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Signal Processing Framework for Virtual Headphone Listening Tests in a Noisy Environment

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ABSTRACT

A signal processing framework is introduced to enable parallel evaluation of headphones in a virtual listening test. It is otherwise impractical to conduct a blind comparison of several headphones. The ambient noise isolation capability of headphones has become an important design feature, since the mobile usage of earphones takes place in noisy listening environments. Therefore, the proposed signal processing framework allows a noise signal to be fed through a filter simulating the ambient sound isolation at the same time when music is played. This enables the simultaneous evaluation of the timbre and background noise characteristics, which together define the total headphone listening experience. Methods to design FIR filters for compensating the reference headphone response and for simulating the frequency response and isolation curve of the headphones to be tested are presented. Furthermore, a real-time test environment implemented using Matlab and Playrec is described.

1. INTRODUCTION

The usage of headphones in people's everyday lives has increased dramatically during the past few years. Furthermore, the listening environments have also changed along with the success of mobile music players and smartphones (according to Gartner, smartphone sales grew 72% in 2010 [1], Apple reported in October 2011 that the total number of iPods sold worldwide was 300 million, and the European Union's Scientific Committee on Emerging and Newly Identified Health Risks (SCENIHR) estimated sales in the EU of all portable audio devices was 184–246 million units over the years 2004–2007 [2]). Thus, the typical environment where people use their headphones has changed from quiet homes and offices to more noisy environments, such as busses, airplanes, places with heavy traffic, and, in general, outdoors. This sets new requirements on headphone design. Thus, ambient noise isolation, passive or active, is nowadays an important part of the whole headphone listening experience. When headphones are chosen correctly in terms of sound quality and ambient sound isolation they can offer a high-quality listening experience, even when compared to loudspeaker listening. However, the spatial presentation can be quite different between headphones and loudspeakers without a proper externalization method, see e.g., [3, 4].

The most straightforward method to evaluate headphones is to listen to different headphones consecutively. However, subjective evaluation of headphones can be cumbersome due to the short human auditory memory. The auditory memory can hold complex sound images in memory only for a few seconds at a time. This becomes a problem in consecutive headphone listening test, because it takes time to take off and put on again the different headphones. Furthermore, in-ear headphones also has hygiene issues, since they are inserted into the ear canal. Moreover, arranging blind listening tests is not possible if the testee has to alternate between different headphones. Visual cues and prejudices are known to affect the results of a listening test and they should be eliminated as well as possible when the focus is on evaluating the acoustic qualities [5].

Hiekkanen *et al.* presented a virtualized listening test for loudspeakers [6] and Hirvonen *et al.* introduced a virtual listening test methodology to evaluate the sound quality of headphones [7]. The purpose of this study is to develop a signal processing framework for virtualized listening tests for headphones, which can be used to evaluate the quality of sound while taking the ambient noise isolation into consideration. That is, the evaluation of the sound quality of the headphones can also be done in simulated noisy environments.

Figure 1 shows the block diagram of the signal processing framework. A pair of Sennheiser HD 650 reference class headphones is equalized to have a flat response at the ear drum (headphone compensation). Furthermore, the test signal is filtered with a filter designed based on the frequency response measurements from the evaluated headphones (headphone filter) and the noise signal is filtered according to the measured isolation curve of the headphones (isolation filter). This enables an easy way to simulate

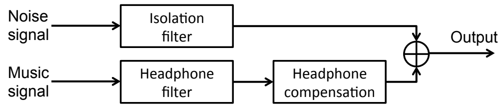

Fig. 1: Block diagram of the signal processing framework.

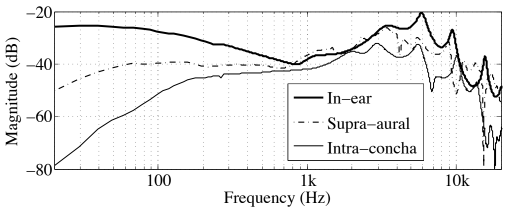

Fig. 2: Frequency responses of three different headphone types.

different headphones virtually, based on the measured frequency responses and isolation curves of these headphones.

2. HEADPHONE MEASUREMENTS

A set of different types of headphones was measured in order to obtain their frequency responses and isolation curves. Basically, there are four different types of headphones: circum-aural headphones, which completely cover the ear; supra-aural headphones, which are placed on the pinna; intra-concha headphones, which are placed loosely in the concha cavity of the ear; and in-ear/insert headphones, which are inserted into the ear canal. The measurements were conducted in a listening room using the Brüel & Kjær's Head And Torso Simulator (HATS) model 4128C with type 3.3 ear simulator [8].

