Finite-element simulation study of directional microphones

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In modern hearing aids, the performance of directional microphone systems is typically dependent on both the acoustics around the hearing aid and on the signal processing algorithms. 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.

In the present work, the directional characteristics of a specific hearing aid are modelled in free field as well as on a head in free field. The results are then compared to measured data on a manikin head. A finite-element model is used for simulating the acoustic field around the hearing aid. The model calculates the sound pressure at the two microphones as a function of frequency and plane wave incidence angle. The two microphone signals then serve as the inputs to a directional signal processing algorithm.

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 model may be used 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.

INTRODUCTION

Firstly, this paper introduces a simple analytical model for the spatial response of a directional system consisting of two point microphones in free field. Secondly, a finite-element based study introduces results when the hearing aid is placed in free field. A short section then introduces the differences between the near-field and far-field characteristics and the basics of the reciprocity principle. The spatial response or head related transfer function (HRTF) of the KEMAR manikin head is then compared to measurements. This mainly serves as a test of the model. Finally, the hearing aid is placed on the KEMAR head and the spatial responses are simulated.

SIMPLE DIRECTIONAL SYSTEM

A simple microphone system consisting of two point microphones is depicted in Fig. 1. The front (f) and back (b) microphones are separated by a distance d. A plane wave with wave number $\boldsymbol{k}$ is incident on the system at an angle θ. The spatial response of the system is found using simple geometry. The pressure at the front and back microphones is

$$P_f = A \exp(i\omega\Delta T) \qquad \text{(Eq. 1)}$$

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$$P_b = A\exp(-i\omega\Delta T) \quad \text{(Eq. 2)}$$

$$\Delta T = \frac{1}{c}\frac{d}{2}\cos\theta \quad \text{(Eq. 3)}$$

where the time difference in wave front arrival times at the microphones is ΔT and the phase is $\omega\Delta T$. The speed of sound is c and the amplitude of the incoming wave is A. The spacial response of the omnidirectional (omni) $H_o(\omega,\theta)$ and the figure-of-eight or bidirectional (bidir) $H_b(\omega,\theta)$ are then

$$H_b(\omega,\theta) = P_f - P_b = (1 - \exp(-i\omega 2\Delta T))b\exp(i\omega\Delta T) \quad \text{(Eq. 4)}$$

$$H_o(\omega,\theta) = P_f + P_b = (1 + \exp(-i\omega 2\Delta T))b\exp(i\omega\Delta T) \quad \text{(Eq. 5)}$$

with $\Delta T=\Delta T(\theta)$. These two directional patterns represent the simplest linear combination of the two microphone signals. The two ideal far-field directional responses are compared to model and measurements in the later sections of this paper.

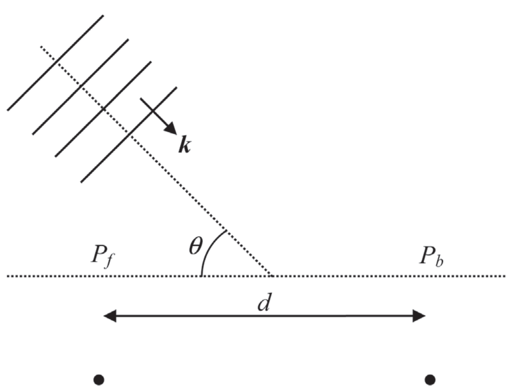

Fig. 1: Set of point microphones which can be used as a simplified directional system. A plane wave with wave number ***k*** is incident on the system at angle θ.

HEARING AID IN FREE FIELD

In this paper we study the characteristics of the Widex Inteo IN-*m* hearing aid (HA). The HA is placed in free field, isolated from other interfering objects (geometries). One way in which a detailed picture of the near field region may be obtained is by utilizing the linearity of the problem. Splitting the acoustic pressure into an incoming (i) and a scattered (s) wave we have

$$P = P_i + P_s = P_s + \exp\left(i\omega t + \boldsymbol{k} \cdot \boldsymbol{x}\right), \qquad \text{(Eq. 6)}$$

where $\boldsymbol{k}$ is the wave number, ω the angular frequency, t is time, and $\boldsymbol{x}$ position in space. In this way we solve for the scattered pressure field and get detailed information about the pressure distribution around the HA. The method has the disadvantage that a new simulation has to run for every wave direction $\boldsymbol{k}$ and every frequency f (see next section). Thus getting a full spatial response is very time consuming. An example of the sound pressure distribution around the HA is given in Fig. 2. The wave is incident from the front and the frequency is f = 5000 Hz. The directional bidir and omni characteristics for this system are presented in Fig. 3.

