DETECTION AND COMPENSATION FOR ACOUSTIC LEAKAGE FOR HEARING AIDS

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We discuss a Receiver in Canal (RIC) system and methods for detection and compensation of the acoustic leak between the ear canal and ambient environment.

1. Introduction

With certain types of hearing aids there is a significant acoustic leakage between the ambient environment and the user's ear canal, past in-the-ear part of the hearing device and its dome into the ear. This acoustic leakage could be due to the loose or open fitting nature of the hearing device, which promotes comfort for the user. Acoustic leakage is increased with open fitting.

However, an additional acoustic leakage decreases passive attenuation of the ambient noise at the user's eardrum. The resulting poor passive acoustic attenuation can lead to lower quality user experience of the desired user audio content, due to low signal-to-noise ratio and/or speech intelligibility especially in environments with high ambient or background noise levels.

Also sound produced by the acoustic driver in the ear can be noticeably decreased due to an (uncontrolled) leakage. The difference in sound in the ear of about 30 dB at 100 Hz for different leakage conditions, as illustrated in Figure 1, can happen in real ears.

There are currently two methods known to correct for acoustic leakage in a hearing device: the first one is to compensate for it via signal processing algorithms, the second would be to indicate to the user to manually either re-position the hearing device or change the dome. Such algorithms include either generating more sound by the receiver to compensate for leak loss or generating the sound in antiphase to reduce ambient sound entering the ear via the leak channel.

In present state of the art we have the following shortcomings:

- Leakage compensation by changing the dome or asking the user to move the hearing device lacks robustness and requires the listener to perform some action.
- Usually, leakage compensation is performed via algorithms. However, in some cases, it is not possible to perform an equalization of tens of dB to boost the driver signal at low frequencies.

2. A receiver in canal (RIC) system for leakage measurement and control

For a better listening experience a Valve-Microphone system can be used to analyze the acoustic leakage state and to compensate for the leakage if necessary.
This system, as shown in Figure 2, consists out of a Valve in the Ear Canal (VRIC) and a pair of microphones, preferably with a microphone listening to ambient sound (further referred as Mic-Out) and a second microphone listening to the inside of the ear canal (further referred as Mic-In). The valve is a mechanical system designed to be switched between the two different states: closed state and open state. In the closed state the acoustic connection channel

between the ear and the ambient environment is blocked either for the purpose of higher Hearing Aid (HA) amplification or for streaming broadband audio free of ambient noise. In the open state this acoustic channel is open for the purpose of occlusion reduction.

