Effect of subject misalignment during HRTF measurements on spatial acoustic resonances

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Introduction

Individual head-related transfer functions (HRTFs) provide an accurate representation of the filtering of sound at the listener's individual head and shoulder geometry, for any given sound incidence direction. A complicated interference pattern of sound waves around the geometrical structure produces distinct spectral and spatial features, which are crucial for our auditory localization ability. It is therefore important to capture the latter in sufficient detail, in order to provide authentic virtual acoustic scenes [1]. Acoustical measurement setups for HRTFs are often evaluated by means of artificial heads or simple spherical shapes. Previously performed measurements or simulations on these geometrical objects, as well as the known analytical solution in case of the sphere, can be used for comparison, allowing the use of multiple distance metrics in the time, frequency and spatial domain [2][3]. These metrics mostly describe a global error between two data sets. In fact, it is quite difficult to accurately describe the distortions introduced by the system, due to, on the one hand, the excess of spatial and spectral features in HRTFs, and on the other hand, the relatively flat spectrum of spherical transfer functions (STFs). On that account, a new measurement object is designed to have a less complex directivity pattern, yet possess pronounced features that can be more easily traced in the frequency and spatial domain.

In the following, design aspects are discussed, and results from numerical simulations performed on the object are presented. As one possible source of error in HRTF data sets is the movement of participants during the measurement, the effect of incorrect positioning of the object within the measurement setup is further analyzed.

Object Design

The new measurement object, in the following referred to as *resonator sphere*, comprises a hollow sphere with two orifices on the middle (horizontal) plane at $\varphi_{0,L/R} = \pm 70°$. Two small hollow cylinders can be attached there, as can be seen in Figure 1, to measure what is henceforth termed a *Resonator Sphere Transfer Function* (RSTF) as its directivity. Substituting small shells for the cylindrical extensions (see spare part in the figure) allows also for the acquisition of a *Spherical Transfer Function* (STF), and therefore a direct comparison to the analytical solution for wave incidence onto a sphere [4]. The object allows for binaural recordings, guaranteeing the compatibility with error metrics assessing changes to binaural cues and symmetry (interaural cross-correlation) behavior [3]. A further advantage of recording a left and right ear signal is that it allows for the use of classical processing steps, usually applied when post-processing raw HRTF measurements. E.g. an alignment of interaural time differences (ITD) can be performed to correct for minor errors in the initial orientation of the object during the measurement, something only possible due to the presence of a second channel. It should be noted that the cylindrical resonators are not meant to resemble the human ear canal, but rather a generalized case of resonance structures of the pinna. The dimensions are therefore chosen so as to allow the excitation of both longitudinal and transverse modes (and combinations thereof).

Figure 1: Side and top view of the *resonator sphere*. KE4 microphones are inserted through a bottom opening of the PVC sphere, and fastened to the bases of the small cylinders.

Due to the simplification of geometry, a reduced complexity of the directivity can be observed, compared to HRTFs. In Figure 2, magnitude spectra of the "left ear" RSTF are displayed for the horizontal plane. The azimuth angle $\varphi = 70°$ corresponds to the left cylinder position. For sound incidence from the opposite direction ($\varphi = 250°$), a *"bright spot"* ensuing from constructive interference is visible between two areas with lower magnitudes.

Numerical Simulations

Numerical simulations are performed by means of the COMSOL Multiphysics modeling software [5] using the Boundary Element Method (BEM). A point source is inserted into one cylinder, slightly offset from its base surface. The ensuing acoustic potential on the boundary surface of the *resonator sphere* is calculated, then extrapolated to a spherical receiver array of 1.2 m radius, which corresponds to the loudspeaker positions during an HRTF measurement. The triangular mesh is updated for each simulated frequency, if necessary, ensuring a max-

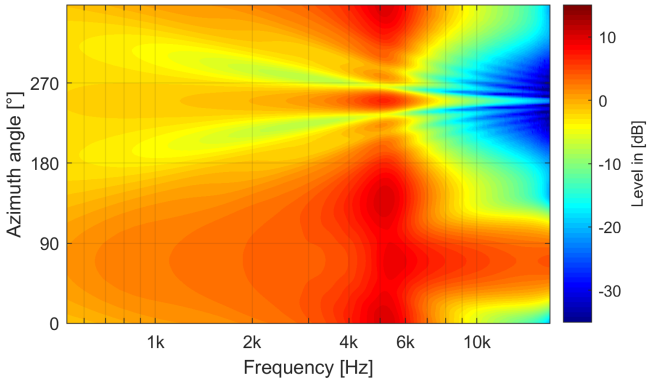

Figure 2: RSTF magnitude spectra along the horizontal plane. The spatial behavior shows less complexity, compared to a conventional HRTF, due to the lack of fine and intertwined pinna structures.

