Physical modeling of individual head-related transfer functions

Roland Sottek and Klaus Genuit

HEAD acoustics GmbH, Ebertstr. 30 a, D-52134 Herzogenrath, Germany, Roland.Sottek@head-acoustics.de

SUMMARY

Applications of virtual auditory space need individual head-related transfer functions (HRTFs) to simulate realistic scenarios. To avoid costly measurements a physical model of HRTFs has been developed considering the influence of a few acoustically relevant objects. Individual variations of HRTFs correspond to variations of geometrical parameters. In a first step, the head has been modeled by a rigid sphere[1] and the pinna with cavum conchae by elliptical disks; the position of the ear reference point is one of the most important parameters [1]. The correlation between calculated and measured HRTFs is significantly higher if the influence of shoulder/torso is modeled by an additional rigid sphere. In a second step, the shapes of head and shoulder/torso have been approximated with oblate respective prolate spheroids in order to get even better results. Sound field calculations have been performed using the boundary element method and analytical methods (solution of the wave equation, use of Huygens' integral formula) [2]. Computation time has been reduced by a factor of about 100 using and optimizing the source simulation technique for the diffraction problem of spheroids.

INTRODUCTION

"A person who enters a multimedia shop is scanned by a camera and some instants later his/her individual HRTF set is ready to be sold for the use in advanced 3D applications" [3]. This scenario may be real live in a few years. At the moment the offer is: tell me your main geometrical parameters and in a few hours you will get your HRTF set, simulated up to 12 kHz using the acoustically most relevant objects. It is even possible to combine the HRTF set using a toolbox with different precalculated heads, shoulders and ears to get a solution in a very short time.

PHYSICAL MODEL

HRTFs are influenced by several reflecting and diffracting bodies in a very complicated way. It would be desirable to separate the influence of each body and to superpose all partial results to one total result, thus having a better insight into the influence of main geometrical quantities.
Considering only two objects, three terms representing the total sound field disturbance should occur: one term produced by object 1 (object 2 not present), one term produced by object 2 (object 1 not present) and a third term describing the interaction between object 1 and object 2.

Using the boundary element method (BEM) three diffraction problems for each sound incidence of interest have been solved:

- Object 1: Head (rigid oblate spheroid), calculation of sound pressure $\underline{p_H}$ at the reference position $\vec{r}_0$ (left or right ear).
- Object 2: Shoulder and torso (rigid prolate spheroid), calculation of sound pressure $\underline{p_{Sh}}$ at the reference position $\vec{r}_0$.
- Object 1 and 2: Head with shoulder and torso, calculation of sound pressure $\underline{p_{H+Sh}}$ at the reference position $\vec{r}_0$.

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[1] A simplified approach for the sound field of a rigid spheroid in a plane wave has been used, too.

The discussion of the BEM results has shown that the third term describing the interaction between head and shoulder/torso can be neglected. The resulting sound pressure $\underline{\tilde{p}}_{H+Sh}$ at the reference position $\vec{r}_0$ is then given by

$$\frac{\underline{\tilde{p}}_{H+Sh}}{\underline{p}_0} = 1 + \frac{\underline{p}_H - \underline{p}_0}{\underline{p}_0} + \frac{\underline{p}_{Sh} - \underline{p}_0}{\underline{p}_0}.$$

The sound pressure at the reference position $\vec{r}_0$ is the superposition of the plane wave (sound pressure $\underline{p}_0$) and the parts from head and shoulder/torso due to diffraction [2].

Table 1 shows the acoustically most relevant objects and the corresponding geometrical parameters. Pinna and cavum conchae have been approximated by an elliptical disk with an eccentric elliptical cave. The diffraction problem of plates can be solved using Huygens' integral formula according to [1]. The ear reference point $\vec{r}_0$ is the crossing point of the ear canal axis with the disk representing the pinna.

TABLE 1: Acoustically relevant objects, simplified shapes and their geometrical parameters

Object	**Model**	**Geometrical parameters**
head	oblate spheroid	width, height, relative position to reference point
shoulder/torso	prolate spheroid	width, height, relative position to reference point
pinna	elliptical disk	width, height, relative position to reference point, orientation
cavum conchae	elliptical cave	width, height, relative position to reference point, orientation

The elliptical disks produce sound field disturbances which are added to the parts produced by head and shoulder/torso using complex arithmetic. Whereas in the case of head and shoulder/torso the interaction between both structures could be neglected, a correction has to be made for the pinna, because the part of the head behind the pinna does not contribute to the total sound pressure at the ear reference point [1]. This has been done by calculating the projection of the pinna on the tangential plane of the head. Then the sound field disturbance produced by this virtual disk has been subtracted from the total field. That simplified method is applicable here because the dimensions of the pinna are small compared to the dimensions of the head. The influence of the ear has been considered only for the ipsilateral half sphere.

The position of the ear reference point is the most important parameter for the simulation. An experiment using a diametrical arrangement of both ears and perpendicular sound incidence results in nearly the same sound pressure at both ears. Realistic interaural level differences can be achieved only with a well-reproduced position of the ear reference point.

The interaural time delay (ITD) can be described by two parts, one "geometrical" term which takes into account different delays from the source location to the reference points (left and right ear) and another part considering the influence of reflection and diffraction at the different bodies. The geometrical part has been calculated based on a source distance of 3 m to avoid negative delays for both ears. The second part results from the algorithms described in the next paragraph.

SOUND FIELD CALCULATION

The calculation of HRTFs using the BEM needs very long computation times. To speed up the simulation analytical models can be used. Analytical solutions of diffraction problems exist for a small number of simply shaped bodies: e.g. spheres, spheroids or cylinders.

