# Assessment of otoacoustic emission probe fit at the workfloor

Vincent Nadon, Annelies Bockstael, Dick Botteldooren
INTEC, Acoustics Research group, Ghent University, Sint-Pietersnieuwstraat 41, B-9000 Ghent, Belgium

Jeremie Voix
École de technologie supérieure, 1100, Notre-Dame Ouest, Montreal, Quebec, H3C 1K3, Canada

**Summary**

In the workplace, practices in occupational health to prevent noise-induced hearing loss (NIHL) are currently based on a group average of exposure/damage relationships. These practices do not take into account the individual susceptibility to NIHL which is an important factor in a worker's actual risk of hearing loss. To evaluate and improve the effectiveness of personal hearing protection at the workfloor, an in-field measurement procedure of otoacoustic emissions (OAE) has been developed and validated. Unsupervised evaluation of OAE probe placement during the work shift is an important challenge for in-field OAE measurement. In this regard, proper OAE probe fit in the ear canal is a major concern in order to provide optimal passive noise attenuation to ensure that the worker's hearing is protected and improve signal-to-noise ratio of OAE measurements. In the following study, a lumped elements model of an occluded ear canal is used; first, to analyze the effects of probe fit leakage on the loudspeaker transfer function. Second, to validate the proposed method by comparing the model's transfer functions with those estimated during experiments with an OAE probe and tube setup. Afterwards, the probe's passive noise attenuation is calculated for different leaks by measuring sound pressure level inside and outside the occluded tube. Finally, the relationship between the probe's passive attenuation, miniature loudspeaker response and leakage is established. This proposed approach could assess the probe fit *in situ* and solve problems of unsupervised evaluation of probe placement by automatically warning the wearer of an improper fit after the loudspeaker response measurement.

**PACS no. 43.58.+z, 43.60.+d, 43.64.Jb**

## 1. Introduction

In noisy workplace environments, risk of noise-induced hearing loss (NIHL) due to occupational noise exposure is reduced using personal hearing protection devices (HPD). Even though different methods are available to assess passive noise attenuation individually [1, 2], one factor of uncertainty is the exposure level under the hearing protector and the susceptibility to NIHL which varies between individuals [3].

These problems could be solved by providing a special type of HPD to workers assessing the individual's auditory fatigue induced by daily noise exposure. Such a device would warn the worker or his superior in real-time when a (temporary) change in the worker's inner ear dynamics is detected. To monitor the diurnal effect of noise exposure, and thus prevent permanent changes in hearing sensitivity, an in-ear hearing protection device featuring otoacoustic emission (OAE) monitoring is a promising solution.

Distortion product OAEs (DPOAEs) are measured by sending two pure tone stimuli to the ear, $f_1$ and $f_2$ with a $f_2/f_1$ ratio of 1.22, generated by the two miniature loudspeakers within the OAE probe. Low-level cubic distortion signals (i.e. $f_{dp} = 2f_1 - f_2$) are generated by the active non-linear process of the outer hair cells (OHC), taking place inside the inner ear. The distortion product responses travel back from the inner ear to the outer ear where they can be recorded by an in-ear microphone (IEM) placed inside the ear canal. If the OHC inside the inner ear are fatigued or damaged —for instance due to previous excessive noise exposure— the amplitude of DPOAEs is found to be lower than if they were healthy. While the measured DPOAE signals are not directly related to the individual *absolute* hearing thresholds as assessed with a trathese individual's DPOAEs can be used to track the *relative* change in hearing sensitivity [4]. Measuring DPOAEs outside a controlled environment —i.e. in-field hearing screening— is currently strongly hampered by their susceptibility to interfering environmental noise [5]. As typical DPOAE sound pressure levels (SPL) fall between -20 dB to 20 dB depending on stimuli levels and health of OHC [6].

The authors have designed a new type of DPOAE probe suitable for in-field measurements [7]. This probe includes two miniature loudspeakers with an in-ear microphone (IEM-I), as normally found in standard DPOAE probes, with an additional outer ear reference microphone (OEM-I) mounted flush on the outer faceplate of the earpiece embedded OAE probe. The probe was designed to use interchangeable custom fitted eartips, therefore providing optimal passive attenuation for every individual worker. To further improve the signal-to-noise ratio (SNR), the authors have developed a noise rejection algorithm topology designed for DPOAE measurements in-field [7]. Two DPOAE probes, one in each ear, are necessary for such algorithm and therefore the probes would be worn by workers at all times during their work shift. Wearing the two probes simultaneously would also protect the worker's hearing against environmental noise with the probe's passive attenuation. For optimal performance of such algorithm scheme, a proper fit of the DPOAE probe, is required in order to acoustically seal the ear canal from external sounds and isolate the in-ear microphones. Ensuring proper fit of the DPOAE probe would also improve the workers' effective hearing protection level.