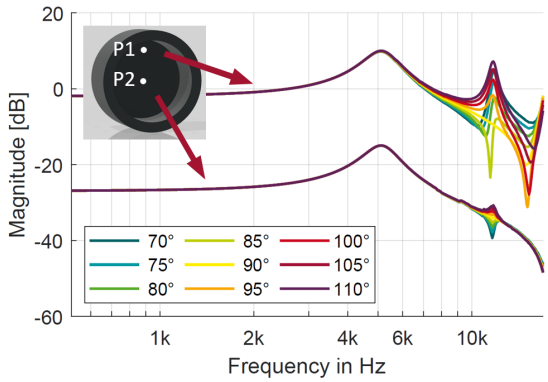

Figure 3: Spectral variation of the transfer function of a detached cylindrical resonator for varying zenith angles and different excitation locations. The longitudinal mode (around 5 kHz) remains constant, while the transverse modes (12 kHz and above) vary more or less strongly with elevation, depending on the position of the simulated point source.

imum edge size of $\lambda/6$. This condition is imposed in addition to geometrical meshing constraints.

Resonance Behavior

Modal excitation in the cylinder is best analyzed in absence of the sphere. BEM simulations of the sound field are performed on a single detached cylinder. Longitudinal (axial) modes show very little change over spatial direction with regards to peak quality and magnitude. In contrast, the emitted sound field of transverse modes inherently shows a stronger variation over space. This can be explained since transverse modes show radial and circumferential variations of phase within each cross-section of the cylinder, whereas longitudinal resonances ideally possess a constant phase at the orifice, comparable to a circular piston.

Frequency spectra for different elevations and constant azimuth (perpendicular to the orifice) are shown in Figure 3 for two different point source positions within the cylinder. Both are shifted upwards from the cylinder axis: P1 by 7mm, P2 only slightly by 0.5mm. As expected, transverse modes are hardly excited close to the center of the cylinder and, reciprocally, will not be detected by an ideal microphone positioned at the cylinder axis. However, since microphones possess an extended receiver surface, some excitation should be detected even when positioned centrally. (Note that Figure 2 is based on a simulation at point P1.) Choosing a relatively short height for the cylinders avoids having unnecessarily many longitudinal modes superimpose the transverse modes, the latter being of more similar nature to HRTF features induced by pinna interactions. Accordingly, it seems that better applicability to the evaluation of HRTF measurements is given for wider inner diameters of the cylinder, which admit transverse resonances within the simulated frequency range. Motivated therein, the cylinder dimensions shown in Figure 1 are opted for.

Displacement Error

Optical tracking data of subject movement is acquired from an HRTF measurement series, conducted in the hemi-anechoic chamber of the Institute of Technical Acoustics in Aachen, Germany. Interleaved exponential sweeps are emitted by 64 loudspeakers arranged in a curved array, spanning the zenith angles of 0° to 160° in 2.5° steps. This so-called HRTF *arc*, which is hung from the ceiling, rotates continuously around the participant. KE3 microphones are inserted at the left and right ear canal entrances, respectively. In addition to the acoustical measurement, the head position is tracked over time and the participant is given live visual feedback via a graphical user interface (GUI) [6] to correct their posture throughout the measurement procedure. A few minutes of training (i.e. learning to adjust one's position and orientation according to the proposed corrections) prior to the measurement helps shorten the initial settling time before the target posture is found by the participant. Afterwards, the tolerance range of ±1cm in x, y and z direction is mostly maintained. The small ensuing errors within this range may be negligible, as the corresponding angular shifts in elevation or azimuth are very small.

Aside from these minimal movements *around* the mean head position, however, a potential offset between the mean position and the center of the HRTF *arc* needs to be considered. Coarse positioning of the listener may lead to several cm in error. While this can be avoided through precise positioning, a *worst case* is considered in this paper, also taking into account that the measurements and simulations are performed on static objects which are not moved during the measurement, avoiding additional distortions introduced in case of human subjects. Assuming the target position and orientation of the *resonator sphere* to be as depicted in Figure 4, it is evident that for a lateral shift (along the y axis), the largest azimuth error occurs at the front and back directions, whereas lateral angles (around $\varphi = 90°$) are affected by the least angular mismatch or none.

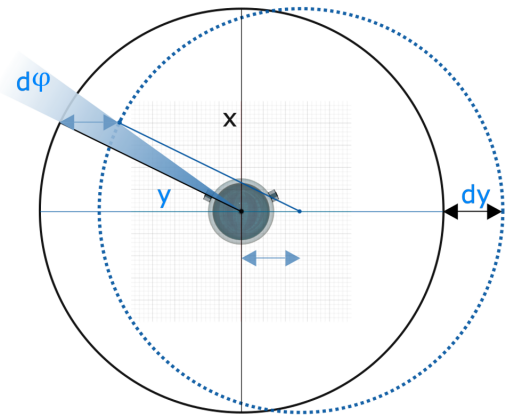

Figure 4: Angular mismatch due to sideward misalignment of the measured object with the center of the loudspeaker array.

