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Evaluation of dummy-head HRTFs in the horizontal plane based on the peak-valley structure in one-degree spatial resolution

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ABSTRACT

Dummy-heads are often used for standardized measurements where modeling of the human head and torso is relevant. Monaural Head-Related Transfer Functions of a Brüel & Kjaer dummy were measured in the horizontal plane in one-degree spatial resolution. Evaluation is made by plotting the peak-valley structure in frequency. Special frequency and spatial domains can be determined based on the variations of the HRTFs that are relevant to understand physical properties of the dummy-head in measurements and processes of human directional hearing. Symmetries and similarities of measured HRTFs help to scrutinize the perception of directional information in the monaural and binaural evaluation, the "noisy domain" in frequency and space where shadowing of the head occur as well as the filtering effect of the pinna.

1 INTRODUCTION

Dummy-heads (also known as head and torso simulators) are often used in spatial hearing research. They model the average human head's and body's shape, size and acoustical properties (such as pinna, ear canal, eardrum impedance etc.). Such equipment is suited for long-term acoustical and noise measurements instead of omnidirectional microphones [1-17].

On the other hand, they can only partially model the human body and its geometry. Usually, they do not have clothing, hair and they do not have any individual properties of the size and shape of pinnae, head, nose etc. It is well known from the literature that binaural recordings, recordings of the HRTFs (Head-Related Transfer Functions) are inferior to recordings made on real human subjects. Solving localizations tasks, extracting directional information and spatial properties of the auditory scene during playback through headphones and dummy-head HRTFs is more difficult than it is with individually recorded HRTFs.

An exhaustive investigation was made using a dummy-head for recording the HRTFs in one-degree spatial resolution horizontally and in 5 degrees resolution vertically [18-21]. The goal was to investigate the spectral representation of measured transfer functions, the variation of the peak-valley structure using the "naked" torso as well as using hair and clothing on it.

2 MEASUREMENT SETUP

The measurement setup includes the Brüel & Kjaer Head and Torso Simulator Type 4128 placed on a turntable in the anechoic room. The turntable can be controlled by a computer in 1 degree steps. Accuracy and repeatability was deeply investigated in order to create a measurement system suited for long-term accurate measurements [18]. Changes of 1 dB in the measured transfer functions can be evaluated. Pseudo random white noise signal was used as stimuli and results were collected for both ears simultaneously.

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The measured data was accumulated and averaged and after applying the FFT the magnitude of the transfer functions were plotted as function of frequency. The HRTFs were calculated as usual:

$$HRTF = \frac{P_1(jw)}{P_2(jw)} \qquad (1)$$

where P_1 is the sound pressure at the eardrum and P_2 is the sound pressure in the origin of the head-related coordinate system at the same signal and sound source, but recorded with a unidirectional microphone [5].

The HRTFs are defined in the Head-Related Coordinate System as seen in Fig.1. The two main parameters are: azimuth (φ) and elevation (δ). The shape of the human body and pinnae determine the directional dependent HRTFs. Therefore, they are individual and from the same direction a large deviation between subjects is natural [10, 12, 15].

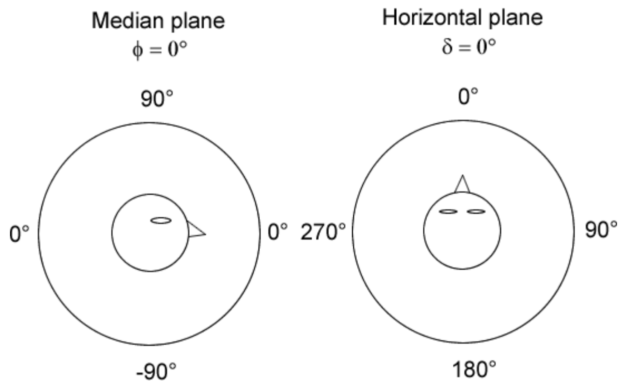


Fig.1. The head-related coordinate system.