The sound field of a rigid sphere in a plane wave has been calculated using solutions of the wave equation in spherical coordinates [4]. In a first step, head as well as shoulder/torso have been modeled using rigid spheres with mean radii instead of using spheroids.

Another numerical approach to calculate the sound field of a spheroid has been carried out using the source simulation technique. This numerical method is very efficient and more stable than the BEM. This technique could be applied also for more complicated bodies: The vibrating body is replaced by a system of sources located within the envelope of the radiator. The task is to calculate the complex weights of each source to satisfy the boundary conditions on the surface of the body: e.g. the resulting normal velocity should vanish on the surface. In most cases only an approximate solution can be obtained which minimizes the boundary error. This leads to a linear system of equations with some hundred unknowns [5].

For oblate and prolate spheroids the large system of equations can be split into some smaller systems: that means less computation time and higher stability. To set up the linear system of equations two-dimensional integrals have to be calculated, but for the special shape one integration can be calculated analytically: another reduction of computation time. The system of equations has to be solved for each frequency of interest and in general for each direction of sound incidence. But with known weights it is possible to calculate the sound pressure at each point on the surface and outside the body.

Taking into account the symmetry of the spheroid, it is only necessary to solve systems of equations for 0, 15, ..., 90 degrees azimuth to compute the whole set of HRTFs with 15 degrees resolution in azimuth and free choice of elevation. The head has been modeled using one source location: at the center of the spheroid, the sources for the torso have been placed at three locations: at the center of the spheroid and to the left and to the right on the longer axis.

The best order of the sources has been found iteratively: A high order enables a more accurate physical model at a high computational effort, but may also result in an ill-conditioned system of equations, especially at low frequencies. Therefore the order increases towards higher frequencies verifying that both accuracy and stability of the solution are sufficient.

The calculation of the complex sound pressure has been carried out for 30 frequencies from 400 Hz up to 12 kHz on a logarithmic scale. For the use of HRTFs in 3D applications a linear frequency scale is usually needed. Amplitude and phase have been interpolated linearly in the frequency domain using logarithmic scales for frequency and amplitude, resp. linear scales for frequency and unwrapped phase. In a preprocessing step the average group delay has been removed to reduce large phase differences between neighbored frequency points. This delay has been added again after the linear interpolation. The HRTFs have been extrapolated for frequencies above 12 kHz based on the last third of calculated values, but avoiding increasing amplitude. For low frequencies HRTFs tend to be 0 dB.

INFLUENCE OF SHOULDER AND TORSO

The influence of shoulder and torso on the HRTFs has been studied using an artificial head (HMS II.1). Measurements have been performed with/without shoulder and torso in an anechoic room for 0, 30 and 60 degrees elevation and a resolution of 15 degrees azimuth. The results of those measurements should give information about the influence of shoulder and torso to refine and/or verify the physical model.

Figures 1 and 2 show results concerning the influence of shoulder/torso for frontal sound incidence in the horizontal plane. The correspondence between measured and calculated results is impressive, taking into consideration the very simplified geometry used for the simulation. Results for other directions of sound incidence show slightly larger differences.

Shoulder and torso emphasize differences between HRTFs for sound incidence from the front and the rear because the head is not really centered above the shoulder but shifted to the front. This shift causes different delays between direct sound and shoulder reflection.

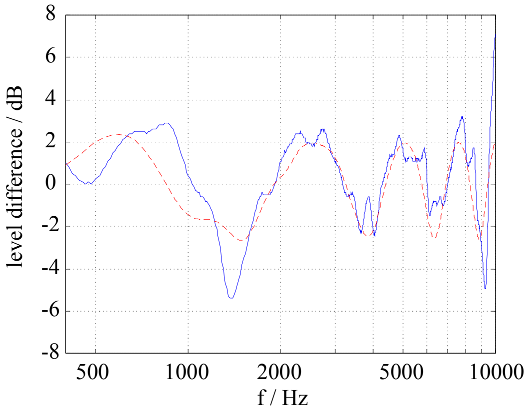

FIGURE 1: Differences between the HRTF of HMS II.1 with shoulder/torso and the HRTF of the same system without shoulder/torso for frontal sound incidence in the horizontal plane, solid line: measurements, dotted line: simulation.

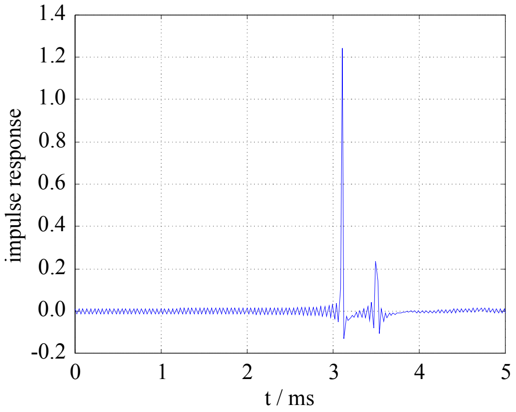

FIGURE 2: The simulated impulse responses are very short (about 1 ms + ITD) and show a clear structure. There is no need to equalize for example the influence of the ear canal which can be seen in measured functions.

DISCUSSION

In general, a good correspondence between measured and calculated HRTFs has been found. A point of interest for further development is the direction-dependent part of the cavum conchae: a part of the cavum conchae back wall acts as a reflecting facet for certain directions of sound [1]. These reflections are responsible for a sharp minimum of the HRTFs in a frequency range between 8 and 10 kHz (e.g. for frontal sound incidence). The results depend on the position and the area of the reflecting facet and on the distance to the ear reference point. For the HMS II.1 with its simplified geometry these parameters can be estimated, but for real ears no method has been found at the moment to get meaningful values for the complicated structure of the cavum conchae. Additional investigations are necessary to verify the meaning of this effect on localization and how an individual geometry of the cavum conchae has to be modeled.

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