The frequency response was measured with a swept-sine technique [9]; a sine sweep was reproduced with the headphones and measured from the drum reference point (DRP) of the HATS. Figure 2 shows three individual measurement results (relative magnitude), measured with different types of headphones. As can be seen, the in-ear headphone has the strongest bass reproduction due to the tight fitting into the ear canal, whereas the intra-concha headphone lacks lower frequencies altogether. Mea-

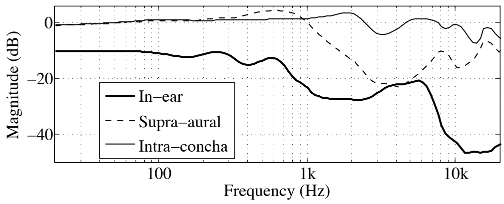

Fig. 3: Isolation curves of three different headphone types (with 1/3 octave smoothing).

suring the nonlinear distortion characteristics of the headphones was found to be unnecessary, since all modern headphones are practically linear at reasonable playback levels.

The HATS provides realistic reproduction of the acoustic properties of an average adult human head and torso [8]. However, each person has a different head and torso anatomy, which creates unique frequency responses at their ear drums. Thus, the HATS measurements may not be completely accurate for all people, but they are highly consistent, which makes the comparison between different headphones reasonable. That is, when there are timbre differences between a person and the HATS, the differences are similar with all headphones.

The isolation measurement was conducted using four Genelec loudspeakers, a subwoofer, and the HATS. A diffuse sound field was generated inside the listening room by reproducing pink noise with the loudspeaker setup. First, the generated noise was recorded with the HATS at DRP without headphones, after which the noise was recorded at the same DRP with headphones placed on the HATS. The isolation results were obtained as a deconvolution between the two recorded noise signals.

Figure 3 illustrates a set of measured isolation curves, where the isolation provided by the headphones is shown as a function of frequency (dB re 20 μPa). A third-octave smoothing has been applied to all responses. As can be expected, the in-ear headphone offers the best isolation, since it occludes the ear canal completely. However, it should be noted that the type 3.3 artificial ear can provide a greater seal between the in-ear headphone and the ear canal than would occur on humans: thus resulting in overestimation of the isolation at low frequencies [10]. Furthermore, the supra-aural headphone isolates high frequencies quite well, whereas the isolation of the intra-concha headphone is rather negligible at all frequencies.

Moreover, some headphones have active noise control, which actively enhances the isolation of ambient sounds, especially at low frequencies. This can be measured and simulated as well.

3. CALIBRATION OF THE HEADPHONES

A pair of Sennheiser HD 650 reference class headphones was measured as described in Section 2. The idea of the calibration was to create a flat frequency response at the listener's ear drum. The inverted frequency response was calculated by using linear prediction filter coefficients (LPC), which result in a minimum-phase all-pole filter that can easily be inverted. The order of the LPC was 30.

Other headphone frequency response compensation methods are described, e.g., in [6, 7, 11]. Generally, peaks in the frequency response of a filter should be avoided, since peaks are more audible than equivalent dips [6, 12]. Thus, the rather large peak in the inverted frequency response around 18 kHz was suppressed with the following regularization technique:

$$h'_1(n) = \mathrm{FFT}^{-1}\Big\{\Big[\big|H_1(e^{\mathrm{j}\omega})\big| + r(\omega)\Big]e^{\mathrm{j}\theta_1}\Big\}, \qquad (1)$$

where $\left|H_1(e^{j\omega})\right|$ is the magnitude response and θ_1 is the phase angle of the measured HD 650 headphone, $r(\omega)$ is the frequency-dependent regularization term, ω is the angular frequency, j is the imaginary unit, FFT^{-1} means the inverse fast Fourier transform, and $h'_1(n)$ is the regularized impulse response of the HD 650 headphones, which is then inverted with the above-mentioned LPC technique.

Figure 4 shows the measured frequency response of the Sennheiser HD 650 at the DRP of the HATS (thin solid line), the inverted frequency response (dashed line), and the regularized inverse frequency response (thick solid line) where the peak around 18 kHz has been suppressed. The value of $r(\omega)$ was selected to be 0.04 at frequencies above 17 kHz and zero elsewhere.

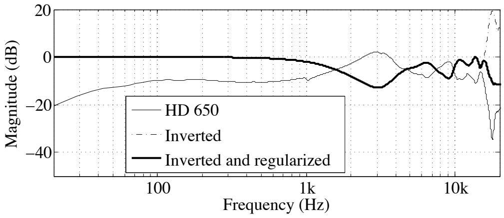

Fig. 4: Measured frequency response of the Sennheiser HD 650 headphones, its inverted frequency response, and regularized and inverted frequency response.