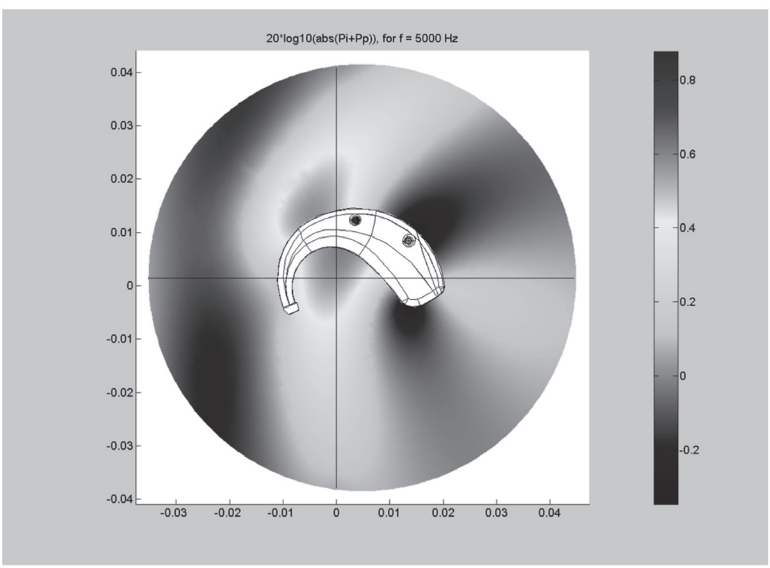

Fig. 2: Sound pressure distribution around the Widex Inteo IN-*m* hearing aid for f = 5000 Hz. The scale is in dB. The wave is incident from the front (along the x-axis).

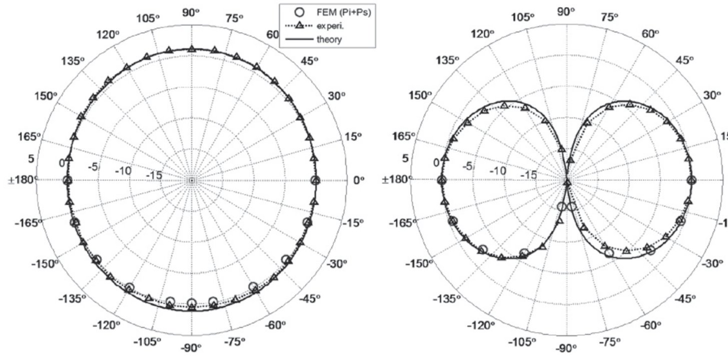

Fig. 3: Omni (left) and bidir (right) characteristics for $f = 5000$ Hz. The solid curves represent the analytical results from Eqs. 4 and 5, the triangles show measurements on the system, and the circles represent results obtained using the finite-element model at a distance of $R = 30$ cm. One circle corresponds to a given wave incidence direction $\boldsymbol{k}$.

RECIPROCITY PRINCIPLE AND FAR-FIELD ANALYSIS

If we are not interested in the near-field details of the interaction between the incoming plane wave and the HA, but only in determining the directional pattern, we may use the reciprocity principle (see Fahy, 1995). This will enable us to speed up the numerical procedure. This method allows us to interchange the source of the acoustic field (a plane wave with given direction $\boldsymbol{k}$) with the measurement point (may be the hearing aid microphone). In this way we get the full spatial directional characteristic of the HA for a given frequency in only one calculation. This method is also used in Fels, 2008 and Fels *et al.*, 2004. For far-field calculations this method introduces the additional problem of large computational domains.

As we are often interested in the far-field characteristic of a hearing aid the necessity of a large computational domain arises. This is numerically not a good idea since the computational time is proportional to the size of the domain raised to the power of three. However, by using the Helmholtz-Kirchhoff (HK) integral, we may reduce the computational domain significantly. With this method, the domain only needs to encapsulate all sources and all geometries. The pressure at any given point in space is then calculated by the HK surface integral of the local (near field) solution.

