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Improving the Performance of Hearing Aids Using Acoustic Simulation

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Abstract: In modern hearing aids, the performance of directional microphone systems is dependent on both the acoustics around the hearing aid and on the specific signal processing algorithms. The sound pressure at the microphone inlets depends on microphone location in the hearing-aid shell, the inlet shape, and on the placement of the hearing aid on the head of the user.

In the present work, the directional characteristics of a specific hearing aid is modeled in free field as well as placed on a head. The numerical results are also compared to measured data for validation. The acoustic equations are implemented using the general PDE formulation capabilities of Comsol [1]. The model enables systematic studies of both the free-field directional characteristics and the true (real world) characteristics of the hearing aid on a head. The results may be applied in the early design phase of new hearing aids. Furthermore, it may be used for optimizing the performance of directional noise reduction algorithms for specific hearing-aid geometries.

Keywords: Acoustics, hearing aid, PML

1 Introduction

Finite element (FE) modeling, in Comsol, is used for many aspects when designing a hearing aid (HA). This may be when (1) analyzing feedback mechanism (mechanical and/or acoustic), e.g., see Ref. [7], (2) characterizing the acoustic properties of new elements for use in a lumped parameter model, (3) studying the properties of microphones and/or receivers (miniature loudspeakers), e.g., see Ref. [6], or (4) when characterizing the acoustic interaction of the HA with incoming sound waves (in free field or when placed on a head). This paper is restricted to the latter and is concerned with aspects of the directional system (as mentioned in the abstract). The governing equations, boundary conditions, and computational domains are firstly introduced. Secondly, we model the head related transfer functions of the KEMAR and compare to experiments. This serves as a test of the model. Thirdly, we shortly discuss what a directional system is. Then, the case of a HA in free field is presented. In the sixth section we study the case of a HA placed on a KEMAR head. Finally, conclusions are given.

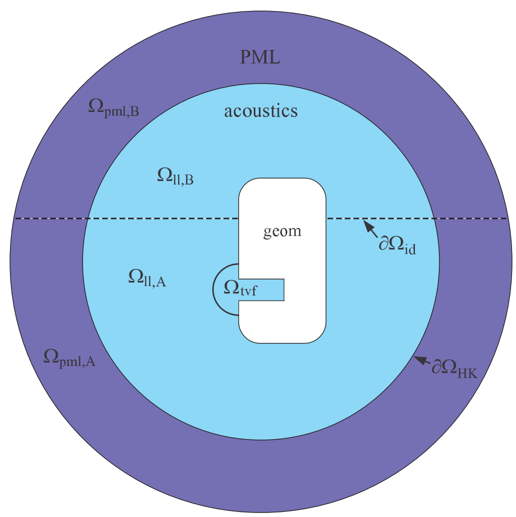

Figure 1: Sketch of the computational domain including boundary and domain labels.

2 System and Governing Equations

In the present work we study the acoustics around a rigid object. This is either a hearing aid, a KEMAR manikin head, or a hearing aid placed on a KEMAR. A sketch of the system is given in Fig. 1, where the label "geom" represents an arbitrary solid geometry. Around the geometry we have the computational domain (light blue) consisting of an acoustic domain $\partial\Omega_{\mathrm{ll}}$ and $\partial\Omega_{\mathrm{tvf}}$, and a perfectly matched layer (PML) domain $\partial\Omega_{\mathrm{pml}}$ (dark blue) to model the open boundary.

The geometry of the hearing aid and the KEMAR is complex. In order for them to be imported into Comsol they have been cut in half, as illustrated by the dotted line in Fig. 1. This prevents confusion between "inside" and "outside" when importing the geometry. The two halves of the system are coupled on $\partial\Omega_{\mathrm{id}}$ using an identity pair condition. Moreover, the PML is also coupled to the computational domain using an identity pair condition. In this way different meshes may be used in the different domains.