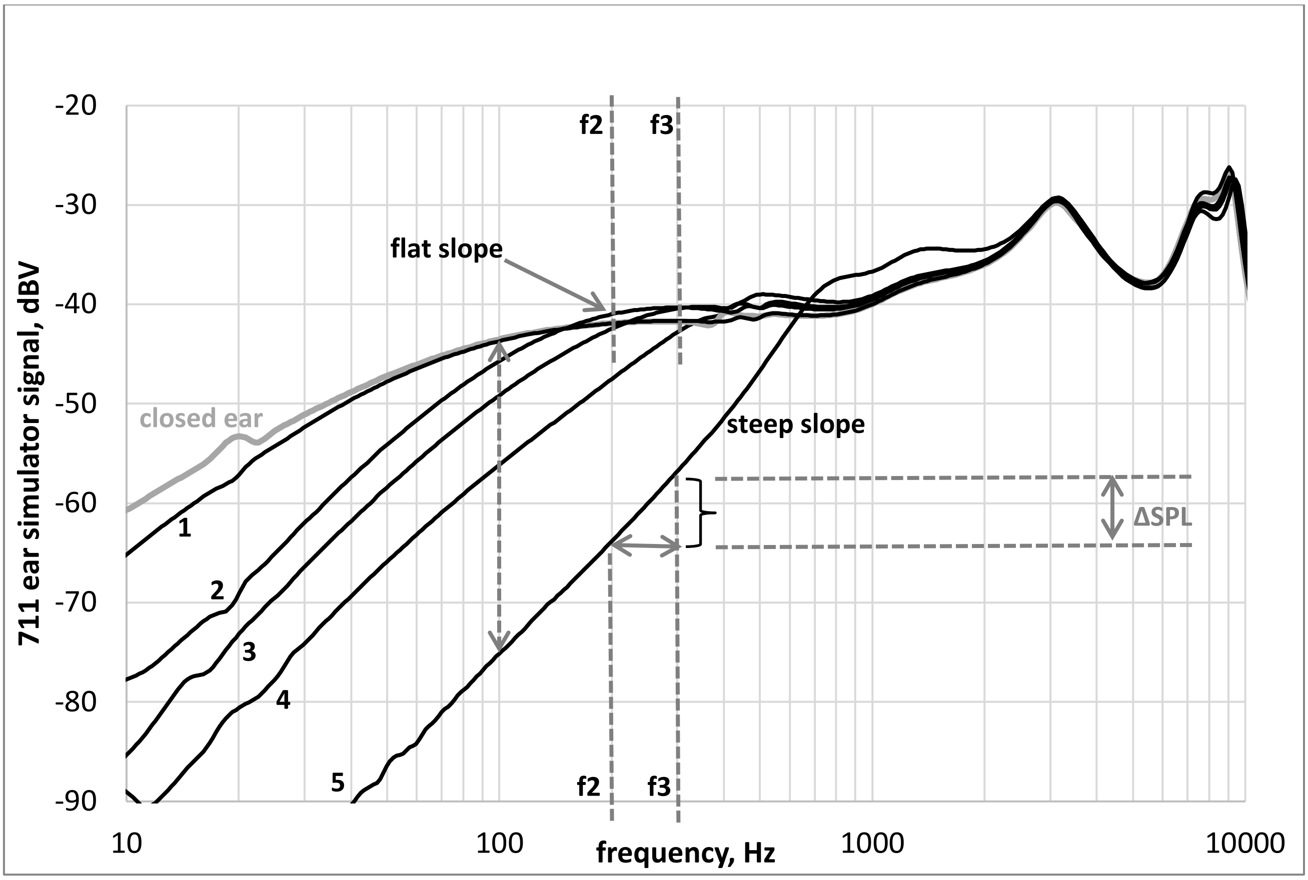

Figure 1: *Example of the impact of the ear (simulator) sealing on the acoustic signal provided by the driver. The main impact is in the low frequencies. The signal is measured by the ear simulator microphone while the driver plays sound in the ear. Several curves for different degree of seal (leakage) are shown in the order of increasing leakage from curve 1 to curve 5. Identical result at low frequencies can be obtained with the RIC module microphone listening to the inside of the ear simulator (Mic-In). The difference in sound pressure level (SPL) at 100 Hz due to the leakage effect is shown with the dashed arrow. This figure also illustrates that the slope of the measured signal vs frequency can be a measure of the degree of leakage. f2 and f3 are the two frequencies used for calculation of the SPL slope in section 3.a.*

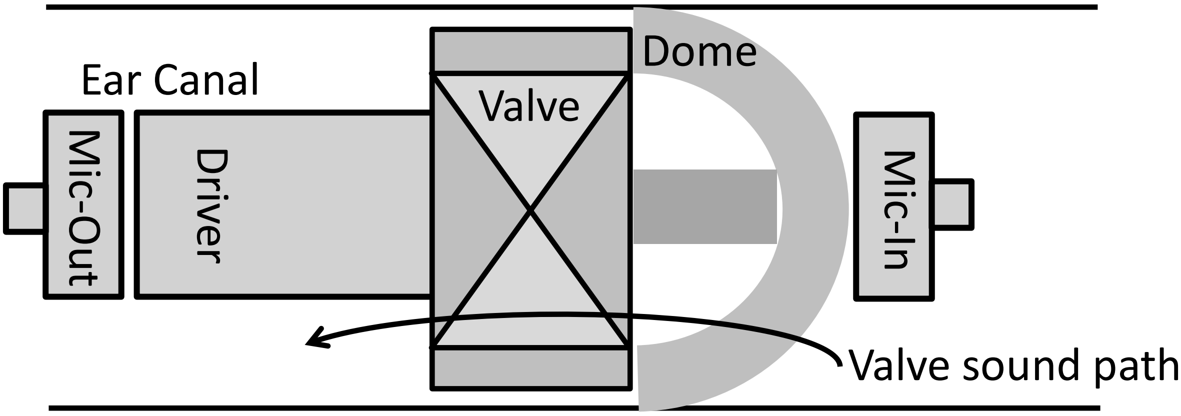

Figure 2: *A RIC device with an acoustic valve and two microphones: Mic-in and Mic-out.*

This system (Figure 2) can be used in two ways:

- with an open valve, when the two microphones are used to measure the remaining passive attenuation in open state to compensate for it for a better natural feeling for the user. In this case the processing algorithm augments the external sound in the ear by boosting high frequencies.