In the following, we have both utilized the reciprocity and the HK-integral to determine the directional characteristics in near and far fields.

KEMAR HRTFs

As a test of the HK-integral formulation and the reciprocity method, we decided firstly to use the finite-element method to calculate the HRTFs of the KEMAR head and compare them to measurements. In Fig. 4, the HRTFs are depicted for 4 different frequencies and two distances. The graphs show the transfer functions in the horizontal plane on a circle with centre between the ears. The dotted curve represents the simulation results of the finite-element model for a radius of 20 cm, the solid curve is simulation for a radius of 100 cm, and the circles are measured data from 100 cm. We see good agreement between the measurements and the modelled results. As the frequency increases, and the wavelength therefore decreases, the interaction with the head/ear becomes clearer. This is, e.g., seen in the increase of notches. The simulation retains all of these notches and details. Note also the larger difference in the location of the notches between far and near field for higher frequencies. An example of the HRTF depicted at the surface of the KEMAR is given in Fig. 5.

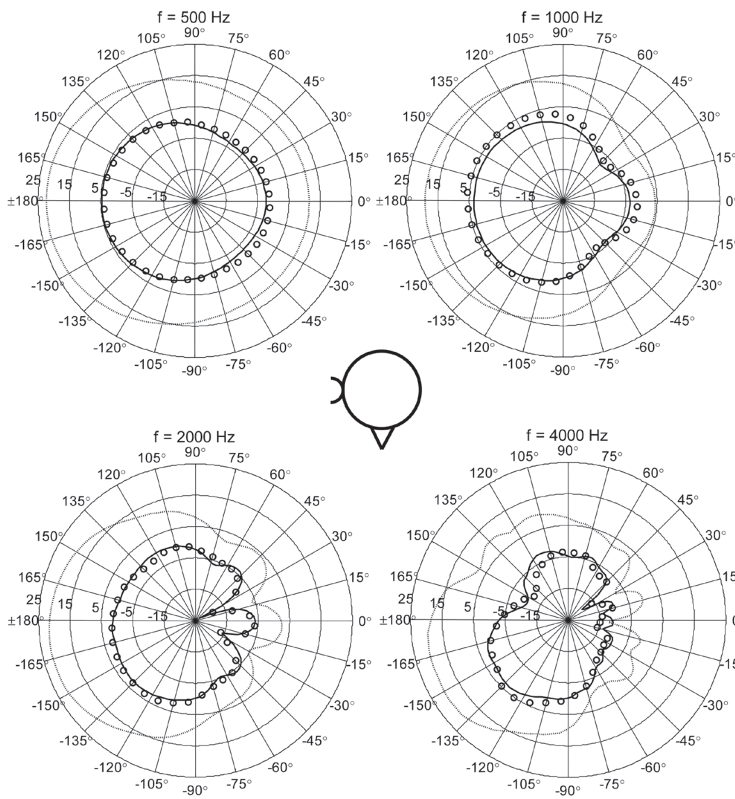

Fig. 4: Directional characteristic (HRTF) of the KEMAR manikin head for $f = 500$, 1000, 2000, and 4000 Hz. The dotted curve is the model for a radius of 20 cm, the solid curve is model at 100 cm, and the circles represent measurements also at 100 cm.

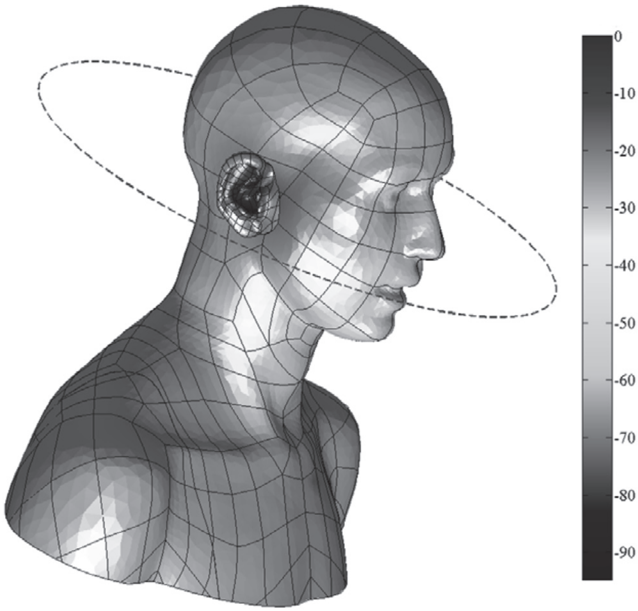

Fig. 5: A 3D representation of the HRTF calculated at the surface of the KEMAR manikin for $f = 4000$ Hz.

