A boundary element model to calculate HRTFs. Comparison between calculated and measured data

W. Kreuzer, P. Majdak, A. Haider
Austrian Academy of Sciences, Acoustics Research Institute, Email: wolgang.kreuzer@oeaw.ac.at

Introduction

The shape of head, torso, and pinna plays an important role in localization of sounds in humans. Reflections, especially at the pinna, act as a filter, which can be described by the head-related transfer functions (HRTFs). An acoustic measurement of one HRTF set including all relevant positions in 3D-space takes tens of minutes, even when sophisticated measurement methods are applied [1]. Another option is the calculation of the HRTFs using numerical methods like the boundary element method (BEM). This method becomes more and more important in the field of acoustic simulation.

One drawback of this method is the fact that the linear system of equations generated by BEM may become very large. If collocation BEM is used, the matrix describing the system has n^2 entries, where n is the number of elements. If BEM is used to calculate HRTFs for frequencies up to 20 kHz, a very fine mesh should be used to achieve acceptable accuracy. Thus, it cannot be implemented without modifications, the consumption of computer memory and calculation time would be too high. Therefore the boundary element method is coupled with the fast multipole method (FMM, [2, 3, 4]). The FMM reduces computational costs for the whole BEM to $\mathcal{O}(n \log^2 n)$ and allows calculations with feasible amounts of computer resources [3].

In this paper results of HRTF simulation for one subject are presented and compared to the data from acoustic measurements. In addition, the effects of temperature, mesh quality and mesh perturbation are presented.

The Model

In order to generate a mesh of the head, 6 scans with a non contact 3-D visual scanner (Minolta VIVID-900) were taken from different angles around the head and combined into one mesh. The resolution of the scanner was higher than necessary, thus the number of nodes was reduced to lower computational costs. In order to be able to calculate HRTFs for high frequencies (up to 22 kHz), the final mesh of the head contains 70.785 elements with an average edge length of 2.1 mm. Figure 1 shows a part of the mesh used for most calculations to illustrate the its size.

1550 additional nodes were positioned around the head in a distance of 1.2 m to represent external sound sources. The elevation angles of these nodes range from $-30°$ to $80°$ in steps of $5°$ and their azimuths range from $0°$ to $360°$ in steps of $2.5°$ (see also Fig 2). The nodes were set according to the positions of the loudspeaker used for the measurement of HRTFs at the institute's lab.

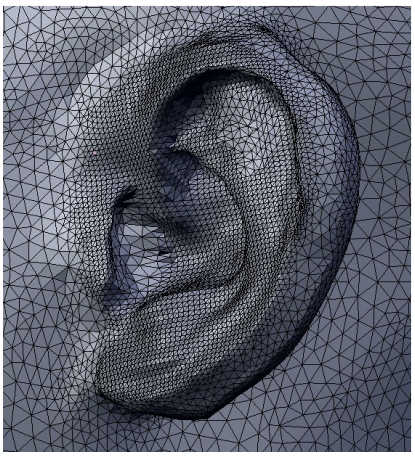

Figure 1: Plot of the mesh around the pinna

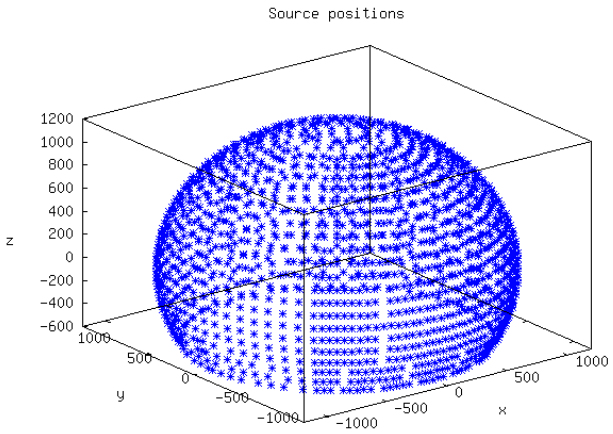

Figure 2: Distribution of sound sources around the head.

