Modal sound field representation of HRTFs

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Abstract

HRTFs are usually stored as frequency spectra or impulse responses obtained at a set of discrete points at a fixed distance from the head. While it is straightforward to access this information at the given points or directions of interest, it is more difficult to obtain values for the HRTFs for other points in the 3D space. Alternatively, the HRTFs can be formulated reciprocally by representing them as a set of modal components of an outgoing spherical wave. The discrete data is thus transformed into a spatially continuous representation of the HRTFs, enabling the evaluation at arbitrary points in both near-field and far-field. In this contribution, the described method is applied to measured individual HRTFs, as described in the previous contribution by Masiero et. al. [1]. Hereby, the imperfections of the measurement equipment are compensated to obtain more accurate results. Different centering techniques are compared with the aim to achieve a compact data set that allows for the calculation of the HRTF at any point in space.

HRTFs in the 3D space

HRTFs are usually measured at discrete points in space, most commonly obtained on a fixed radius. In their actual use, however, binaural cues are required at any point in the three-dimensional space. It is thus necessary to obtain a solution for any other source point. This can be done using suitable interpolation and extrapolation algorithms, in order to obtain valid solutions for points in-between the measured directions and at ranges further away or closer than the measured HRTFs, respectively.

One way to do so is the geometric interpolation combined with a $1/r$-decay and optionally a set of measured near-field HRTFs for the proximity effect [2, 3].

Alternatively the interpolation and extrapolation can be performed by modal decomposition, representing the HRTFs as a reciprocal outgoing spherical wave [4]. Hereby the choice of the acoustical center influences the performance of the decomposition. This method is suitable to obtain similar results to simulations or measurements of near-field HRTFs [10].

Modal decomposition

Applying the principle of reciprocity, the incoming HRTFs can be regarded as an outgoing spherical wave. This method is widely used for simulated data due to an enhanced computational performance of having only a single source. Naturally, all kinds of HRTF data can be regarded reciprocally, allowing to decompose HRTFs in a spherical wave spectrum by applying the spherical harmonic transform (SHT) [5].

While the inverse spherical harmonic transform (ISHT) regard the sampling of spatially continuous base functions and is thus per-se exact, the forward transform is only exact for certain types of spherical samplings [6]. However, individually measured HRTF data are usually obtained on incomplete spherical grids, due to practical limitations in obtaining data on a full sphere surrounding the human body. In this case an exact SHT is not given and approximate solutions have to be employed.

In Figure 1 the geometry of the measurement system used for individual HRTF measurements is depicted. The persons were placed in standing position on a turntable to obtain HRTFs of high spatial density with a limited number of loudspeakers [1]. The chosen spatial sampling is a truncated Gaussian sampling scheme of order 47. A fast measurement procedure employing the multiple exponential sweep method was used [7].

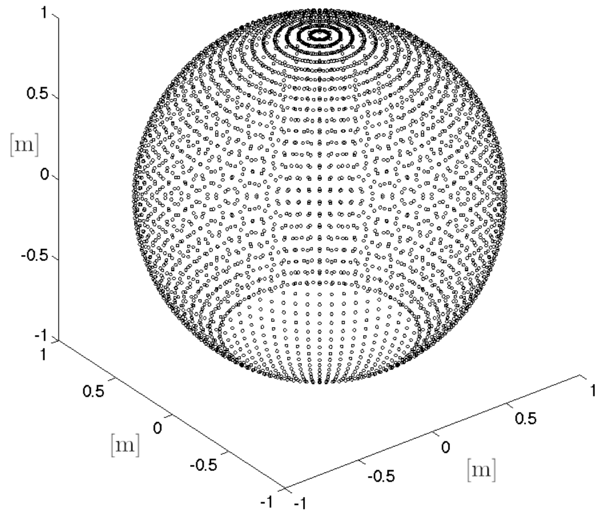


Figure 1: Complete sampling of the measurement arc for individual HRTF measurements, 3840 points arranged on a truncated Gaussian sampling scheme

Using suitable regularization this incomplete set of data can be decomposed in its modal components [4]. Experiments have shown that both interpolation and range extrapolation of the HRTFs can be successfully applied with such a limited set of data [10].