The acoustic domain is further divided into two areas, a lossless domain Ω_{ll} and a lossy domain Ω_{tvf} where thermal and viscous losses are accounted for. In the lossless domain we solve the classical Helmholtz equation

$$\nabla^2 P + k^2 P = 0, \tag{1}$$

where P is the acoustic pressure, $k = \omega/c$ the wave number, c the speed of sound, and ω the angular frequency. In the lossy domain we solve for the pressure p, velocity $\boldsymbol{u} = (u, v, w)$, and temperature T. 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 1 mm in diameter). Details of the thermo-viscous acoustic equations and of the PML are found in Refs. [7, 2, 3, 8].

On the solid surface of the hearing aid and the KEMAR head we have used sound hard walls

$$\boldsymbol{n} \cdot \nabla P = 0, \tag{2}$$

where $\boldsymbol{n}$ is the outward normal to the surface. The lossless and lossy acoustics are coupled by specifying continuity of normal stress and deformation using a weak constraint. The governing equations (acoustics and PML) and boundary conditions are implemented in weak form using the general PDE formulation in Comsol. Finally, because we are also interested in the acoustic pressure in the far field a Helmholtz-Kirchhoff (H-K) convolution integral element has been defined on the boundary $\partial\Omega_{\mathrm{HK}}$. In this regards it is nice to have the geometries defined in an assembly as the surface normals then are well defined. The element is defined in the `fem` structure as:

```
el.elem='elkernel';
el.g={'1'};
el.name='Pff';
el.kernel='helmholtz3D';
el.iorder='10';
el.k=num2str(k);
el.symflags={'0','0','0'};
src.ind={bnd_el};
src.srcn={{'-nx'},{'-ny'},{'-nz'}};
src.srcu={'P'};
src.srcnux={'-nx*Px-ny*Py-nz*Pz'};
el.geomdim{1}={{},{},src};
fem.elem={el};
```

3 Head related transfer functions of KEMAR manikin

The FE model is firstly tested on a known system where measurements are readily accessible. The head related transfer functions (HRTFs) of the KEMAR manikin are modeled and compared to experimental measurements. The HRTF describes how a given sound wave input is filtered by the diffraction and reflection properties of the head, pinna, and torso, before the sound reaches the eardrum. The boundary mesh on the KEMAR manikin head is depicted in Fig. 2. The HRTF H is the transfer function from a source/point in space to the eardrum

$$H = H(\boldsymbol{x}, f) = 20\log(|P(\boldsymbol{x}, f)/P_{\mathrm{ed}}(f)|), \tag{3}$$

where P_{ed} is the pressure at the eardrum, and $\boldsymbol{x}$ is the given point in space.

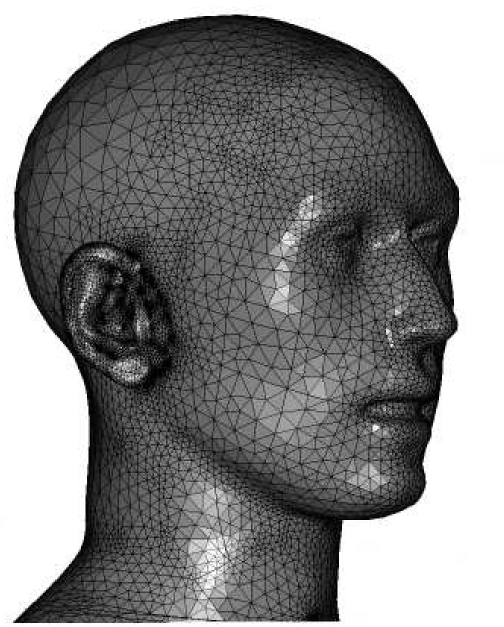

Figure 2: Boundary mesh on the KEMAR manikin.