- with a closed valve when the two microphones are used together with ANC-algorithms for listening experience undisturbed by the external noise, for example for streaming audio. In this case the processing algorithm helps to cancel out any remaining external sound that still gets into the ear due to a present leak.

3. How to measure the leakage

Leak detection with the Valve-Microphone system can be performed in different ways and can prompt the audiologist/wearer to re-adjust the RIC or choose another dome size. It can be used as well to start leak compensation with a DSP algorithm if the leak is still adjustable.

The leak can be characterized in the following ways:

a) Calculating the slope of the SPL measured with Mic-In while receiver plays sound, as illustrated in Figure 1.

b) Measuring the ΔSPL at a given frequency (e.g. 250Hz, chosen here) between the closed and open state of the Valve (Figure 3) while receiver plays sound.

c) Calculating the passive noise reduction (PNR) added when the valve is closed as the ratio of Ambient-to-Ear (A2E) functions PNR = (A2E (Closed Valve)) / (A2E (Open Valve)). The same value can be approximately estimated as the ratio of spectra of Mic-In and Mic-Out signals measured simultaneously (Figure 6).

The combination of (a,b,c) makes the system more robust and helps to analyze the situation better and therefore provide better assistance to the audiologist or end user. The 3 methods will be explained in the following paragraphs.

3.a Slope detection using multiple points on the low frequency slope of the Mic-In signal

Slope detection using multiple points on the low frequency spectrum slope of the signal in the ear is illustrated in Figure 1.
In example, illustrated in Figure 1, we use two frequency points for measurements of the ΔSPL: the first point at 200 Hz and the second point at 300 Hz. These frequencies are chosen low enough to avoid other real ear effects present.
We subtract the SPL in dB at f2=200Hz from SPL in dB at f3=300Hz. ΔSPL=SPL(f3)- SPL(f2) corresponds to a certain slope per decade:

- When ΔSPL = 1.5 dB the increase per decade is 9 dB. Below this number we can consider response curves corresponding to a closed fit.

- When ΔSPL = 7.0 dB the increase per decade is 40dB. Around this number we can consider response curves corresponding to a completely open fit.

- When ΔSPL is in between 1.5 and 6.0 we consider the fit to be leaky at various degree of the leak.

3.b Measuring the ΔSPL at a given frequency between the closed and open state of the Valve

Measuring the ΔSPL at 250Hz between the closed and open state of the Valve is illustrated in Figure 3.

