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Free database of low-frequency corrected head-related transfer functions and headphone compensation filters

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ABSTRACT

A database of publicly available head-related transfer functions (HRTFs) of a KEMAR manikin together with headphone compensation filters for various headphone types is presented. The HRTFs are based on previously published data from Wierstorf et al. (2011) that have additionally been corrected for low frequencies. This compensates for missing information due to low excitation energy in this frequency range during the measurement and allows for shorter impulse responses. A further benefit is demonstrated by the interpolation of HRTFs via magnitude and phase which is only possible with consistent phase information. Both the low-frequency correction as well as the generation of the headphone compensation filters are accompanied by Matlab code to document the processing.

1 Introduction

Model-based binaural synthesis relies on the usage of head-related transfer functions (HRTFs) that describe the propagation of sound from a source to the entrances of the ear canals of a listener [1]. Though authentic binaural reproduction requires individual HRTFs [2, 3, 4], recordings with dummy heads or head and torso simulators (HATSs) are widely used as a convenient simplification. Difficulties arise when measuring HRTFs with common loudspeakers as they lack energy at very low frequencies. This leads to random results in this frequency range that should be corrected [5].

When reproducing the HRTFs over headphones, the transfer function of the headphones including the path to the entrances of the ear canals – together termed headphone transfer function (HpTF) – has to be compensated for by inverting the HpTF, which yields the headphone compensation filters. Though this too is a matter of individual differences, using non-individual compensation filters is easier to realise. Furthermore, results from Brinkmann and Lindau [6] suggest that combining non-individual HRTFs with non-individual headphone compensation filters leads to superior results regarding colouration.

To provide measured data to be used by the public and to encourage open and reproducible research, this contribution presents free databases both of low-frequency corrected HRTFs as well as HpTFs for different types of headphones. Both databases are accompanied by Matlab code that discloses the processing steps and produces the low-frequency corrected HRTFs and the headphone compensation filters out of the respective original data.

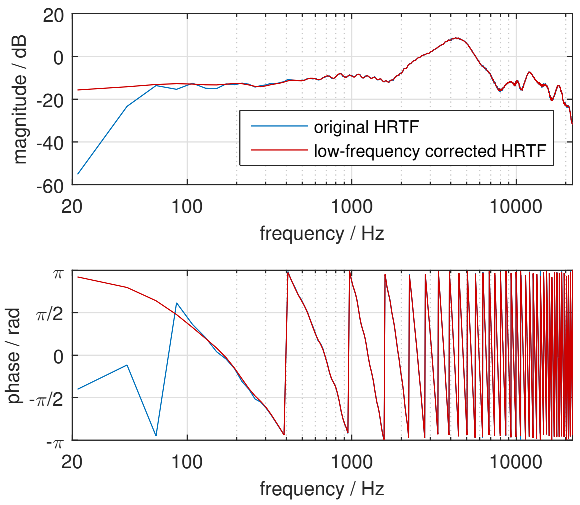

Fig. 1: HRTFs for 0° (frontal sound incidence), left ear, before and after low-frequency correction.

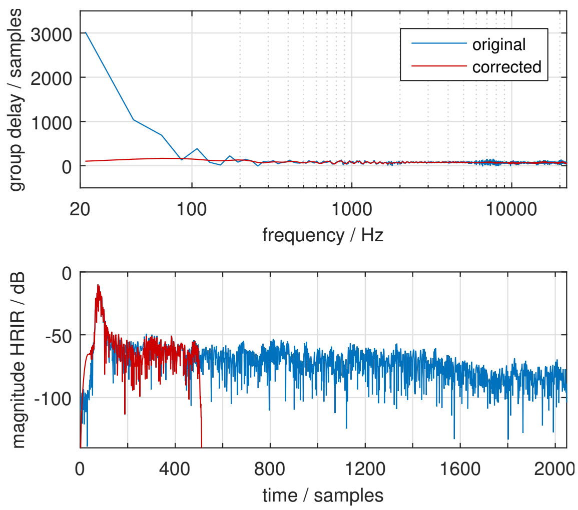

Fig. 2: Group delay and magnitude of head-related impulse response (HRIR) for 0° (frontal sound incidence), left ear, before and after low-frequency correction.

The HRTFs and HpTFs have been measured on two different KEMAR manikins of type 45BA with differing installations of the microphones. In case of the HRTF measurements, the microphones have wrongly been set back a few millimeters inside the head. The additionally arising small cavity causes an increase of several dB at 4–5 kHz. This can be amended by using the dedicated headphone compensation filters of [7] for three different headphone models that can be downloaded[1] under a *Creative Commons Attribution-NonCommercial-ShareAlike 3.0* license. Combination of the HRTFs with the here presented headphone compensation filters is not recommended, but these filters can be used together with e.g. the freely available database [8] which contains binaural room impulse responses of a 64-channel loudspeaker array.

