Influence of TCAPS on HRTFs and on sound source localization precision

Lorenz Kröner[1,2], Alexandre Garcia[2], Véronique Zimpfer[1]
[1] Deutsch-Französisches Forschungsinstitut Saint-Louis, 68300 Saint-Louis, Frankreich, Email: lorenz.kroener@isl.eu
[2] Conservatoire national des arts et metiers, 75003 Paris, Frankreich

Introduction and Context

Sound source localization in the median plane is performed by the human auditory system, with little effort by the human itself. The geometry of the auricle, resp. pinnae attenuates or boosts certain frequencies of the incoming sound, depending on the angle of incidence. This effect is describe by the angle and frequency dependent Head-Related Transfer Function (HRTF). As the geometry of the auricle varies from subject to subject and left-right symmetry is not necessarily given for one subject, the HRTF is highly individual. The brain gets continuously trained to the individual HRTF during a human's lifetime: confusions get resolved and accuracy gets increased by simple head movements. In certain environments it is necessary to wear hearing protections due to dangerous high level noise. Wearing any auditory equipment, including headphones, earphones, earplugs, hearing protections, hearing aids, or tactical communication and protection systems (TCAPS) modifies the geometry of the pinnae, resulting in important changes of the HRTF. The listener's brain cannot adapt instantaneously to the modified HRTF, leading to a less precise sound source localization. In listening test it was obtained that the major type of error is due to front-back confusions [1] [2]. The presented work in this article is the preparatory step, necessary to complete an investigation about the relation between auditory equipment introduced HRTF modifications and sound source localization accuracy, wearing these auditory equipment. The focus is set to front-back sound source localization, as front-back confusions are the most imported error types when localizing sound with modified pinnaes. Five models of different TCAPS were analyzed on three dummy head configurations, to analyze the influence of auditory equipment on HRTFs.

HRTF Measurement

Measurement Setup

The measurements of the HRTFs were conducted in an anechoic chamber with a volume of 42.34 m^3 and a reverberation time RT_{60} of 60 ms for frequencies above 500 Hz. A logarithmic sine sweep ranging from 16 Hz to 20 kHz with 1600 logarithmic spread frequency points was used as test signal $x(t)$. This signal was generated by Stanford Research Systems SR780 Dynamic Signal Analyzer, amplified by Dayton Audio MA1260 power amplifier and played back via a JBL Control 1Pro loudspeaker. A reference point was attributed to each object to perform coherent distance measurements from this point. The reference point for a dummy head is the center of its interaural axis and for loudspeakers and microphones it is the center of the membrane (for single membrane models) or the average of the centers of the membranes (for multi membrane models). Any positions of such objects are with regard to the positions of their reference points. The loudspeaker and the dummy head were distanced of 3 m and mounted equally in the center of the room height. The signals captured by the dummy heads' left and right microphone were routed through a signal conditioner (either B&K Type 5935L or B&K Type 1704) and then to the inputs of the SR780. The input signals of SR780 are called $y_(l)(t)$, resp. $y_(r)(t)$.The sound pressure at the head's center position was 91 dB SPL.

The coordinate system for determining the direction of sound incidence is centered at the reference point of the current object, e.g. for a dummy head it is center on the mid point of the inter aural axis. The HRTFs are measured at sixteen equally spaced positions on the horizontal plane. The simulation of the angle of sound incidence was realized reciprocally: Due to technical limitations the dummy head had to be rotated around its vertical axis (z-axis) while the loudspeaker remained fixed at its position. Event thought the receiver (dummy head) rotated and the source (loudspeaker) stayed fixed, the angles mentioned in the following have to be seen as if the sources turns counter clockwise (mathematically positive way) around the receiver. The HRTF was measured at 16 equally spaced angle positions ranging from 0° azimuth to 337.5° azimuth while conserving 0° elevation.