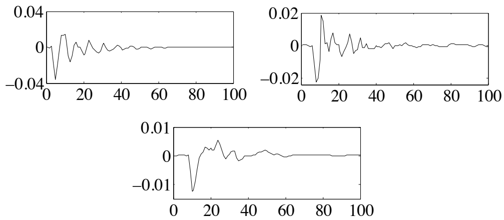

Fig. 5: Measured impulse responses of an in-ear (top left), supra-aural (top right), and intra-concha (bottom) headphone. Horizontal axis: samples.

4. IMPLEMENTATION OF THE LISTENING TEST FRAMEWORK

When the frequency response of the reference headphones has been compensated, it is possible to simulate different headphones by constructing linear filters based on the measured frequency responses. Furthermore, the simulation of the ambient sound isolation can be conducted by filtering a noise signal with a proper filter constructed based on the measured isolation curves.

The impulse responses measured with the HATS are extremely short and have an excellent signal-to-noise ratio (SNR). Thus, an FIR filter can be designed directly from the measured impulse responses. Figure 5 shows the windowed impulse responses of the three headphones (rectangular window). As can be seen, the impulse responses are, in fact, really short, i.e. approximately 100 samples (2.3 ms) at the sample rate of 44100 Hz.

The isolation filter was constructed similarly to the frequency response filter. That is, the impulse response, which was derived by the deconvolution (see Section 2) is used as an FIR filter. The FIR filter can then be used to simulate the isolation of a headphone by filtering ambient noise with it. The order of the isolation filter is approximately 200.

The straightforward filter design enables a convenient way to include new headphones into the listening test framework. Only two measurements per headphones are needed to design the required filters.

4.1. Graphical Test Environment

A test environment with a graphical user interface (GUI) was implemented in order to test the developed signal processing framework. The GUI and the signal processing framework was implemented with Matlab and Playrec. Playrec is a free cross-platform utility for Matlab, which provides versatile access to soundcards and enables real-time signal processing in Matlab [13]. All samples are buffered so Matlab can continue running the remaining script while playback and recording occur.

Figure 6 shows the implemented graphical test environment (GTE) for the virtualized headphone listening. The user is able to choose a music sample from amongst a set of predetermined samples and can also choose the pair of headphones that he/she wants to listen to the music sample with. The GTE then shows the frequency response and the isolation curve of the selected headphones. Furthermore, the flat response (i.e., only the headphone compensation) and the completely unprocessed options are also included.

The simulated background noise used in the GTE is pink noise. It is then possible to listen to only the selected music sample with the simulated frequency response of the selected headphones; only the background noise, where the isolation of the selected headphones is taken into consideration; or both the music and the noise signals together. Furthermore, the playback mode and the headphones can be changed while the music sample is playing.

The signal processing in Playrec was implemented in 1/3 second frames, with one frame buffer. This gives the GTE a response time of 1/3 – 2/3 seconds, when either the playback mode or headphones is changed. Thus, the implementation can be considered to run

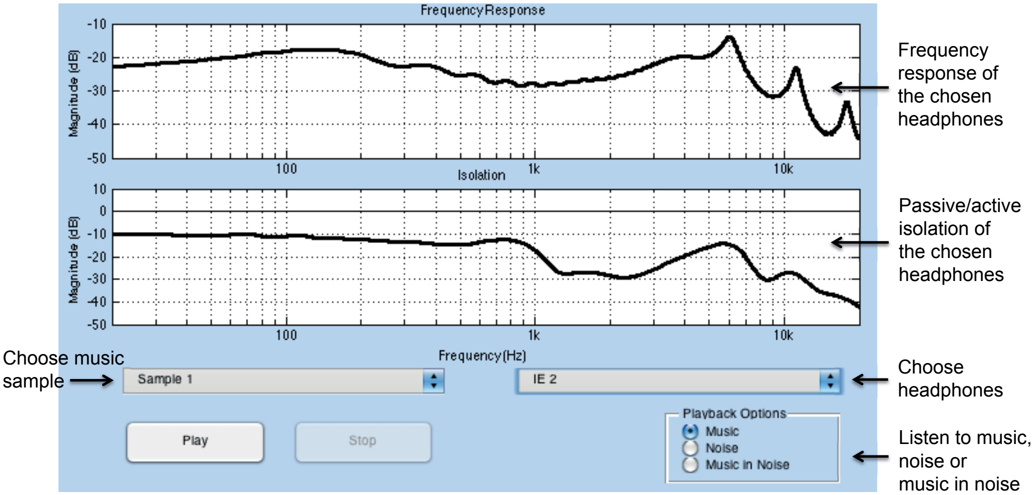

Fig. 6: The graphical user interface of the test environment.

in real time with some latency, which is not critical in this case. The frames could be made even smaller, which would reduce the response time, but that would require more computing power.