3 EVALUATION OF DUMMY-HEAD HRTFS IN THE HORIZONTAL PLANE BASED ON DEVIATIONS IN THE PEAK-VALLEY STRUCTURE OF THE BARE TORSO

3.1 Movement of the Sound Source in the most Sensitive Region

In this section we analyze the horizontal plane HRTF-set recorded in a resolution of 1°. Due to the median plane symmetry the analysis is made only for one ear. We search for typical changes in the peak-valley structure both in frequency and magnitude by azimuthal movements of the sound source. The procedure corresponds to *plotting of ten nearby HRTFs together* as the source moves from φ=0° in the horizontal plane around the head. The "thickness" of the plotted lines delivers relevant information about the effect of azimuthal turning: if the figure containing ten HRTFs is "thin", the similarity between nearby HRTFs is large; if the figure is "thick", the HRTFs vary significantly as the sound source is moving.

In the region 0°-30° there is a constant increase of the overall HRTF level up to 3-5 dB independently from the frequency (Fig.2). Furthermore, the peak at 9 kHz increases by 7-9 dB. Other deviations of the nearby HRTFs are limited under 1 dB except between 2-10 kHz where this limit is 2 dB.

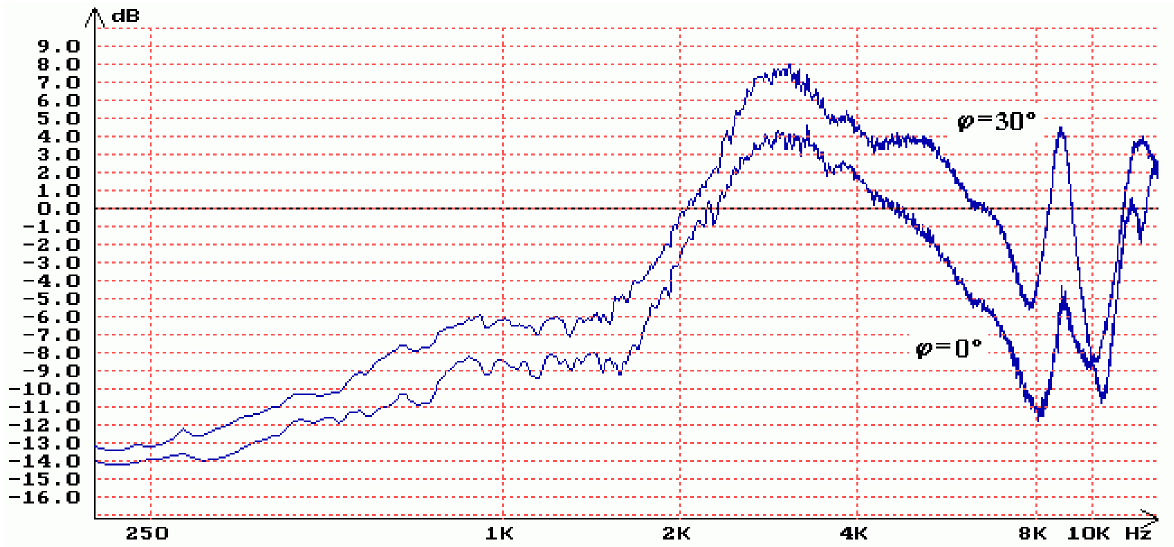


Fig.2. Horizontal plane HRTFs from the directions φ=0° and φ=30°. The overall signal level increased without significant changes of the peak-valley structure. The peak at 9 kHz increased about 9 dB.

