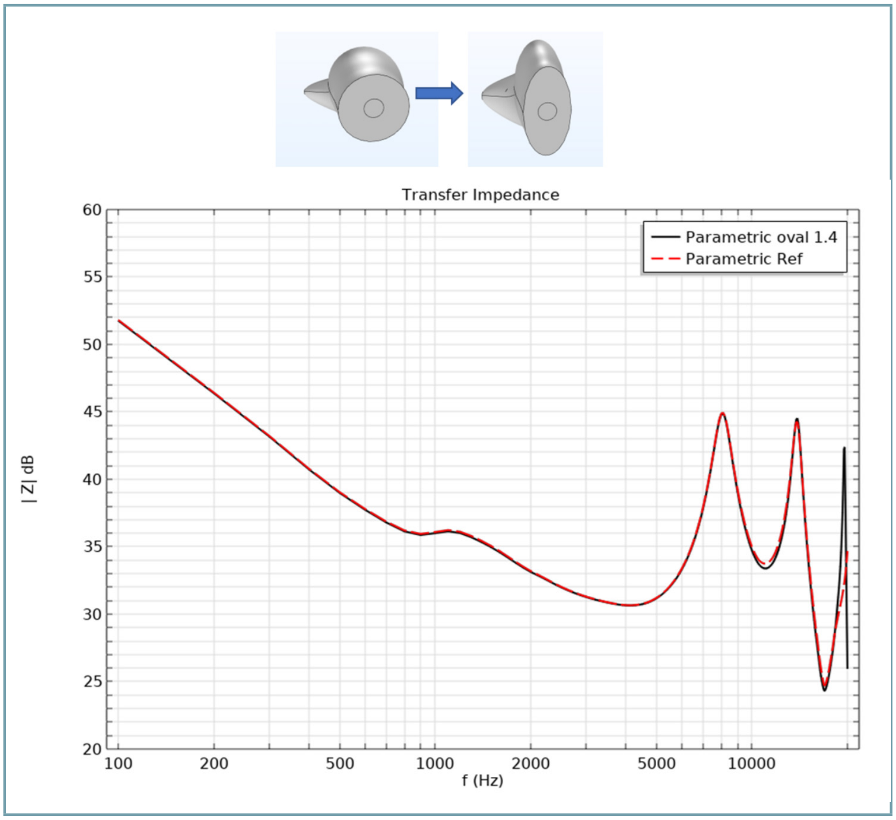


FIGURE 6.
The parametrized reference ear canal has a circular cross section. If this is changed into an oval shape, and the eardrum area is kept constant, the changes are very small.

If we instead make the ear canal cross-section more triangularly shaped it does not change the transfer impedance (Figure 7) and if we straighten the ear canal it does not change the transfer impedance much either (Figure 8) except for the change due to the slightly decreased length of the canal.

FIGURE 7.

Changing the ear canal cross section to some other shape like the more triangular shape indicated will result in some negligible changes to the transfer function.

