An extraaural headphone for optimized binaural reproduction

(Ein extraauraler Kopfhörer für die optimierte Wiedergabe binauraler Signale)

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Abstract

For playback of binaural signals a flat frequency response of the reproduction chain is desired. Typically used headphones may induce spectral coloration if not properly compensated. Although most headphones are said to provide approximations of a diffuse- or free-field equalization, headphone transfer functions (HpTFs) may differ significantly between different manufacturers and models. Moreover, HpTFs of circum- and supraaural headphones are susceptible to leakage and high frequency variability introduced by repositioning. From former studies, many of these effects could be expected to be minimized when using an extraaural headphone with a linear frequency response. Additionally, such a design can be used straightforward for individual headphone compensation and for low frequency extension with a subwoofer while best approaching the "free field equivalent coupling"-criterion demanded for binaural playback devices. The paper discusses the technical development of a prototype of such a headphone.

1. Introduction

Head related transfer functions (HRTFs, free field case) or binaural room impulse responses (BRIRs, for sound fields within enclosures) convey most acoustical signal properties that are relevant for spatial hearing. In utilizing a dummy head or even better an automated head and torso simulator (HATS) [1] BRIR-datasets can be measured for different head orientations (cf. Fig. 1, left). Anechoic monophonic audio can then be convolved with the BRIRs in real-time and appropriate to the current head orientation of the listener - monitored by a head tracker - resulting in so-called dynamic binaural reproduction (cf. Fig. 1, right). To restore the originally measured sound field at the eardrum a filter is required to compensate for the potential spectral coloration of the recording and playback system.

Frequency response distortion and corresponding timbre deviations are assumed to be the most perturbing artifact when comparing binaural reproduction directly to acoustic reality [1], [3]. They can primarily assigned to the use of non-individual HRTFs and/or poorly compensated HpTFs. Commercially available circum- and supraaural headphones typically convey approximations of a diffuse- or free field equalization to improve the compatibility regarding listening to stereophonic loudspeaker signals. As there is, however, no common equalization standard, HpTFs may differ significantly between different manufacturers and

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models. Thus, when using headphones for binaural reproduction, frequency responses have to be linearized individually for each headphone. It has also been shown that HpTFs of circum- and supraaural headphones strongly differ due to varying wearing positions. Such differences not only arise between individuals but also within the individual after repeated repositioning [2], [3]. Most frequency response variability is observed in the high frequency range, where highly resonant peaks and notches vary when repositioning the headphones. Moreover, low frequency response is susceptible to varying leakage. From a comparison of circum-, supra and extraaural headphones Schärer et al. [3] found minimum frequency response variability – both for the low and high frequency region – for an extraaural type of headphone.

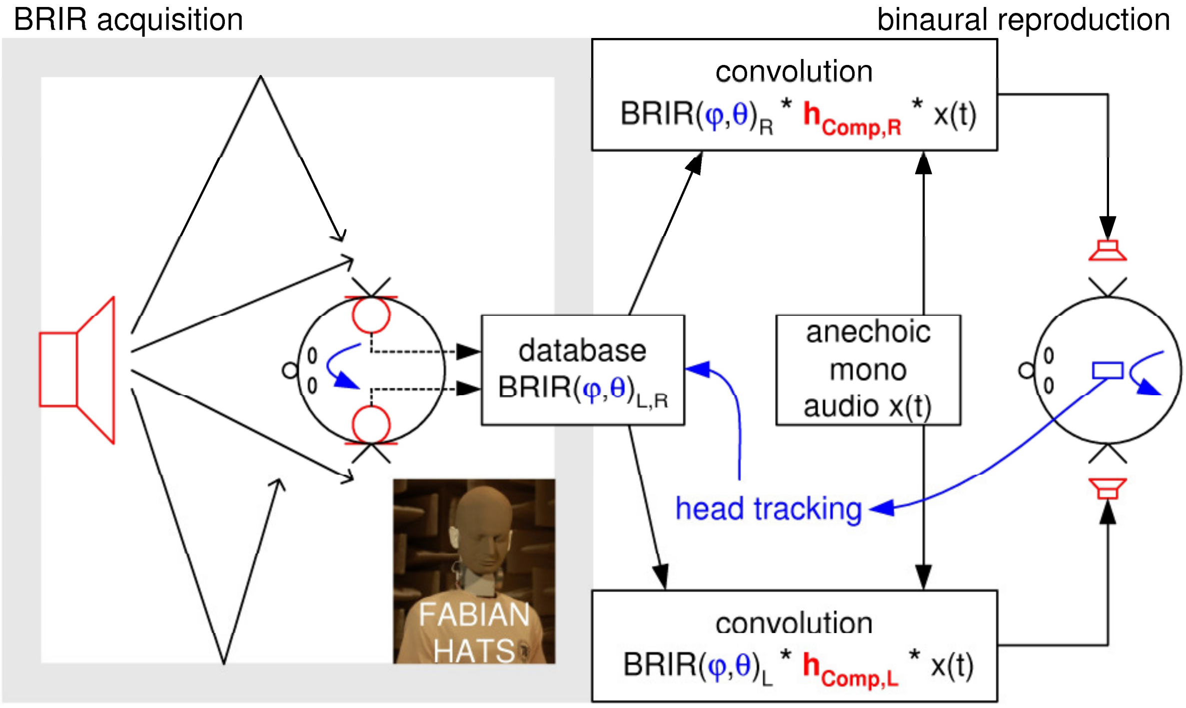

Figure 1: Data based binaural reproduction: BRIR acquisition (discretely for several head orientations) and dynamic playback.