The signal level reached at 30° remains constant until 80°. The plotted HRTFs are very similar. This is very interesting because this would assume low spatial discrimination in the region. The positive-going edges are very thin; the changing of the azimuth is only noticeable on the height or deepness of a peak or valley (Fig.3.). Only the changes in the domain between 7-8 kHz are not limited under 1 dB. Some increase of the peaks and valleys at 8, 10 and 12 kHz is also noticeable. Minimal changes (1-1,5 dB) within repeated measurements and asymmetrical spectral variations of the HRTFs about the interaural axis were also found by *Carlile and Pralong* supporting our observations [22, 23]. They show the so called minimum audible field (MAF) sensitivity function, which describes the minimum detectable pressure level, determined at the position of the subject's head for a free-field stimulus in the median plane. This is also defined as a binaural measure of sensitivity for a free-field sound but it can be applied to the monaural HRTFs. It seems there is a marginal increase in sensitivity under binaural listening conditions.

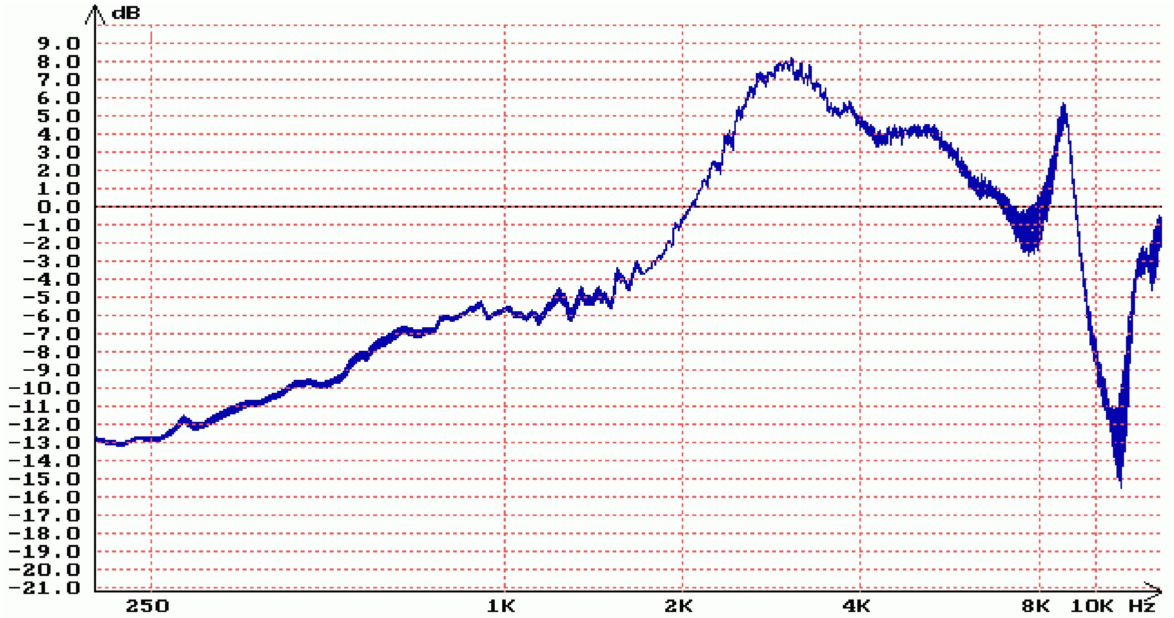


Fig.3. Typical changes in the peak-valley structure of the HRTFs in the horizontal plane. Ten figures are plotted between 40 and 50 degree in 1° resolution. The positive-going edges are very "thin" and changing of the azimuth is only noticeable on the height or deepness of a peak or valley.

As the source moves on, the "thickness" of the plotted HRTF curves increases. Between 70°-110° the most important peak at 3 kHz and the valley at 4 kHz is falling down by 4 and 9 dB on aggregate respectively. The positive- and negative-going edges are still very thin, but the height of the peaks and valleys is changing significantly, up to 5-7 dB (Fig.4).

The effect of the pinna at 11 kHz between 70°-90° is discussed in [18, 19]. The HRTFs from this direction have a random frequency-shift effect. This means that the HRTFs are almost identical during repeated measurements, except between 11 and 12 kHz, where a small frequency shift of about 25-30 Hz appears causing large differences (up to 15 dB) in the quotient of the magnitude responses.