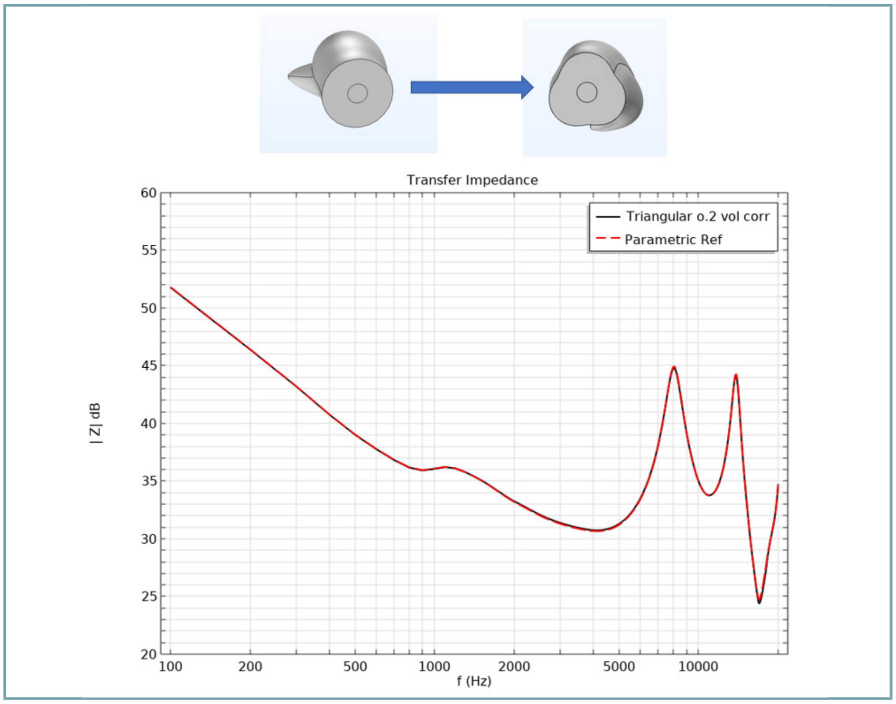
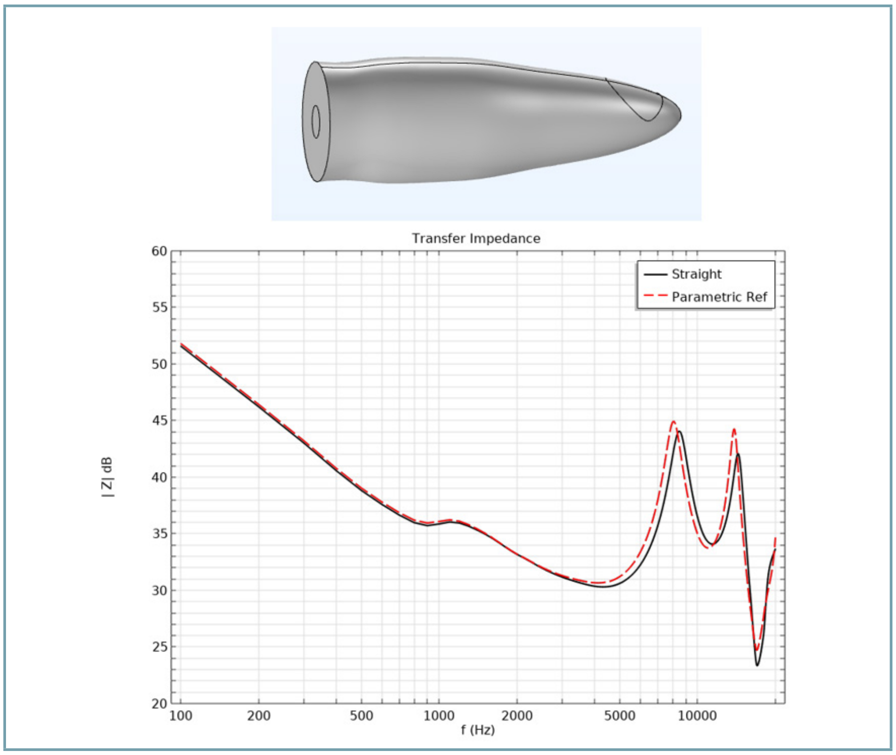


FIGURE 8.

If we make the ear canal a straight, round shape, with the same cross section changes as the original reference, we get some small differences around 0.5 to 1.5 dB at higher frequencies above 5 kHz due to the slightly shifted resonance frequencies, mainly due to the slightly decreased length of the canal



The conclusion drawn is that, fundamentally, it matters little whether the canal is straight, cylindrical, oval, triangle shaped or "human-like" with bends.

EAR CANAL SIZE MATTERS

Now we have observed the impact of altering the shape of the ear canal, where its length and volume have been fixed. But what happens if we modified these dimensions, considering that individuals have varying volume sizes of their ear canal, and the length is defined by the insertion depth of the DUT?