The surface of the head was assumed to be hard reflecting. For the simulations, one element near the entrance of the ear canal was chosen as the receiver element.

It was also of interest how the shoulder affects the HRTFs. Therefore an artificial shoulder mesh was added to the head based on photographs of the subject from different angles. Overall computation time for 200 different frequencies was about 5 hours on a Linux cluster containing 5 computers with dual Opteron processors (2.0 GHz) and 16 GB RAM each.

The measurement of the HRTFs was made in a semi-anechoic room. The subject was seated in the center of an arc with 22 loudspeakers mounted at fixed elevations

between −30° and 80° and had microphones (KE-4-211-2, Sennheiser) placed in his ear canals. An exponential sweep with a duration of 1728.8 ms and a frequency from 50 Hz to 20 kHz was used to measure each HRTF for one azimuth. Then, the subject was rotated by 2.5° to measure HRTFs for the next azimuth (see also [1]).

Results

After the HRTFs were measured or calculated, the magnitude of the common transfer function (CTF) was calculated by averaging the log-amplitude spectra of all equalized HRTFs. Finally the directional transfer functions (DTF) were calculated by filtering the HRTFs with the inverse complex CTF. The DTFs were used in the comparison between measured and calculated data. Measured and calculated data were only compared up to frequencies of 16 kHz, because for the median-plane localization, frequencies in the range of 3.5 to 16 kHz are essential [5].

Comparison of measured and calculated data

To see the influence of the mesh quality on the HRTFs an additional mesh with less number of nodes was created. The reduction of nodes introduces a smoothing to the mesh, especially at the pinna. As it can be seen in Figure 4, such a reduction of mesh quality has great influence in the DTFs. Certain features, for example the notch between 8 and 12 kHz are not present in the calculations (Figure 4 left panels). When comparing measured and calculated results, it seems that the calculated results are a "smoothed" version of the measured data. The general form is given but some details are missing or shifted in frequency. One reason for this difference may be that during the mesh generation certain geometrical features of the pinna got lost. Another explanation for the difference between measurement and calculation may lie in the choice of the receiver element for the BEM-simulation. Figure 3 shows the sound pressure distribution at the left pinna at a frequency of 11 kHz. The sound source is placed in front of the head with an elevation angle of 45°. A very sharp interference pattern can be found near the receiver element and a shift of the element within a few mm would lead to different results in the calculated DTF-data.

A similar situation is given when looking at the results for the vertical plane. Up to 8 kHz both calculation and measurement agree, but for higher frequencies fine structure gets lost in the calculations. In Figure 5 we see the effect of the shoulder on the HRTFs. Additional interference patterns in the DTFs appear which are also given in the measurement.

Temperature and Mesh-perturbation

To simulate the effect of different temperature on HRTFs, calculations were done with different values for the speed of sound and density of air (see Table 1).

To check the stability of the BEM-model with respect to measurement errors, HRTFs have been calculated with a slightly perturbed mesh, i.e. all nodes where moved with random vectors of 0.5 mm length.

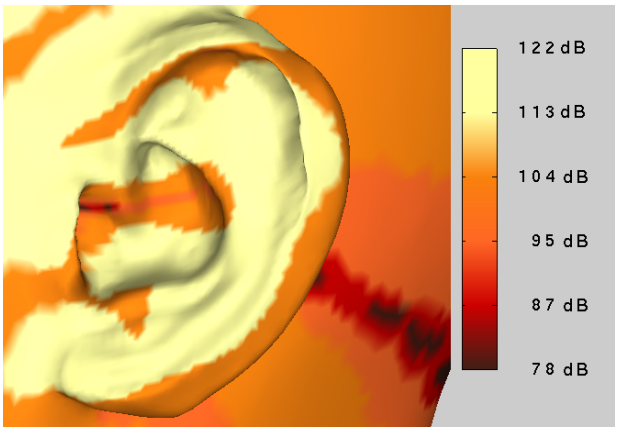

Figure 3: Pressure distribution at the left pinna for a source in the vertical plane at an elevation of 45° for a frequency of 11 kHz

