Measurements of Artificial Head Transfer Functions for Auralization and Virtual Auditory Environment

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SUMMARY

The human external ear can be considered as a linear filter with two channels. Its acoustical transfer properties, attributable to pinna, head, shoulder and torso, depend dominantly on the directions of sound incident. Head-related transfer functions (HRTFs) are commonly used for describing the acoustical properties of such a directional filter. In the present paper two kinds of artificial heads have been used for capturing HRTFs. Pseudo random noise was applied for achieving HRTFs. These HRTFs can be used in a wide variety of applications. Evaluation of both monaural features and interaural intensity or time features may help finding potential cues of the human external ear. A systematic comparison between the two artificial heads is also performed using these data. Some major results from an extensive evaluation of measured HRTFs are demonstrated. Their applications in binaural auralization and virtual auditory environment are described briefly.

INTRODUCTION

The last three decades have revolutionised our concepts of sound transformation in the external ear [1-3]. A comprehensive explanation of physics of the external ear can be found in [2]. It is widely recognised that the human external ear can be considered, in the sense of telecommunication, as a linear filter with two channels. Its transfer characteristics vary as a function of sound source location. HRTFs are used for describing the acoustical transfer behaviours of this kind of filter. In recent years, measurements of HRTFs of both human subjects and artificial heads (AHs) conducted in several laboratories have been reported (see e.g. [4-8]), amongst others, collecting HRTFs for further binaural signal processing was probably first found in [5]. Techniques for measuring HRTFs have been profoundly developed using powerful pseudo random noises (see e.g. [5,9]). The measured HRTFs can be used both in fundamental research for further understanding the human external ear and in a variety of applications: e.g. binaural measurement technology, binaural auralization and virtual auditory environment. With recent advances in binaural technology and virtual reality, some basic questions stimulate further investigations such as (a) systematic comparison of different AHs and individual subjects, (b) validation of external ear models [4,10,11], (c) optimization of spatial interpolation methods, (d) digital data reduction for efficient description of human head. In the present work, HRTF measurements of AHs have been carried out with a high directional resolution not obtained previously. A systematic comparison between two artificial heads and a number of subjects is also performed. Preliminary evaluation results are reported. The applications in the binaural auralization procedure and virtual auditory environment are also discussed.
MEASUREMENT OF HRTFS OF ARTIFICIAL HEADS

In the present work, two kinds of AHs have been under investigation. One head possesses a detailed replica of a 'typical' human external ear (HMS I [12]) while the other is designed according to a simplified mathematically describable geometry (HMS II [13]). In the anechoic chamber of HEAD acoustics a loudspeaker radiating pseudo random noise is mounted on an arc which enables the elevation angle to be selected between -5° and +90° in 1° steps. The distance between the middle of heads and the sound source amounts to 2 m. A set-up equipped with a computer-controlled stepping motor ensures the artificial heads to be turned automatically in the horizontal plane such that an azimuth can be excessively adjusted between 0° and 360° in a smallest step of 0.9° (see Fig. 1). For the elevation from -5° to +90° the head has to be arranged upside-down. The precise re-positioning is monitored by three laser beams in front, on the left and right side of the head respectively. The mechanical arrangement and the time-variance of the electronic devices involved present serious limitations for achieving a high directional resolution of the measurement. Hence a number of different reproducibility tests have been carried out. The measurement reproducibility is tested with respect to loudspeaker (L-S), head (HD) and stepping motor (SM) re-positioning respectively. The difference of the magnitude spectra in the frequency range (0.2-16 kHz) can be used as a measure of reproducibility. This resulted in measurement differences of ±0.5 dB. The overall long-term (with LS, HD and SM all re-positioned) reproducibility in a time interval of 3 months can be found within ±1 dB. Using this set-up HRTFs of AHs at a given elevation can be automatically measured in a high directional resolution (see Table 1).

Given loudspeaker elevation, the automatic measurement procedure starts with radiating a periodic pseudo random signal of 4096 points. After 10 averaged recordings of the response in each ear canal to this signal, the stepping motor turns the head to the adjacent azimuth. For the highest resolution achieved in the present work the recordings are performed at 400 discrete azimuth angles for one given elevation.