In order to computationally efficiently determine the HRTFs we use the reciprocity principle [5, 4]. This means that we interchange the source at $\boldsymbol{x}$ with the eardrum (measurement point). In doing so we get the HRTF for all points in space for a given frequency in one run. To get the HRTF values outside the computational domain (radius > 50 cm) we apply the H-K convolution integral. Measurements and model results are compared in Fig. 3. The HRTFs are depicted for $\boldsymbol{x}$ in the horizontal plane that goes through the center point between the ears. From the graphs we see good agreement between measurements and model. In the next sections the directional patterns of hearing aids are studied.

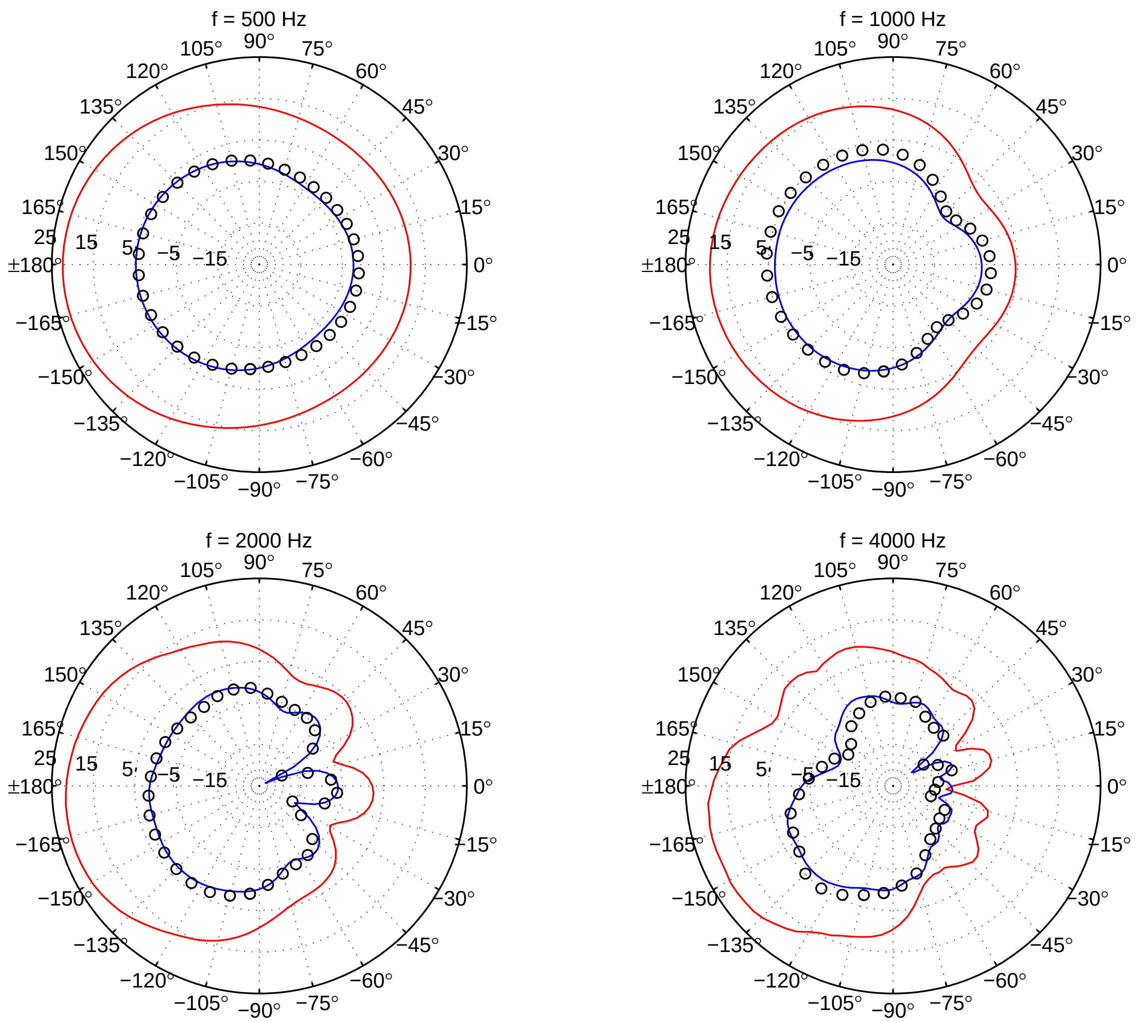

Figure 3: HRTFs of the KEMAR manikin in the horizontal plane with center between the ears. At a distance of 100 cm measurements are given as circles and model results as a blue solid line. The red solid line represents the HRTF at a distance of 20 cm. Front is towards -90^o.