Temperature	Speed of sound	Density
−15° C	322.3 m/s	1.36 kg/m^3
0° C	331.3 m/s	1.292 kg/m^3
15° C	340.5 m/s	1.225 kg/m^3
30° C	349.0 m/s	1.165 kg/m^3

Table 1: Values for speed of sound and density of air for different temperatures

The model proved to be quite robust against small perturbations and temperature effects. HRTFs for different temperatures show only a small frequency shift and the small perturbation has also only a minor effect. It has to be mentioned though, that perturbations of 1 mm or greater already have a significant effect on the results. As an example Figure 6 shows the results of measured and calculated data for four positions in the horizontal plane (front, right, back and left). It can be seen that different temperatures only result in a small shift in frequency. For all calculations the mesh without shoulder has been used.

Conclusion

A boundary element model to calculate HRTFs for the whole frequency range was presented. Comparison with measured HRTFs show that both measurement and calculation agree up to a frequency of 8 kHz. For higher frequencies still some work has to be done to improve the BEM-model. Certain characteristic patterns of the HRTFs which are present in the measurement cannot be found in the calculated data. The lack of these patterns may be caused by the generation procedure of the mesh. Also the placement of the receiver element at the pinna seems to have some influence on the HRTFs.

On the other hand, the model itself seems to be quite robust with respect to temperature and to small changes in the mesh as long as "characteristic" features of the pinna are preserved. It will be part of future research to use the model to find out more about these