Choice of the acoustical center

HRTFs are usually defined as acoustical transfer paths from sound source to the ear openings referenced to the transfer path of the same sound source to an omnidirectional free field microphone in the position of the head center [8].

This reference point is also used in HRTF data bases meaning identical head position for both left ear and right ear HRTFs. For the decomposition in spherical harmonics coefficients, however, an alternative focal point might be preferable for a compact description.

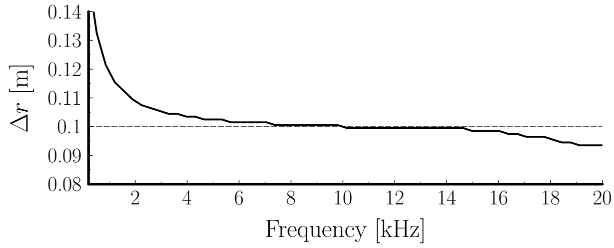
In this study the modal decomposition of HRTFs was evaluated by studying the effect of a varying focal point. With an order-limited representation of the HRTFs (energy of the SH coefficients at low frequencies), the result can be used with a higher effective resolution in applications with limited SH order. Suitable measures for quantifying the order distribution in the spherical harmonic domain are given by Ben Hagai [9]. From the given measures, the center of power algorithm performed the best for the noise-free examples of analytic spherical cap model and BEM simulation of HRTFs [10, 11].

The coefficients of the spherical wave spectrum b_{nm} are weighted by their order n to obtain the measure

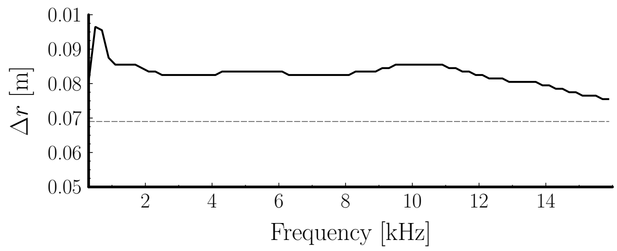
$$J_2 = \frac{\sum_{n=0}^{N}\sum_{m=-n}^{n} n|b_{nm}|^2}{||\mathbf{b}||_2^2}$$

with m the degree and $||\mathbf{b}||_2^2 = \sum_{n=0}^{N}\sum_{m=-n}^{n} |b_{nm}|^2$. The minimum of J_2 can be regarded as the optimal displacement for these examples. In Fig. 2 this optimal displacement from the center of the sphere and the dummy-head, respectively, in direction to the actual sound source is depicted. The dashed lines represent the location of the actual source.

It can be seen that the optimal focal point for a spherical harmonic decomposition varies with frequency, with low frequencies having an acoustical center further outward of the scattering body. The cap model shows a generally high match of the acoustical center and the position of the actual sound source, whereas the more complex geometry of the dummy-head seems to possess its acoustical center some centimeters in front of the ear opening.



(a) Analytical spherical cap model, cf. [11]



(b) BEM simulation of dummy head, cf. [10]

Figure 2: Optimal location of the acoustical center from the center of the sphere (a) or head (b) to obtain a low-order SH representation using the J_2 measure. Dashed line regards the actual source position.

Conclusions

With the shown methods it is possible to represent HRTFs as a superposition of modal field components. This enables the calculation of the HRTFs as the transfer function for any point in space to the ears of the listener. Missing parts of the HRTFs as obtained on a spherically distributed measurement grid can be filled by the use of suitable regularization algorithms. Applying their modal field representation in applications with limited SH-order, a new choice of focal point allows a more compact description of the HRTFs without losing as much effective resolution as with a head-centered representation of the same HRTFs.

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