

## An extraaural headphone system for optimized binaural reproduction

Vera Erbes, Frank Schultz, Alexander Lindau, Stefan Weinzierl

*Audio Communication Group, TU Berlin, Einsteinufer 17c, D-10587 Berlin, Germany*

*Email: {v.erbes, frank.schultz, alexander.lindau, stefan.weinzierl}@tu-berlin.de*

### Introduction

The transparent binaural reproduction of virtual acoustic environments requires a headphone system with high spectral bandwidth, with a transfer function as linear as possible, a high signal-to-noise ratio (SNR), sufficient crosstalk attenuation and a frequency response which is robust with respect to repositioning and inter-individually differing morphology [1],[2]. Additionally, for in-situ comparisons with real sound fields and for low-frequency extension with subwoofers, such a system should be sufficiently transparent to exterior sound fields and comply to the 'free air equivalent coupling'-criterion (FEC) i.e. approach the acoustic impedance of free air as seen from the ear canal entrances [1]. Moreover, it should be easy to perform an individual headphone transfer function compensation, e.g. with miniature in-ear microphones [3]. Finally, the system should be combinable with other technical components of virtual environments such as 3D shutter glasses, head mounted displays and head tracking sensors.

For this purpose, an extraaural headphone system was developed (BK211, fig. 1), featuring an extraaural headset, an IIR-/FIR-filter DSP-system and a low noise power amplifier. Measurements show that the system fulfills the requirements specified above better than other commercially available headphones.

### The extraaural headphone system

The body of the BK211 headset was fabricated based on a designed 3D-CAD model using the selective laser sintering (SLS) rapid prototyping technique (fig. 1, left). For the left and right channel it incorporates an acoustically separated closed-box loudspeaker design with an effective volume of about 300 ml driven by a 2" full range electrodynamic transducer (Peerless 830970). Five centimeters were chosen as the average 'transducer to ear canal entrance'-distance while a turning knob allows adjusting the headset to an individual head diameter within a typical range of variation ( $\pm 15$  mm, cf. [4]). To decouple structure-born sound and to increase wearing comfort the headset features resiliently mounted cushions which are tuned to a frequency two octaves below the typical lower cut-off frequency ( $f_c = 55$  Hz) of the headphone system. The weight of a completely assembled headset is approximately 1 kg.

Already for a first prototype of the extraaural headphone crosstalk attenuation was shown to be 23 dB in average up to 2 kHz and increasing to 60 dB at higher frequencies [4], which was considered to be sufficiently small even without additional crosstalk cancellation. Using bound-

ary element method (BEM) simulations, the FEC criterion was shown to be perfectly fulfilled up to 3 kHz [4] and still FEC-compliant according to [1] above this frequency.

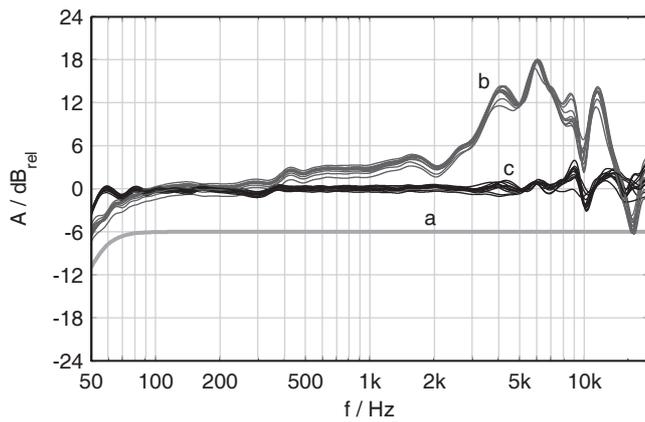
The headset is to be used with a dedicated driving unit which integrates a two-channel DSP section and low noise power amplifiers in a standard 2U 19" rack housing (fig. 1, right). The maximum input voltage of the unit is  $4.9 V_{\text{peak}}$  which matches the typical output level of professional studio sound cards. The whole signal chain is designed to realize an inaudible self noise while providing sufficient gain for spectral compensation to reach the target transfer function – a 4<sup>th</sup>-order Butterworth high-pass at  $f_c = 55$  Hz. Using IIR-filtering this target function is realized on axis at a distance of 5 cm in the free field within  $\pm 2$  dB. A full-scale pink noise with a crest factor of 13 dB – assumed typical for music material – which will be filtered according to the target function, yields  $1.1 V_{\text{rms}}$  at the  $4 \Omega$ -rated amplifier output. In this case the noise floor is  $27.5 \mu V_{\text{rms}}$  resulting in 92 dB SNR. Assuming moderate sound pressure levels (SPL) about 85 – 90 dB<sub>SPL</sub> at the ear canal entrance the noise floor falls below the threshold of hearing. Total harmonic distortion (THD) then reaches  $< -40$  dB above 200 Hz and does not exceed  $-15$  dB for the lowest frequencies of the target function.



