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Balanced inlet design for microphone vibration sensitivity cancellation in hearing aids

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ABSTRACT

Feedback is currently the main gain limiting factor in hearing aids. In a hearing aid acoustic-mechanical design, feedback path analysis and minimization is therefore a key aspect for the overall system performance. Acoustic feedback due to the sound leaking out of the ear mold and reaching the microphone through air is one of the better-known causes of feedback; however, other important and less well-understood feedback paths are caused by the microphone picking up vibrations induced by the high pressure levels in internal sound tubes exciting the surrounding structures and by the loudspeaker vibration itself. A microphone is sensitive to vibrations due to its membrane inertia and internal air volume inertia; however, when the microphone is placed at the end of a sound inlet, as in the case of hearing aids, the inertia of the air volume contained in the inlet will also contribute to it. In this paper, a new inlet design that makes the two contributions cancel each other out, reducing the total vibration sensitivity, is presented. The design is based on the understanding of the two vibration sensitivity mechanisms, and optimized on a vibro-acoustic finite element model of the hearing aid. The final design is then validated through experimental measurements.

Keywords: Vibration Sensitivity, Vibroacoustics, Hearing Aids
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1. INTRODUCTION

The basic function of a hearing aid is to capture the sound that reaches the ear of its user and reproduce a sufficiently amplified version of it inside the impaired ear. It is therefore a main requirement for such a device to be able to deliver a high acoustic gain, while keeping a relatively small physical size for comfort and aesthetic reasons. A Hearing Instrument (HI) must contain at least three components to accomplish its main function: a microphone, an amplifier and a loudspeaker (denominated "receiver" in the industry argot), which, given the dimensions of the instruments, sit close together inside the device [1]. It is therefore easy to imagine that the amplified acoustic signal that is reproduced by the receiver will to some extent be sensed by the microphone, forwarded to the amplifier and again to the receiver, creating a feedback loop in the signal path that amplifies certain frequency components and generates a disturbing acoustic noise. This phenomenon is known as feedback, and the maximum amplification that a HI can provide is limited by the level at which audible feedback occurs. Even though modern HIs incorporate feedback cancellation algorithms that contribute to decrease audible feedback, the added signal processing has a negative effect on the resulting sound quality. Therefore, reducing the need for digital feedback handling by coming up with a mechanical design that minimizes vibroacoustic feedback paths it is a key point for improving final performance.

In this paper, we focus on the design of microphone inlets for minimization of vibration-induced feedback. The hearing instrument is subjected to significant vibration while operating, both due to receiver vibrations and to high internal acoustic pressure that excites the walls of the sound channels [2]. In turn, the microphone produces an unwanted voltage output due to this vibration as a consequence of two effects: pressure build-up in the inlet cavities and vibration sensitivity of the microphone. In traditional microphone inlet designs in hearing aids, the microphone output voltage produced by the two effects adds up in phase, producing a higher output voltage when the two effects are combined. In this paper, we suggest a new microphone inlet design technique that flips the phase of one of the contributions so that they cancel each other out if the dimensions of the inlet are tuned correctly.

2. METHODOLOGY

In this section, the physical phenomena that give rise to microphone vibration sensitivity are described for a simple inlet design, and thereafter the newly developed inlet design methodology is described.

2.1 Traditional inlet design

Figure 1 shows a 2D schematic drawing of a microphone placed in a hearing instrument body, where the microphone port is connected to the air surrounding the instrument by a simple straight inlet.

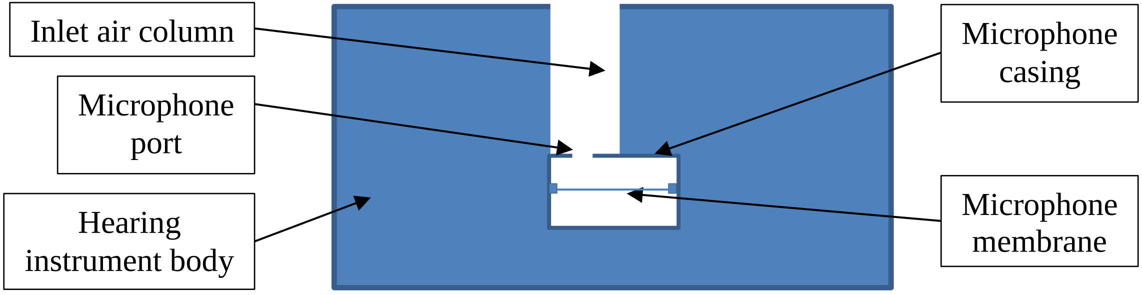

Figure 1 - Simple inlet design schematic drawing

In this section, the vibration sensitivity of the system is analysed by describing the different phenomena that give rise to a microphone output voltage signal when the hearing body vibrates.

2.1.1 Membrane inertia

Loudspeakers and microphones are electro-acoustic transducers that convert electrical signals into acoustic ones or vice versa; this conversion involves an intermediate step where the signal is transformed into mechanical vibrations, which makes both devices not only acoustic transducers but also vibration ones. For this reason, a microphone will produce an unwanted output voltage when it is subjected to vibration, and the amplitude and phase of this voltage due to a certain level of vibration is determined by its vibration sensitivity.