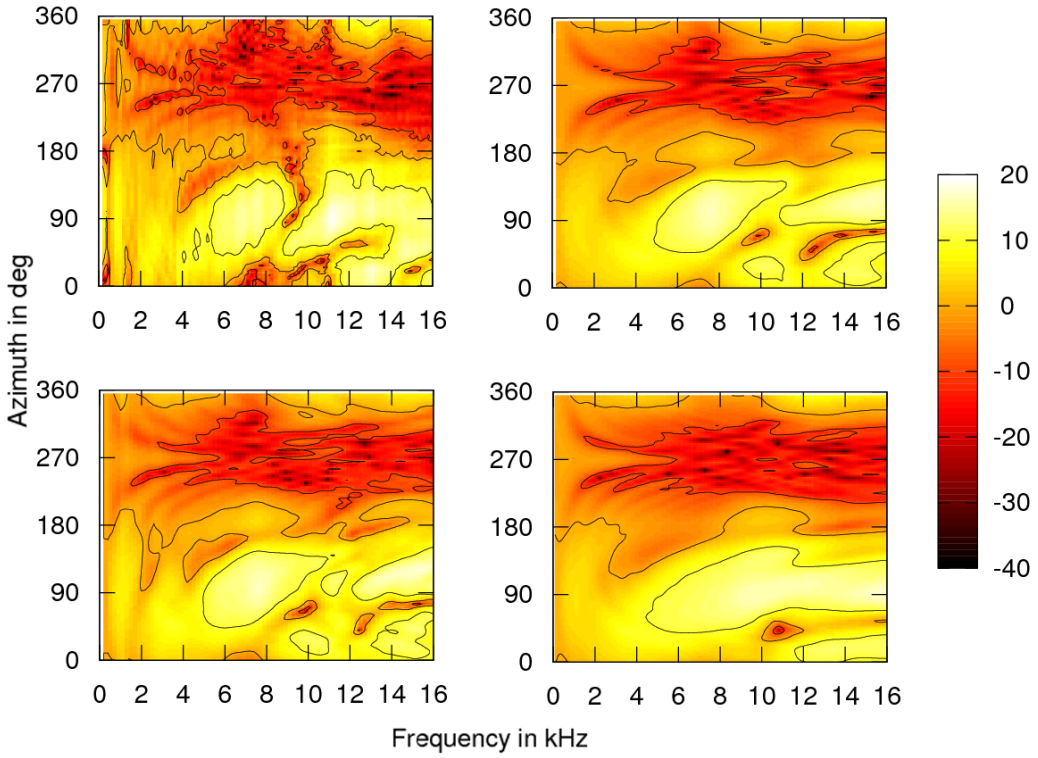

Figure 4: Comparison of simulated and measured DTFs in the horizontal plane (elevation = 0°). Top-left: Measured data, Top-right: Simulated data without shoulder mesh, Bottom-left: Simulated data with shoulder mesh, Bottom-right: Simulated data with the low-quality mesh.

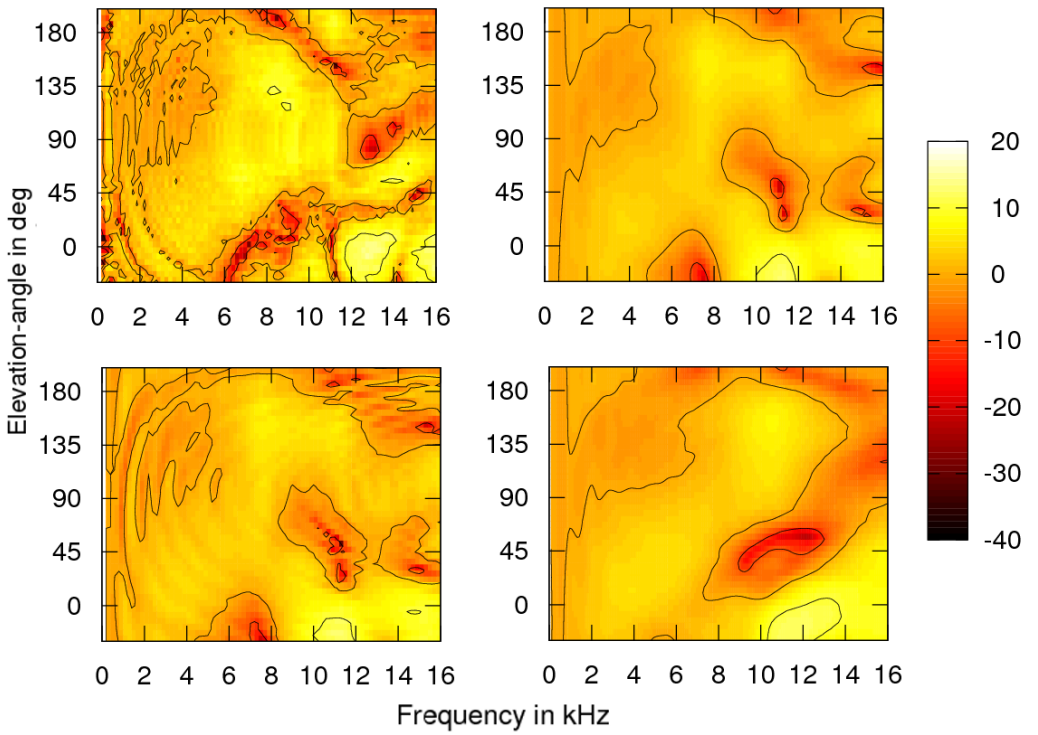

Figure 5: Comparison of simulated and measured DTFs in the vertical plane (azimuth = 0°). Top-left: Measured data, Top-right: Simulated data without shoulder mesh, Bottom-left: Simulated data with shoulder mesh, Bottom-right: Simulated data with the low-quality mesh.