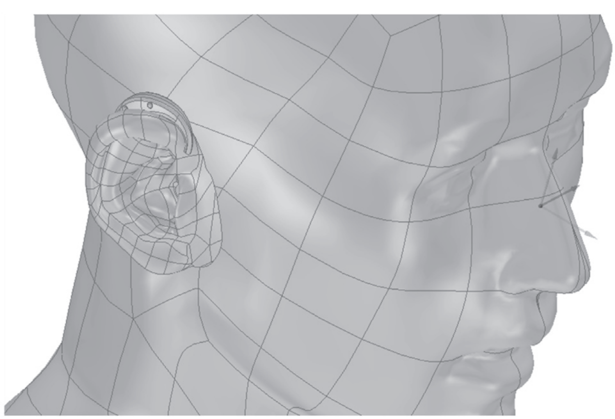

Fig. 6: 3D CAD drawing of the hearing aid placed on the KEMAR manikin head.

HEARING AID ON KEMAR MANIKIN

When the hearing aid is placed on a head, the characteristic free-field directional patterns are distorted. To study this effect, we model the directional patterns for the HA placed on the KEMAR head. An example of the CAD geometry is shown in Fig. 6. The omnidirectional and bidirectional characteristics are plotted in Fig. 7 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_0 for the directions coming from the head side (−60° to 60°, 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-of-eight shape is skewed and rotated when the HA is placed on the head. For sounds coming from the front (−90°) we see that there are no changes compared to the ideal free-field case.

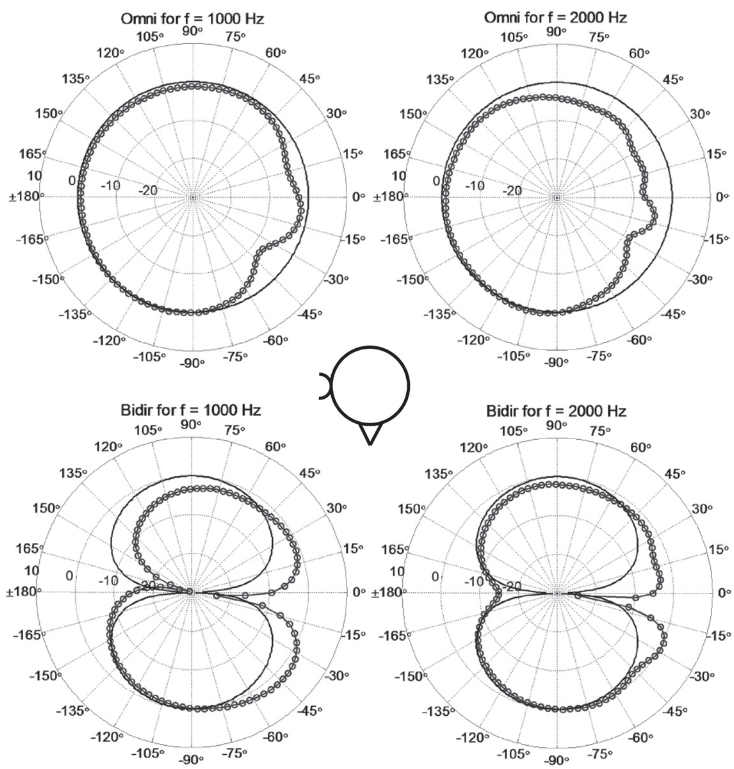

Fig. 7: Comparison of ideal free-field (solid line) and on-the-head (dots) directional characteristics for the hearing aid at a distance of 200 cm. The hearing aid is located on the right ear as depicted in Fig. 6.

CONCLUSION

This study has served as a validation of the finite-element model used for determining characteristic directional patterns of hearing aids (HAs). We have seen good agreement between modelling results and measurements in the case of free-field measurements and when studying HRTFs of the KEMAR head. Finally, we have used a finite-element model to investigate the case when the HA is placed on a head. 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. We may also study proximity effects of the directional patterns or even optimize the hearing aid geometry and microphone inlets.

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