2 Low-frequency corrected head-related transfer functions

2.1 Measurement of head-related transfer functions

The HRTFs of a G.R.A.S. KEMAR 45BA with large pinnae and G.R.A.S. 40AO pressure microphones have been measured in the horizontal plane in one-degree steps. The measurement was performed in the anechoic chamber of the Department of Engineering Acoustics at Technische Universität Berlin by using sine sweeps as excitation signals. Post-processing included correction of positional inaccuracies and compensation of the transfer function of the measurement loudspeaker. Leading zeros in the impulse responses have been reduced to a pre-delay corresponding to a source-to-receiver distance of 0.5 m. The measurement and post-processing are described in detail in [7]. This original data is freely available for download[2] in different file formats under a *Creative Commons Attribution-NonCommercial-ShareAlike 3.0* license[3].

The HRTFs have been measured for different source-to-listener distances from 0.5 to 3 m. In this contribution only the HRTFs for a distance of 3 m have been further processed with low-frequency correction as these constitute the best approximation to the most commonly used far-field HRTFs. However, the procedure described below can be applied to the other data sets as well.

[1] `http://dev.qu.tu-berlin.de/projects/measurements`

[2] `http://dev.qu.tu-berlin.de/projects/measurements`

[3] `http://creativecommons.org/licenses/by-nc-sa/3.0`

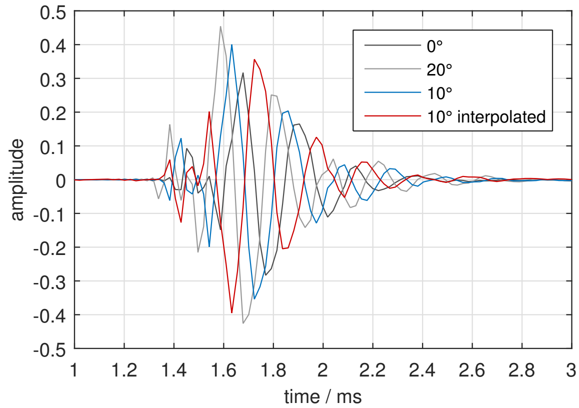

Fig. 3: Linear interpolation in the frequency domain of two originally measured HRTFs with corrupt phase at low frequencies (light and dark grey), interpolation result in red, ground truth HRTF for comparison in blue.

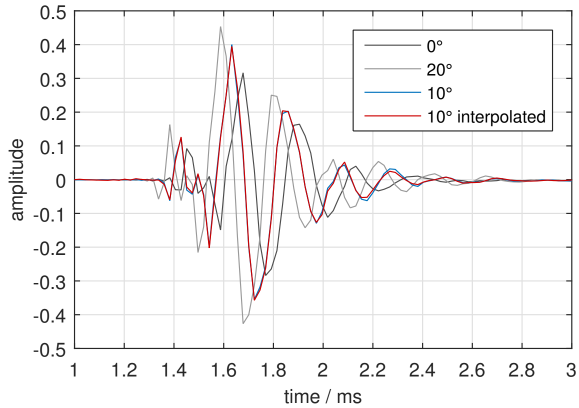

Fig. 4: Linear interpolation in the frequency domain of two low-frequency corrected HRTFs (light and dark grey), interpolation result in red, ground truth HRTF for comparison in blue.

2.2 Low-frequency correction

To compensate for the corrupt data of HRTFs at low frequencies measured with loudspeakers that lack energy in this frequency range, different strategies have been proposed. The missing information has been completed by means of geometric models of head and torso [9], with results from the boundary element method [10] or by cross-over filtering with an adequate low-frequency response [11]. All methods have in common that they lead to a monotonic function for the phase and an approximately linear magnitude response at low frequencies. This can be expected as the HATS does not present an obstacle to sound waves with large wavelengths. This finding directly translates into the approach by Xie [5] where the magnitude response is set to a constant value and the phase is extrapolated linearly. This method is chosen here.

The accompanying Matlab script performs the low-frequency correction on the original HRTFs from Wierstorf et al. [7] in the frequency domain. The magnitude below 100 Hz is replaced by the mean value from 100–300 Hz and the phase is linearly extrapolated from the same frequency range under the assumption that the data in this frequency range is reliable. See figure 1 for an example of the correction for the 0° HRTF of the left ear.

The correction of the low-frequency range of the HRTFs bears the advantage that the implausibly high group delays at low frequencies are lowered, see figure 2, and the HRTFs can be truncated to 512 samples which saves storage space and makes their usage computationally more efficient. The truncation additionally causes a slight deviation of the magnitude response at low frequencies from being perfectly linear as can be seen in figure 1.

