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3pNS6. Adaptive feedforward control for active noise cancellation in-ear headphones

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Noise can be disturbing, stressful or even harmful. Headphones with active noise cancellation (ANC) can enhance the user's comfort, especially when travelling. On a plane or a train, in the street or at work, these headphones give the possibility to reduce unwanted noise. The range of ANC headphones on the market is constantly increasing. Circumaural and supra-aural headphones with different control strategies have been available for a long time; over the last few years the product lines have been expanded to in-ear headphones. These headphones already have quite a good passive attenuation and are equipped with feedforward control for active noise cancellation. The best results in attenuation are achieved by semi-adaptive digital controls, which choose the best filter depending on the noise spectrum and can be manually adapted to the user. A fully adaptive control has already been proven to be very effective in aviation headsets and other ANC applications. Besides the market analysis of ANC headphones we would like to present an adaptive feedforward control for in-ear headphones and highlight the advantages compared to a static feedforward control.

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INTRODUCTION

Noise can be disturbing, stressful or even harmful. Headphones with active noise control (ANC) can enhance the user's comfort, especially when travelling. Whether you are on a plane or a train, in the street or at work, they give you the possibility to reduce unwanted noise.

At the end of the 1980s Bose and Sennheiser introduced their first ANC aviation headsets to the market [1]. In the years to follow, different circumaural and supra-aural customer ANC headphones became available alongside the professional lines of headphones. These ANC headphones are equipped with two basic control strategies, feedback and feedforward. The controls can be used either separately or in combination, see Figure 1. For feedback control the noise is picked up by an error microphone inside the headphone, filtered and fed back to the loudspeaker. On the contrary for feedforward control the noise is recorded with a reference microphone situated outside the headphone. This signal is filtered and played over the loudspeaker to interfere with the noise inside the ear [1].

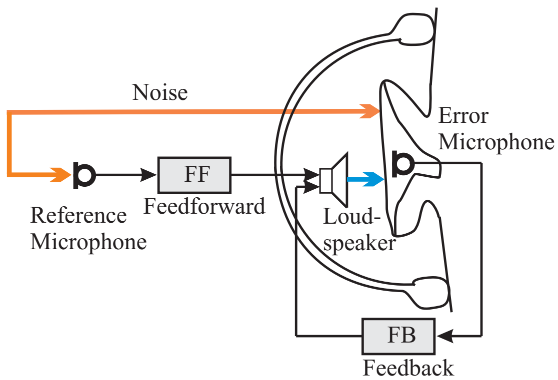

FIGURE 1. Combined feedback and feedforward control of supra-aural headphones.

Over the last few years the product lines have been expanded to ANC in-ear headphones. These headphones already have quite a good passive attenuation and are equipped with feedforward control for active noise cancellation. The small and lightweight design is especially useful for consumer products. Best attenuations are achieved by semi-adaptive or manually adjustable digital controls. These controls are equipped with different pre-adjusted filters. They either switch automatically depending on the outer noise spectrum or the controller can be manually chosen by the user. Examples for in-ear headphones with these digitals controls are the Sony MDR-NC300D and the Sennheiser CXC 700. Furthermore, both controls can be manually adapted to the ear geometry of the user by adjusting a parameter.

Serveral studies showed the advantages of a fully adaptive control for supraaural headphones [1],[2],[3]. Finally, in 2011 the first product with a fully adaptive feedforward control, the Sennheiser aviation headset S1 Digital came into the market. An adaptive feedforward control for in-ear headphones will be presented in the following chapters. The control was tested on a group of persons. Furthermore, the attenuation of the adaptive filter will be compared to the attenuation of the usually used static filters.

ADAPTIVE FEEDFORWARD CONTROL FOR IN-EAR HEADPHONES

Figure 2 shows a schematic drawing of an in-ear headphone with a reference microphone and an error microphone. In addition, the block diagram of the adaptive feedforward control with the necessary signals can be seen [4]. The error microphone picks up the error signal $e(n)$ resulting from the superposition of the disturbing noise $d(n)$ and the anti-noise $y'(n)$. The secondary path S is the transfer function from the filter W to the error microphone. It includes the acoustic path inside the ear as well as the necessary signal transformations, for example analog-digital and digital-analog conversions. The filter W is a finite-impulse response filter (FIR) with the filter coefficients $\vec{w}(n)$. It calculates the loudspeaker output from the reference signal $x(n)$. The filter coefficients are constantly optimized with the FxLMS-algorithm (filtered-reference-least-mean-square) with the step size μ [4].

$$\vec{w}(n+1) = \vec{w}(n) + \mu e(n)\vec{x}'(n)$$

Therefore, the reference has to be filtered by using an estimate of the secondary path $\hat{S}$. This signal $x'(n)$ is stored in the vector $\vec{x}'(n)$.