A slightly modified Finnish version of the GTE was informally presented to an audience. The audience reported the GTE to be useful and instructive, because the differences in the frequency responses and ambient sound isolation capabilities of different headphones were heard instantly. For example, pink noise with a 70-dB A-weighted RMS level is attenuated 6 dB with supra-aural, 0 dB with intra-concha, and 18 dB with in-ear headphones.

5. APPLICATIONS

The proposed signal processing framework can offer similar virtualized listening test scenarios for headphones as Hiekkanen *et al.* have proposed for loudspeakers [6] and Lokki *et al.* have proposed for an entire concert hall [14]. The proposed framework also enables blind headphone listening tests, which are virtually impossible to conduct if test subjects have to wear each of the different headphones, since subjects inevitably recognize at least the type of the headphones, if not the manufacturer or the model.

The test signals can be practically anything: music, speech, or different noise samples. This makes the listening test framework quite versatile, since it can be used easily in speech and music applications. Furthermore, it is possible to use real recordings or simulated ambient noise, depending on the needs of the application.

The main advantages of the system are its ability to compare various headphones quickly in parallel, which has been cumbersome to accomplish with conventional listening test methods, and the possibility to evaluate the acoustic isolation of the headphones simultaneously.

6. CONCLUSIONS

The fact that headphones are often used in noisy environments implies that the auditory experience achieved with a certain pair of headphones cannot be evaluated solely by listening to the headphones in a quiet environment. Superb sound quality of the headphones is not enough, if the isolation of ambient sounds is poor and background noise masks the signal being listened to. Hence, evaluating headphones in a noisy environment is important as well.

This paper described a signal processing framework for virtual listening tests for headphones. The framework enables virtualized listening tests for evaluating the sound quality of headphones as well as their ability to attenuate ambient sounds. The framework requires a pair of headphones, which are calibrated to have a flat response at the ear drum of a listener, as well as the frequency response and ambient sound isolation measurements of the headphones under evaluation.

An example of the headphone calibration and filter design as well as an implementation of a graphical test environment were presented. The headphone compensation was implemented with a 30th-order FIR filter, and the frequency response and isolation filters were implemented with FIR filters of order 100 and 200, respectively. However, the signal processing framework is highly versatile and is not limited to the introduced calibration technique or filter designs.

7. ACKNOWLEDGMENT

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8. REFERENCES

[1] Gartner. "Gartner says worldwide mobile device sales to end users reached 1.6 billion units in 2010; smartphone sales grew 72 percent in 2010". www.gartner.com/it/page.jsp?id=1543014, February 2011.

[2] European Comission. "Potential health risks of exposure to noise from personal music players and mobile phones including a music playing function". Technical report, Scientific Committee on Emerging and Newly Identified Health Risks SCENIHR, 2008.

[3] O. Kirkeby. A balanced stereo widening network for headphones. In *AES 22nd International Conference on Virtual, Synthetic and Entertainment Audio, Espoo, Finland*, pages 117–120, June 2002.

[4] T. Liitola. *Headphone Sound Externalization*. Master's thesis, Helsinki University of Technology, Espoo, Finland, 2006, http://www.acoustics.hut.fi/publications/files/theses/liitola_mst.pdf.

[5] M. Opitz. Headphone listening tests. In *AES 121st Convention, San Francisco, CA, USA*, October 2006.

[6] T. Hiekkanen, A. Mäkivirta, and M. Karjalainen. Virtualized listening tests for loudspeakers. In *AES 124th Convention, Amsterdam, The Netherlands*, May 2008.

[7] T. Hirvonen, M. Vaalgamaa, J. Backman, and M. Karjalainen. Listening test methodology for headphone evaluation. In *AES 114th Convention, Amsterdam, The Netherlands*, March 2003.

[8] Brüel & Kjær. *Product Data Sheet: Head and Torso Simulators – Types 4128-C and 4128-D.*

[9] A. Farina. Simultaneous measurement of impulse response and distortion with a swept-sine technique. In *AES 108th Convention, Paris, France*, February 2000.

[10] ITU-T. *Recommendation P.380. Electro-acoustic measurements on headsets*. Series P: Telephone Transmission Quality, Telephone Installations, Local Line Networks. International Telecommunication Union, 11/2003.

[11] G. Lorho. Subjective evaluation of headphone target frequency responses. In *AES 126th Convention, Munich, Germany*, May 2009.

[12] R. Bücklein. The audibility of frequency response irregularities. *J. Audio Eng. Soc.*, 29(3):126–131, March 1981.

[13] R. Humphrey. Playrec, multi-channel Matlab audio, http://www.playrec.co.uk, 2006-2008.

[14] T. Lokki, J. Pätynen, A. Kuusinen, H. Vertanen, and S. Tervo. Concert hall acoustics assessment with individually elicited attributes. *J. Acoust. Soc. Am.*, 130(2):835–849, August 2011.