2.3 Application: interpolation of head-related transfer functions

The low-frequency correction and subsequently possible truncation of the HRTFs is not only a matter of computational efficiency but also crucial to allow for interpolation of HRTFs in the frequency domain, separately for magnitude and phase. As random phase values at low frequencies prohibit a proper phase unwrapping, interpolation of HRTFs with uncorrected low-frequency content can lead to unexpected results, e.g. the inversion of the interpolated response. Figures 3 and 4 demonstrate this effect. The HRTF for the left ear and a direction of 10° (i.e. source slightly to the left) is linearly interpolated out of the HRTFs for 0° and 20°. The interpolation is performed in the frequency domain via separate interpolation of magnitude and phase with the help of the Sound Field Synthesis Toolbox[4] [12]. As can be seen, the interpolation based on the original data with the corrupt phase in figure 3

[4] `http://github.com/sfstoolbox/sfs-matlab`, release 2.3.0, `http://dx.doi.org/10.5281/zenodo.345435`

leads to an inverted impulse response for the 10° direction while the interpolation based on the low-frequency corrected HRTFs in figure 4 shows the expected orientation.

3 Headphone compensation filters

3.1 Measurement of headphone transfer functions

HpTFs have been measured on a G.R.A.S. KEMAR 45BA with large pinnae and G.R.A.S. 40AO pressure microphones for the following headphone types:

- Sennheiser HD 600,
- Thomson HED415N,
- AKG K271 MKII,
- AKG K601,
- AKG K612 PRO.

All headphones are circumaural except the Thomson HED415N, which is a supraaural low-cost headphone.

The impulse responses have been measured with linear sweeps with bass emphasis and 2^{19} samples length at a sampling rate of 44.1 kHz. Reproduction and recording were performed with an RME FireFace UC. For every headphone, 10 measurements were performed. Repositioning the headphones on the HATS between the measurements allows for averaging out differences due to slightly varying positions of the headphones. Average HpTFs for all five headphone types can be found in figure 5.

3.2 Calculation of compensation filters

As HpTFs typically belong to non-minimum phase systems, direct inversion is not possible [13]. Different methods have been proposed to handle this problem resulting in different advantages and drawbacks. Schärer and Lindau [14] compared several approaches perceptually, revealing the method of regularisation in the frequency domain as the best choice which is also used here.

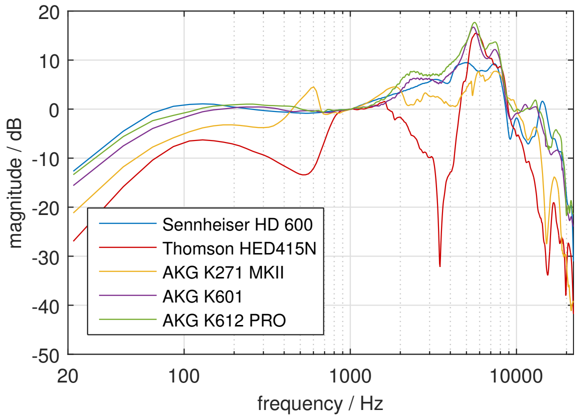

Fig. 5: Magnitude of average HpTFs for measured headphone types normalised to values at 1 kHz.

To calculate the compensation filters, the measurements need to be inspected to identify outlying measurements that appear not to be representative for the measured headphones. These are left out. The remaining impulse responses are windowed with a half Blackman-Harris window with low side lobe levels to get rid of the noise tail and truncated to the target length of the compensation filters. The average of the impulse responses is calculated as complex mean in the frequency domain. With a target bandpass for the audible frequency range and a regularisation filter with high-shelf characteristic, the linear-phase compensation filters are calculated in the frequency domain. The published code can be adapted to process any given set of HpTFs.

When not using own HpTFs of a headphone with a specific serial number in your possession, it is recommended to use filters that are averaged out of measurements of the left and right channel for one or more headphones of the same type, i.e. the filters for left and right channel are the same. When measuring on a KEMAR, this shows the additional advantage that the slight (approx. 0.5 dB) level difference between left and right HpTFs due to different installation depths of the microphones is not falsely compensated for. As the shape of the KEMAR manikin is not exactly symmetric, the different microphone installation depths result from purposely differing recesses for the pinnae on the left and right side. This leads to a level difference due to the inverse square law which is only of importance for very close sources which is the case when measuring HpTFs.

4 Free database

Data and code described here are freely available for download[5,6] under the *Creative Commons Attribution 4.0 International* license[7], the accompanying code is licensed under the MIT license, see header of scripts for more information. The HRTFs are published in the Spatially Oriented Format for Acoustics (SOFA)[8] standardised in [15].

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[7] `http://creativecommons.org/licenses/by/4.0`

[8] `http://www.sofaconventions.org`

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