In hearing aids, Electret Condenser Microphones (ECM) are most used, and Micro-Electro-Mechanical Systems (MEMS) [3] microphones have been recently introduced [1]. These types of microphones generate a voltage proportional to the distance between their membrane, which vibrates when hit by sound waves, and a fixed back plate. Their vibration sensitivity in the direction perpendicular to the diaphragm is partly due to the membrane inertia: the membrane will tend to keep moving in the same direction due to its mass, which introduces a small difference between the membrane and the microphone case displacements when the microphone case vibrates. A change in the relative position between the membrane and the back plate is therefore introduced, as illustrated in Figure 2, which yields an output voltage. When the hearing aid is accelerated, the force per unit area (pressure) on the diaphragm can be calculated as [4]

$$p = \sigma \ddot{x} \qquad (1)$$

where σ is the mass per unit area of the membrane, and $\ddot{x}$ is the acceleration of the system.

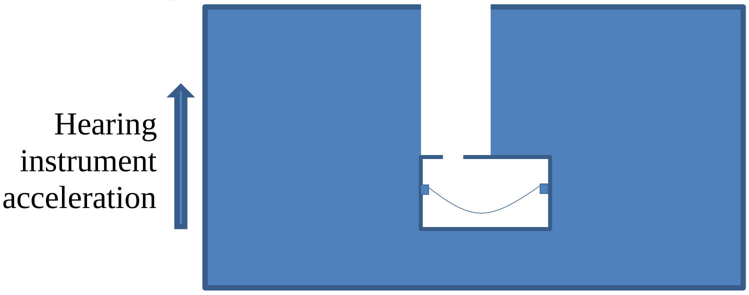

Figure 2 - Vibration sensitivity due to membrane inertia

2.1.2 Pressure build-up inside the microphone

The mass of the air contained in the microphone casing will add an inertial load to that due to the membrane mass. If the dimensions of the microphone are small compared to the acoustic wavelength at the frequency of vibration, the air inside the casing will move at a uniform velocity. Since velocity is the gradient of the pressure, a pressure field that varies linearly with maximums of opposite signs close to the walls perpendicular to the direction of vibration will be created, as shown in Figure 3. The pressure will deflect the membrane in the same direction that the membrane inertia effect does for the same direction of the acceleration; therefore, the two effects add up together, resulting in the total internal microphone vibration sensitivity in the direction perpendicular to the diaphragm.

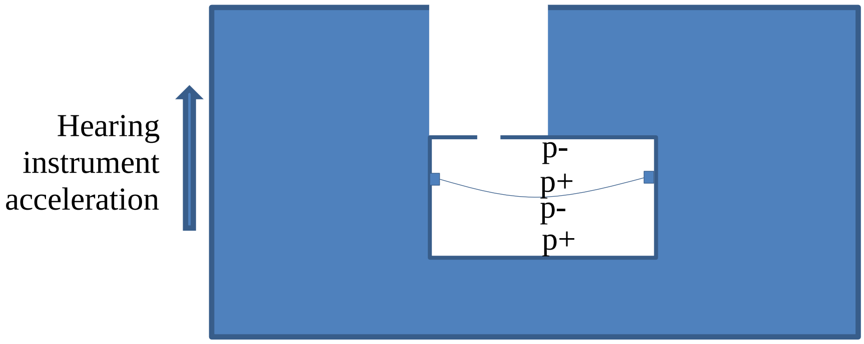

Figure 3 - Pressure build-up inside the microphone due to vertical vibration. "p+" indicates a positive pressure, and "p-" indicates a negative pressure.

For MEMS microphones, the port and membrane are usually not placed at the centre of the casing due to integrated circuitry taking up space inside of it, as shown in Figure 4. This asymmetry yields a small vibration sensitivity in the direction parallel to the diaphragm due to pressure build-up inside the microphone when the system vibrates.

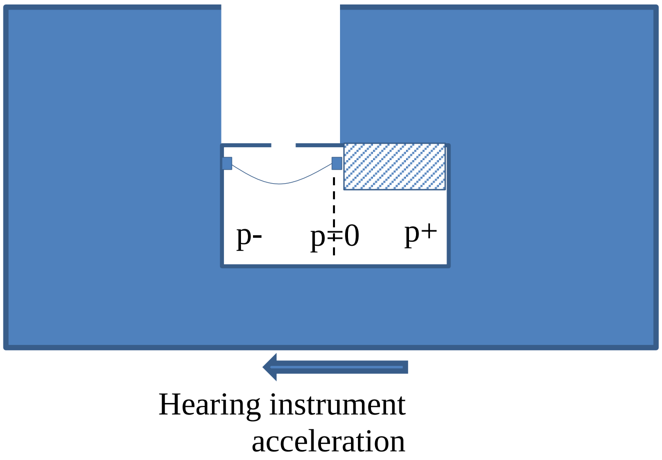

Figure 4 - Pressure build-up inside the microphone due to sideways vibration

If the dimensions of a closed cavity are small compared to a wavelength, the pressure developed close to a wall perpendicular to the vibration direction can be calculated as [5]

$$p = \frac{1}{2}\rho_0 l\ddot{x} \qquad (2)$$

where ρ_0 is the air density, l is the length of the cavity, and $\ddot{x}$ is the acceleration of the system.