The aim of the current paper is to develop a method for proper assessment of DPOAE probe fit *in-situ* without assistance of an occupational hygienist. The envisioned method would be integrated in the DPOAE system's [7] measurement routine. In this paper, effects of different sizes of leaks on the probe's miniature loudspeaker frequency response were simulated using a lumped element model of the loudspeaker in a 2cc cavity; bearing in mind that a leak, or improper fit, would affect the frequency response measured by the IEM. The simulated model was experimentally verified by fitting a DPOAE probe with mounting putty in a 2cc cavity. Leaks of different diameter were created in the probe and tube setup. The frequency response of the loudspeaker in the four leak conditions was measured using the IEM and compared with the simulated response. In addition, a 250 Hz pure tone was measured with the probe's IEM and was compared to a reference tone inside the Auditory Research Platform's (ARP) [8] DSPs to establish a comparison parameter for automatic evaluation of probe fit.

## 2. Materials and Methods

To measure the acoustic signals inside the tube the prototype earpiece-embedded OAE probe was used [7]. The DPOAE measurement system incorporating microphone conditioning amplifier and the ARP, developed within the Sonomax-ETS Industrial Chair in In-Ear Technologies (CRITIAS)[8], was used to generate logarithmic sine frequency sweep and pure tones inside the tube and to evaluate differences in SPL at 250 Hz between a leaky and non-leaky system. In usual DPOAE measurement operations, the system is used to generate primary tones with the miniature loudspeakers and process as well as record the DPOAE response from the IEM using the ARP. A 6cc (max) plastic syringe, adjusted to 2cc residual volume with probe fit, was used as a cavity for DPOAE probe fit experiments as seen in Fig. 1. A portable recorder system was used to capture the signals from the IEM and OEM. An external loudspeaker was used to generate white noise in order to characterize the passive attenuation of the probe fitted inside the tube as shown in Fig. 2.

For the prototype DPOAE earpiece, two high-quality miniature balanced armature loudspeakers with a wide-band frequency range are used in order to generate acoustic signals with minimal sound distortion on the audio frequency range for proper DPOAE measurements. The probe's IEM is placed towards the inside of the tube usually to measure DPOAE's, but in this study it was used to measure the frequency response of the miniature loudspeaker and the residual noise during the identification of the passive attenuation transfer function. The OEM is used to measure the external noise for the identification of the probe's passive attenuation transfer function.

In order to seal the tube for the experiments, about 0.6 cm thick of mounting putty was placed on the probe to fit it in inside the tube. Needles of different radius $r_1$=0.025, $r_2$=0.04 and $r_3$=0.06 cm were used to make a hole of known length and diameter in the mounting putty to simulate a probe fit leak, they were removed right away to not clog the hole. The needle sizes were used in ascending order to increase the hole size after measurements for each condition. The length of the leak ($l_l$=0.6 cm) was realistic bearing in mind that the earplug section actually sealing the first bend of the ear canal is normally no longer than 1 cm [9].

In the designed DPOAE measurement system [7], the earpiece is connected to a signal conditioning amplifier designed by the authors [7] in order to maximize the dynamic range of the DSP's ADC and filter undesired electrical interference and the microphones' DC supply. Logarithmic sine frequency sweep and pure tone signals used to characterize the miniature loudspeaker response are generated by the ARP which was connected via USB port to a laptop PC in order to control the DSPs inside. The ARP was also used to