A further important criterion, namely the ability of ‘free-air equivalent coupling’ (FEC), was introduced by Møller et al. [2]. The ‘pressure division ratio’ (PDR) as a measure for the FEC ability indicates how much the ear canal entrance is loaded differently by the acoustical headphone impedance as when compared to the radiation impedance of an unobstructed sound field as seen from the ear canal entrances. Moreover, the logarithms magnitude of the PDR directly indicates resulting frequency response distortion in decibels. Results of [2] showed that the tested extraaural headphones were superior in terms of "free-air equivalent coupling" when compared to other circum- and supraaural headphones.
A headphone optimized for binaural reproduction should therefore provide the following properties:

- a flat headphone transfer function (HpTF)
- a minimum inter- and intra-individual HpTF variability
- the ability for easy individual HpTF-compensation
- the compliance with the "free-air equivalent coupling“-criterion

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- the opportunity for straight forward coupling of subwoofers when aiming at full-range reproduction

The focus of the current study was to evaluate, in how far an extraaural headphone with suitable frequency response compensation could fulfill the named criteria above. Since there is no comparable commercially extraaural headphone available at the moment, a prototype had to be newly developed as an important component for a binaural reference system to be used in the context of rendering virtual acoustic environments.

2. Development of the BK109 prototype

To circumvent the tedious and time-consuming development of a specific driver for this application, a closed-box loudspeaker design using a suitable and readily available miniature driver was intended. More precisely, 2”-miniature electrodynamic loudspeaker drivers were assumed to provide an optimal combination of frequency bandwidth, acoustical power performance, directivity, size, mass and volume for the new extraaural headphone. A large sample of 2”-drivers was measured applying cabinets with a desired target volume of V ≈ 200 ml. From that examination, satisfying Thiele-Small parameters and a wide linear frequency response (200 Hz-15 kHz) made the Tymphany Peerless drivers 830970 and 830983 appear to be most suitable for our purposes.

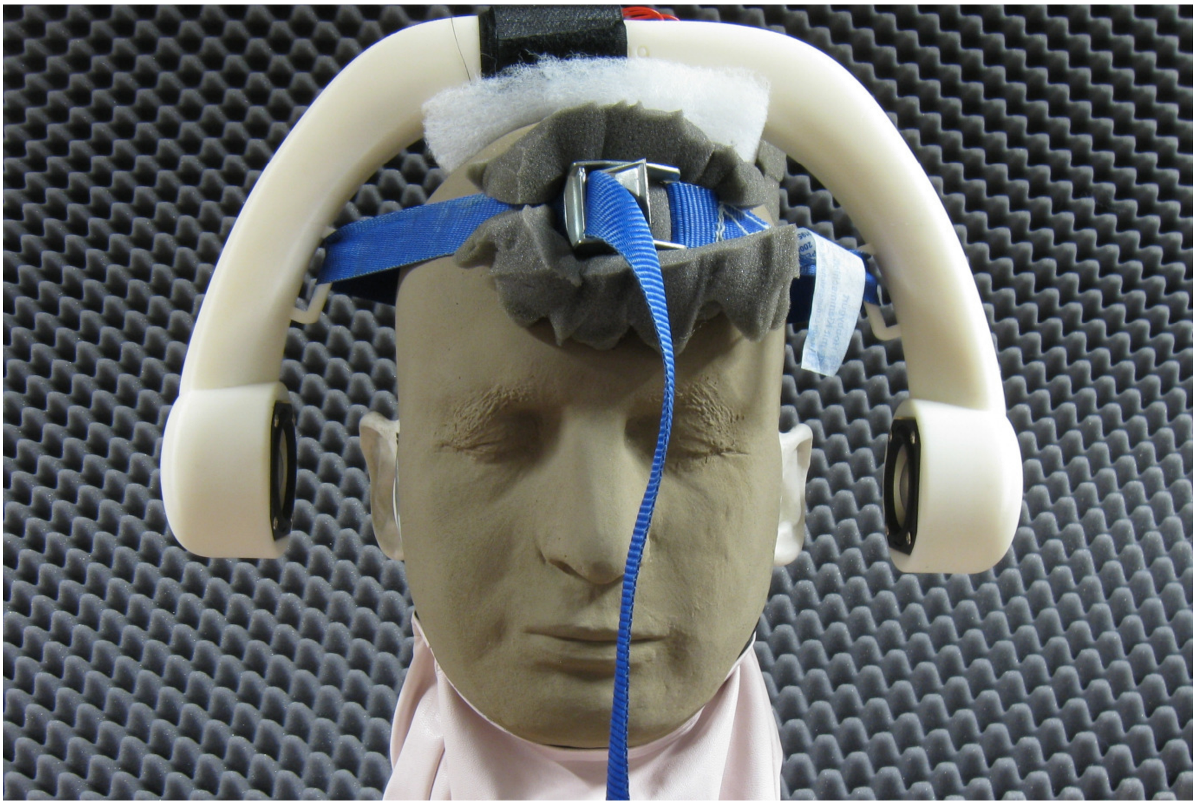

Figure 2: Prototype of BK109 mounted provisorily on the FABIAN HATS.

2.1. CAD and prototyping

Taking into account human population’s variability in morphology obtained from anthropometric databases [9], [10], [11] the form factor of the closed-box cabinet was

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designed to fit on the 5 % largest heads regarding the height of the head and the relative vertical position of the ears. For the acoustic development a reference distance of 5 cm from ear canal entrance to the speaker membrane – assumed a typical case of a later wearing situation – was arbitrarily chosen. Concerning the variability of head width a minimum distance less than 4.6 cm is expected for 5 % of population (largest head width); while a maximum distance of 6.4 cm could be exceeded by 5 % of the population, namely those with smallest head widths. The prototype - named *BK109*, abbreviated for "Binauraler Kopfhörer I 2009" - was modeled in 3D-CAD software and was built using the fused deposition modeling rapid prototyping method (FDM) using acrylonitrile butadiene styrene (ABS). Fig. 2 shows the prototype mounted provisorily by a strap on the FABIAN HATS [1]. To align the membranes' geometrical centers with the height of the ear canal entrances, foam layers were applied during all measurements. The weight of the prototype including wiring and loudspeakers is ca. 600 g, which could in future be minimized by reducing the wall thickness of the cabinet.