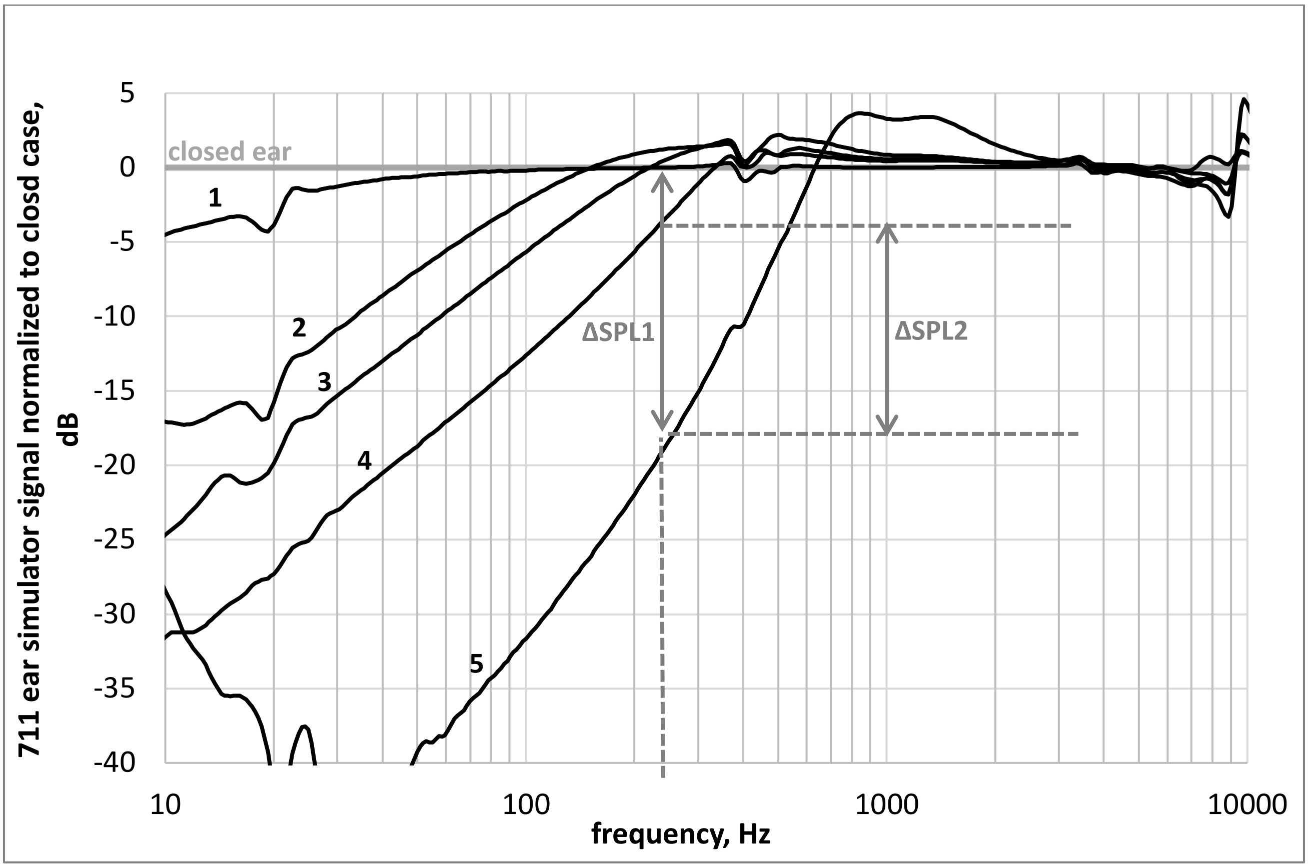

Figure 3: *SPL curves from Figure 1 normalized to the ideally sealed (closed ear) case. If closed valve state corresponds to closed ear then opening the valve would really make a significant difference, as shown with ΔSPL1. In case if closed valve state has an uncontrolled leak involved, like described by curve 4, then opening the valve will have less effect, as shown with ΔSPL2. Here it is assumed that case 5 corresponds to open valve state.*

The difference at a given frequency between the closed and open valve states can be used as a measure of the degree of leakage. In case of increasing leakage in the reference (closed) case the difference between the closed and open valve states will be less.

The difference in SPL at 250Hz between the open and closed state of the valve can be a measure for the openness (leak). Measuring this value in the real ear will also indicate if a leak is present. For example, if the ΔSPL at 250Hz is less than 15 dB the fitting is probably leaky and closing the valve does not have big impact on the SPL measured by Mic-In.

More frequency points can be used for the slope measurements as described in section 3.a and for the SPL difference measurements of section 3.b (f2, f3, f4 etc.). Also, a test could be performed to ensure the correct definition of these frequencies: for example, to keep SPL measured by Mic-IN >40dB, or well above the ambient noise level in the ear during the test.

3.c Calculating the passive noise reduction

While methods 3.a and 3.b are based on sound produced by the driver, 3.c utilizes the effect of the external (ambient) sound getting into the ear. Ambient noise reaching inside the ear (simulator), also referred to as ambient-to-ear (A2E) function, for seal cases of Figures 1 and 3 is given in Figure 4.

Figure 5 gives curves of Figure 4, normalized to the OPEN EAR case, being the case of an open ear (simulator). The passive noise reduction (PNR) as frequency dependent ratio, PNR = A2E/A2E_Open can be a measure of openness of the ear canal. In Figure 5 each PNR curve is fitted with a simple second order low pass filter model (Figure 7). This allows to determine the leak frequency which can be a numerical parameter describing the degree of leak (openness).

An alternative way of calculating the passive noise reduction is illustrated in Figure 6.