**Figure 1:** Headphone system BK211: extraaural headset (left) and DSP-driven amplifier unit (right).

### HpTF compensation

As the BK211 has been linearized for the free field situation, the headphone transfer function (HpTF) measured at the blocked ear canal reveals different sources of frequency response distortion, including the lateral near field head related transfer function (HRTF) and a standing wave pattern originating from the distance between loudspeaker membrane and the head (cf. fig. 2, label b). When reproducing individual binaural recordings the HpTF of the BK211 should be linearized based on individual HpTF measurements [3]. For HpTF-linearization a bandpass characteristic (fig. 2, label a, comprising a 55 Hz Butterworth 4<sup>th</sup>-order high-pass and a 21 kHz



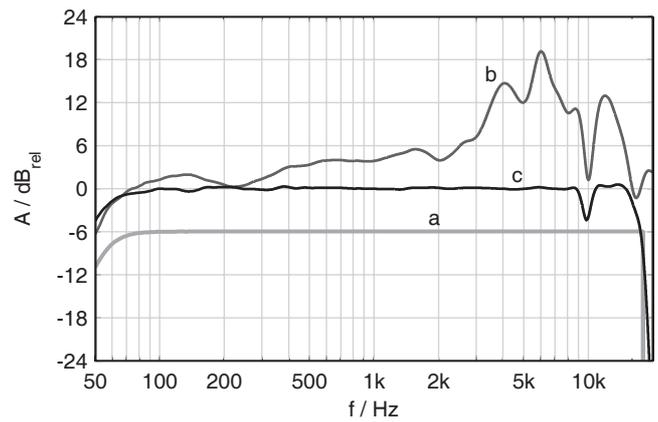
**Figure 2:** Individual linearization of BK211 with repositioning between measurements: a) desired target response (shifted by -6 dB), b) 11 measured HpTFs with 1/6 oct. smoothing, c) linearized HpTFs with 1/6 oct. smoothing; the compensation filter was derived from the complex average of case b using a high-shelve filter regularized LMS-inversion.

Kaiser-Bessel windowed FIR low-pass with 60 dB stop band rejection) was used as a target response. Based on the complex average of 11 HpTFs measured with repositioning between measurements an inversion filter (FIR-order  $2^{12}$  for the sampling frequency 44.1 kHz) was generated using a high-shelve (15 dB gain, half-pad gain at 4 kHz) regularized least mean square approach according to [5]. Linearized HpTFs are shown in fig. 2 (label c). Up to 3 kHz a nearly perfect linearization (variation of  $\pm 1$  dB) can be observed. At higher frequencies the linearization is affected by repositioning variability and limited compensation due to the high-shelve regularization. Compared to alternative supra- and circumaural headphones, however, the overall irregularity of the linearized HpTFs is considerably reduced [1],[2].

Due to the extraaural design, the BK211 headset does not have to be taken on and off to perform in-ear microphone measurements for compensation. Thus, an even more precise linearization of the HpTF can be achieved with only a single measurement (cf. fig. 3). With a compensation filter designed to linearize the complete spectrum except for the notches at 10 kHz and 17 kHz to avoid potential ringing artifacts due to excessive boosting ('PEQ-method' in [3]), 1/6 octave smoothed deviations from the target bandpass (here 55 Hz Butterworth 4<sup>th</sup>-order high-pass, 18 kHz Kaiser-Bessel windowed FIR low-pass with 60 dB stop band rejection) are within  $\pm 0.5$  dB outside of the area of the notches. The -3 dB cut-off frequencies can then be stated 55 Hz and 16 kHz in order to avoid highest frequency partial oscillations of the membrane.

## Discussion and Conclusion

We presented the extraaural headphone system BK211 optimized for binaural sound reproduction in the context of virtual reality applications. It comes as an integrated DSP/amplifier/headset solution featuring a crosstalk attenuation of at least 23 dB and a noise floor below the threshold of hearing while providing a maximum SPL of



**Figure 3:** Individual linearization of BK211 without repositioning: a) desired target response (shifted by -6 dB), b) HpTF with 1/6 oct. smoothing, c) linearized HpTF with 1/6 oct. smoothing; the compensation filter was derived from case b using a parametrical filter regularized LMS-inversion.

101 dB<sub>SPL</sub> (sine) for a linearized HpTF. The extraaural design was shown to reduce intra-individual HpTF variability and to provide a simple approach to generate accurate individual compensation filters by using miniature in-ear microphones. The internal DSP can be additionally used to provide a) a variable crossover frequency when extending the low frequency reproduction with a subwoofer, b) a diffuse-field filter for using the BK211 in a typical recording studio scenario, c) a storage for individual HpTF compensation filters for optimal binaural reproduction. The BK211 headphone system can easily be equipped with head tracking sensors (pre-built to fit for Polhemus Fastrak sensors) and can be combined with 3D glasses or small head mounted displays for application in multimodal virtual reality environments.

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