A set of combinations of three dummy head configurations c.f Figure 1 and four TCAPS models, c.f. Figure 2 were used for the HRTF measurements. Two models of the TCAPS are in ear models level dependent noise attenuation. Further there is one active earmuff and one passive earmuff. The TCAPS model BANG allowed to mount two different types of earplugs: a 3-flange earplug or a customized premolded earplug. The natural HRTF of the dummy heads were measured, but also the HRTF which is obtained when the dummy heads wear different TCAPS. The dummy head configurations were the following combinations of head simulators, resp. head-torso simulators, in combination with ear simulators: ISL dummy head & Type 3.4, ISL dummy head & Type 3.3, and B&K head-torso simulator & Type 3.3. The ear simulators are accordingly to the proposed specifications in [3]. Table 1 summarizes the combinations of dummy heads and TCAPS for which HRTF measurements were conducted.

Figure 1: Dummy head configurations: ISL & 3.4, ISL & 3.3, B&K & 3.3 [Taken from [4]](from left to right).

Figure 2: TCAPS models used for this study. 1st row: ISL *Bang* (left), Nacre *QuietPro* (right). 2nd row: ZTac *Z111* (left), 3M *Peltor X5A* (right).

HRTF calculation

The free field HRTF was obtained by equalizing the transfer function of the measurement chain in the recorded signals. The measurement chain's transfer function was obtained by replacing the dummy head by a B&K Type 4192 reference microphone, while conserving the remaining measurement setup. It was verified that the microphone was mounted at exactly the same position where the dummy head was mounted before. In the following the name HRTF designates the free field HRTF.

Instead of the HRTFs itself, a compact representation called "ipsi-, contra lateral front-back (icfb) difference" is chosen for visualization and further purpose. For this the median plane is subdivided into its four quadrants 1 to 4, starting with quadrant 1 between 0° and 90°, continuing counter clock wise to quadrant 4. The mean HRTF is calculated for the ipsi lateral and contra lateral ear and each of the four quadrants, resulting in eight HRTFs. The difference between the HRTFs of the back and front quadrants are determined. The assumption of perfect left-right symmetry for the dummy heads and the artificial pinnaes allows a further mean calculation over the signals from left and right ear, leaving two functions: one functions for the ipsi lateral and the other for the contra lateral ear. A filter bank of 26 gamma tone filters from [1] is applied to each curve to reduce the number of frequency samples.

Table 1: Combinations of dummy heads and TCAPS for which HRTF data is available are marked by ×.

TCAPS	Dummy head configuration		
	ISL & 3.4	ISL & 3.3	B&K & 3.3
none	×	×	×
BANG (3-flange)		×	×
BANG (custom)	×	×	
QuietPro	×	×	×
Z111		×	×
X5A		×	×

Results

The icfb-differences of the dummy heads without wearing any hearing protection, resp. their natural hearing condition are shown in Figures 3 and 4. Positive magnitude values indicate that a sound from the front results in a higher SPL at the dummy head's microphone than the same sound when it is played from the back. Negative magnitude values indicate that a sound from the back results in higher SPLs than the same sound from the opposite direction. It can be obtained that all three curves have the same trends. Below 1 kHz the icfb difference the ipsilateral ear is near 0 dB, followed by an important peak at around 4 kHz with a magnitude of at least 8 dB.

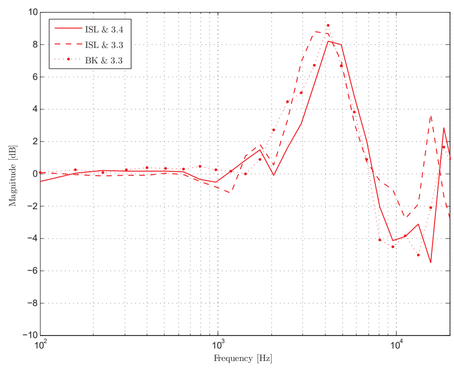

Figure 3: ICFB difference for ipsi lateral ear of dummy heads ISL & 3.4, ISL & 3.3, and B&K & 3.3.