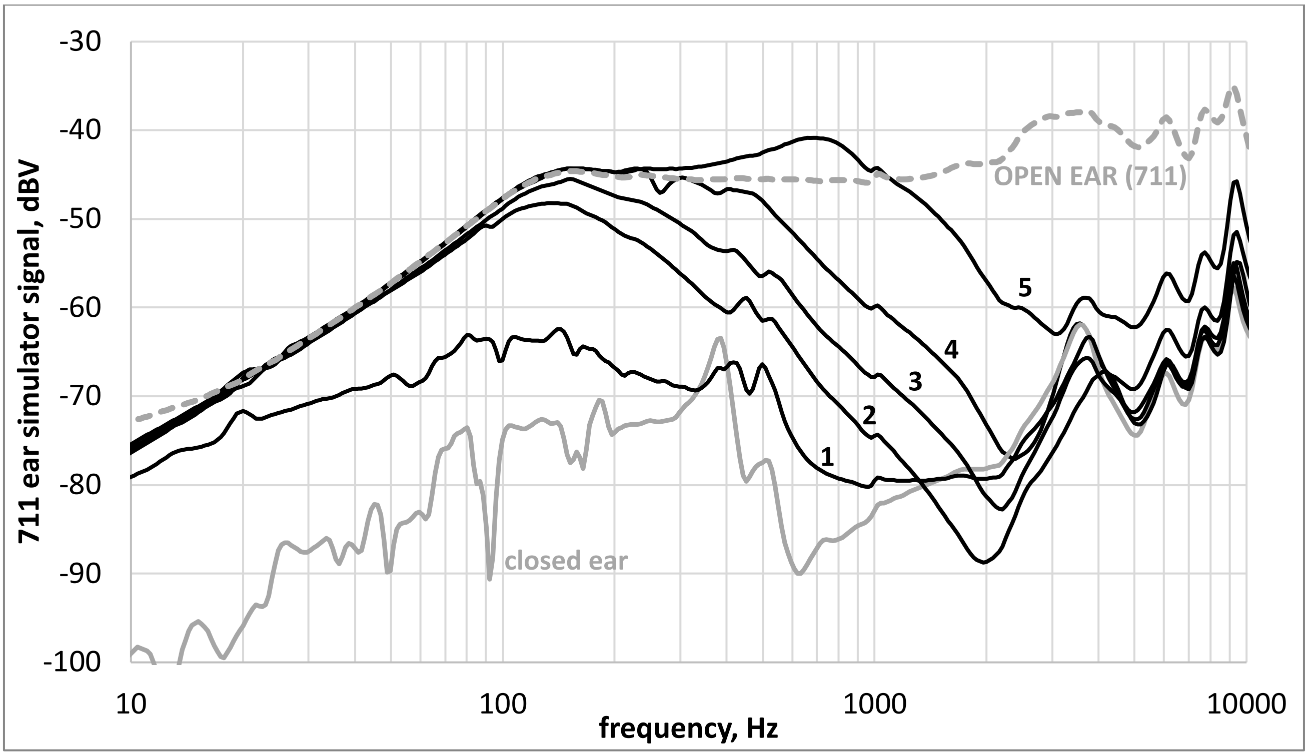

Figure 4: *Ambient noise reaching inside the ear (simulator) for seal cases of Figures 1 and 3.*