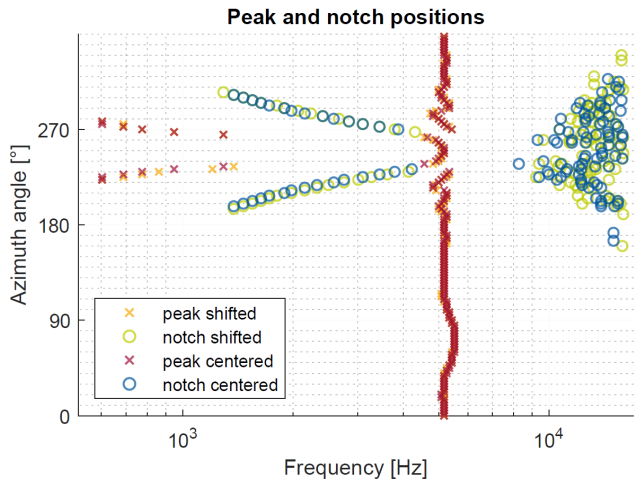

Figure 5: 1D Maximum and minimum search in frequency spectra along the horizontal plane ($\vartheta = 90°$). Peak and notch positions differ between the centered and shifted RSTF simulation. The error appears in the shape of a spatial and/or spectral shift, depending on the considered incidence angle.

The exemplary case of a sideward displacement of 5 cm leads to a frontal error $\Delta\varphi_0 = 2.39°$, which is close to the azimuth resolution of the data ($\Delta\varphi_{res} = 2.5°$). As a result, spectral features close to $\varphi = 0°$ and $180°$ are detected in adjacent azimuthal points. This can be seen in Figure 5, depicting spectral peak and notch positions of a left RSTF on the horizontal plane. Low-frequency notches around 1.5 to 2kHz of the laterally shifted simulation (green circles) appear as a copy of the notches in the centered simulation (blue circles), yet displaced in azimuth to spatial points nearby. Different behavior can be seen for directions farther from the median plane. An error of $\Delta\varphi_{70} = 0.83°$ arises perpendicular to the cylinder orifice (at $\varphi_{0,L}$), lying clearly below the azimuthal resolution of the data. Nonetheless, the altered spatial sampling positions of the directivity might lead to capturing slightly different features, especially when close to a sharp spatial notch. This observation is most evident in the high frequency range, where more complex directivity patterns are found. Therefore, the straight-forward approach of assigning spectral features to their shifted counterparts is not feasible for high frequencies.

Directional correction algorithms can morph the two coordinate systems and assign the measured transfer functions to their correct respective sound incidence directions during the measurement. In the case of a shift of a peak or notch along the frequency axis, however, the error would not be revoked by this procedure, possibly leading to perceptual errors in HRTFs. Still, the directivity of the *resonator sphere* is less complex than in the case of HRTFs, promising an easier evaluation of the remaining errors after applying spatial corrections.

Conclusion and Outlook

The presented simulation results emphasize the impact of microphone positioning on HRTFs, which has been previously examined in several studies (e.g. [7]). The ear canal entrance is not centered within the conchal cavity, therefore excited transverse resonances can be acoustically perceived by the listener, as well as recorded in HRTF measurements. In this context, the new object allows for further investigations into and optimization of numerical simulations of HRTFs. Acoustical measurements could then be properly contrasted with the simulation results without unwanted distortions. The comparatively less complex spatial behavior of the RSTF can serve a better evaluation of HRTF measurement setups and their subsequent optimization.

References

[1] Oberem, J.; Masiero, B.; and Fels, J.: Experiments on authenticity and plausibility of binaural reproduction via headphones employing different recording methods. Applied Acoustics 114 (2016)

[2] Richter, J.-G.; Behler, G. and Fels, J.: Evaluation of a fast HRTF measurement system. Audio Engineering Society Convention 140 (2016)

[3] Andreopoulou, A.; Begault, D. R. and Katz, B. F.G.: Inter-laboratory round robin HRTF measurement comparison. IEEE Journal of Selected Topics in Signal Processing 9-5(2015)

[4] Rabinowitz, W. M.; Maxwell, J.; Shao, Y. and Wei, M.: Sound Localization Cues for a Magnified Head: Implications from Sound Diffraction about a Rigid Sphere. Presence: Teleoperators and Virtual Environments 2.2 (1993)

[5] COMSOL Multiphysics Reference Manual, version 5.4, COMSOL, Inc, www.comsol.com `http://www.cs.wisc.edu/~ghost/`

[6] Richter, J.-G.: Fast measurement of individual head-related transfer functions. Lehr-und Forschungsgebiet für Medizinische Akustik (2019)

[7] Riederer, K. A.: Part IIIa: Effect of microphone position changes on blocked cavum conchae head-related transfer functions. Proc. of 18th International Congress on Acoustics (2004)