2.2. Technical development

For equalization of the BK109 headphone a non-standard IIR-biquad filtering approach was intended [4], [5]. Therefore, a dedicated VST2.4 plug-in had to be developed. Additionally, FIR-filtering using zero-latency convolution was realized by using the plug-in keFIR v1.3. A professional two channel power amplifier (> 20 W at 4 Ω) was deployed to drive the headphone.

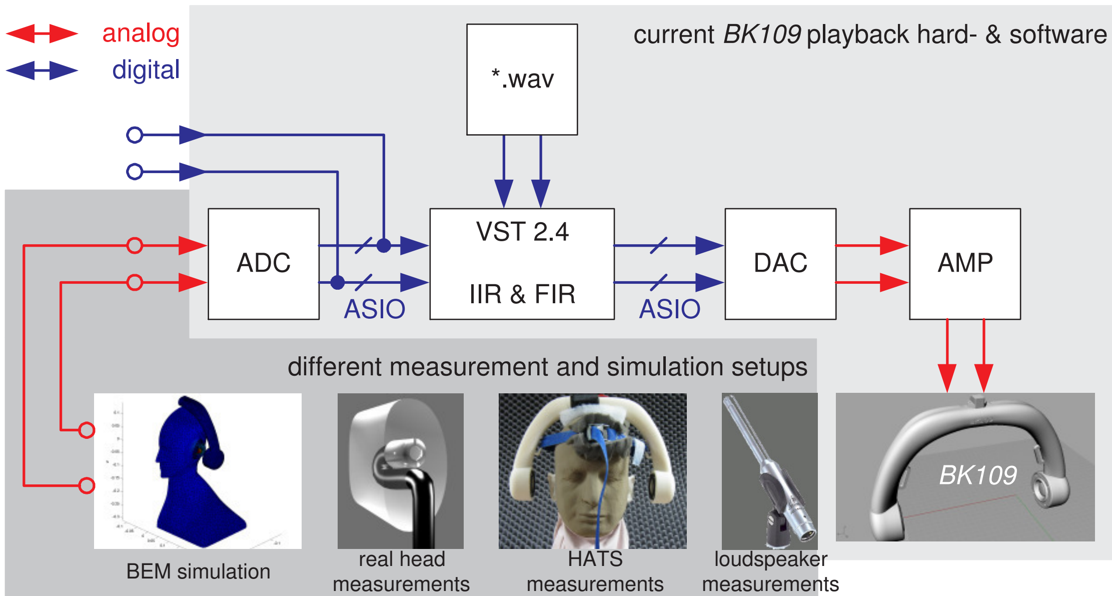

Figure 3: Signal flow chart for BK109 and measurements setups.

Since the extraaural headphone is in fact a small loudspeaker, ear-coupler measurements as usually applied in the industrial development of circum- or supraaural headphones did not appear to be a suitable measurement method. Instead, typical loudspeaker measurements, such as nearfield frequency response and the total harmonic distortion (THD) related to the reference distance of 5 cm were performed in the first and second development stage (see

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sec. 2.3, 2.4). In the third stage the channel crosstalk was measured on the FABIAN HATS [1] (2.5). The additional acoustical load when the headphone partly covers the ear entrance was simulated with the boundary element method (BEM) in the fourth development step (2.6). Fig. 3 shows a depiction of the typical signal flow and the different measurement setups used. Note that due to the symmetrical headphone setup only left ear channel measurements are presented below.

2.3. Nearfield target frequency response

Quasi-anechoic nearfield frequency responses were measured using a free-field calibrated and linear compensated pressure microphone in a distance of 5 cm from the membrane center. Firstly, on-axis measurements with an unfilled cabinet volume ($V \approx 200$ ml) confirmed a 2^{nd}-order high-pass system behavior which is typical for closed-box designs. The pole quality Q was about 1.02 at a pole frequency f_c of ca. 232 Hz. A notch at ca. 500 Hz ($Q \approx 4$) indicated a destructive standing wave pattern due to the cabinet dimensions. This issue was also confirmed by electrical impedance measurements.