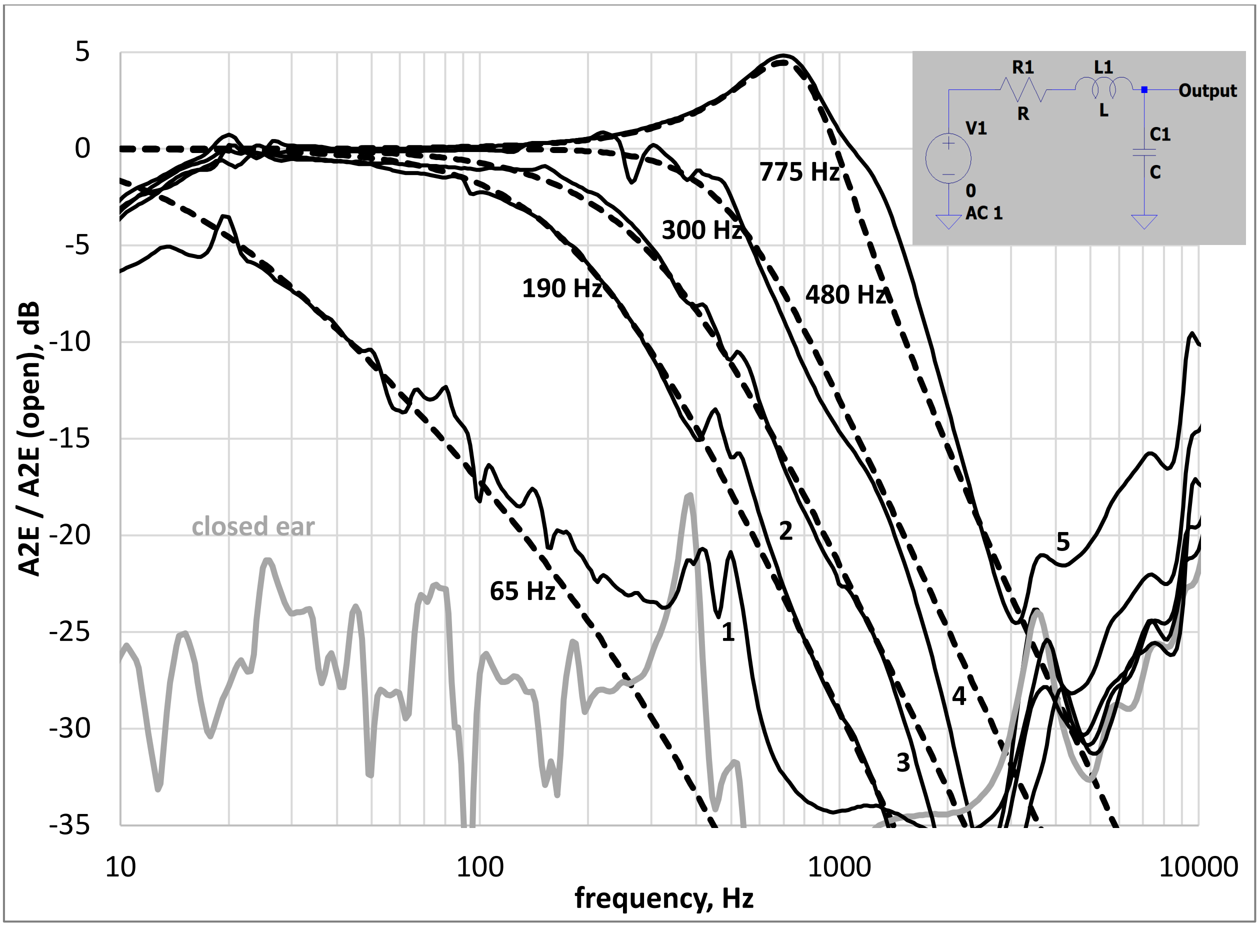

Figure 5: *Passive attenuation curves calculated as PNR = A2E/A2E_Open: ambient signal in the ear, as shown in Figure 4, normalized to the OPEN EAR case, being the case of an open ear (simulator). For each experimental curve a best fitting model is given by a dashed curve. The model is explained in Figure 7. The leak frequency value is given for every model curve.*

For low frequencies, below ear (simulator) resonance being about 3000 Hz, the ear simulator microphone in open case (no module inserted) is measuring the same SPL as outer microphone (Mic-Out) in case the module is inserted.

Also, in a good design of a RIC, with proper separation between the Mic-In inlet and the driver outlet, Mic-In is measuring the same SPL as ear (simulator) microphone until as high frequency as close to the quarter wavelength frequency of the ear simulator, e.g. 6000 Hz, corresponding to the quarter wavelength distance between the Mic-IN and the ear (simulator) microphone.

This means that there is an alternative way of calculating PNR = A2E/A2E_Open as:

$$PNR = A2E / A2E\_Open = (Mic\text{-}IN) / (Mic\text{-}Out) \qquad (1)$$

The result calculated as (Mic-IN) / (Mic-Out) is given in Figure 6. Model curves are identical to the ones in Figure 5. Experimental PNR calculated as (Mic-IN) / (Mic-Out) is slightly different from PNR calculated as ear (simulator) microphone normalized to the open case (Figure 5).