To study the influence of TCAPS, each of a dummy head's natural icfb difference curve is compared against the TCAPS icfb difference curve with the same dummy head. For the ipsi and contra lateral side there are 26 frequency bins to compare. As the magnitude JND lies at about ±1 dB [5], data points which have a spacing within this interval are considered as equal. Two metrics are shown in Table 2. The first row in each cell describes the number of frequencies where the icfb difference magnitudes of the natural and TCAPS listening conditions vary less than 1 dB. The second row in each cell contains the root mean square (RMS) error between the curves of the natural and the TCAPS listening conditions. The

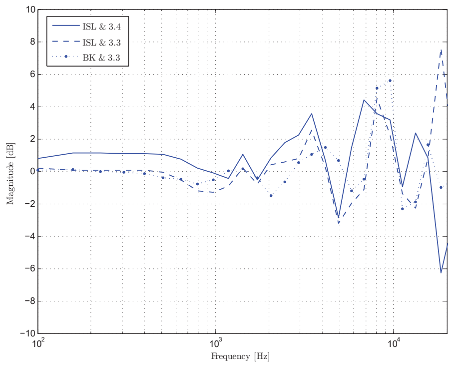

Figure 4: ICFB difference for contra lateral ear of dummy heads ISL & 3.4, ISL & 3.3, and B&K & 3.3.

best matching of the ipsi lateral curves is obtained for the models BANG and QuietPro between 15 and 17 matches out of 26. The RMS error varies for these two models between 1.93 dB and 3.62 dB. The models Z111 and X5A have nearly the same results: Matches are achieved in 6 to 10 times and the RMS error does not fall below 4.51 dB.

Table 2: Upper row in the cells: Amount of frequencies points where the natural icfb difference and TCAPS icfb difference curves are considered as equal. Lower row in the cells: RMS error in dB. Data for ispi lateral side marked in red, contra lateral in blue.

TCAPS	Dummy head configuration		
	ISL & 3.4	ISL & 3.3	B&K & 3.3
BANG (3-flange)		14 – 15 2.98 – 2.39	17 – 12 2.63 – 3.58
BANG (custom)	15 – 4 3.62 – 4.25	15 – 15 2.79 – 2.88	
QuietPro	13 – 7 1.93 – 3.73	15 – 13 3.38 – 2.72	14 – 18 3.57 – 2.54
Z111		10 – 9 4.93 – 3.57	8 – 7 4.51 – 7.66
X5A		6 – 7 4.56 – 5.66	8 – 10 4.83 – 3.03

The detailed icfb difference curves are given for the following combinations of dummy heads and TCAPS: ISL & 3.3 with Bang (3-flange) 5, ISL & 3.3 with Bang (custom) 6, ISL & 3.3 with QueitPro 7, B&K & 3.3 with QueitPro 8. Below 1 kHz neither the graph for the ipsi lateral nor the graph for the contra lateral is changed. The 4 kHz peaks in the ipsi lateral signals are diminished by up to 6 dB and followed by a peak in negative direction between 6 kHz to 8 kHz of −6 dB. On the contra lateral side the magnitude of the front back difference is increase by the TCAPS in the frequency range of 4 kHz to 6 kHz. Above 10 kHz the change of the icfb difference depends on the TCAPS, both for the ipsi lateral and contral lateral side.

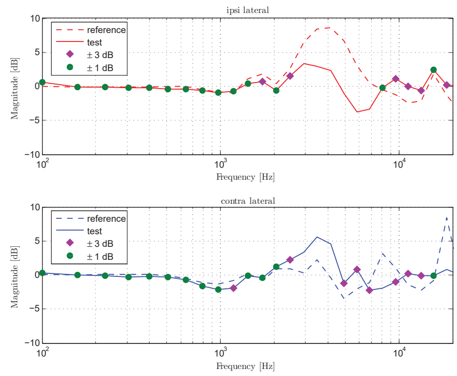

Figure 5: ICFB difference of dummy head ISL & 3.3: natural (labeled as reference) vs. Bang (3-flange) (labeled as test).

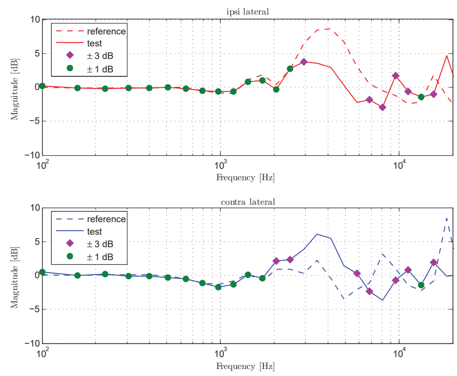

Figure 6: ICFB difference of dummy head ISL & 3.3: natural (labeled as reference) vs. Bang (custom) (labeled as test).