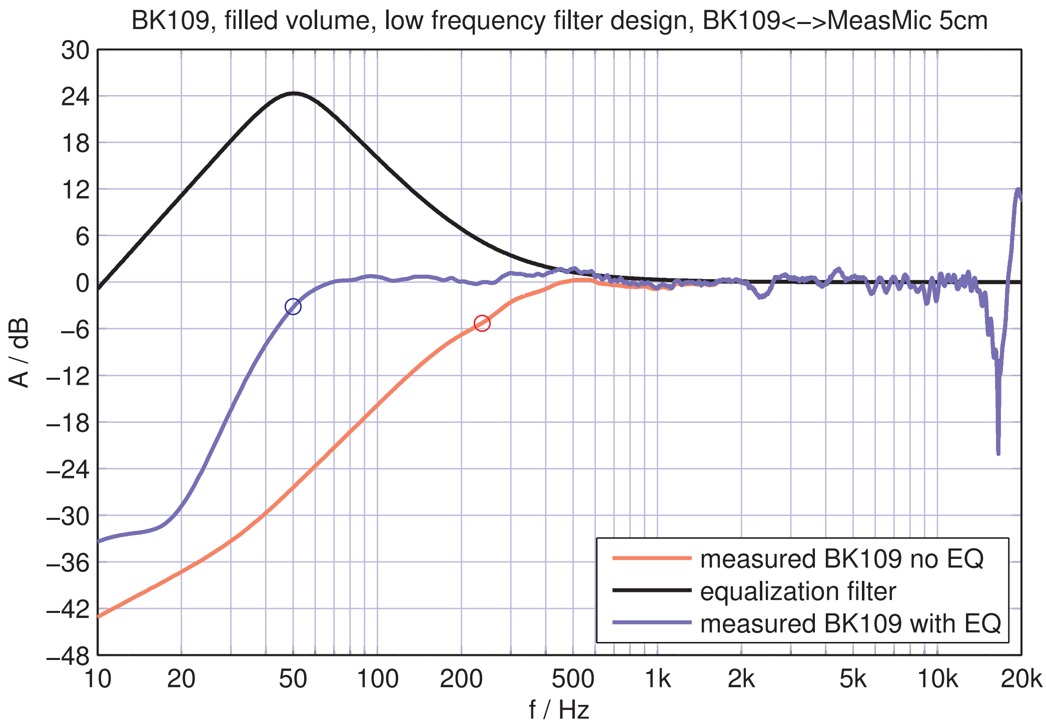

Figure 4: Nearfield frequency response target curve of BK109.

When regarding cabinet dimensions, the slight amplitude increase of about 3 dB between ca. 3-6 kHz can be identified as the so-called baffle step. At ca. 16 kHz we observed a destructive and at 19 kHz a constructive partial mode. This modal membrane behavior was also confirmed by driver measurements using a Klippel R&D system.

The effect of the cabinet resonance at 500 Hz was eliminated by completely filling the cabinet with damping material, leading in turn to a slightly underdamped pole quality of 0.55 and a pole frequency shifted to 237 Hz. The baffle step was equalized using a conventional 2^{nd}-order parametric IIR-filter. Further, it is recommended to leave the relatively strong high

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frequency partial modes unequalized. The red graph in fig. 4 shows the resulting nearfield frequency response after applying the aforementioned corrections.

As nearfield target frequency response we specified a 50 Hz 4^{th}-order Butterworth high-pass (see blue curve in fig. 4). Therefore – and in turn applying the so-called Linkwitz Transform [4] – a 2^{nd}-order low-shelve filter and a 2^{nd}-order high-pass filter were added to the signal path. These filters (see black curve in fig. 4 for combined filter response, cf. [5]) lead to a low frequency range extension of more than two octaves. However, this requires noticeable signal amplification in the low frequency range. A maximum gain of ca. 24 dB can be observed at the new pole frequency of 50 Hz. The resulting frequency response varies about ± 1.5dB between 50 Hz and 15 kHz (-3dB band edges). On-axis and off-axis (~11°, 21°) nearfield frequency responses can differ by ca. 2 dB for frequencies larger than 8 kHz due to the directivity of the driver.

2.4. Total harmonic distortion (THD)

The THD was measured using the same measurement setup as for the nearfield target frequency response, i.e. using again the free-field calibrated and linear compensated pressure microphone in 5 cm distance from the membrane center. The THD was measured for sound pressure levels of 77, 83, 89 and 95 dB_{SPL} at the microphone (fig. 5).

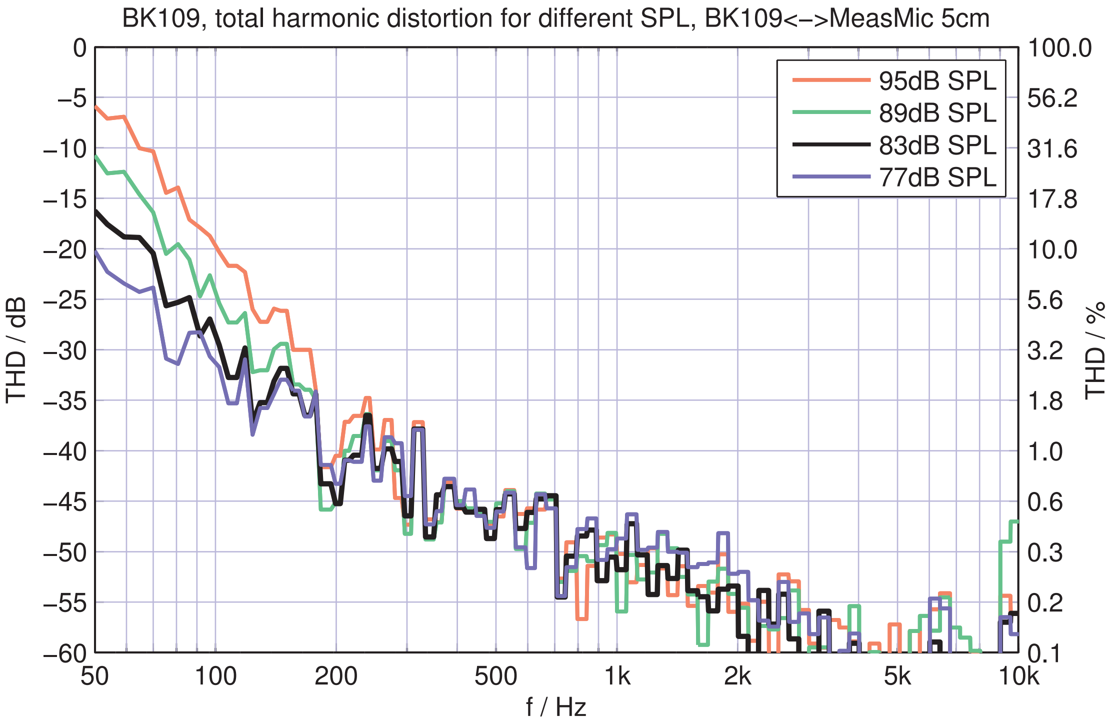

Figure 5: Total harmonic distortion of BK109.