Decrease of the overall signal level at the middle frequency components is conspicuous between 90°-140°. At 4 kHz this can reach 20 dB (Fig.5). The signal level increases again between 140°-180°. This area can be influenced very much by affecting the acoustical environment near the head.

In the direction "back" we have thin lines again referring to a median plane source, where no interaural level differences appear and the auditory system needs all the HRTF information for the localization.

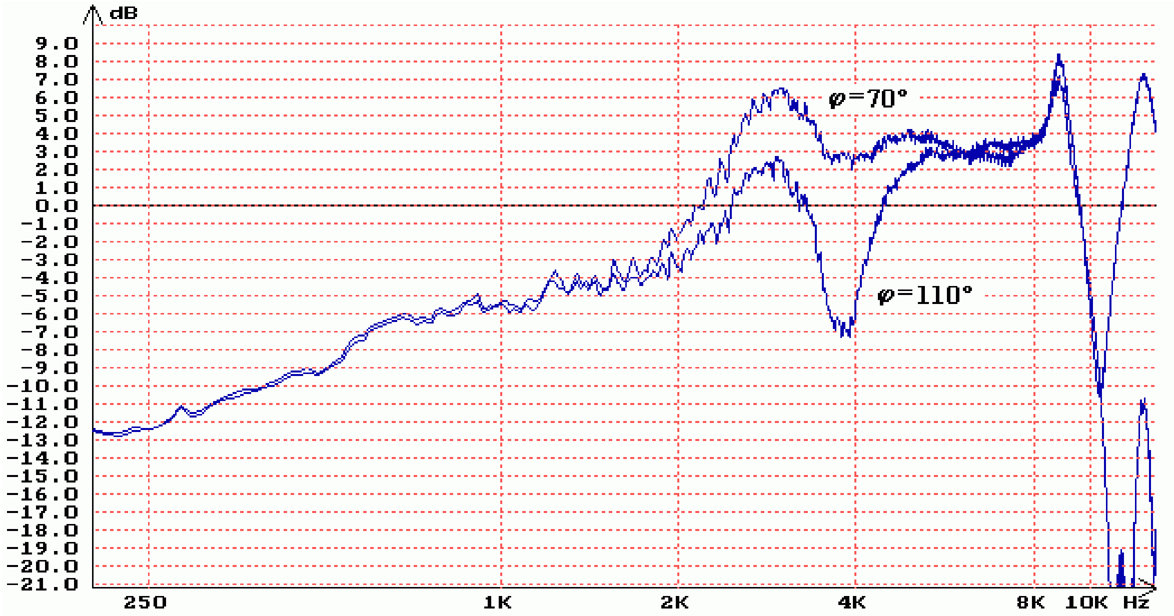


Fig.4. Horizontal plane HRTFs from the directions φ=70° and φ=110°. The valley at 4 kHz decreased about 9 dB.