4 Directional patterns of hearing aids

Most modern hearing aids (HAs) have two microphones, which enables spatial filtering of sounds. The simplest linear combination of the front (f) and back (b) microphone signals is the omnidirectional (omni) H_o and figure-eight or bidirectional (bidir) H_b spatial response,

$$H_o = H_o(\boldsymbol{x}, \omega) = P_f + P_b \qquad (4)$$
$$H_b = H_b(\boldsymbol{x}, \omega) = P_f - P_b \qquad (5)$$

where P is the pressure at the microphone. In the following we will study these two simple spatial responses. In actual HAs complex adaptive signal processing algorithms combine the two signals in order to filter out, e.g., spatially localized noise sources. In order to optimize the directional algorithms it is important to study variations in the shape of the response H. This shape is dependent on the geometry of the HA, on head shape, and on the placement of the HA on the ear. Directional patterns are often only measured in one plane, whereas, a FE simulation yields the full 3D spatial response. Moreover, it is possible, with a FE model, to simulate the response of new HA geometries which still only exist as CAD figures on the computers of the mechanical designers.

5 Hearing aid in free field

Standard benchmark measurements on HAs include the directional response in free field, when isolated from other interfering objects (geometries). The geometry of the HA used here is given in Fig. 4.

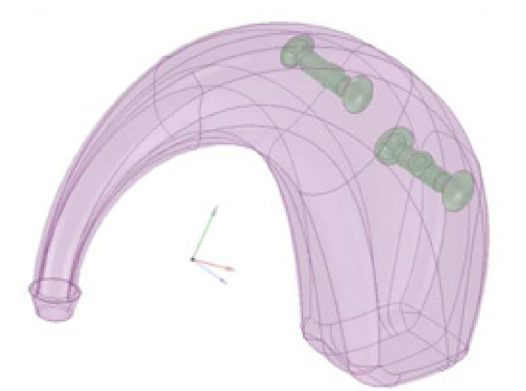

Figure 4: Geometry of the Widex Inteo IN-m hearing aid including the microphone inlets.

The omni and bidir spatial response at 5000 Hz of the HA is depicted in Fig. 5. The model results are compared to experimental measurements and show good agreement. These results are also obtained using the reciprocity principle, i.e., numerically the microphone membranes are the sources of the sound.

In certain cases the design of the HA microphone system, e.g., inlet shape, require details of the pressure in the near field for a given incident wave. Here reciprocity is not applicable but it is necessary to solve the exact problem. This may be done by utilizing the linearity of the governing equations [9]. Splitting the pressure into an incoming (i) and a scattered (s) wave it applies that

$$P = P_s + P_i = P_s + \exp(\boldsymbol{k} \cdot \boldsymbol{x}) \qquad (6)$$

where, in this case, the incident wave is a plane wave with direction $\boldsymbol{k}$. The dependent variable to solve for is then P_s. Note that we operate in the Fourier frequency domain. An example of the pressure field around the HA is given in Fig. 6 for a plane wave incident from the front.