2.1.3 Pressure build-up in the inlet air column

The air particles in the inlet air column also present inertia effects when the hearing aid body vibrates, which results in pressure build-up in the inlet. When the hearing aid casing accelerates upwards, the air particles will compress at the bottom, where the microphone sits, creating a positive pressure that pushes the membrane towards the back plate, as shown in Figure 5. When accelerating downwards, the air column will depress in front of the microphone, creating a negative pressure. This pressure will be sensed by the microphone and added up in phase to that resulting from internal vibration sensitivity effects, generating a higher microphone output voltage in combination.

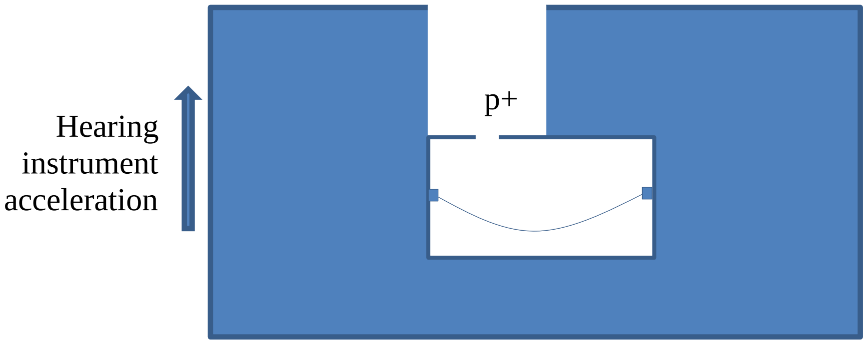

Figure 5 - Pressure build-up at the inlet air column for vertical vibration

Assuming that the pressure at the inlet opening is 0, the pressure at the microphone port can be calculated as

$$p = \rho_0 l \ddot{x} \qquad (3)$$

where ρ_0 is the air density, l is the length of the inlet and $\ddot{x}$ is the acceleration of the system.

Regarding vibration parallel to the diaphragm, the pressure build-up inside the inlet will yield a 0 pressure at the microphone port if that one is sitting at the centre of the inlet, as shown in Figure 6. Therefore, this inlet configuration will not result in additional microphone output voltage due to sideways vibration.

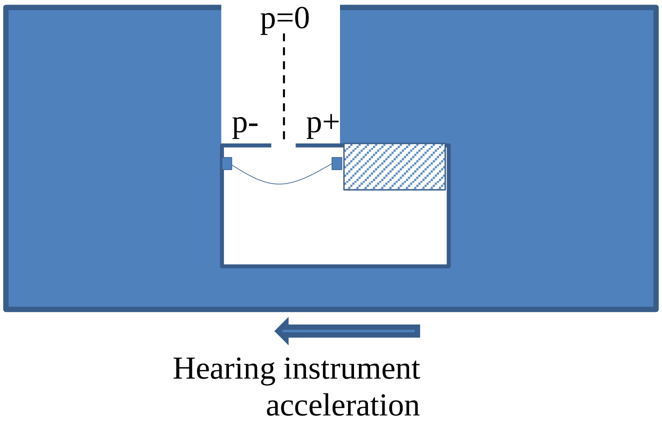

Figure 6 - Pressure build-up in the inlet air column for sideways vibration

2.2 Balanced inlet design

A strategy to design an inlet where the pressure build-up due to vibration counteracts the inherent microphone vibration sensitivity is suggested here. In this section, vibration sensitivity in the direction perpendicular to the microphone diaphragm is approached first, and secondly, vibration sensitivity in the direction parallel to the diaphragm is discussed.

2.2.1 Vibration perpendicular to diaphragm

For the simple inlet design, the microphone output voltage due to the membrane and the air column inertia effects has the same sign and will be added in phase, producing a higher output voltage in combination. The balanced inlet strategy consists in designing an inlet solution that allows for flipping the microphone upside-down, so that the two effects will add up in opposite phase, cancelling each other out if the dimensions of the inlet are designed correctly. The pressure build-up at the microphone port due to vibration of the air inside the inlet can be calculated as in Equation 3, where l is still the distance between the inlet opening and the microphone port, as shown in Figure 7. If the length l of the inlet is adjusted so that the resulting pressure build-up equals that originated due to the microphone internal vibration sensitivity, the two effects will cancel out completely.

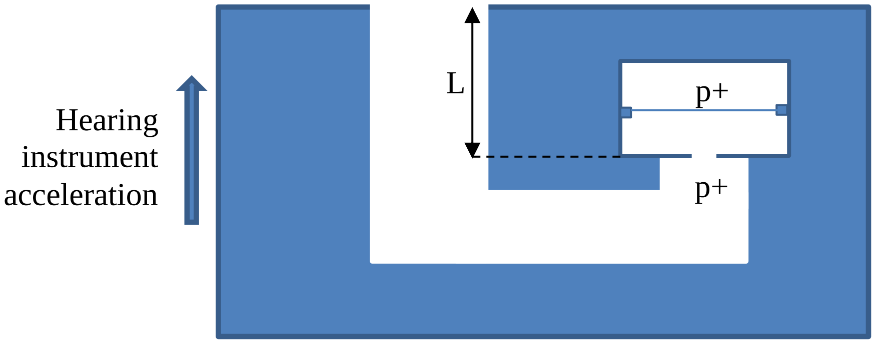

Figure 7 - Balanced inlet for vertical vibration schematic drawing

2.2.2 Vibration parallel to the diaphragm

The microphone sensitivity in the direction parallel to the diaphragm can be compensated by adjusting the horizontal dimension of the inlet, indicated as *W* in Figure 8, so that the pressure build-up in the inlet when the microphone vibrates sideways equals the pressure build-up inside the microphone casing. The pressure build-up in the inlet can be calculated as in Equation 2, with l being the dimeniosn *W*. In the example in Figure 8, it becomes apparent that *W* should equal the width of the microphone in order to obtain a perfect cancellation, which is not possible to achieve in a 2D design as the schematic drawing shown here, but is possible in 3D, as will be seen in Section 3.