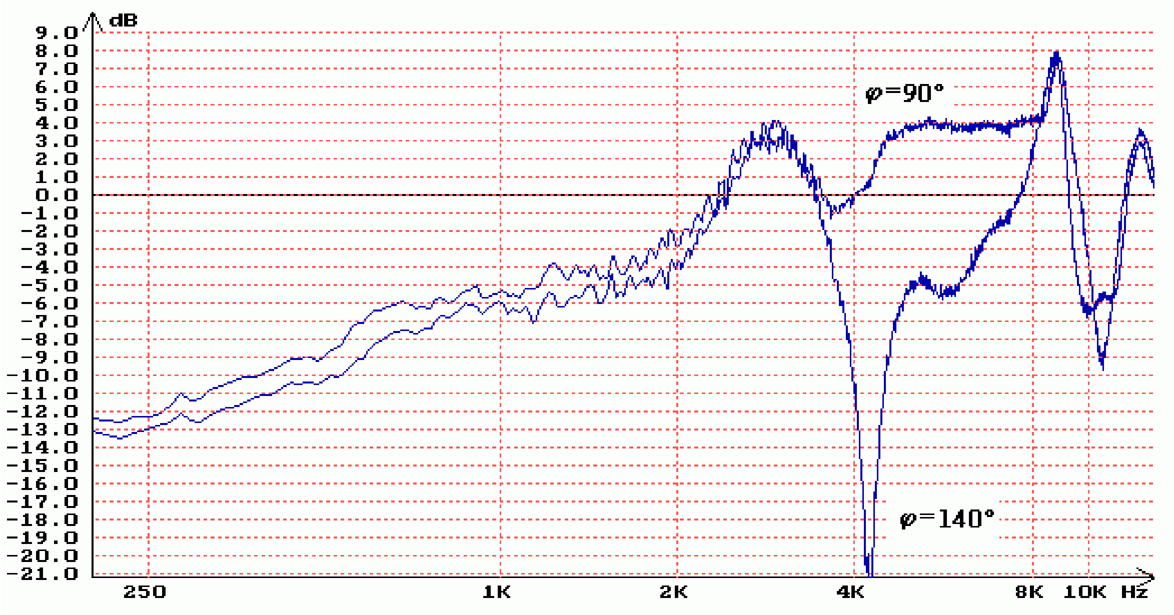
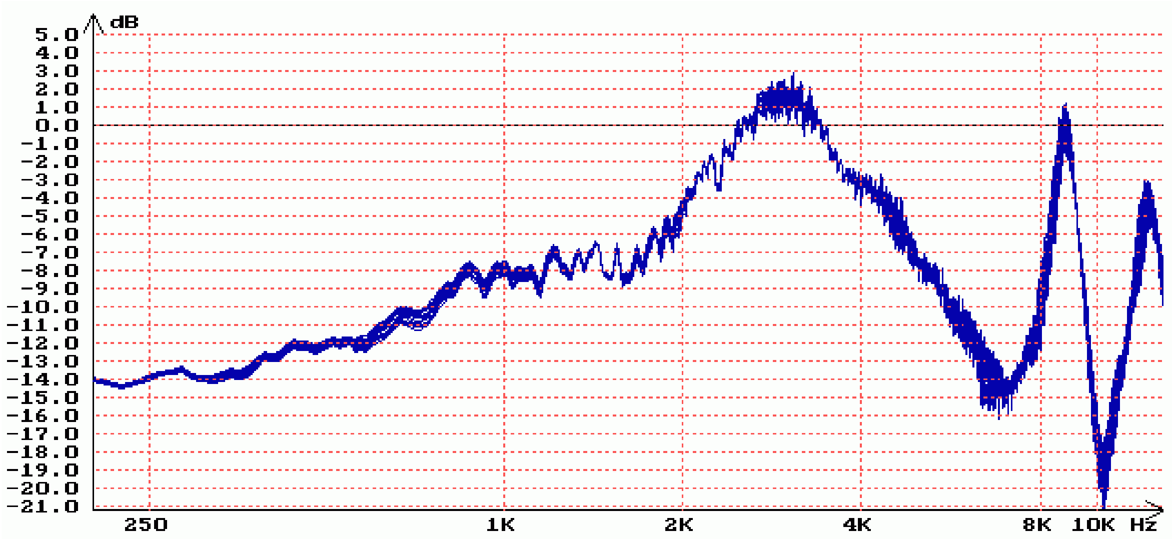


Fig.5. Horizontal plane HRTFs from the directions φ=90° and φ=140°. Only the domain between 4-8 kHz changes significantly.

