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Finite-element study of directional microphones in a hearing aid

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Abstract
A detailed finite element (FE) model has been implemented in order to assess the performance of a two microphone directional system in a hearing aid. Length scales in the microphone inlets are small necessitating the inclusion of thermal and viscous losses in the governing equations. The lossy region is coupled to lossless acoustics around the hearing aid. Perfectly matched layers are used to model open non-reflecting boundaries. The acoustic reciprocity principle is used to allow rapid characterization of the full spatial response of the microphone system: the microphones are used as sources for the acoustic field.

The directional characteristics for a specific hearing aid are validated by comparing to measurements. The implemented FE model allows early characterization and benchmarking of new microphone-system designs in hearing aids, before physical models are built.

Keywords: FEM, thermo-viscous acoustics, reciprocity principle, hearing aid

1 Introduction

Modern hearing aids generally have two microphones that pick up sound. This two microphone system is used to create a directional microphone that is used for spatial noise reduction. The directional system utilizes the well defined distance between the microphones. This equals a well defined phase shift between the microphone signals that is dependent on the direction of the incoming sound. The performance of the directional microphone systems is dependent on both the acoustics around the hearing aid, on the signal processing algorithms and on how well the acoustics are accounted for. The sound pressure at the microphone inlets depends on the position of the microphones in the hearing-aid shell, the shapes of the inlets, and on the precise position of the hearing aid on the head of the user [11].

Figure 1 depicts a schematic two microphone directional system. The microphone inlets have different inlet geometries and so different transfer functions. They are represented on the right figure as different phase shifts $\varphi = \varphi(\omega)$ and amplitude scaling $A = A(\omega)$. The spatial noise reduction works by introducing a phase shift $\varphi_{dir} = \varphi_{dir}(\omega)$ on one microphone signal (here the back microphone) and then adding the two signals. If the phase shift $\varphi_{dir} = 0°$ we get a so-called omni-directional microphone pattern, if it is $\varphi_{dir} = 180°$ we get a bi-directional pattern (they are simulated in section 5). Other directional patterns, e.g., a cardioide, are obtained for a given time delay $\varphi_{dir} = \omega\Delta T$.

If front and back amplitudes and phases ($A_{f/b}$ and $\varphi_{f/b}$) are different they need to be understood and accounted for in the signal processing system. This is especially true for increasing frequencies where the system becomes more sensitive to phase shifts and amplitude scaling.

In the following work we present a finite element (FE) model to study the acoustics around the hearing aid and more specifically of the microphone inlets. The model is implemented in Comsol Multiphysics [12]. We, firstly, present the governing equations which need to account for the small length scales in and around the microphone inlets. We then go on to shortly presenting the acoustic reciprocity principle and the implementation in Comsol. We then present an example of an actual hearing aid. Finally, we give some concluding remarks.

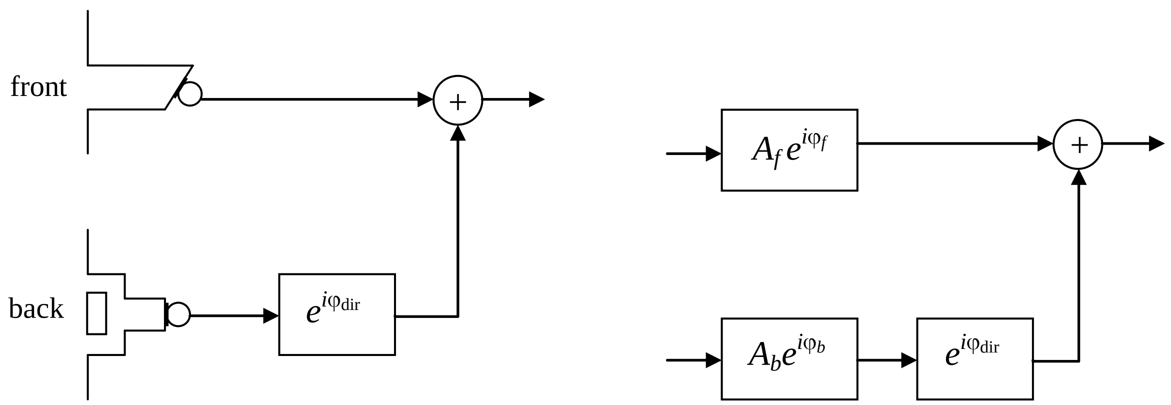

Figure 1 – (*left*) Schematic representation of a two microphone system with two different microphone inlet geometries. (*right*) the same system where the microphone inlets are reduced to a phase shift $\varphi = \varphi(\omega)$ and amplitude scaling $A = A(\omega)$, contributions.