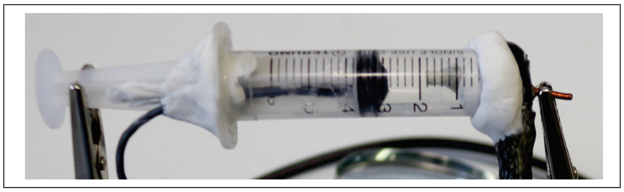

Figure 1. Picture of the measurement tube and probe setup

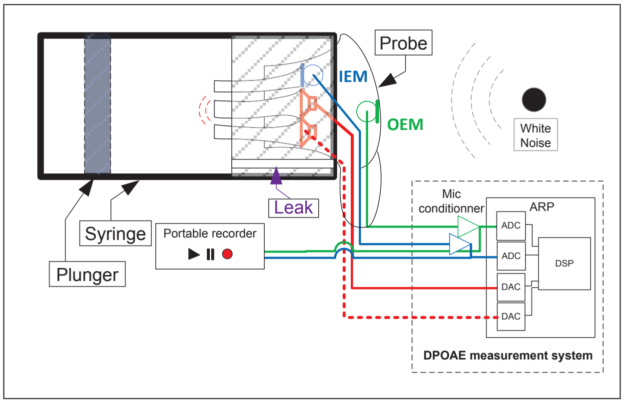


Figure 2. Schematic of tube and probe setup with portable recorder and DPOAE measurement system

calculate the $R_{A/D}$ ratio based on the probe's processed IEM signal input.

An audio recording system including a TASCAM DR-680 portable recorder (TEAC, CA, USA) was used for the acquisition of the IEM and OEM signals with a 24 bits ADC resolution (Fig. 2). The recording gain was adjusted to optimize input range for low levels with an upper limit at 94 dB (SPL) to ensure proper calibration of microphones initially. The DR-680 provided good synchronization between microphone signals with sampling frequency set at 48 kHz. Raw audio files were then transferred to a laptop computer equipped with MATLAB® (Mathworks, MA, USA) to post-process the signals. The simulations of the acoustical circuit model (Fig. 3) were also executed as a MATLAB script using Eq. 1 to 4. Measurements were carried in a quiet room without additional soundproofing materials.

## 2.1. Simulation of a probe fit leak

Since loudspeakers are electro-acoustic transducers, electrical parameters can be determined based on the acoustical parameters of a given loudspeaker and vice-versa. A two-port model established with Voltage (V) and Current (I) represents the electrical parameters, along with acoustical quantities Pressure (P) and Velocity (U). $Z_e$ is the electrical impedance when $U = 0$, $T_a$ is the transduction ratio and $Z_a$ is the acoustical output impedance. $Z_e$, $T_a$ and $Z_a$ are also known as Hunt parameters [10, 11].

Hunt parameters can be used afterwards to model the miniature loudspeaker in the cavity as an

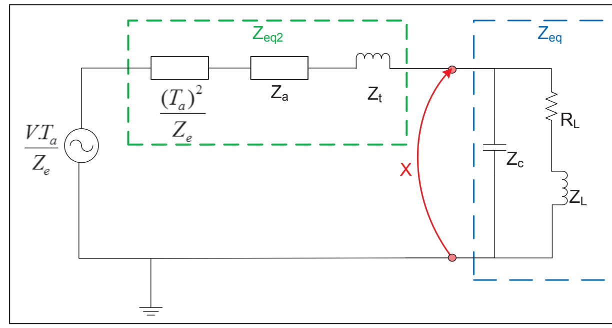


Figure 3. Lumped element, acoustical circuit model of a miniature loudspeaker with its port tube placed in a cavity with a leaky probe fit.

electronic lumped elements model through electro-acoustical analogies [12]. For the following paper, Hunt parameters for the miniature loudspeaker used in experiments were calculated beforehand [10]. Therefore, $Z_e$, $T_a$ and $Z_a$ are used as is in the simulated model. The circuit shown in Fig. 3 is an equivalent, simplified, circuit and therefore $T_a^2/Z_e$ is actually the equivalent electrical impedance of the loudspeaker after removing the transduction ratio component of the circuit. The small tube glued to the miniature loudspeaker port, represented as $Z_t$, must be taken into account in the simulated acoustical circuit (see Fig. 3 and Eq. 4). $Z_{eq2}$ represents the miniature loudspeaker with the tube glued on the port (Fig. 3).

The tube shaped leak shown in Fig. 2 can be modelled as an acoustic mass [12], here denoted as the inductance ($Z_L$), in series with the acoustic resistance ($R_L$) as in Fig. 3 , representing the friction of the air inside the small leak hole [13]. This resistor-inductance leak model is placed in parallel with the tube cavity's (Fig. 2) acoustic capacitance ($Z_c$). The leaky system acts as a high-pass filter with a resonance due to the presence of two reactive components, acoustic mass ($Z_L$) of the leak and acoustic capacitance ($Z_c$) of the cavity. The high-pass filter will cause a drop in lower frequency levels which can then be detected with a microphone. The resonance is also known as Helmholtz resonance and is normally used in bass reflex loudspeaker enclosures to boost the low frequency response [13, 14].

