Equalization for Binaural Synthesis with Headphone

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Introduction

When comparing the binaural presentation of sound events, clear differences regarding overall quality between headphones and crosstalk-canceled loudspeaker reproduction are reported. In particular, "in-head localization" occurs more often with headphone than with loudspeaker reproduction. It seems that listeners are less sensitive to loudspeaker distortion, either sound-wise or spatially, then to headphone distortion. The reason for this phenomena is a not sufficiently precise equalization of the head-headphone system. When stimuli are played through headphones, an alteration of the sound signal in the ear occurs caused by resonances and nonlinearities in the headphones and also by the coupling of the headphones to the ear canal. To provide a defined interface for psychoacoustic listening tests with headphones, the headphones must be adequately equalized.

The variance of headphone transfer functions (HpTF) with fitting has already been extensively investigated [1, 2]. It has also been shown that the spectral differences caused by distinct headphone fittings are perceivable by listeners [3]. But a unique method that provides for different types of headphones satisfactory results is not yet accomplished. Yet, a better understanding of how a headphone behaves will allow a better design of appropriate equalization filters.

Therefore, the HpTF of two circumaural headphones were measured (a dynamic and an electrostatic type headphone) with an artificial head and with several subjects using a miniature microphone in the blocked ear canal. Moreover, the HpTF was also measured with the headphone in free field and placed against a rigid plane wall. Hence, the effect of the volume and the coupling on the HpTF can be observed.

Headphone Characterization

A series of measurements was made with the goal to better describe the behavior of headphones, either alone or coupled with the human external auditory system.

First the free field radiation of the headphone was measured. These measurements confirmed two aspects that are expected for every typical sound source: the headphones present low sensitivity at lower frequencies, caused by the low radiation impedance in this region, and the presence of near field effects, i.e., variations on the sound field observed near the entrance of the phone for frequencies above 4 kHz.

But circumaural headphones are always used placed against the listeners head. To verify the behavior of the headphones when closed, but still without the influence of the listener's pinna, they were placed against a wooden plate with a microphone in its center, resulting in a closed cavity. An extra miniature microphone was placed in front inside the cavity. As expected, with a closed volume the transmission of lower frequencies is improved. By moving the plate with the microphone it is possible to verify the presence of modes in the higher frequency range. The sound field at the position of the extra microphone does not change when the plate is moved, showing no evidence of influence of the plate on the internal sound field. This means that the resonances are not only caused by the ear geometry, some of them are intrinsic from the headphone geometry. So a headphone can be modeled as an acoustical cavity for frequencies up to 4 kHz and above that effects from standing waves must be taken into consideration.

Headphone Fitting

In normal condition of use, headphones will always have an "internal geometry", the pinna, that will directly influence the sound field inside the cavity. So a new series of measurements was made with the help of a dummy head. The HpTF has little variance up to about 4 kHz. In this region just a constant level variation can be noted, caused by different leakage with the fitting, as commented by Toole [2]. In this frequency range the headphone works as an acoustic cavity. For higher frequencies we can observe resonances that vary with the headphone fitting and the geometry of the listeners' ears. This occurs because at this frequency range standing waves start to build up inside the headphone cavity and also on the external ear structure [4], meaning that in this region the HpTF behavior is highly individual.

For an ideal equalization, it would be necessary to know at all times the sound pressure at the entrance of the ear canal without having a microphone there. But the transfer function of a generic point inside the cavity to the ear canal also varies with the headphone fitting. This implies that a microphone place inside the headphone's cavity cannot be used as a reference for the equalization. Also the headphone's electrical impedance will not serve as a reference for equalization. Measurements with the dynamic headphone showed that variation on the headphone fitting does affect its electrical impedance, but the verified alterations are very small, almost comparable to noise, and they do not directly correlate with the difference in the HpTF.

So for precise equalization a measurement of the HpTF will be necessary. But the HpTF will vary with the headphone fitting. On the other hand, when the listeners are allowed to place the headphone as it is most comfortable for them, the variation in measured HpTF reduces considerably, suggesting that an individual headphone filter can be designed [5].

Individual Fitting

Since the dummy head is a passive listener, the variance of the HpTF measured with it is expected to be higher than in the case when the listener is allowed to place the headphone at its most comfortable fit. A series of individual HpTF measurements was carried out with 15 subjects. The same behavior observed in the measurements with the dummy head can be seen in the individual measurements. In lower frequencies, only level differences are present while at higher frequencies we observe the presence of very individual resonance structures.

Each subject was asked to place the headphone four times with the most comfortable fit and four times with extreme fits, i.e. with ears positioned as much as possible to the front, back, top and bottom of the headphone interior. This should give an overview of the extremes of how the individual HpTF varies. No trends could be observed at the four measured extreme positions. Nonetheless, by having confirmed the low measurement variability when the listener is allowed to fit the headphone, just the variability of these measurements should be considered when designing the equalization filter.

Equalization

A first very naive attempt of headphone equalization is to measure once the HpTF and to design a filter as the inverse of this measured HpTF. Obviously this will lead to perfect equalization for that fitting, but the slightest displacement of the headphone already destroys the equalization in higher frequency range, with peak irregularities as high as 10 dB.

Thus it is clear that the use of a single HpTF, measured after the user has placed the headphone at the most comfortable fit, is not enough to generate an equalization filter. But also taking the average of several measured HpTF will most certainly result in an equalized response containing high frequency irregularities.

Bücklein has shown through speech intelligibility tests that human listeners are more sensitive to spectrum irregularities in the form of peaks than to equivalent valleys [6]. Assuming that this behavior extends also to spatial perception, it makes sense to design an equalization filter that avoids the occurrence of resonance peaks in the entrance of the ear canal. Lindau and Brinkmann suggested some designs inspired by the work of Bücklein [7].

Another design method was proposed by the authors for a perceptually robust equalization filter, inverting not the average but the upper limit of several measured HpTFs [8]. This leads to an equalized response whose potential irregularities will be in the form of valleys and not peaks. The upper limit is calculated from the average plus two times the standard deviation from the amplitude of the measured HpTFs. Since phase information is lost at this process, minimum phase is used. To keep the FIR filter short, avoiding latency at the reproduction chain, the headphone is not equalized for frequencies below 100 Hz.

Conclusion

The HpTFs of two open-type headphones were measured. It was verified that these headphones work as an acoustical cavity up to 4 kHz and the HpTF varies very little with fitting in this frequency range, differences occurring mainly because of different leakage levels. At higher frequencies a varying resonance structure is observed, caused by the intrinsic modes from the headphone cavity and modes building in the pinna of the listener. Also, the position of the pinna inside the headphone cavity alters the standing wave structure in the headphone cavity, altering the complete sound field in the headphone cavity. If the listener is allowed to fit the headphone at the most comfortable position, the variation of the measured HpTF is reduced and, thus, an individual equalization filter can be designed.

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