2 Governing equations

In the present work we study the acoustics around a rigid object, namely the hearing aid. A sketch of the system is given in Fig. 2, where the label "solid" exemplifies an arbitrary hearing aid geometry. Around the geometry we have the computational domain consisting of an acoustic domain (blue) $\Omega_{ll} \cap \Omega_{tvf}$, and a perfectly matched layer (PML) domain (light green) to model the open boundary. The acoustic domain is divided into two areas, a lossless domain (ll) and a lossy domain (tvf) where thermal and viscous losses are accounted for.

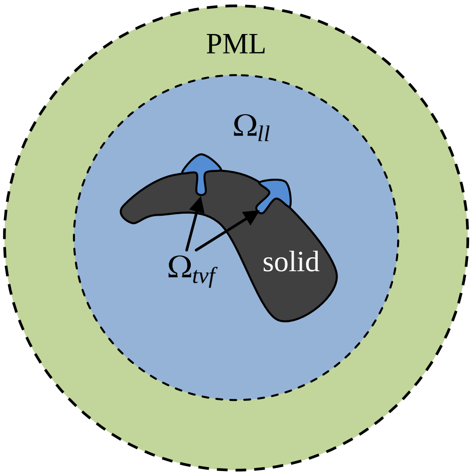

Figure 2 – Schematic representation of the computational domains, with the acoustic lossless (ll) domain and lossy domain (tvf), and the perfectly matched layer (PML) domain.

In the lossless domain Ω_{ll} we solve the classical Helmholtz equation

, (1)

where *P* is the acoustic pressure, $k = \omega/c$ the wave number, c the speed of sound, ω the angular frequency, and S a possible source term.

In the lossy domain Ω_{tvf} we solve a full linearized version of the Navier-Strokes equation, an equation of continuity, and a linear energy transport equation; the so called thermo-viscous acoustic problem. In a time harmonic form the equations are

(2)

(3)

(4)

where the dependent variables are pressure p, velocity $\boldsymbol{u} = (u,v,w)$, and temperature T. The static values of pressure, density, and temperature are p_0, T_0, and ρ_0. The specific heat capacity at constant pressure is C_p, λ is the dilatational viscosity, and μ is the dynamic viscosity. Further details are found in Refs. [1,2,3,4]. The lossy acoustics are only applied in regions where dimensions are comparable to the viscous boundary layer, e.g., in microphone inlets on a hearing aid (they are typically 1 mm in diameter).

Whenever sound propagates in the vicinity of a wall viscous shear is present and forces the velocity to zero at the wall (no slip condition). In the same time the presence of the wall allows for heat transfer to take place between the fluid and the wall. These two phenomena together create the acoustic boundary layer. The thickness of the viscous boundary layer δ_v may be found by solving the so-called boundary layer equation for the flow. The thickness of the layer over a flat plate is

(5)

for air the viscous layer is 0.22 mm at 100 Hz.

The perfectly matched layer (PML) is used to simulate an open boundary. In this domain we introduce a coordinate transformation of the independent variable $\boldsymbol{x} = (z,y,z)$ into a complex quantity. This introduces an exponential damping of outgoing waves. See Refs. [8,9,10] for further details.

On the solid surface of the hearing aid we impose sound hard walls (no slip condition). The lossless and lossy acoustics are coupled by specifying continuity of normal stress and deformation using a weak constraint.

3 Reciprocity

A system is said to be reciprocal when the transmission of sound (vibrations) from a source A to a receiver B has a simple relation with the transmission from B to A. In the case of systems that are well described by linear acoustics such relations exist [5,6,7]. This fact may help us in computational acoustics to reduce computation time. This is the case when we need to determine a directional pattern for a microphone system. In this case a direct model would need to be run for every desired direction of the incoming wave P_i, and we would solve for a scattered wave P_s, with the total pressure $P = P_s + P_i(\boldsymbol{k},\omega)$ (direction $\boldsymbol{k}$ of the incoming wave and frequency ω). By using a reciprocity relation we may instead computationally place a source at the microphone position and "measure" all points around the hearing aid in one go. The latter method only requires one computation for every desired frequency. The acoustic pressure in the far field outside the computational domain is determined using the Helmholtz-Kirchhoff convolution integral. The integral is applied at the boundary between the lossless and the PML domains (see Fig. 2).