The acoustical analogy circuit's component values (Fig. 3) can be calculated out of the physical dimensions of the experimental setup (Fig. 2) with Eq. 1 to 4 . Eq. 1 and 2 represent the leak [13], Eq. 3 is the cavity compliance impedance and Eq. 4 is the miniature loudspeaker tubing impedance [12].

$$R_{L_i} = \frac{1}{\pi r_i^2}\rho_0\sqrt{2\omega\nu}\left(\frac{l_l}{r_i} + (1^*)\right) \tag{1}$$

$$Z_{L_i} = j\omega\rho_0\frac{(l_l + (1^*)l_l')}{\pi r_i^2} \tag{2}$$

$$Z_c = \frac{1}{j\omega C_{2cc}} \tag{3}$$

$$Z_t = \frac{j\rho_0 c_0}{S} \tan\left(\frac{\omega l_x}{c_0}\right) \quad (4)$$

In Eq. 1 to 4 variables are defined as $\rho_0$ : air density at $20^oC = 1.204 kg/m^3$ , $c_0$ : speed of sound at $20^oC = 343.2\ m/s$ , $\nu$ : kinetic coefficient of viscosity at $20^oC = 1.56 * 10^{-5} m^2/s$ , $S$ : surface of the miniature loudspeaker tube $= \pi(0.08)^2 * 10^{-4} m^2$ , $l_x$ : length of the miniature loudspeaker tube $= 0.0115\ m$ , $C_{2cc}$ : acoustic capacitance of the tube cavity in function of Volume $V_c = \frac{V_c}{\rho_0 c_0^2} = 1.41 * 10^{-11} m^5/N$ , $l_l$ : leak length $= 0.006\ m$ , $l_l'$ : leak length end correction (if both tube ends are considered, replace 1* by 2 in Eq. 1 and 2) $= 0.85 r_i$ , $f$ : frequency in Hertz , $\omega$ : angular speed $= 2\pi f$ , $V_1$ : voltage applied to the miniature loudspeaker's terminals in $Vrms$.

The circuit representing the miniature loudspeaker in the tube with/without leak (Fig. 3) was simulated using an input voltage $V_1 = 0.094 Vrms$. To solve the acoustical circuit model, equivalent impedances and simple voltage divider were calculated as follows : $Z_{eq} = \left((R_{L_i} + Z_{L_i})^{-1} + Z_c^{-1}\right)^{-1}$, $Z_{eq2} = \frac{T_a^2}{Z_e} + Z_a + Z_t$, $|X| = \left|\frac{V_1 T_a}{Z_e} * \frac{Z_{eq}}{Z_{eq}+Z_{eq2}}\right|$. The SPL output ($|X|$) was then converted to dB in reference to 20$\mu$Pa, this output represents the signal captured by the probe IEM inside the tube cavity in the experimental setup.

### 2.2. Experimental measurements

Measurements of the miniature loudspeaker frequency response, $R_{A/D}$ ratio inside the DSP and probe passive attenuation using the setup shown in Fig. 2 were repeated three times and levels were averaged for each leak condition. After each repetition, the probe was taken out of the tube cavity and refitted for the following measurement repetition.

The SPLs generated by the probe miniature loudspeaker were calibrated beforehand for 65 dB (SPL) at 250 Hz. This procedure was done by first measuring the level generated by a Svantek calibrator SV30A (Warsaw, Poland) set for 94 dB (SPL) at 1 kHz with the probe IEM recorded using the TASCAM portable recorder and then verifying if the correct level was observed in MATLAB, levels were matched using an adjustment factor. Secondly, the probe IEM was used to capture the 65 dB (SPL) 250 Hz pure tone generated by the miniature loudspeaker. The SPL was then observed in MATLAB and a small adjustment was made to the output gain of the DSP driving the miniature loudspeaker to match 65 dB (SPL).

#### 2.2.1. Measurement of miniature loudspeaker frequency response with the DPOAE probe IEM

To measure the frequency response of the miniature loudspeaker, a logarithmic sine frequency sweep was generated using the DSP inside the ARP of the DPOAE measurement system. The SPL was captured by the probe's IEM.