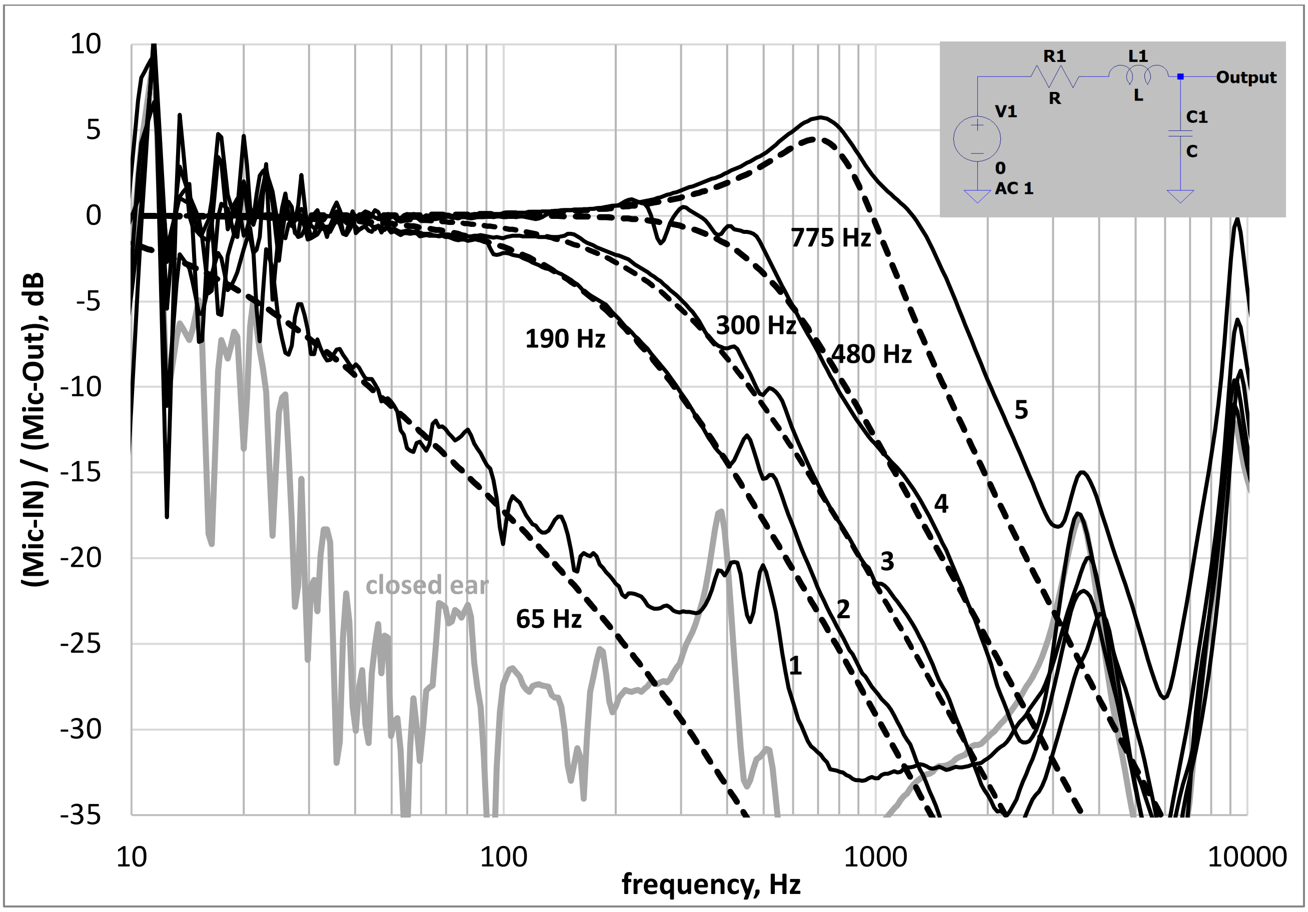

Figure 6: *Passive attenuation curves calculated as ratio of the spectrum of Mic-In and Mic-Out: PNR = (Mic-In)/(Mic-Out). For each experimental curve a corresponding model is given by a dashed curve. The model is explained in Figure 7. The leak frequency value is given for every model curve. Model curves are identical to the ones in Figure 5. Experimental PNR calculated as (Mic-In)/(Mic-Out) is slightly different from PNR calculated as ear (simulator) microphone signal normalized to open ear case (Figure 5).*

One curve in Figures 5 and 6 shows more attenuation at lower frequencies than the others. It corresponds to leak frequency of 65 Hz. This will be true for a good seal of the dome in closed valve case. In case of significant leakage, the leak frequency will increase, as shown in Figures 5 and 6.

The behavior shown in Figures 5 and 6 can be described by the following simple model given in Figure 7.

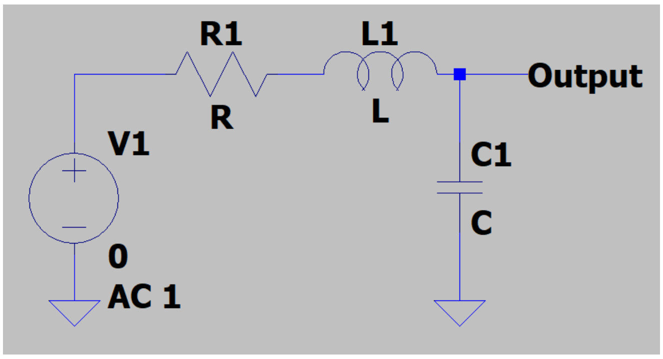

Figure 7: A simple acoustic circuit that describes ambient pressure entering the ear canal through a leak channel. Here **V1** represents the ambient pressure outside the ear, acoustic resistance **R1** and acoustic mass **L1** represent the real ear leak. **C1** is acoustical compliance of the ear volume.