4 Implementation and geometry

The governing equations (acoustics and PML) and boundary conditions are implemented in weak form using the general PDE formulation in the commercial FE software Comsol Multiphysics [12]. A CAD drawing of the hearing aid is also imported and meshed using Comsol. Figure 3 shows the hearing aid geometry and the geometry of the front microphone inlet. Length scales are such that the full lossy acoustic model is necessary.

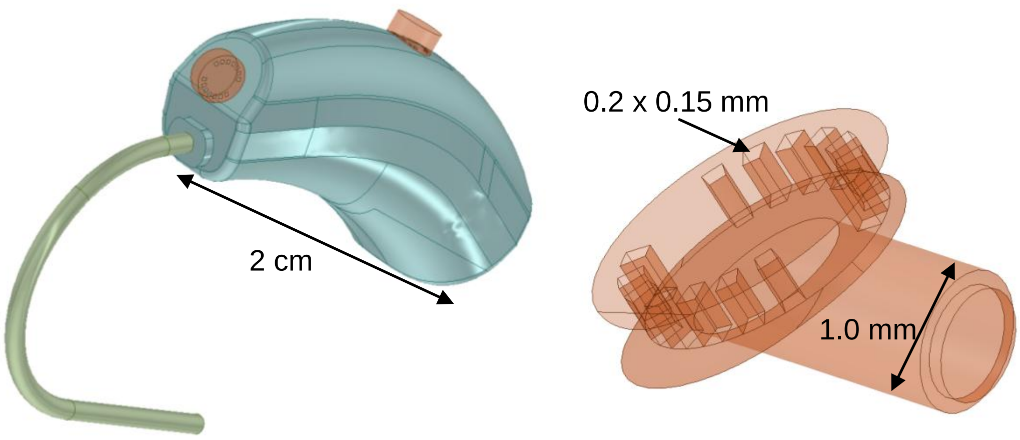

Figure 3 – (*left*) Geometry of the Widex Passion hearing aid and (*right*) geometry of the front microphone inlet with annotation of selected dimensions.

5 Hearing aid directional characteristics

Using the model described above we have determined the directional characteristic of the hearing aid. That is, the direction and distance dependent transfer function H(R,φ,θ), given in spherical coordinates. The reciprocity principle has been used in order to get the full spatial picture. The analyzed geometry is that of the Passion hearing aid depicted in Fig. 3.

While the simulation gives a full 3D response experimental measurements are generally done in the horizontal plane (φ = constant). A polar plot comparing measured and simulated results is given in Fig. 4 for *f* = 1000 Hz. We see that the bidirectional characteristic is skewed. This is due to the fact that the difference in front and back microphone inlet geometry is not compensated for in this case. We thus see that the model precisely captures the acoustics of the inlets. The effect is also present in the omni mode, however, it is much less pronounced as the front and back signals are added. The full 3D bidir spatial response for 1000 Hz is illustrated in Fig. 5.

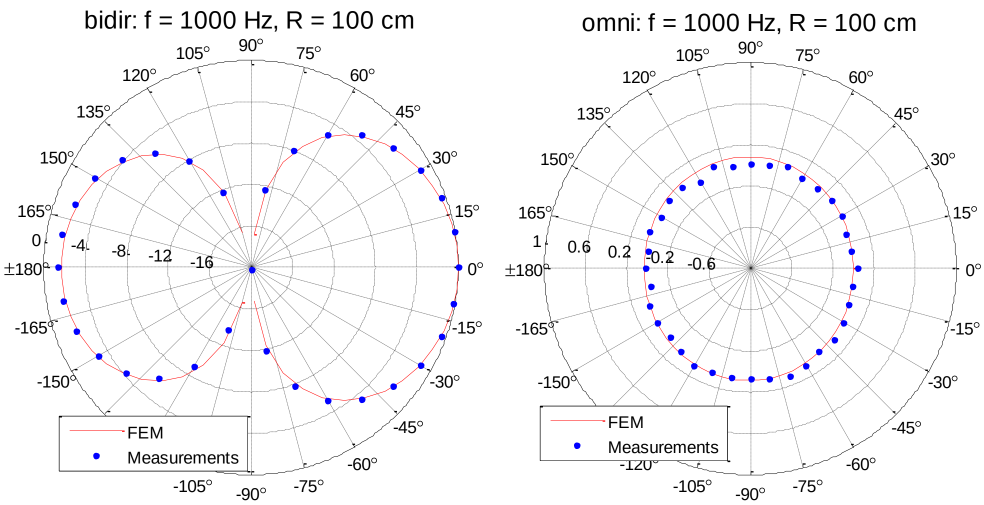

Figure 4 – Comparison of simulated and measured bidir (left) and omni (right) directional characteristic for *f* = 1000 Hz.