#### 2.2.2. Measurement of $R_{A/D}$ ratio in the DSP

Bearing in mind that the developed DPOAE system will be used in-field without expert supervision during otoacoustic emission measurements, the evaluation of the probe fit must be simple and quick without disturbing the user's activity. Therefore, an algorithm inside the DSP was designed to calculate differences in SPLs captured by the IEM used for measurements according to a reference pure tone signal (250 Hz) generated and measured solely inside the DSP while the probe is placed in the cavity. The analog (A) voltage output of the probe IEM measured by the DSP was averaged using a running Root Mean Square (RMS) averaging and then divided by the reference digital (D) signal averaged using running RMS in order to calculate a ratio, also referred here as $R_{A/D}$ ratio. Differences in such $R_{A/D}$ ratio can be used afterwards to automatically evaluate if the probe fit is good (baseline $R_{A/D}$ ratio) or leaky ($R_{A/D}$ ratio different from the baseline).

#### 2.2.3. Measurement of the probe passive attenuation in the tube

To measure the passive attenuation provided by the DPOAE probe in the tube cavity, a small external loudspeaker was used to generate white noise (Fig.2). The level of white noise disturbance was set at 70 dB(A) at the probe's OEM position using a Svantek SVAN959 (Warsaw, Poland) sound level meter. The passive noise reduction provided by the probe sealing the tube cavity is evaluated using the difference between the probe's measured OEM and IEM SPLs per octave band.

## 3. Results

### 3.1. Simulated and measured frequency response

Magnitude of frequency responses were normalized throughout this paper in order to ease the comparison between the manufacturer's specifications, simulated and measured responses. The acoustical circuit model simulated in a non-leaky setup (Fig. 3 ), where $R_L$ and $Z_L$ are removed, gives a frequency response similar to the miniature loudspeaker's manufacturer specifications (Fig. 4). Considering that the length of tubing glued to the miniature loudspeaker's port used in experiments and reproduced in the simulations was different than specified in the manufacturer's datasheet, it is normal that the peak frequency is shifted slightly. The frequency response measured with the experimental setup shown in Fig. 2, shows that the minimum at 4885 Hz (between the two resonances) is lower in all measured conditions than simulated conditions (Fig. 4).

As shown in Fig. 4, there are very small differences in measured SPLs at 250 Hz between $r_1$ and $r_2$ (-3.29 vs -4.21 dB on average), especially considering

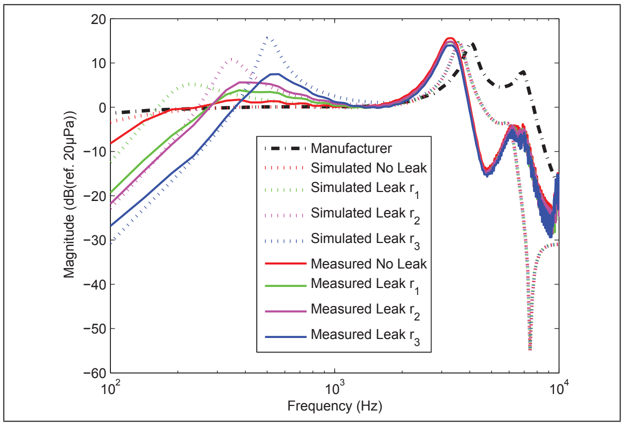


Figure 4. Simulation and single measurement frequency responses of a miniature loudspeaker for different leak sizes in a 2cc cavity.

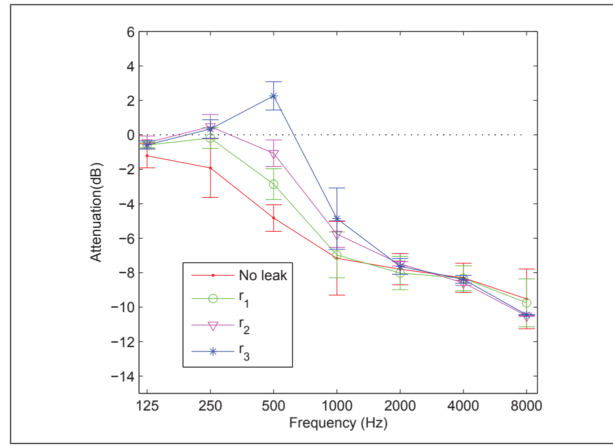


Figure 5. Attenuation measured between the probe's OEM and IEM.