Due to small membrane excursions and the relatively low required electrical power, for frequencies above 200 Hz, the THD is nearly independent from sound pressure level. Above 300 Hz the THD is lower than -40 dB (i.e. < 1%). Due to the high amplification of low frequencies the THD increases steeply towards lower frequencies. At 83 dB_{SPL} and 100 Hz (black curve in fig. 5) the THD is about -30 dB (i.e. ca. 3%), at 50 Hz THD is ca. -16 dB (ca.

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16%). A strong increase of THD can be observed at very high sound pressure levels (95 dB_{SPL}, red curve in fig. 5).

2.5. Channel crosstalk

In order to measure the channel crosstalk the BK109 headphone was mounted on the FABIAN HATS (fig. 2). Idle noise amplitude response measurements were performed first, which for left and right channel are shown as the two lower curves in fig. 6 (bright red resp. blue). Left and right HpTFs (curves are shown with FIR equalization, cf. fig. 9) were then measured in parallel, while feeding only the left channel driver (deep red and blue curves in fig. 6). Thus the red curve - i.e. the right ear's signal - is showing the crosstalk from the left headphone channel.

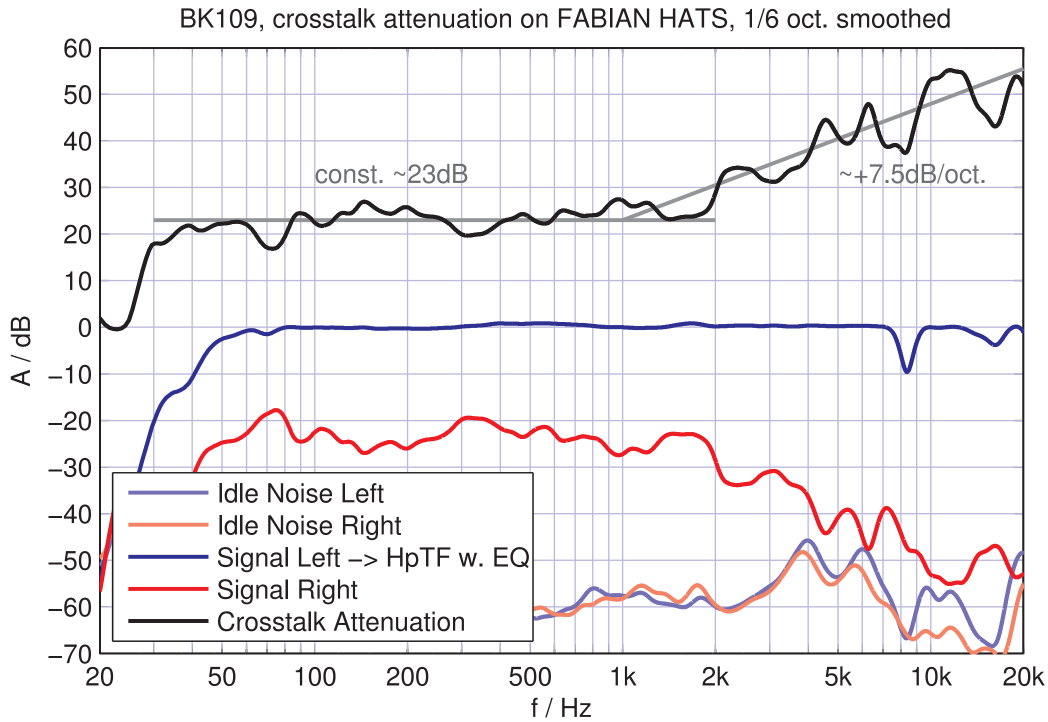

Figure 6: Crosstalk of BK109.

The black curve in fig. 6 shows the resulting crosstalk attenuation calculated as the level difference between the blue and the red curve. For frequencies below 2 kHz the crosstalk attenuation can be considered as nearly constant (ca. 23 dB), reaching a minimum (i.e. the point of largest crosstalk) of ca. 18dB at 70 Hz. Above 2 kHz the crosstalk attenuation increases nearly constantly with ca. 7.5dB/octave. This can be explained by the acoustic shadowing of the head increasing with frequency. Above 5 kHz crosstalk becomes nearly negligible.

2.6. Acoustical load for ear (FEC-criterion)

For headphone based binaural reproduction the ear's acoustical load will mostly differ from the natural situation of listening in free-air. Therefore, an optimized binaural headphone must not add acoustical load, i.e. the acoustical load of the headphone should at best

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converge to the free-air situation. This property was introduced as the "free-air equivalent coupling"-criterion for headphones by Møller et al. [2]. Additionally in [2] it was shown that only two circumaural headphones of the tested models complied with this criterion. Two extraaural headphones were also found to perform well regarding the FEC-criterion.
We present results from a simulation of the additional acoustic load caused by the headphone. Within model restrictions similar results compared to Møller's measurement method are expected to be found. For the simulation we used boundary element method (BEM) which involved a) meshing the CAD model of the BK109 and b) a densely meshed model of the latest dummy head of Institute of Technical Acoustics at RWTH Aachen. The vibrating membrane was defined as a uniformly distributed velocity profile at the input of the ear canal. All surfaces were assumed to be ideally reflecting, the speaker's membrane of the BK109 was modeled as surface with acoustic admittance derived by the Thiele-Small parameters of the shortened acoustic transducer (corresponds to a driving voltage source, which is almost identical to a conventional power amplifier with low source impedance). The acoustical load on the ear canal input was calculated from the simulated surface potential by integrating over the membrane area of the exciting membrane (i.e. ear canal entrance). Hence, the results reveal the fundamental mode impedance loads. By simulating the 'free-air' situation (head without headphone) as well as the head with headphone situation, the difference between both loadings could be calculated.