If we increase or decrease the ear canal volume the transfer impedance also changes quite a bit (Figure 9). It is observed that in the frequency range from 2 kHz to around 6 kHz, the transfer impedance increases as the volume decreases, and decreases as the volume increases. A similar trend is noted below approximately 1 kHz, although it is less pronounced. This is because, in this frequency range, the relevant ear canal volume includes the middle ear volume behind the eardrum, which has been kept constant in this simulation. While one might argue that a person with a larger ear canal might also have a larger middle ear volume, this has not been accounted for in this analysis.

Additionally, it is evident that the positions of the resonances at 8 kHz and 16 kHz remain unaffected by volume changes, as these are determined by the distance between the input plane and the eardrum.

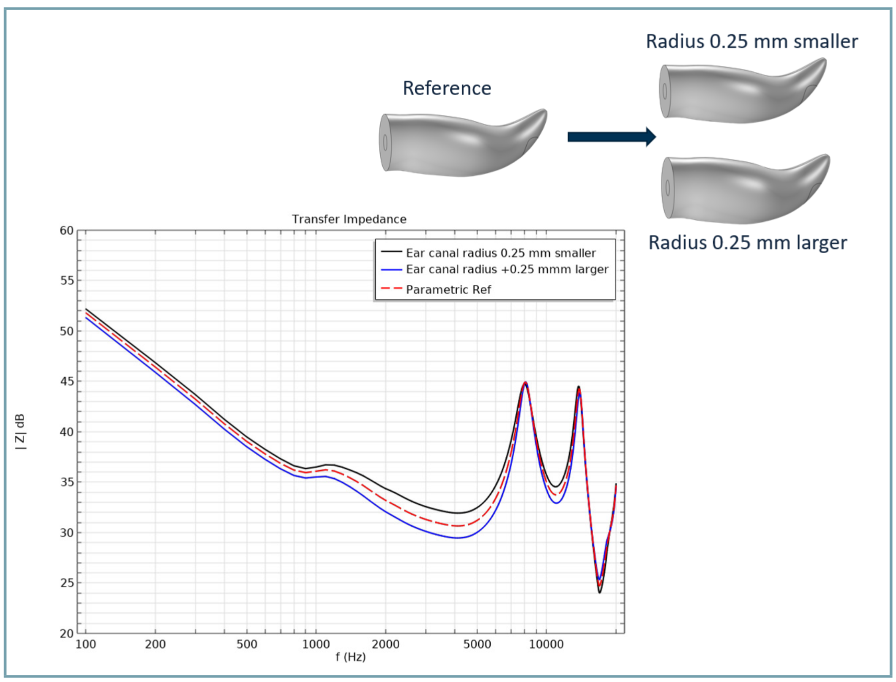


FIGURE 9.
Modifying the ear canal volume through a reduction or increase in the radius by 0.25 mm (approximately 6-7% in the reference plane) leads to fluctuations of 1 to 2 dB within the important mid-frequency range spanning from 1 kHz to 8 kHz.

POSITIONING AFFECTS MEASUREMENT RESULTS

If we change the insertion depth for the DUT by +/- 2 mm from the reference plane in the ITU-T 4.3ear simulator, we get quite different results (Figure 10). At low frequencies, the transfer impedance changes with increasing volume due to the longer ear canal length, as previously described. At high frequencies, the position of resonances in the transfer impedance shifts because of the altered distance between the source plane and the eardrum position. This indicates that the transfer impedance is highly sensitive to the precise positioning of the DUT within the ear canal. A slightly more outward placement increases the volume and distance, while a slightly deeper placement reduces them.

A consequence of the more "human-like" ear canal shape is that the exact position of the DUT within the canal becomes less defined, leading to less consistent transfer impedance measurements. This, in turn, makes it more challenging to compare results across different tests.