the large standard deviations (3.17 and 3.40 dB respectively), this is mostly due to the very small radius difference between the two leaks. More leakage effect is seen when comparing the biggest leak ($r_3$) with the no leak condition (-10.43±3.45 vs -1.50±2.06 dB respectively). SPLs at 250 Hz in both simulation and experiments decrease as the leak radius increases. All leak conditions give higher SPLs than the no leak condition between 280 Hz and 1000 Hz, due to the Helmholtz resonance coming from the effect of the probe leak in the cavity. This effect is mimicked in the acoustic circuit model with $R_L$ and $Z_L$ which represent the leak (Fig. 3). This Helmholtz resonance is more visible for the $r_3$ leak at 526 Hz (Fig. 4). Bigger deviation between simulated and measured response in frequencies below 330 Hz for the $r_1$ leak condition might indicate some additional damping in the experimental setup which is more visible for smaller leaks, such damping is discussed in Section 4.

### 3.2. Measured $R_{A/D}$ ratio in DSP

$R_{A/D}$ ratios averaged over the three measurements for the no leak, $r_1$, $r_2$, $r_3$ leak conditions were respectively of 12.37±0.19, 14.62±3.26, 15.47±2.77, 20.52±2.72. These results show that as the leak radius increases the ratio also increases. The difference in $R_{A/D}$ ratio between the no leak and $r_3$ leak radius condition shows enough magnitude (8.15 dB) to be easily detected by an algorithm for automatic evaluation of probe fit quality in-field.

### 3.3. Measured passive attenuation of the probe in tube

The relationship between the loudspeaker response and the amount of passive attenuation provided by the DPOAE probe was assessed to eventually evaluate the probe fit in-field by solely measuring the $R_{A/D}$ ratio. The passive attenuation provided by the probe with mounting putty in the tube cavity is averaged over the three measurements and is shown in Fig. 5. Results indicate that the mounting putty and the syringe did not provide much passive attenuation (-4.83 dB at 500 Hz in the no leak condition), but was sufficient to show a realistic pattern for humans.

## 4. Discussion

As observed in Fig. 4, accuracy of the simulated model for frequencies over 4 kHz could be improved by modelling the cavity with a more complex cavity model such as the model from the B&K type 4195 (Brüel & Kjær, Nærum, Denmark) coupler [15].

Additional damping observed in the measured response when compared to the simulation results, especially for Helmholtz resonances and in frequencies below 330 Hz (Fig. 4), indicates that some physical properties of the experimental setup are not modelled. One possibility could be that the softness of the rubber material covering the syringe plunger is not modelled in the acoustical circuit (Fig. 3). Therefore, an additional acoustical impedance branch might be needed in parallel with the cavity's impedance $Z_c$ in order to model this plunger surface which can be seen as an eardrum and modelled as an RLC circuit [16].

Although differences in measured SPL and $R_{A/D}$ ratios are subtle between $r_1$ and $r_2$ conditions (<1 dB) due to the size of the very small leak holes' radius which are also close to each other and that it is difficult to reproduce the hole perfectly for every manipulation. Overall, when looking at the no leak and $r_3$ leak conditions the differences in the $R_{A/D}$ ratio are sufficient to be detected. Since bigger leaks could be expected in tests with humans, more leak effect would be expected on the frequency response and could be automatically detected. The standard deviation could be decreased by doing more repetitions of the measurements.

The $R_{A/D}$ ratio is a relevant leak indicator (8.15 dB between no leak and $r_3$ leak conditions) which follows the measured SPL at 250 Hz and the probe's passive attenuation. However, the ratios measured may not represent the exact value that would be measured in human ear canals. Therefore, the method must also be validated in humans in the future and new ratio criteria would be established.

To improve the passive attenuation of the setup, the syringe could be replaced by an adjustable thick brass cavity. Although such improvement could make the effects of the leak conditions more noticeable and closer to what would be expected in humans, the passive attenuation in the current study was sufficient to show leak effects.

The Helmholtz resonance effect could have an impact on the evaluation of a proper probe fit by misleading the user into thinking that a better seal is obtained since the $R_{A/D}$ ratio would decrease instead of normally increasing for bigger leaks. For smaller leak diameters, the resonance frequency will be lower (Fig. 4), but considering a known fixed eartip length sealing the ear canal [9] it is possible to detect a leak by first establishing a baseline with an optimal seal. $R_{A/D}$ ratios relative to this baseline should always increase if the ratio is measured at a frequency lower than the expected resonance. The $R_{A/D}$ ratio measured at 250 Hz is therefore an accurate indicator of a leak in the probe's seal for leak lengths shorter than 1 cm.