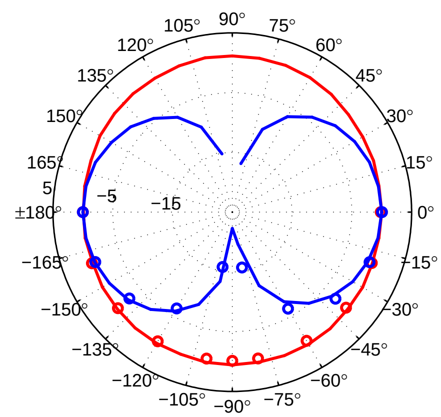

Figure 5: Omni (red) and bidir (blue) response of the HA at $f = 5000$ Hz. Circle markers represent measurements and the solid line the FE results.

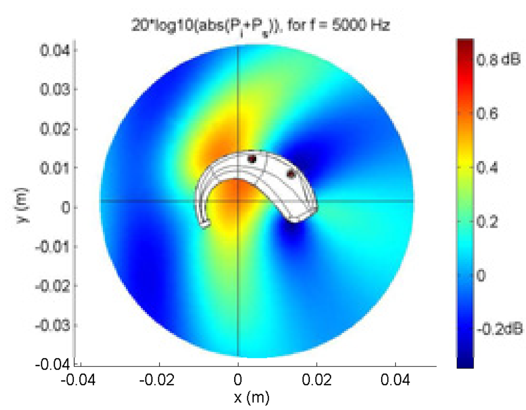

Figure 6: Sound pressure distribution around the HA for $f = 5000$ Hz. A plane wave is incident from the front (along the x-axis).

6 Hearing aid on KEMAR manikin

When the HA is placed on a head the characteristic free-field directional patterns are distorted. To illustrate this effect, the directional patterns for the HA placed on the KEMAR head are modeled. An example of the CAD geometry is shown in Fig. 7. The calculated omni and bidir characteristics are plotted for two frequencies in Fig. 8 and compared to the ideal free-field case. The curves are obviously distorted, compared to the free-field case, but we note that they maintain their characteristic shapes. In the omni case we see the head shadow effect as a decrease in H_o for the directions coming from the head side (-60^o to 60^o, the shadow side). However, in the bidir case, where the two microphone signals are subtracted, it seems that a source to the shadow side of the head is better heard for regions next to the notch. The two notches in the bidir characteristic are preserved even though they are either distorted or less pronounced. Generally, the figure-eight shape is skewed and rotated when the HA is placed on the head. For sounds coming from the front (-90^o) we see that there are no changes compared to the ideal free-field case.

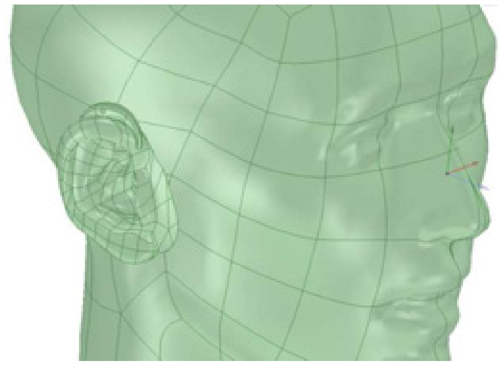

Figure 7: CAD drawing of the hearing aid placed on the KEMAR manikin head.