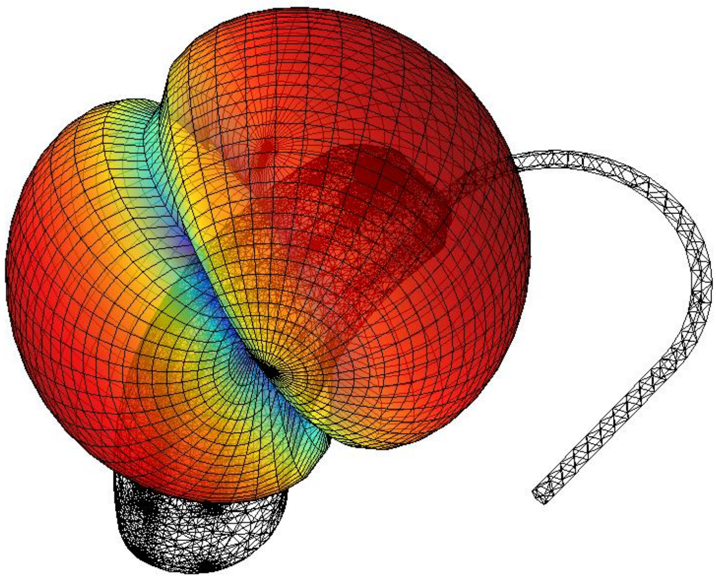

Figure 5 – Representation of the full 3D bidirectional spatial characteristic.

Conclusions

This study has served as a validation of the finite-element (FE) model used for determining characteristic directional patterns of hearing aids (HAs). The model includes losses (where necessary) and utilizes the acoustic reciprocity principle to determine the full spatial response in one computation. We see good agreement between modeling results and measurements. The model enables us to study the sound field around the HA both locally and in the far field. In this way, we may characterize the HA geometry (including microphone inlets) in terms of directional patterns. Hence, the finite-element tool allows for early characterization of the directional response of new hearing aid geometries, based on the CAD drawings of the HAs.

References

[1] D. T. Blackstock, *Fundamentals of physical acoustics*, John Wiley & Sons, Inc., 2000.

[2] L.D. Landau and E. M. Lifshitz, *Fluid mechanics, course of the theoretical physics, volume 6*, Elsevier Science Limited, 2003.

[3] W. M. Beltman, P. J. M. van der Hoogt, R. M. E. J. Spiering, and H. Tijdeman, Implementation and experimental validation of a new viscothermal acoustic finite element for acousto-elastic problems, J. Sound Vib. 216, 159 (1998).

[4] M. Malinen, M. Lyly, P. Råaback, A. Kärkkäinen, and L. Kärkkäinen, *A finite element method for the modeling of thermo-viscous effects in acoustics*, ECCOMAS 2004.

[5] G. Chertock, *General reciprocity relation*, J. Acoust. Soc. Am. 34, 1962, pp 989.

[6] Y.-C. Cho, *Reciprocity principle in duct acoustics*, J. Acoust. Soc. Am. 67, 1980, pp 1431.

[7] T. ten Wolde, *Reciprocity measurements in acoustical and mechano-acoustical systems. Review of theory and applications*, NAG/DAGA 2009 - Rotterdam, 2009.

[8] J.-P. Berenger, *A perfectly matched layer for the absorption of electromagnetic waves*, J. Comp. Phys., 114, 1994, pp 185.

[9] M. Zampolli, A. Tesei, F. B. Jensen, N. Malm, and J. B. Blottman III, *A computationally efficient finite element model with perfectly matched layers applied to scattering from axially symmetric objects*, J. Acoust. Soc. Am. 122, 2007, pp 1472.

[10] M. J. Herring Jensen, *Sound Attenuation by Hearing Aid Earmold Tubing*, Comsol conference 2008, Hannover, Germany.

[11] M. J. Herring Jensen, *Improving the Performance of Hearing Aids Using Acoustic Simulations*, Comsol conference 2009, Milan, Italy.

[12] Comsol Multiphysics 3.5a, www.comsol.com.