Discussion

Even thought the icfb difference representation is based on filtering and several mean calculations the resulting curves in Figure 3 and 4 show similarities to the boosted bands and directional bands which has been introduced in 1969 by Blauert [6]. He defines a boosted band for frontal sound incidence in the interval from approximately 2 kHz to 8 kHz with a maximal SPL difference of about 7 kHz. The peak at 4 kHz in the icfb difference representation matches the same frequency interval but the magnitude varies up to 2 dB. This might be due to different measurement setups and different measurement envi-

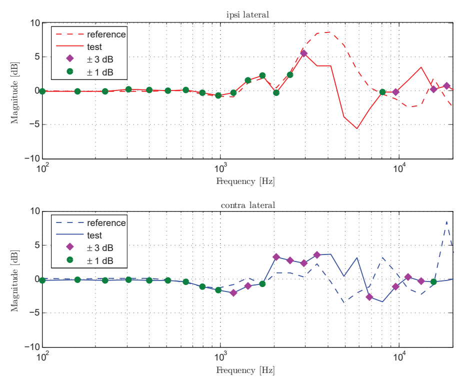

Figure 7: ICFB difference of dummy head ISL & 3.3: natural (labeled as reference) vs. QuietPro (labeled as test).

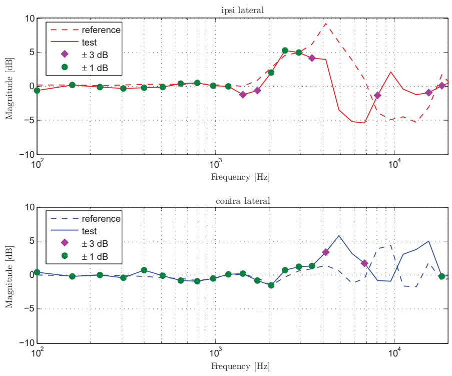

Figure 8: ICFB difference of dummy head B&K & 3.3: natural (labeled as reference) vs. QuietPro (labeled as test).

ronments. Comparing the 4 kHz peaks for each dummy head configuration with Blauert's directional band for frontal sound incidence around 4 kHz it can be seen that they are located in the same frequency interval. It can be concluded that the mean calculation for the icfb difference representation keeps the main directional characteristic of the pinnae's frequency filtering.

The change in the icfb difference introduced by the TCAPS largely exceeds the JND of 1 dB and thus the auditory system is sensitive to the modified frequency content. The most important changes appear in the frequency range around 4 kHz of Blauert's directional band and boosted band for frontal sound incidence. With an audible modification of the directional bands, it becomes clear that sound localization gets a difficult task and front back errors are inevitable.

Regarding the RMS error in Table 2 the in ear TCAPS models seem to modify the icfb differences the least, compared to earmuff TCAPS. Nevertheless there are differences in the amount how in ear TCAPS modify the icfb difference. The BANG model, regardless of using the 3-flange or the custom earplug, introduces less RMS error when used on a dummy head with Type 3.3 pinnae than the QuietPro model. This can also be obtained on the corresponding icfb difference curves, where the negative peak around 6 kHz to 8 kHz is less important in Figures 5 and 6 than in Figures 7 and 8. The earplugs of the QuietPro model have larger dimensions and they jut out of the ear much more than the earplugs of the BANG model, resulting in more geometric modifications of the pinna and HRTF changes. Using the smallest possible earplugs, e.g. in the ear canal devices, should results in the weakest icfb difference modifications.

Subsequent Work

Recently the setup for localization performance measurements has been finished. This setup is mentioned to prove that the obtained icfb difference modifications influence the sound localization accuracy to gain insight about the sound source localization performance of human subjects when they wear these TCAPS. The statistical evaluation of this localization test will be used together with the present results to identify the link between sound source localization performance and HRTF degradation. Different approaches for prototypes of new generation TCAPS which are intended to keep the natural spectral cues will be developed and tested. These approaches will be based on earmuffs and earplugs, extending them with an increased number of acoustic receivers and transmitters and signal processing techniques.

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