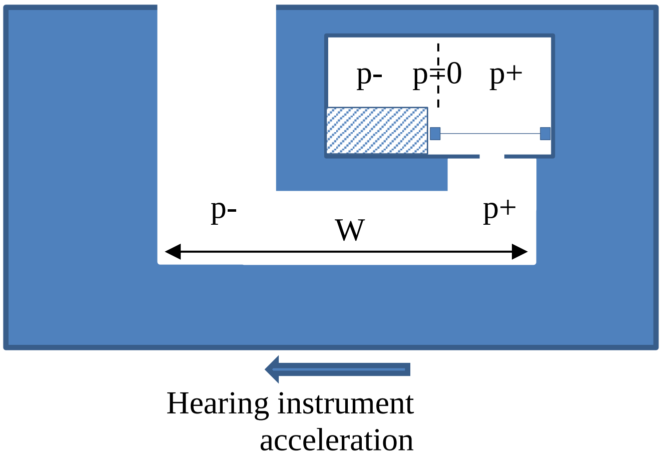

Figure 8 - Balanced inlet for sideways vibration schematic drawing

2.2.3 Additional considerations

The compensation methods described in the previous subsections are based on assuming a zero pressure at the inlet opening. However, in real hearing aids, the vibration of the hearing aid body itself will also create a pressure at the inlet opening, which needs to be taken into consideration. The inlet dimensions should therefore be adjusted so that the pressure that the microphone senses due to the three contributions cancels out,

$$p_{out} + p_{inlet} + p_{mic\ sens} = 0 \qquad (4)$$

where $\mathrm{p_{out}}$ is the pressure at the inlet opening, $\mathrm{p_{inlet}}$ is the pressure build-up inside the inlet, and $\mathrm{p_{mic\ sens}}$ is the pressure perceived by the microphone due to its internal vibration sensitivity.

The size of the inlets in hearing aids is usually on the order of millimetres, or even tenths of a millimetre, which makes visco-thermal losses relevant when calculating pressure in the cavities. Visco-thermal losses will add damping, which introduces a phase shift on the acoustic field. This will create some phase mismatch between the different contributions, preventing the balancing from being perfect. Still, a significant cancellation effect can be achieved in practice, as will be seen in the next section.

3. TEST CASE: BALANCED INLET FOR BTE HEARING AID

In this section, a balanced inlet design for a generic Behind The Ear (BTE) hearing instrument geometry is described. In order to take into account the complexity of the geometries and different effects that take part in the system response, a Finite Element Model (FEM) of the system is developed and used for optimization of the inlet dimensions for optimal vibration sensitivity cancellation in both the perpendicular and the parallel to the diaphragm vibration directions. The performance of the balanced inlet design is analysed and the introduced improvement is evaluated by comparison to the performance of a traditional inlet design in the same conditions.

3.1 Description of the system

A simplified hearing aid geometry, shown in Figure 9, is used for the study, where the hearing instrument main body is a solid. The solid has a cut out for the receiver (loudspeaker), the microphone, the microphone inlet and an air canal that connects the receiver spout to the outside of the solid body. The end of the sound canal is connected to a standard BTE PVC tube, which connects the hearing aid to a 2cc coupler. Pictures of the system in real world can be seen in Figure 14 and Figure 15.