<table>
<thead>
<tr>
<th>Elevation range</th>
<th>Elevation resolution</th>
<th>Azimuth resolution</th>
</tr>
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<tbody>
<tr>
<td>Elevation ±50°</td>
<td>1°</td>
<td>0.9°</td>
</tr>
<tr>
<td>Elevation ±50°-±80°</td>
<td>2°</td>
<td>1.8°</td>
</tr>
<tr>
<td>Elevation ±80°-±90°</td>
<td>5°</td>
<td>3.6°</td>
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EXTENSIVE EVALUATION OF HRTFS

The measurement results can be processed for further evaluation of free-field, monaural and interaural HRTFs (see [2] for the definitions). Particularly from interaural HRTFs the interaural level difference (ILD) and time difference (ITD) can be directly derived in terms of magnitude and phase spectra. An AH, simulating the human external ear, produces specific frequency-dependent changes of sound signals when passing through it. The auditory system of a subject evaluates the sound events according to these specific changes to build up corresponding auditory events [2]. The directional hearing outside the median plane is due dominantly to the frequency-dependent interaural differences (IDs) of this directional filter. Fig. 2 shows the magnitude spectra of interaural HRTFs of the AHs in the horizontal plane with a resolution not obtained previously. As one can see from the interaural level differences (ILDs) in Fig. 2, the distinct structures indicate the characteristic directional filtering effect. Particularly two 'mountain ranges' in the frequency range above 1 kHz distinctly characterize the directional cues of two ears. Several magnitude spectra of monaural HRTFs of KEMAR, HMS I and HMS II as well as six human subjects are shown in Fig. 3 indicating the derivation range among different subjects and AHs. In both parts of Fig. 4 the magnitude spectra of monaural HRTFs of the two heads are plotted. As one can see from Fig. 3 and Fig. 4, the correlation of the two heads, already evident in psychoacoustic investigations [4,13], is confirmed by these physical measurements of the HRTFs. Changing the elevation angle, specific changes in such patterns shed light on directional cues of human external...
ear in nearly all incident directions. Further evaluations in different aspects are now being undertaken. Development of algorithms for binaural evaluation of AH signals is also expected.

AURALIZATION AND VIRTUAL AUDITORY ENVIRONMENT

Taking measured data in form of monaural HRTFs, corresponding head-related impulse responses (HRIRs) are derived for implementing a binaural mixing console (BMC). About 80 taps are used for representing each HRIR. FIR filters for performing digital linear convolution are adopted on Motorola DSP 56002 chips operating at a clock frequency of 40 MHz. The achievable update rate of HRIRs amounts to 80/sec at present, i.e., 80 different directions can be altered in real time within one second, without generating any 'clips' in continuous audio signals. At the present state such a BMC features 16 channels. Using BMC one can transfer any audio signal into a binaural signal at any discrete direction listed in Tab. 1. Moreover, sound source movement achievable using BMC opens up new dimensions for audio engineering. Such a high directional resolution of measured HRTFs is then necessary. Since relative time delay and gain can be individually adjusted among different channels, binaural auralization [15] of room acoustic properties in terms of considering some major early reflections can also be realized in real time using a 16-channel BMC. To this end, a kind of pre-filtering featuring 50 taps, in addition to directional filtering, is also involved in each channel, e.g., for implementing frequency-dependent wall-absorption. An advanced application of such BMCs can be found in the realization of virtual auditory environment [16] where for directional filtering two BMCs are operated in parallel for real-time directional filtering. In this application, the relative spatial information of the subject's head (head position and movement relative to the 'virtual sound source') is necessary for a fixed virtual space and provided by a special tracker system [16]. A sophisticated virtual auditory environment realization is reported in [16].


Fig.1: Measurement set-up in an anechoic chamber equipped with a stepping motor.

Fig.2: Magnitude spectra of the internal HRTFs of HMS II as a function of azimuth at elevation 0 degree, azimuth setp 0.9 degree.
Fig. 3: Magnitude spectra of monaural HRTFs of three AHs and six human subjects. The data of KEMAR are taken from [7]. Left ear, in horizontal plane at azimuth 30, 60 and 90 degree, reference direction (0, 0)

Fig. 4: Magnitude spectra of monaural HRTFs of (a) HMS I and (b) HMS II at elevation 0 degree, azimuth step 0.9 degree, right ear, reference direction (0, 0)