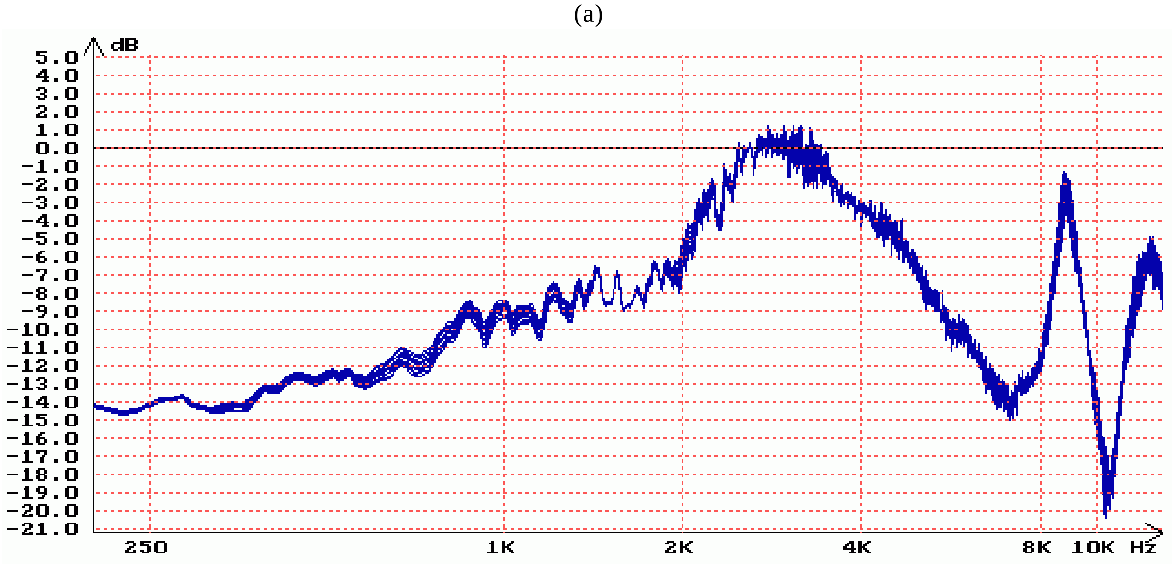
3.2 Symmetry and the Head-shadow Area

The HRTFs have a ±20° symmetry to the direction back (180 degrees). An interesting result is that the same ±20° symmetry is visible at the "frontal" direction (Fig.6-7).

The head-shadow causes level decrease and random effects in the HRTFs [5, 6, 7, 10]. Over 200° the overall signal level decreases ca. 2 dB/10° and the overall line thickness is getting thicker also ca. by 2 dB/10° above 1 kHz. The minimum of the sensitivity of the hearing system is between 250°-260° (Fig.8). Symmetrical to this region a little improvement begins, but only after 300° are the usual peaks and valleys recognizable (3, 9, 12, 15 kHz) with a thickness of 4-5 dB. The domain 340-360 degrees are comparable with 0-20° (Fig.7).



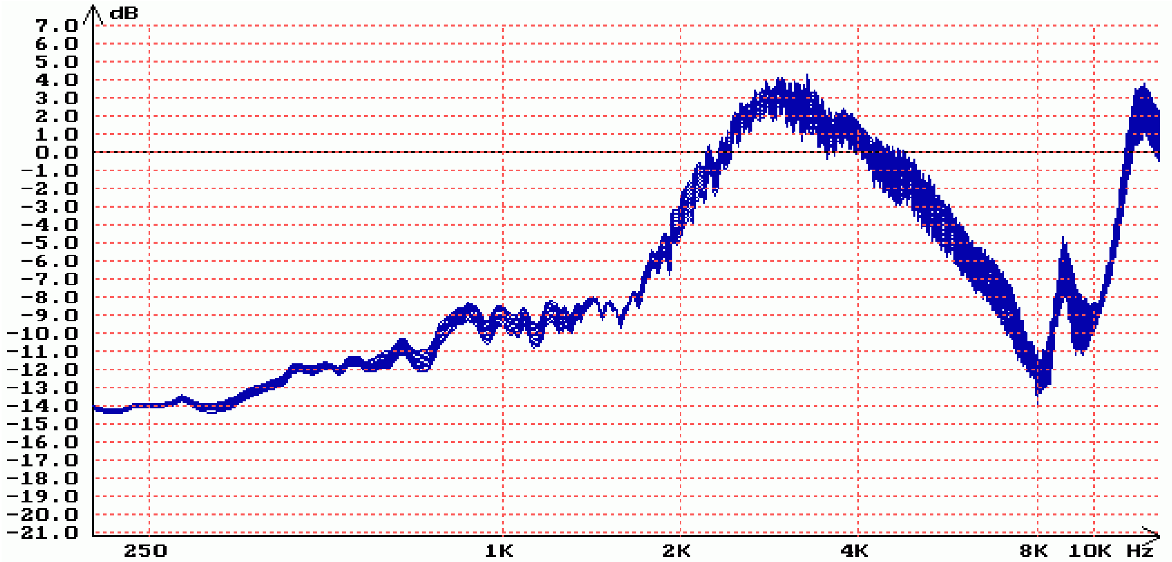
(a)