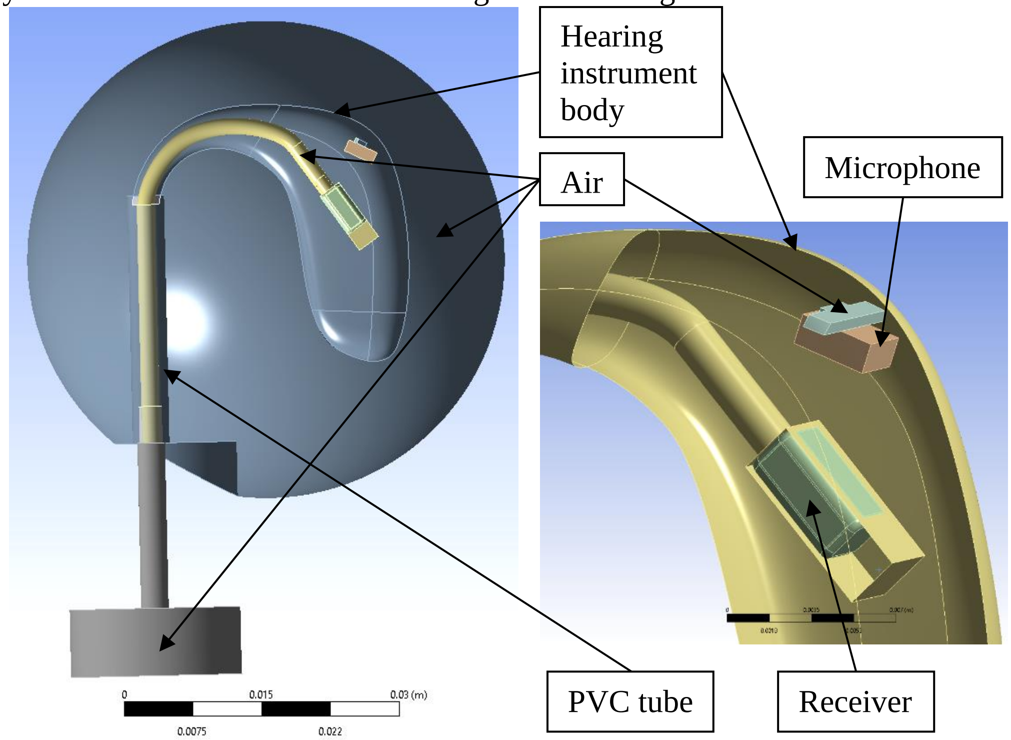

Figure 9 - System under study

The transducers used for this study are a Sonion 2600 balanced armature receiver and a Knowles MM25 MEMS microphone. The receiver walls are bonded to the solid body so that the vibration from the receiver will be directly transmitted to the hearing instrument body. This is never the case in real hearing aid designs, where the receiver is connected to the rest of the hearing aid through a suspension that attenuates vibration. However, the purpose here is to show the effects of the inlet design on vibration sensitivity of the microphones, which can be better appreciated by inducing high vibration levels on the system. In Figure 9, the microphone sits in the traditional way, with the sound port facing upwards, and a T shaped inlet connects the port to the outer air on the two sides of the hearing aid body. This inlet shape will be used as a “reference inlet”, to which the balanced inlet performance will be compared.

3.2 Modelling

The geometry shown in Figure 9 has been created in the commercial FEM software ANSYS Mechanical Release 19.0. The FE model is fully coupled in that Fluid-Structure Interaction is implemented at all surfaces inside and outside the hearing aid and PVC bodies. The 2cc coupler is modelled as an air volume with rigid walls instead. The air surrounding the system is modelled by an air sphere with a second order absorbing boundary condition on its surface that models the Sommerfield radiation condition [6]. Visco-thermal losses are also included in the model using the Boundary Layer Impedance (BLI) method implemented in ANSYS FLUID elements [7].

The microphone and the receiver are modelled by implementation into ANSYS of lumped element models provided by the transducer suppliers that include acoustic and vibration performance. The materials for the solid parts are modelled as isotropic, using measured data for the density, Poisson’s ratio and Young’s modulus, which is frequency-dependent in the case of PVC.

3.3 Balanced inlet design

In the balanced inlet design, the microphone is placed so that its port is facing down. The inlet, as shown in Figure 10, is located below the microphone, extending to the sides and up, connecting to the outer air through an opening on each side of the hearing aid. The opening locations coincide with those of the reference inlet.

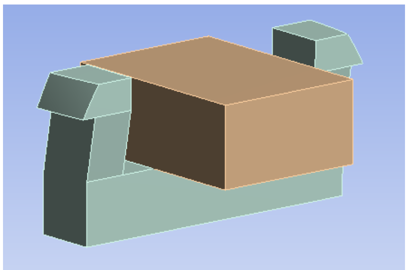

Figure 10 - Balanced inlet design

Given that the inlet opening positions are fixed, the vertical and horizontal dimensions of the inlet, shown in Figure 11, can be optimized independently. For that purpose, two optimization problems are set up. In the first one, the system is excited by a force perpendicular to the microphone diaphragm, and the height H is optimized for minimal microphone output voltage. In the second problem, a similar procedure is followed, where a force parallel to the diaphragm is applied and the dimension W is varied. Since the physical phenomena that the balancing effect is based on are true for wavelengths that are large compared to the inlet and microphone dimensions, the optimization is carried out for the lowest frequency of interest in the current study, 100 Hz.

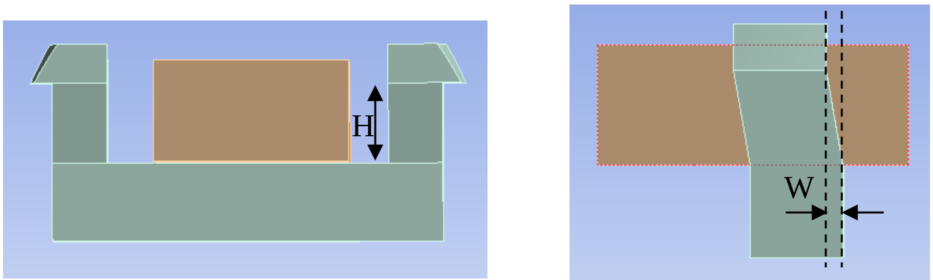

Figure 11 - Balanced inlet optimized sizes

The output microphone voltage level as a function of *H* and *W* when the system is excited in the vertical and the horizontal directions, respectively, can be seen in Figure 12. As a result, a dimension *H* of 1.04 mm and a dimension *W* of 0.2 mm are found to yield the optimal cancellation.

