GENERATING INVERSE FILTERS FOR HPTF EQUALIZATION AS PART OF HEADPHONE PLAYBACK OF BINAURAL AUDIO

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1 Introduction

To generate realistic 3D sound via playback of binaural audio over headphones, the pressure input to the eardrum should match that experienced in the actual sound field. For practical reasons, binaural recordings are not typically made at the eardrum. It is easier and safer to perform binaural recordings at the entrance to a blocked ear canal. However, correction is then required for the acoustical changes created by a blocked ear canal, the effect of headphones occluding the ear, and the fact that sound propagation from the headphone to the eardrum significantly alters the eardrum pressure. These effects can be combined and used to generate an equalization filter that will result in the required ear drum pressure. While the frequency response of the filter is important, for implementation in the time domain as a convolution, the impulse response should not introduce temporal artifacts.

2 Method

Rather than compensate for the influence acoustical changes impart by the headphone, many researchers have relied on Free-Air Equivalent Coupling (FEC) headphones [1]. However, even open-headphones only fulfill this condition at lower frequencies.

Based on estimates of the listener's ear canal effective length and area, as well as published models for the eardrum impedance [2], the ear canal input impedance was calculated using an acoustical transmission line. The ear canal radiation impedance was determined using the baffled piston formula. For the headphone output impedance, reliance was made on published data for similar headphones [3]. Using these inputs with an equivalent circuit analysis, it was possible to determine the Pressure Division Ratio (PDR), which compensates for the effect of a block ear canal as per equation 1.

The Frequency Response Function of the headphone ($FRF_{b,hp}$) was measured at the blocked ear canal entrance using the same microphones as for the binaural recording, which causes the microphone response to cancel as part of the equalization process. An inverse Headphone Transfer Function (HpTF) filter deemed G was then generated based on equation 2.

$$PDR = \frac{Z_{in} + Z_{hp}}{Z_{in} + Z_{rad}} \quad (1) \qquad G = \frac{1}{HpTF} = \frac{PDR}{FRF_{b,hp}} \quad (2)$$

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Since direct inversion of the HpTF was found to cause temporal artifacts which, depending on the HpTF, could be unstable, a Band Pass Filter (BPF) from 20 Hz to 20,000 was included as part of the inverse, and regularization was performed using an effort term (B) weighted towards frequencies above 9000 Hz [4]. The BPF introduced a time delay, which eliminated the temporal issues by shifting the impulse response. Regularization limited the high-frequency effort of the filter for correction of large dips in the estimated HpTF; this helps to ensure a stable inverse. Regularization also decreased post-ring in the impulse response at the expense of slightly more pre-ringing and reduced the potential for equalization error of large peaks that could shift due to headphone re-positioning. The inverse filter with regularization was determined based on equation 3.

$$G_r = \frac{BPF}{HpTF + B} \quad (3)$$

To test the audio quality of the inverse filter, a binaural recording of pink noise played back through separate channels of a 7.1 home theatre system was made. Externalization and localization accuracy was evaluated while seated within the home theatre by A/B comparison between a normalized version of the original recording and one processed with the inverse filter. The two recordings were also compared directly to the sound coming from the loudspeakers.

To evaluate the temporal characteristics, a binaural recording of urban sounds was made and processed with the inverse filter. During listening it was possible to switch between the normalized original recording and the version processed with the inverse filter without interrupting playback. Specific sound events within the recording were looped to allow for any temporal changes to be heard.

3 Results

The inverse filters were generated using estimates of the ear canal length and area, inspection of the filter response, and listening tests. However, it is also be possible to indirectly measure the length and area using acoustical techniques [5], [6], potentially with a more accurate result.

The inverse filter magnitude response (with and without regularization) is included below as Figure 1. The effect of regularization can clearly be seen above 9000 Hz. The effort term was adjusted to limit the equalization to approximately 10 dB at high-frequencies, while minimizing the creation of the peak-doublets that can be seen to occur when large narrow peaks are attenuated by regularization.

The estimated effect of both inverse filters on the eardrum sound pressure were determined using an equivalent circuit model of the ear with a transmission line for the ear canal. The results are illustrated in Figure 2, whereby a full correction can be seen without regularization and reduced high-frequency correction can be seen with regularization.