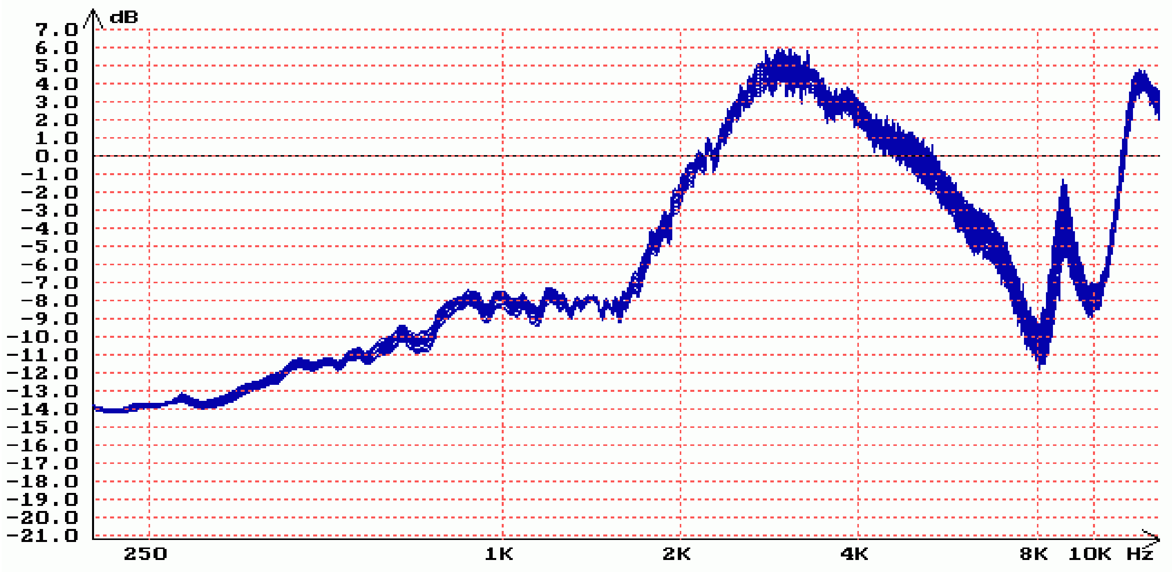
(b)

Fig.6. Two figures show ten plotted HRTFs in 1° resolution in the horizontal plane for comparison

(a) φ=170°-179°, (b) φ=180°-189°. Note the median plane symmetry to the φ=180°-axe in the local maximum area of the monaural sensitivity. The HRTFs in figure (a) „look like" those from figure (b). Compare with Fig.7.



(a)



(b)

Fig.7. Two figures show ten plotted HRTFs in 1° resolution in the horizontal plane for comparison

(a) φ=350°-359°, (b) φ=0°-9°. Note the median plane symmetry to the φ=0°-axe in the binaural sensitivity domain. The HRTFs in figure (a) „look like" those from figure (b). Compare with Fig.6.