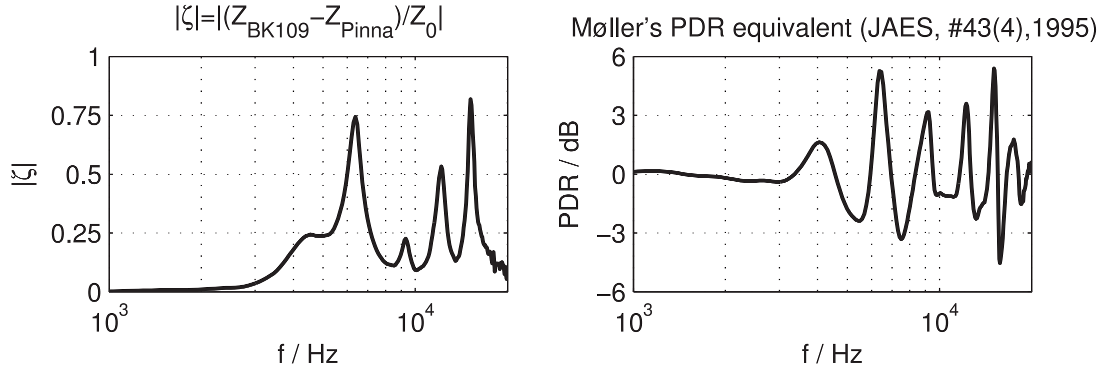

Figure 7: Results of BEM simulation of acoustical impedance of BK109: left plot: additional acoustical load caused by BK 109 relative to free air (should be 0 for perfect impedance matching), right plot: magnitude response distortion resulting from impedance mismatch (PDR ratio acc. to [2], should be 0 dB for perfect impedance matching).

The left graphic in fig. 7 shows the relative modulus of additional load when referring to the free-air impedance Z_0. Below 3 kHz no additional load will be produced by the BK109. At about 6, 9, 12 and 15 kHz narrow resonances occur, which result from standing-wave patterns due to reflections between head and transducer membrane and housing. In these narrow-band frequency ranges an additional load of $|\frac{3}{4} Z_0|$ is observed. For all other frequencies > 3 kHz the additional load will not exceed $|\frac{1}{4} Z_0|$. The pressure division ratio (PDR) advocated for evaluation of the FEC-criterion may also give further insights. From [2] we know that the PDR can directly be interpreted as frequency response distortion within the binaural reproduction signal chain. Ideally a PDR ≈ 1 (i.e. 0 dB) should be achieved, which implies that no additional load is produced by the headphone and in turn no additional frequency response distortion will be introduced. The right plot of fig. 7 shows the PDR calculated from our numerical simulation results. Below 3 kHz the PDR can be considered

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flat with deviation +0.1 / -0.3 dB. Above 3 kHz the deviation will become larger, but never exceeds ± 5.5 dB. These results are comparable to the individual PDRs of the two extraaural headphones declared as FEC-compliant in [2]. Hence, the BK109 should also be considered as a FEC-compliant headphone. However, validating measurements should be conducted in the future to prove our preliminary simulation results.

3. Validation measurements

In order to assess both the quality of the equalization itself and the amount of variability of the HpTFs while repositioning, series of measurements were conducted on a) a dummy head (cf. sect. 3.1) and b) on real subjects' heads. The latter were realized using newly developed silicone earplugs with flush-cast miniature electret condenser microphones which can easily be placed in or be removed from subjects' ear canal entrances while using a extraaural headphone [6] (cf. sect. 3.2).

3.1. Intra-individual HpTF variability

We used our FABIAN HATS to assess HpTF variability for a single subject. Therefore, the headphone was reseated on the HATS ten times, while each time measuring a new HpTF. The repositioning was done as precisely as possible. Results (singular and averaged HpTFs) are shown in fig. 8. For further comparison the corresponding HRTF of the HATS for lateral sound incidence is displayed, too.

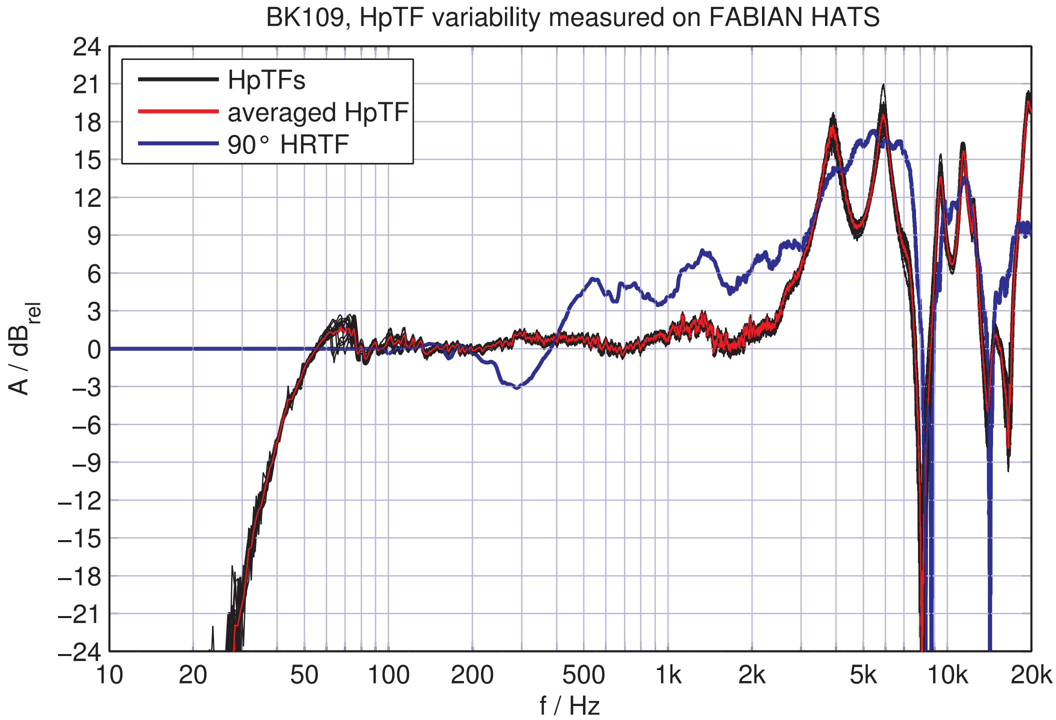

Figure 8: HpTF variability due to repeated repositioning on FABIAN HATS.