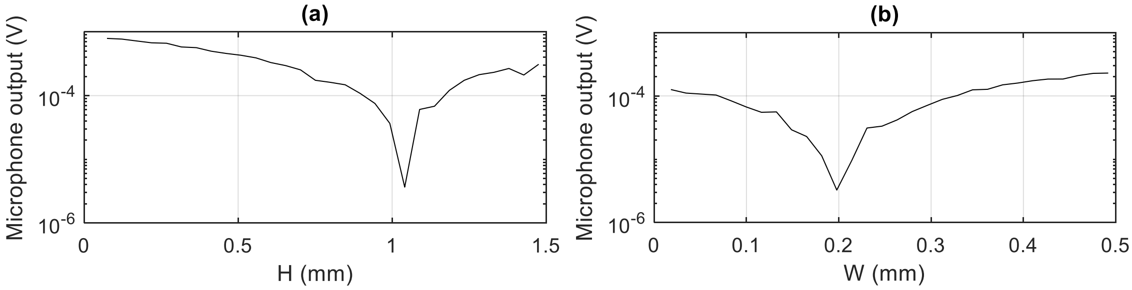

Figure 12 - Microphone output due to (a) vertical vibration and (b) horizontal vibration as a function of (a) inlet dimension H and (b) inlet dimension W

3.4 Performance results

In order to evaluate the effects of the inlet design on the instrument feedback performance, the loop gain of the system is evaluated for both the reference and the balanced inlet designs. The loop gain is the difference between the sound pressure level at the 2cc coupler and the sound pressure level perceived by the microphone, which is obtained by dividing its output voltage by the acoustic sensitivity. For comparison, a "snoop gain" can be calculated as well, which is the difference between sound pressure levels at the coupler and at the inlet opening; i.e. what the microphone would perceive if it was insensitive to vibrations and without the effects of the inlet. The performance has been evaluated both in simulations and experimentally in the frequency range between 100 Hz and 10 kHz, where performance is most critical due to speech frequency content.

3.4.1 Simulation results

The simulated "snoop gain" and loop gain for the reference and the balanced inlet designs using the FE model described above when the system is driven by the receiver at 100 logarithmically spaced frequencies between 100 Hz and 10 kHz can be seen in Figure 13.

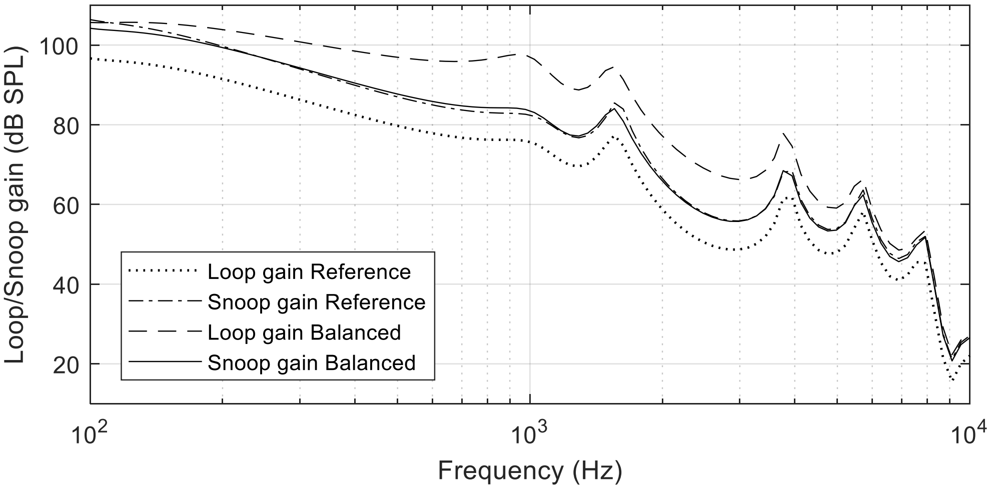

Figure 13 -Simulated loop gain and "snoop gain" for the reference and balanced inlets

The "snoop gain" curves for the reference and the balanced inlets are on top of each other, showing that the pressure at the inlet opening is the same in both cases. For the reference inlet, the loop gain curve is below the "snoop gain" curve across the whole frequency range, indicating that the sound pressure level perceived by the microphone is higher than the actual sound pressure level at the inlet opening. The microphone vibration sensitivity is therefore having a negative effect on the loop gain for the reference inlet. On the other hand, the loop gain for the balanced inlet is higher than the “snoop gain”, indicating that the balanced inlet not only suppresses the negative effects of the microphone vibration sensitivity, but also uses it to compensate for the pressure at the inlet opening created by the hearing instrument vibration, effectively improving the loop gain compared to having an inlet-microphone system with no vibration sensitivity at all.

The loop gain curve presents high levels with a smooth gradual decrease between 100 Hz and 1 kHz, while peaks and valleys are observed at higher frequencies due to resonances in the hearing aid tubing. Improvements of 18, 12 and 8 dB SPL are obtained, respectively, for the critical dips in the loop gain curve observed at the frequencies of 3, 5 and 7 kHz when comparing the balanced inlet to the reference inlet performances.

