Design of a Fast Individual HRTF Measurement System

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Abstract

In order to improve the quality of binaural based virtual reality systems, the use of individual head-related transfer functions (HRTF) plays a major role. As techniques for head geometry scanning and numerical simulations are still very complex and time consuming, an acoustical measurement system is still the most viable approach for acquiring individual HRTFs. Furthermore, with adequately designed hardware and excitation signals, measurement time can be reduced to a few minutes while keeping sufficient spatial resolution. This paper presents a system for individual HRTF measurements developed at the Institute of Technical Acoustics in Aachen, reporting the design methodology for the loudspeakers, which have a drop-like form to minimize diffraction and radiate as similar as possible to an ideal point source in a wide frequency band. The loudspeaker supporting arc is constructed with thin metal sticks in a truss structure in order to minimize further disturbing reflections. Loudspeakers are placed on the arc according to a Gaussian sampling grid. Special attention has been given to the correct equalization of loudspeakers and microphones. Results were validated by comparing the HRTFs of an artificial head measured with the new setup against the measurements made with a reference setup.

Design Concept

This paper introduces a new HRTF measurement setup, designed and manufactured to deliver an optimal trade-off between measurement duration and accuracy as shorter measurement times will increase the comfort of the subject at the same time that it will reduce displacement error during the measurement.

Fast HRTF measurements can be achieved based on the principle of reciprocity. But as a broad-band measurement system is desired, a reciprocal setup was discarded. A direct HRTF measurement setup requires two miniature microphones, placed ideally in the entrance of the blocked ear canal [1], and at least one loudspeaker. The best compromise between cost and speed is obtained via a hybrid setup where a group of loudspeakers are fixed on an arc and either the arc or the subject is rotated.

Sound Source

An ideal loudspeaker for a HRTF measurement setup should meet the following design criteria: broad-band reproduction, low non-linearity, and smooth directivity in frontal direction. A loudspeaker driver was chosen which had a small membrane radius (32 mm) thus delivering only moderate sound pressure levels but, on the other hand, presenting an almost omni-directional directivity pattern and a broad range frequency response (300 Hz to 16 kHz). This characteristic is of primordial importance, as near-field acoustic measurements require the sound source to radiate as similar as possible to an ideal point source in the frequency range of interest.

To radiate in the low frequency region the chosen driver needs an enclosure. An optimization of the enclosure was carried out to minimize edge diffraction. A drop-like enclosure showed a lower influence in the radiated sound field and was therefore chosen as the form for the loudspeaker enclosure. The final loudspeaker designed and its frequency response can be seen at [2].

Supporting Arc

The design of the arc to support the loudspeakers is also focused on minimizing its influence on the radiated sound field, i.e. to avoid reflection and diffraction effects. The supporting arc was therefore designed with thin metal rods in a truss structure seeking to minimize disturbing scattering effects while providing sufficient stability. Frequency response of the drop-like loudspeaker measured with and without the supporting arc showed variation of less than 1 dB.

For virtual reality applications the use of near-field HRTFs is highly interesting. Range extrapolation describes “a way to obtain the range dependence of the HRTF from existing measurements conducted at a single range!” [3]. Since outward range extrapolation is numerically more stable than inward extrapolation, a small radius of 1 m was chosen for the arc. As a person has to stay in the middle of the loudspeaker array, the use of a complete circle is not feasible, hence an arc allowing measurements of elevation angle from $-60°$ to $90°$ was chosen.

Equalization

According to Blauert [4], “the *free-field HRTF* relates sound pressure at a point in the auditory canal [...] to the sound pressure [...] at a point corresponding to the center of the head [...] while the subject is not present.” Ideally, if the both measurements are conducted with the same loudspeaker and microphone, their influence will be canceled out, remaining just the ratio between the HRTF and the Green’s function corresponding to the distance between the sound source and the center of the head. In the special case of measuring the HRTF of an artificial head, special care must be taken with the microphone equalization, as for higher frequencies “the diffraction effects at the diaphragm and the enclosure of the microphone can cause a considerable modification to the sound field into which the microphone is inserted" [5]. When measuring p_{head} the microphone housing is hidden inside the artificial head. During reference measurements the housing is fully exposed to the sound field and its influence is described by E_{housing}. This implies that the undesired influence of the microphone housing does not cancel out