From fig. 8 we find, that the intended low frequency target frequency response, i.e. the 50 Hz 4^{th}-order Butterworth high-pass slope is preserved fairly well while exhibiting a very small reposition variability of about ±1dB. Maximum absolute deviations of about ±1.5 dB from

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the target curve can be observed at ca. 70 Hz. In the mid frequency range up to 2 kHz an almost linear frequency response is approached showing little reposition variability of about ±1.5 dB. For higher frequencies (above 2 kHz) two phenomena can be observed. At first one finds that some characteristics of a nearfield lateral HRTF are included in the measured HpTFs. This is illustrated for instance by the increase of magnitude between 3-6 kHz, and the notches at 8 kHz and 14 kHz typically resulting from pinna resonances and anti-resonances. Secondly, standing waves produce high quality resonances at 4, 6, 9, 11 kHz resp. anti-resonances at 5 and 10 kHz (reflected also in the impedance plots of fig. 7). This is mostly due repeated reflections between the rigid membrane and cabinet and the more or less rigid dummy head. The specific center frequencies of peaks and notches are obviously related to the reference distance of ~5 cm. The reposition variability stays low at about ±1.5 dB on average, showing some local extremes of ±3 dB at the 6 kHz resonance.
The inversion of the average HpTF was realized using a frequency domain LMS-algorithm with high-shelve regularization [7]. The FIR-filter order was set to 4095, which ensured reasonable frequency resolution ($\Delta f = 10.76$ Hz) even for the low frequencies. The linear-phase target function, i.e. the target amplitude response of the final equalized headphone, consisted of the 50 Hz high-pass slope (4th-order Butterworth) in series with a 21 kHz low-pass slope (Kaiser-Bessel windowed-FIR design, 60 dB stop-band attenuation). In the future a 16 kHz low-pass slope should be applied in order to avoid equalization of the high frequency partial modes.

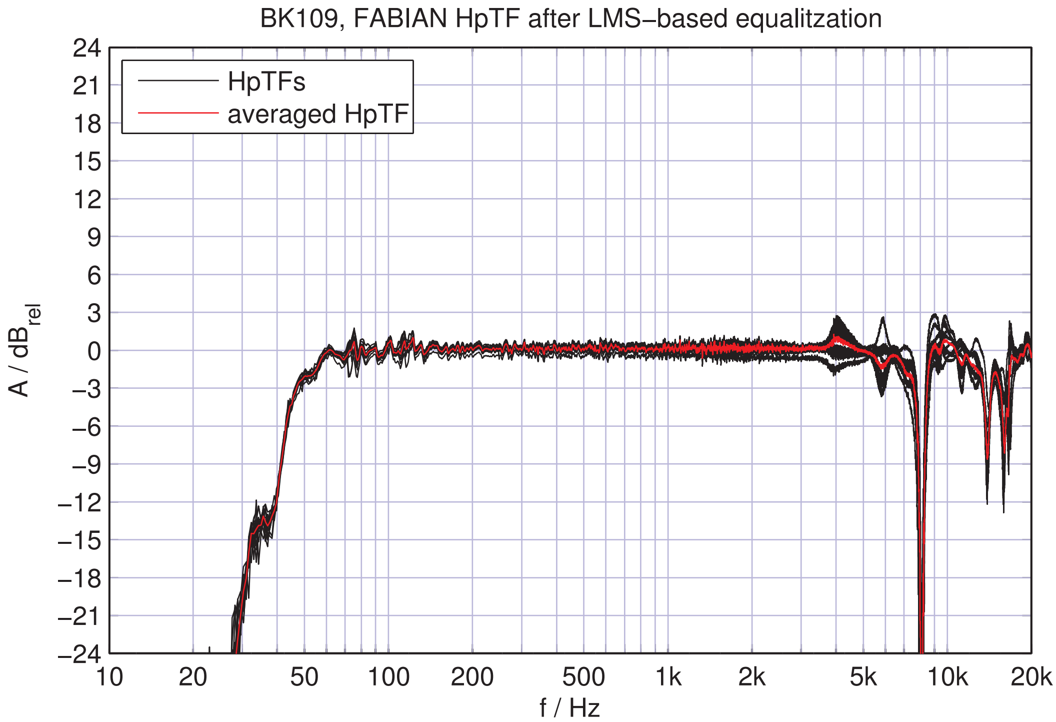

Figure 9: LMS-based HpTF equalization, variability due to repeated repositioning.

After applying the equalization, HpTF variability due to repeated repositioning was measured once again on the FABIAN HATS (cf. fig. 9). Again, black curves indicate singular HpTF measurements, whereas the averaged HpTF is shown in red. The intended linear nearfield target frequency response is achieved very well for frequencies below 3 kHz. A perceptual advantage of the high-shelve filter regularized LMS-algorithm is that it leaves

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high quality notches in highest frequency range nearly uncorrected in turn avoiding ringing filters. However, intermediate quality peaks in the high frequency HpTF are compensated with varying success leading to reposition variability about ±2.5 dB and more. In the end the averaged HpTF is linear within -1 dB and +0.6 dB from 60 Hz to 6000 Hz. Alternative regularization functions [8] could be employed to further improve this result.