The ambient sound pressure reaching the ear due to the model in Figure 7 is given as follows:

$$|V_{Output}| = \frac{V_1}{\sqrt{(-\omega^2 LC + 1)^2 + (\omega RC)^2}} \tag{2}$$

The last expression describes a low-pass filter with possible peak at $f_0 = 1/\sqrt{LC}/(2\pi)$.

In case of open ear canal

$$|V_{Output,OPEN}| = \frac{V_1}{\sqrt{(-\omega^2 L_{OPEN} C + 1)^2 + (\omega R_{OPEN} C)^2}} \approx V_1 \tag{3}$$

We assume $-\omega^2 L_{OPEN} C$ and $\omega R_{OPEN} C$ very small. This assumption should hold for low frequencies e.g. below 3000 kHz (ear canal resonance).

So, for the purpose of fitting the model to measurement, in Figure 5 and 6 we used the ratio:

$$|V_{Output}|/|V_{Output,OPEN}| = \frac{1}{\sqrt{(-\omega^2 LC + 1)^2 + (\omega RC)^2}} \tag{4}$$

Values of $f_0 = 1/\sqrt{LC}/(2\pi)$ are given in Figures 5 and 6 as leak frequency values. These are numerical values that relate to the degree of leak (openness) in method 3.c.

4. Other important features of the system

4.1 Microphone placement, as in Figure 2, enables better ANC (Active Noise Cancelling) than in case of BTE microphone placement. With current BTE microphones, Active Noise Cancelling is a difficult task as the impact of the microphone placement and the acoustic tube must be accounted for. With the present approach of Valve with Mic-In and Mic-out, it is easier to use state-of-the-art ANC for all cases: Feedback, Feedforward and Hybrid.

4.2 If the user inadvertently removes his hearing device from one ear, this can also be detected by checking the leakage detection which will be completely different than in the ear canal.

4.3 If a large leak is detected readjustment by the user or changing the dome size may be prompted. If the leak is small, the DSP can boost the gain at low frequencies.

5. How to interpret the state of the system for self-diagnostics

More details are given in the following diagnostic table regarding the state of the valve, sealing of the ear canal by the dome and possible malfunction:

PNR= (Mic-IN) / (Mic-Out) is low (high passive damping effect) at 100-2000 Hz: low leak frequency in 3.c

	open/closed valve difference at LF is high (3.b)	open/closed valve difference at LF is low (3.b)
Flat slope at LF (see 3.a)	Valve works and it is closed. Receiver, Mic-In and Mic-Out are working. The dome seals the ear canal.	Valve may be stuck in closed state, Receiver may have no output or an issue with Mic-IN
Steep slope at LF (see 3.a)	Valve works and it is open. Receiver and Mic-In are working. Maybe an issue with Mic-Out.	Valve may be stuck in open state or Huge dome leak Receiver and Mic-In are working. Maybe an issue with Mic-Out

PNR= (Mic-IN) / (Mic-Out) is high (low passive damping effect) at 100-2000 Hz: high leak frequency in 3.c

	open/closed valve difference at LF is high (3.b)	open/closed valve difference at LF is low (3.b)
Flat slope at LF (see 3.a)	Receiver and Mic-In are working. Valve in the closed state, Maybe an issue with Mic-Out	Valve may be stuck in open state or Huge dome leak. Receiver may have no output.
Steep slope at LF (see 3.a)	Valve works and it is open. Receiver, Mic-Out and Mic-In are working. The dome seals the ear canal.	Valve may be stuck in open state or Huge dome leak. Receiver and Mic-In are working

6. Summary: advantages of the method

1. Better sound quality due to leak detection and leak control.
2. Leakage detection that can also be applied for OTC products for mild hearing loss.
3. It helps to simplify the initial fitting process by providing leakage data to select the optimal dome size. This can be a self-fitting process (OTC) or a guided process by an audiologist.
4. By knowing the leakage state of the fitting it's possible to optimize HA-parameters such as gain, compression speed, noise reduction, directionality, latency and so on.
5. It enables self-diagnostic of the valve state, seal of the ear canal and microphone performance, which is robust with respect to ear size, noise, etc …