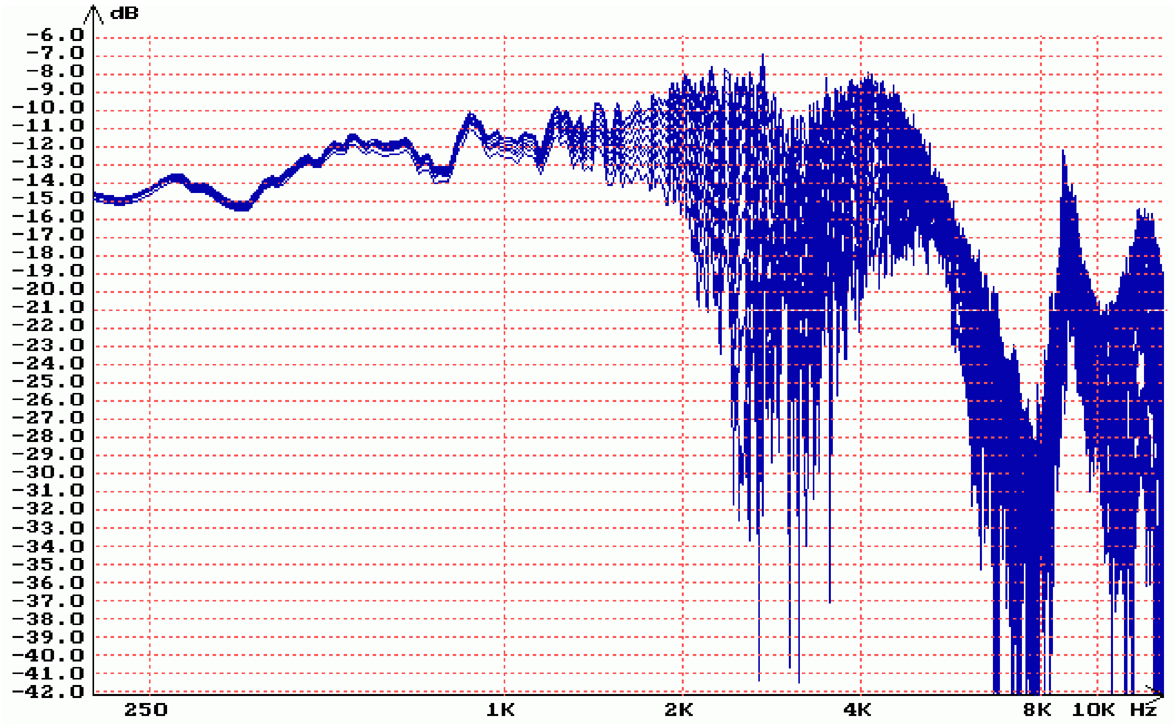


Fig.8. Minimum of the monaural sensitivity in the head-shadow area. Ten HRTFs (a) are plotted between φ=250° and φ=260° in 1 degree resolution. The components above 2 kHz are too variable to allow evaluation of high frequency directional information, but there is no difference below 1600 Hz.

4 SUMMARY

Evaluation of measured dummy-head transfer functions (HRTFs) was made in the horizontal plane in one degree resolution. Spectral properties were investigated by plotting nearby HRTFs in the same figure. Different spatial regions can be determined based on these figures and based on properties such as thickness, deviations and variations of the peaks and valleys in the HRTFs. We have found the minimum of the monaural sensitivity of the hearing system on the contralateral side of the head, in the head-shadow area about 255 degrees. Furthermore, symmetries to the median plane both in frontal and in back directions are clearly visible in a ±20 degrees region. Due to the symmetry of the dummy-head, the same observation and conclusion can be drawn for the other ear as well and in real (binaural) listening situation these two regions overlap. If the ear is in the head-shadow area, only some low-frequency information can be evaluated.

In general we can say that the edges of nearby HRTFs do not vary significantly. This indicates that changing of the azimuth does not really influence the peak-valley structure in the frequency (no shifting) only the height of the peaks and valleys. This is important because objects near the head - such as a cap or hair - produce relevant shifting in the frequency and create new peaks and valleys.

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