3.2. Inter-individual HpTF variability

To assess the HpTF variability of the BK109 across different subjects, measurements of equalized HpTFs were conducted for several individuals. Recently developed silicone earplugs with flush-cast miniature electret condenser microphones allow HpTF measurements on real heads with high accuracy [6]. The earplugs were fitted into the ear canals of the individuals, then, raw and equalized HpTFs were measured while keeping the headphones in position between the two measurements. The inversion of the HpTFs was realized with the LMS-algorithm as described in section 3.1 Results are shown in fig. 10. The red curves represent the raw HpTFs, while linearized HpTFs are plotted as blue curves.

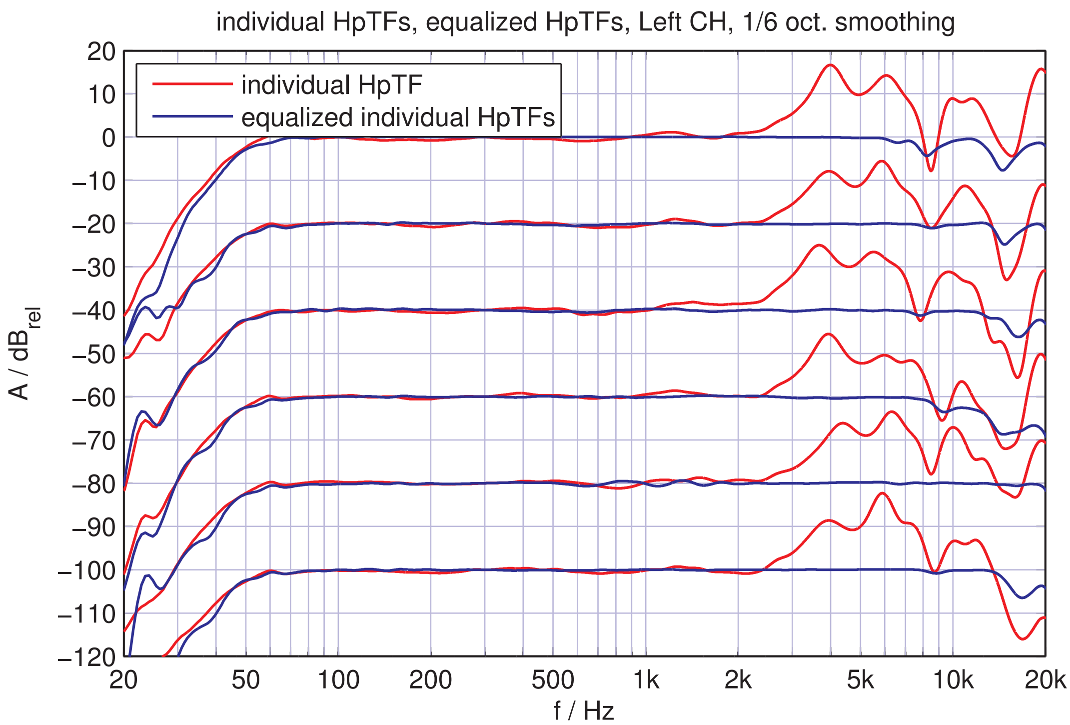

Figure 10: Raw and equalized HpTFs of six different individuals.

Between individuals raw HpTFs differ strongly from above ca. 2 kHz since here the individual acoustical characteristics of the outer ears are most emphasized. This can easily be confirmed when looking at the individual pinna resonances at about 8 kHz which are slightly misaligned between subjects. Furthermore, due to different individual distances between the transducer and the surface of the head the resulting standing waves produce peaks with different quality and at slightly misaligned frequencies (at about 4 and 6 kHz) across subjects. However, the equalized HpTFs of all individuals show both a nearly linear frequency response (± 0.6 dB up to 7 kHz) as well as the intended high-pass slope and are

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thus comparable to the FABIAN HATS' results. Above 7 kHz the quality of the linearization strongly depends on the parameters of the high-shelve regularization.

4. Discussion and conclusion

An extraaural headphone prototype featuring a miniature full-range driver coupled to a closed cabinet was developed and evaluated technically. The comparison of our measurements with other studies [2], [3], [6], [8] supports the assumption that the extraaural headphone is an optimal approach to binaural reproduction. Using dedicated IIR and FIR filtering the BK109 features a flat and full-range nearfield frequency response with tolerable non-linear distortions at moderate sound pressure levels. The THD for low frequencies may become critical for program material with high crest factor at high sound pressure levels. The channel crosstalk – particularly critical in transaural reproduction – is sufficiently small for low frequencies and becomes negligible for higher frequencies. Although an extraaural headphone cannot be expected to exhibit a similarly low crosstalk as closed headphones, it is still superior to dynamic cross-talk cancellation (CTC) methods [12], [13] that are used for transaural reproduction of binaural signals. Recently published CTC approaches [14] may be additionally implemented to improve crosstalk performance. Below 3 kHz the headphone produces no additional acoustical load for the ear. Regarding Møller's FEC-criterion even for high frequencies the extraaural design performs as a "free-air equivalent coupling"-headphone. Intra-individual variability in HpTFs is minimized, because the headphone can be repositioned with sufficient precision. The individual headphone transfer function (HpTF) can be linearized within ±0.6 dB for a frequency-range of 70 Hz to 15 kHz provided that the regularization filter of the LMS-algorithm is correctly tuned.

The current prototype has to be improved with respect to mechanical vibrations of the headphone cabinet and the design of a consumer-friendly mechanical fixing. For stand-alone operation a dedicated DSP and power amplifier will be developed. For the reproduction of stereophonic material the BK109 could be easily extended to feature free- or diffuse field equalization

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