3.4.2Experimental results

The effects of the balanced inlet have also been evaluated experimentally by measuring the loop gain on 3D printed mockups of the hearing aid solid body, where the microphone and receiver are glued, as shown in Figure 14. The measurements are carried out using a Pulse system from B&K, which generates a linearly stepped sine signal at 199 points between 100 Hz and 10 kHz that is then sent to the hearing aid receiver through an

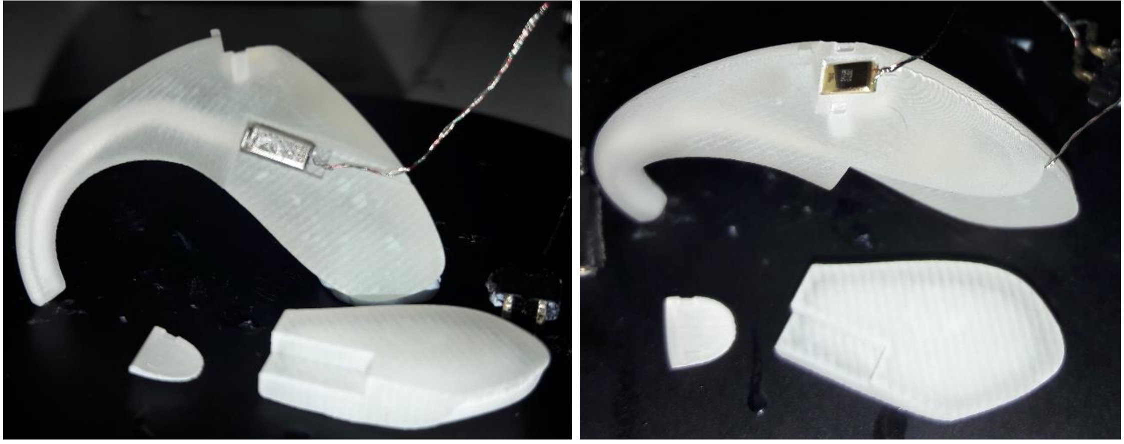

Figure 14 - 3D printed mockups

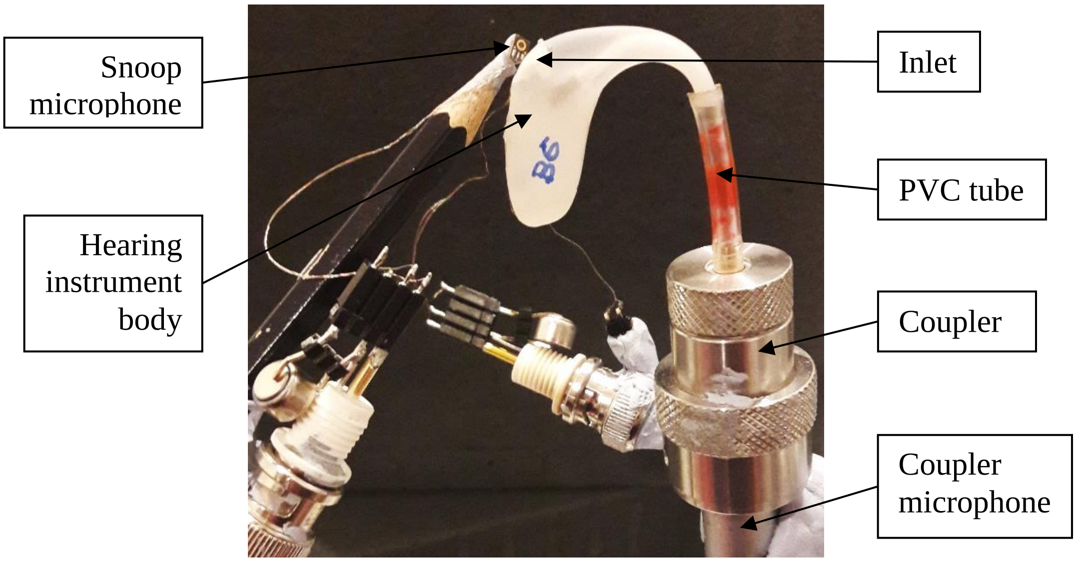

Figure 15 - Measurement setup

amplifier. The receiver acoustic output is sent through a PVC tube into a 2cc coupler, where the pressure is measured by a B&K type 4192 microphone and used together with the hearing aid microphone output signal to calculate the loop gain in Pulse. Additionally, a “snoop” MEMS microphone is placed close to the inlet opening in order to measure the vibration-free sound pressure level at the microphone position. A picture of the measurement setup can be seen in Figure 15.

The measured and simulated loop gain results for both the reference and the balanced inlets are shown in Figure 16. The curves present good agreement in the frequency range between 1.5 and 7 kHz, where the improvement in loop gain introduced by the balanced inlet design on the aforementioned critical dips can be clearly seen.