## 5. CONCLUSIONS

The scope of the study, i.e. visualize leak effects on the frequency response of the DPOAE probe miniature loudspeaker, was achieved. The simulated acoustic circuit model has shown sufficient similarities with the experimental setup to observe that the SPL around 250 Hz decreases as the leak radius increases and could be used to predict probe leak effects in humans. The $R_{A/D}$ ratio was shown to be a suitable indicator for automatic evaluation of probe fit leakage during in-field DPOAE measurements. Although a low frequency resonance due to the Helmholtz resonator effect might cause problems, by knowing the length of the eartip inserted in the ear canal the system can easily be tuned to only consider lower frequencies where the resonance has no effect on the $R_{A/D}$ ratio. As a result, the procedure detailed in this paper to measure the $R_{A/D}$ ratio can be integrated in the designed DPOAE system's measurement routine in an attempt to improve the reliability of in-field DPOAE measurements.

### Acknowledgement

Annelies Bockstael is a postdoctoral fellow of the Research Foundation-Flanders (FWO); the support of this organization is gratefully acknowledged. The ETS-affiliated authors are thankful for the technical support from the *Sonomax-ETS Industrial Research Chair in In-Ear Technology* for prototyping the experimental DPOAE probes. Vincent Nadon is especially grateful to the Institut Robert-Sauvé en santé et sécurité au travail (IRSST) for its financial support for the project.

### References

[1] Voix, J., and Laville, F.: The Objective Measurement of Earplug Field Performance. J. Acoust. Soc. Am., Vol. 125 (2009), 3722-3732.

[2] Bockstael, A., Van Renterghem, T., Botteldooren, D., Dhaenens, W., Keppler, H., Maes, L., Philips, B., Swinnen, F., and Vinck, B. : Verifying the attenuation of earplugs in situ: method validation on human subjects including individualized numerical simulations. J. Acoust. Soc. Am., USA Vol. 125 (2009), 1479-1489.

[3] Henderson, D., Subramaniam, M., and Boettcher, F. A.: Individual Susceptibility to Noise-Induced Hearing loss: An Old Topic Revisited. Ear Hearing, **14(3)** (1993).

[4] Marshall, L., Lapsley Miller, J., and Heller, L.: Distortion-product otoacoustic emissions as a screening tool for noise-induced hearing loss. Noise Health, **3** (2001), 43-60.

[5] Popelka, G. R., Karzon, R. K., Clary, R. A.: Identification of noise sources that influence distortion product otoacoustic emission measurements in human neonates. Ear and hearing, **19(4)** (1998), 319-328.

[6] Delgado, R. E., Ozdamar, O., Rahman, S., and Lopez, C. N.: Adaptive noise cancellation in a multimicrophone system for distortion product otoacoustic emission acquisition. IEEE Trans. Biomed. Eng., **47** (2000), 1154-64.

[7] Nadon V. : Développement d'une oreillette pour la mesure des émissions otoacoustiques, Master Thesis, École de technologie supérieure (2014).

[8] CRITIAS : Chaire de recherche industrielle en technologies intra-auriculaire Sonomax-ETS (CRITIAS), `http://critias.etsmtl.ca/the-technology/arp/` .

[9] Tufts, J. : Canal Segment Length of Custom Earplugs: Effects on Attenuation (and comfort). NHCA (2014).

[10] Bernier, A. : Development of an active hearing protection device for musicians, Technical Report, École de technologie supérieure (2014).

[11] Kim, N., Allen, J. B. : Two-port network analysis and modeling of a balanced armature receiver. Hearing Research, 301 (2013), 156-167.

[12] Kleiner, M. : Electroacoustics. CRC Press (2013).

[13] Beranek, L. L. : Acoustics. McGraw-Hill (1954) 137-138.

[14] Leach, W. M. Jr. : Computer Aided Electro-Acoustic Design with SPICE. Journal Audio Engineering Society, 39(7/8) (1991), 551-562.

[15] B&K. : Ear Simulator for Telephonometry B&K Type 4195 - Application Note (2014). p. 7.

[16] Hiipakka, M. : Measurement Apparatus and Modelling Techniques of Ear Canal Acoustics. Master Thesis, Helsinki University of Technology (2008). p.93.