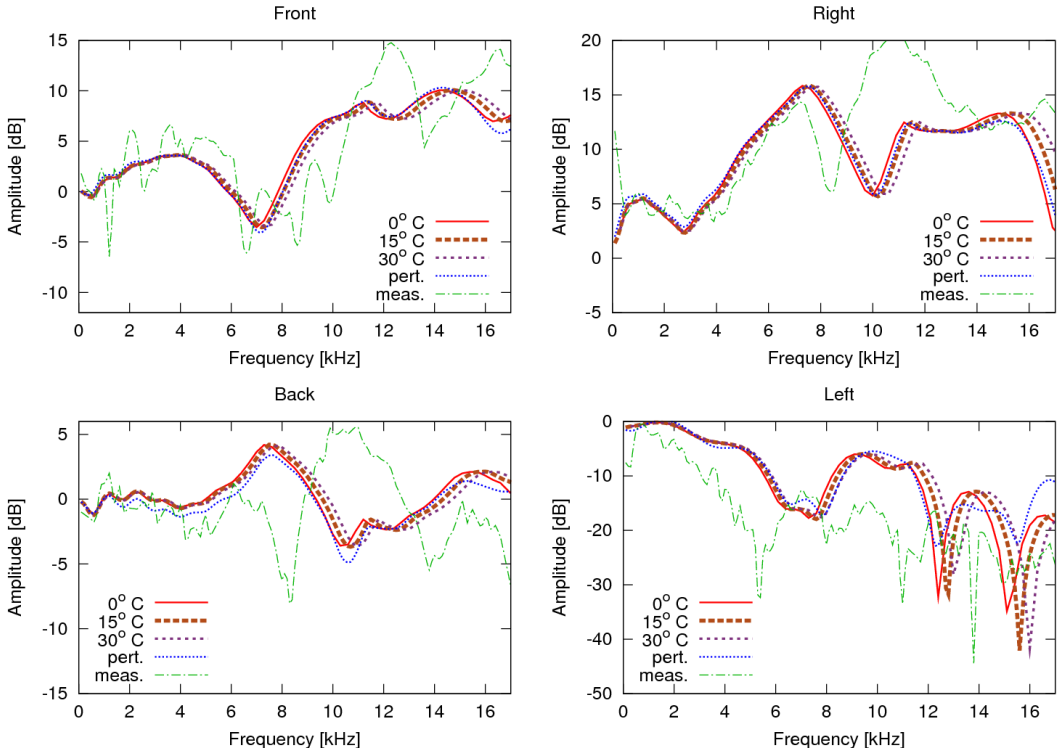

Figure 6: Measured and calculated DTFs for four different positions in the horizontal plane (elevation angle = 0°)

characteristics. Also localization tests will be necessary to evaluate the quality of the HRTF calculations.

Acknowledgments

The authors would like to thank Michael Hofer from the TU Vienna for providing 3-D scans and meshes. We are grateful to Bernhard Laback and Holger Waubke for helping comments. This work was funded by the Austrian Science Fund (Project No. P18401-B15) and the Austrian Academy of Sciences.

References

[1] Majdak, P., Balazs, P., and Laback, B.: Multiple exponential sweep method for fast measurement of Head-Related Transfer Functions, J. Audio Eng. Soc. 55 (2007), 623–637

[2] Greengard, L. and Rokhlin, V.: A Fast Algorithm for Particle Simulations, J. Comput. Phys. 73 (1987), 325–348

[3] Fischer, M. and Gaul, L.: Application of the fast multipole BEM for structural-acoustic simulations, J. Comput. Acoust. 13 (2005), 97–98

[4] Chen, Z.-S., Waubke, H. and Kreuzer W.: A Formulation of the Fast Multipole Boundary Element Method (FMBEM) for Acoustic Radiation and Scattering from Three-dimensional Structures, J. Comput. Acoustics **16** (2008), 1–18

[5] Middlebrooks, J. C. and Green, D. M.: Sound localization by human listeners, Annu Rev Psychol 42 (1991), 135–59.