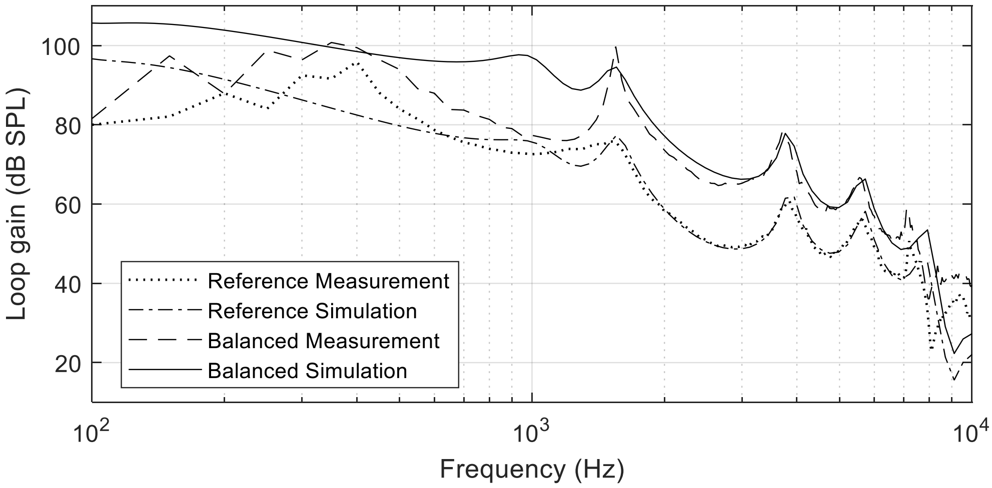

Figure 16 - Measured and simulated loop gain in dB SPL

At lower frequencies, the measurement and simulation results present significant differences, which are thought to be due to inaccuracies in the mockup assembling procedure, where small changes in the contact conditions between transducers and solid parts can have significant impact in the final performance. This hypothesis is supported by the fact that measurements of several ideally identical mockups of the balanced inlet present a wide variation in loop gain levels at those frequencies, as shown in Figure 17.

Above 7 kHz, the measurement and simulation curves also present differences, even though they are constant for the several measured mockups in this case. Those differences are attributed to inaccuracies in the transducer models.

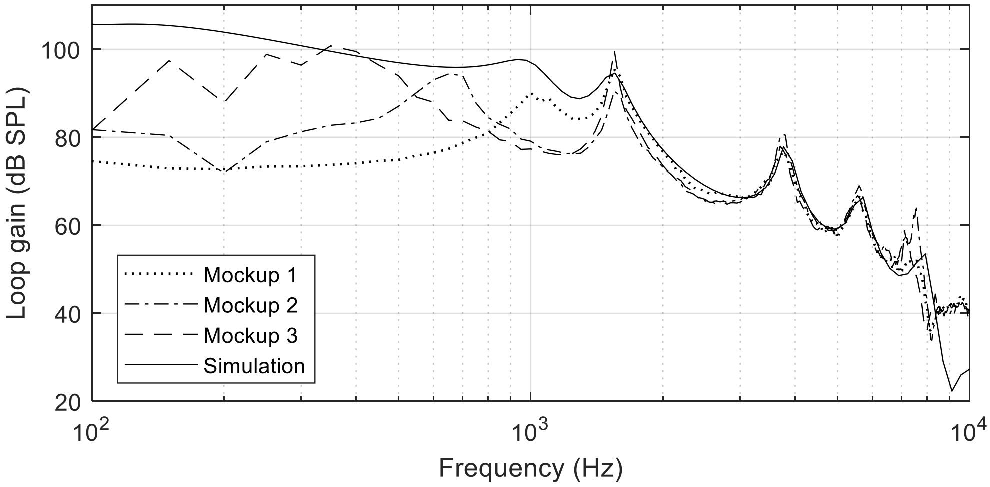

Figure 17 - Spread in loop gain measurements of ideally identical mockups

4. CONCLUSIONS

A methodology for designing inlets in hearing aids that compensate for the vibration sensitivity of the microphones, resulting in a reduction of the vibration sensitivity of the combined system, has been presented. The developed method has been demonstrated for a simplified hearing aid test case, where the performance of an optimized balanced inlet has been compared to the performance of a simple inlet design in terms of vibroacoustic feedback in the hearing aid system. Simulation and experimental results show that the balanced inlet design yields up to 18 dB improvement in loop gain at the critical frequency range, demonstrating that a significant impact on feedback reduction in hearing aids can be achieved with the presented inlet design technique.

5. REFERENCES

[1] H. Dillon, Hearing Aids, New York: Thieme Medical Publishers Inc, 2012.

[2] L. Friis, "Investigation of internal feedback in hearing aids," PhD Thesis, DTU Elektro, Technical University of Denmark, 2008.

[3] P. R. Scheeper, A. G. H. van der Donk, W. Olthuis and P. Bergveld, "A review of silicon microphones," *Sensors and Actuators A: Physical,* vol. 44, no. 1, pp. 1-11, 27 11 1994.

[4] E. Rule, F. J. Suellentrop and T. A. Perls, "Vibration Sensitivity of Condenser Microphones," *The Journal of the Acoustical Society of America,* vol. 32, no. 7, pp. 821-823, 1960.

[5] M. C. Killion, "Vibration Sensitivity Measurements on Subminiature Condenser Microphones," in *49th AES Convention,* New York, 1974.

[6] ANSYS Inc., "Help system, ANSYS Theory Reference, Release 19.0".

[7] R. Bossart, N. Joly and M. Bruneau, "Hybrid numerical and analytical solutions for acoustic boundary problems in thermo-viscous fluids," *Journal of Sound and Vibration,* vol. 263, no. 1, pp. 69-84, 2003.