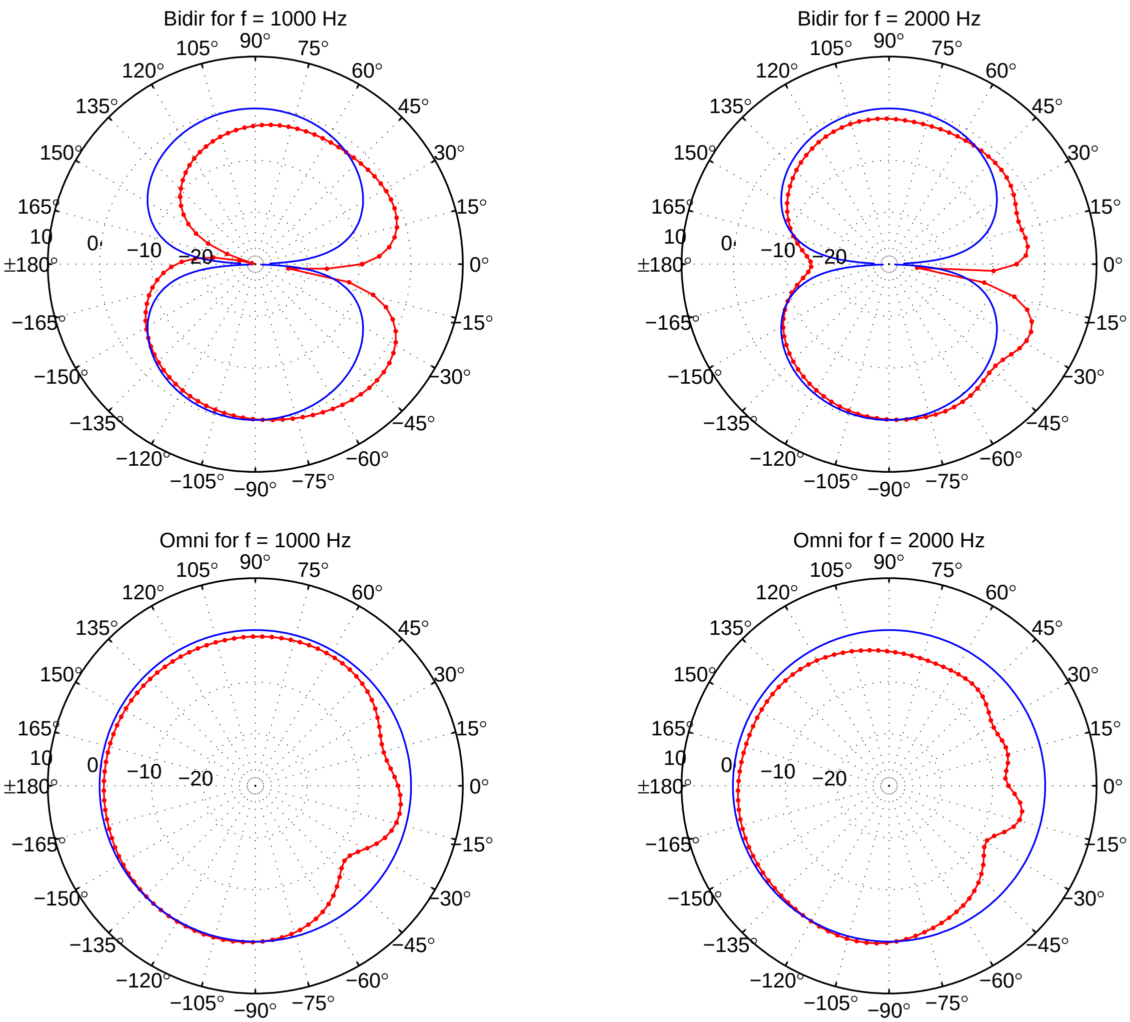

Figure 8: Comparison of the free-field (solid blue line) and the on-the-head (red line with dots) directional characteristics for the HA at a distance of 200 cm. The HA is located on the right ear ($\pm180^o$) and front is towards -90^o.

7 Conclusion

This study has served as a validation of the Comsol finite-element (FE) model used for determining characteristic directional patterns of hearing aids. We have seen good agreement between model results and measurements in the case of free-field measurements and when studying HRTFs of the KEMAR head. Finally, we have used the FE model to investigate the case when the hearing aid is placed on a head. Here the directional patterns get distorted due to head and ear. The model enables us to study the sound field around the hearing aid both locally and in the far field. In this way, we may characterize the hearing aid geometry (including microphone inlets) in terms of directional patterns. Hence, the FE tool allows for early characterization of the directional response of new hearing aid geometries, based on the CAD drawings of the hearing aids. We may also study proximity effects of the directional patterns or even optimize the hearing aid geometry and microphone inlets. Knowledge of the real "distorted" directional patterns may be used for optimizing the performance of the directional noise reduction algorithms.

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