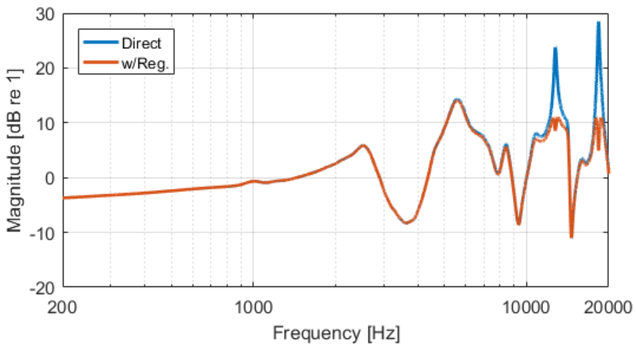

Figure 1: Inverse filter magnitude response

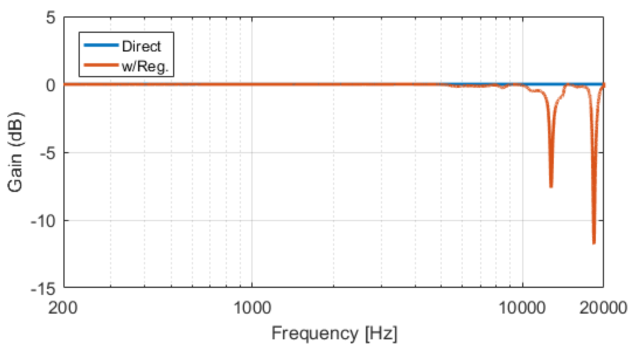

Figure 2: Equalized eardrum response

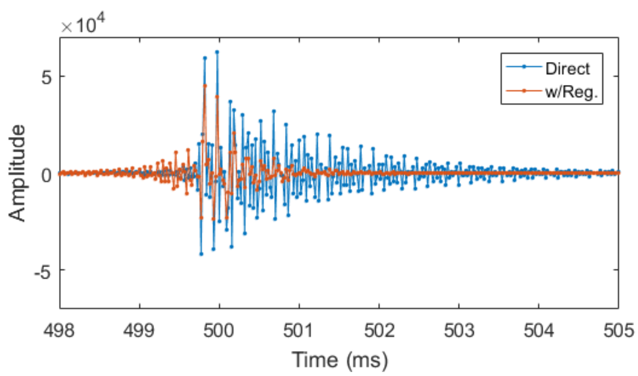

Figure 3: Inverse filter impulse response

Zoomed plots of the resulting impulse responses for both inverse filters delayed by the BPF to the centre of a 1 second impulse window are shown in Figure 3. The version with regularization can be seen to have significantly less post-ringing but some additional pre-ringing.

During the headphone listening test of the home theatre system, it was observed that without HpTF equalization, all channels except the centre externalized and appeared to be coming from the loudspeakers. For the center channel, the sound did not externalize and seemed to be located inside the listener's head. This result from the centre channel was expected since frontal localization is known to be particularly challenging, relying mostly on spectral differences between the ears since level and time cues are not present [2].

When listening with equalization of the HpTF, there was a noticeable improvement in the accuracy of the sound image for all channels. This indicates the equalization filter did not negatively affect the fundamental binaural cues. Even for the centre channel, with inverse HpTF equalization the sound image externalized and pulled forward out of the head; however, the image did not pull all the way to the loudspeaker and seemed to be coming from a point in space in front of the listener. This suggests that the estimated HpTF must be close to the actual HpTF but not an exact match.

For all loudspeaker locations, with inverse HpTF equalization, a noticeable change in high-frequency timbre was heard. This likely occurred due to a mismatch between the estimated HpTF and the actual HpTF of the listener. This mismatch prevents the brain from fully correcting the observed timbre.

When listening to the urban-sound recordings without HpTF equalization, the sound was realistic and did externalize, but seemed to be lacking high-frequency energy. With HpTF equalization, the overall sound quality was improved due to the high-frequency boost and sound sources seemed to originate from a more precise location in space. In terms of phase and temporal effects, there was no audible difference indicating that both the pre-ringing and filter decay of the inverse filter were adequately damped.

4 Conclusion

A method of estimating an HpTF equalization filter applicable to blocked ear canal binaural recordings was developed and tested. Listening test results demonstrated that the filter can improve externalization, localization accuracy, and overall audio quality. With improved means of estimating the required input parameters, it is expected that the technique could be used as part of binaural audio reproduction system.

References

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