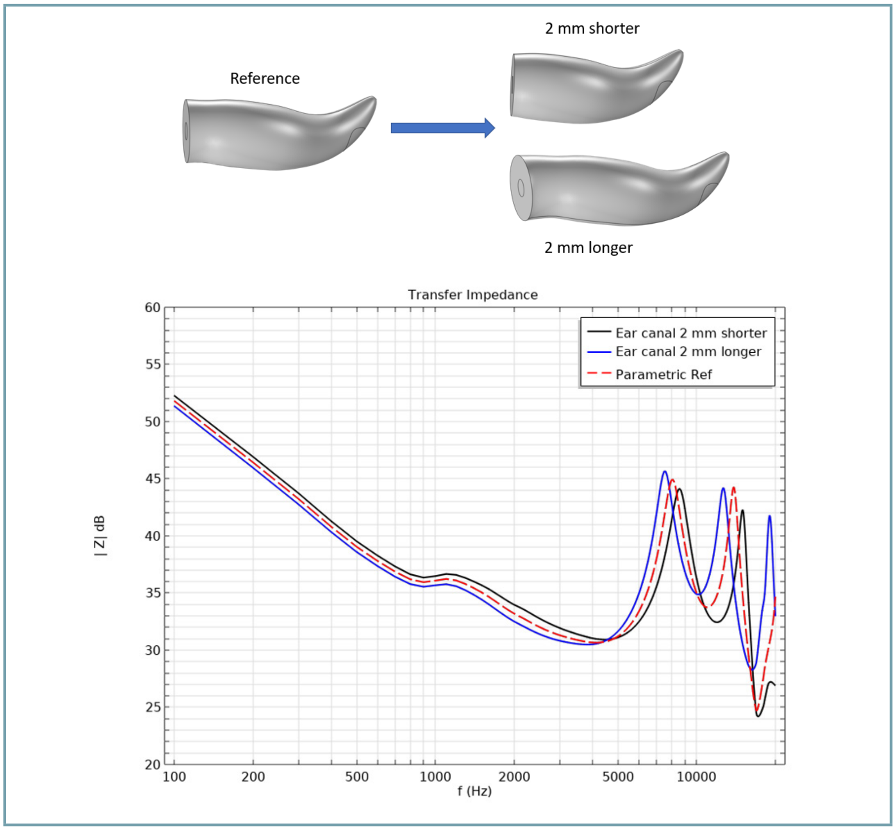


FIGURE 10.
Changing the length of the ear canal, by making it 2 mm shorter or 2 mm longer can be seen to have an effect of around 0.5 dB to 1 dB on the transfer impedance. The most obvious change is the shift of the frequency of resonance peaks linked with the half and the full wavelength.

An Axiometrix Solutions Brand

CONCLUSION

When testing in-ear headphones using ear simulators, one of the primary concerns is the precise positioning of the DUT within the ear canal. This positioning determines the ear canal's volume and length during the test, which in turn affects the acoustic properties of the ear simulator. If the DUT's position varies between tests or differs across different implementations, the results from ear simulator tests may not be directly comparable.

Similarly, the performance of in-ear headphones in an actual human ear will depend on their exact placement within the ear canal, influencing the effective volume and length of the canal.

The specific shape of the ear canal—whether in a simulator or a human ear—is of lesser importance as long as the volumes and lengths are well defined. However, a complicating factor in the low-frequency response is the potential for leaks between the DUT and the ear canal surface. With more complex ear canal geometries, it becomes challenging to maintain consistent leakage from one test to another, making it difficult to evaluate the effects of design changes or modifications.

REFERENCES:

https://www.comsol.com/model/type-4-3-ear-simulator-106741

© 2024 GRAS Sound & Vibration / All Rights Reserved — date 2024-10

About GRAS Sound & Vibration

GRAS Sound & Vibration is a worldwide leader in the sound and vibration industry. We develop and manufacture state-of-the-art measurement microphones and related equipment for industries where acoustic measuring accuracy and repeatability are of the utmost importance. This includes applications and solutions for customers within the fields of aerospace, automotive, audiology, consumer electronics and other highly demanding industries. GRAS microphones are designed to live up to the high quality, durability and accuracy that our customers have come to expect and trust.

GRAS is represented through subsidiaries and distributors in more than 40 countries and is part of Axiometrix Solutions, a leading test solutions provider comprised of globally recognized measurement brands. Read more at www.grasacoustics.com

GRAS Sound & Vibration

Skovlytoften 33, 2840 Holte, Denmark, +45 4566 4046, **www.GRASacoustics.com**

An Axiometrix Solutions Brand