$$\frac{p_{\text{head}}}{p_{\text{ref}}} = \frac{\cancel{L_1} \cdot \text{HRTF}(r) \cdot \cancel{S_1}}{\cancel{L_1} \cdot H(r) \cdot \cancel{S_1} \cdot E_{\text{housing}}}, \tag{1}$$

with L_1 being the loudspeaker's and S_1 the microphone's frequency response. Note that to obtain the HRTF, it is thus necessary to multiply the ratio $p_{\text{head}}/p_{\text{ref}}$ by the Green's function $H(r)$ of the desired distance r by assuming a far-field radiation.

The microphone's housing effect is equivalent to

$$S_1^{\text{ff}} \cdot E_{\text{housing}} = S_1^{\text{pf}}. \tag{2}$$

where S_1^{ff} and S_1^{pf} are respectively the free-field and the pressure-field microphone sensitivity.

For the miniature microphones used for the measurement of individual HRTF these diffraction effects start to occur only at frequencies above 16 kHz and can thus be neglected.

Measurement Results

An artificial head was used as the first "test subject" for the developed set-up as it allows precise positioning and as it will not move during the measurement. The same object had already been measured with another measurement setup, consisting of only one loudspeaker mounted on a swivel arm and the same turntable used with the new arc. The original setup allows the measurement of only one direction at any time and had thus a longer duration related to the movement of the swivel arm. Each direction measurement with this setup took in average 3.2 s. On the other hand, the new arc with its 40 loudspeakers allow interleaving of the excitation signals reducing the average measurement time for each direction to mere 0.06 s [6]. Continuous rotation of the subject during the measurement can reduce the measurement duration even further, though requiring extra signal processing [7].

A simple comparison between both measurements at some representative directions shows very good match in the whole frequency range, as seen in Fig. 1. Some local mismatch is probably caused by influence of the measurement system or other systematic errors. An analysis of the spatial representation of both measurements also showed good agreement.

Conclusions

A novel HRTF measurement set-up to allow fast acquisition of individual HRTFs was proposed. The system is composed of 40 loudspeakers, a supporting fixed arc of a radius of 1 m and a turntable with a head fixation for rotation of the test subjects. A measurement loudspeaker for this specific task has been designed with a

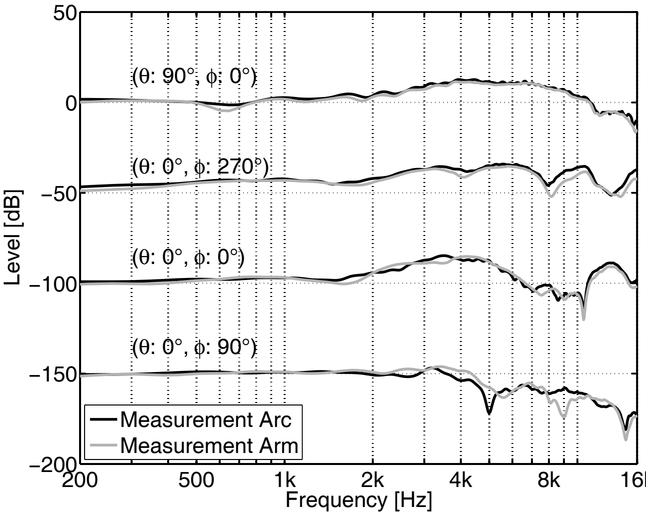

Figure 1: Comparison between HRTF measured for the left ear of an artificial head with the original and the newly presented setup. Curves are shifted by 50 dB for better visibility. θ describes the elevation and ϕ the azimuth of the listener in relation to the sound source.

broad-band frequency response and a defined and stable acoustical center. The first measurement conducted with the new system showed good agreement with reference measurements of the same dummy head. A complete measurement can be concluded in less than five minutes.

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