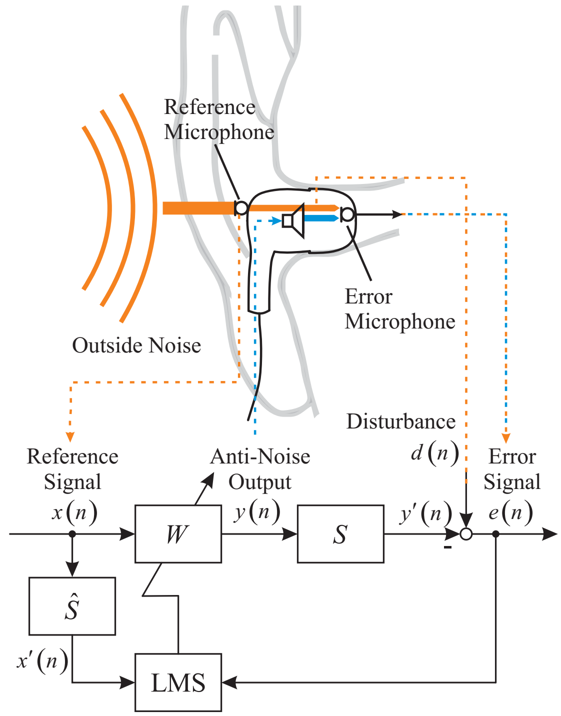

FIGURE 2. Modelling and control diagram of the adaptive feedforward control of in-ear headphones

The control has been implemented on a real-time processor with floating point arithmetic for a prototype in-ear headphone with integrated microphones.

ANALYSIS OF THE ADAPTIVE CONTROL

The available ANC in-ear headphones are normally equipped with a static feedforward control. Therefore, the attenuation of the adaptive filter will be compared to the attenuation of a static one.

In order to design the adaptive feedforward control a model $\hat{S}$ of the secondary path S is needed. The measurements of the secondary path show large intersubject variability especially in the magnitude between the eight persons of the test group, see Figure 3. These differences are mainly caused by various ear geometries and how the headphone fits into the ear canal and the thereby caused sound leakage [5],[6]. In addition to the secondary path, the varying primary path has a significant influence on the optimal filter and, therefore, limits the use of static filters. The primary path describes how the reference signal and the disturbing noise are connected.

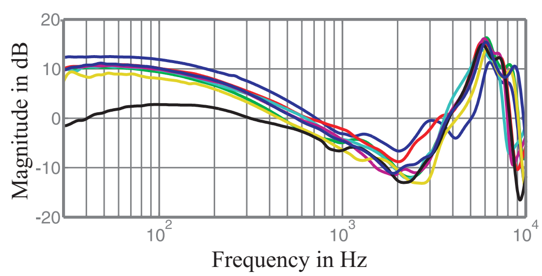

FIGURE 3. Magnitude of frequency response of the secondary paths of the test group.

The adaptive feedforward control was tested on the test group. In spite of all deviations, the control was stable for all test subjects using an average secondary path model. For the presented example an adaptive FIR filter with 80 parameters and the same disturbing noise was used in all cases. It was a random noise with high power in the frequency range from 50 Hz to 2000 Hz. The adapted filter coefficients of W were stored. Furthermore, the achieved active attenuations at the error microphone were measured. Figure 4 shows the adapted filters of the test group in black. The magnitude of the frequency response of the optimal filters varies about 10dB. Because for a static feedforward control just one average filter can be used, this cannot achive the same attenuation on all persons. Hence it is of high interest how good a static filter can be compared to the adaptive one. The dotted red line represents this static filter, which is designed to achieve the best average attenuation for all test subjects in the used noise spectrum.

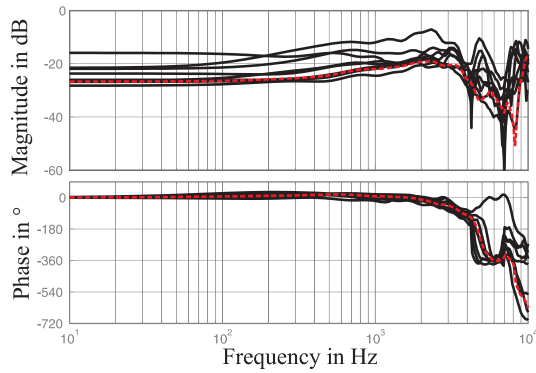

FIGURE 4. Black: Bode plot of the adapted filters of the FxLMS-algorithm for the test group; dotted red: static filter

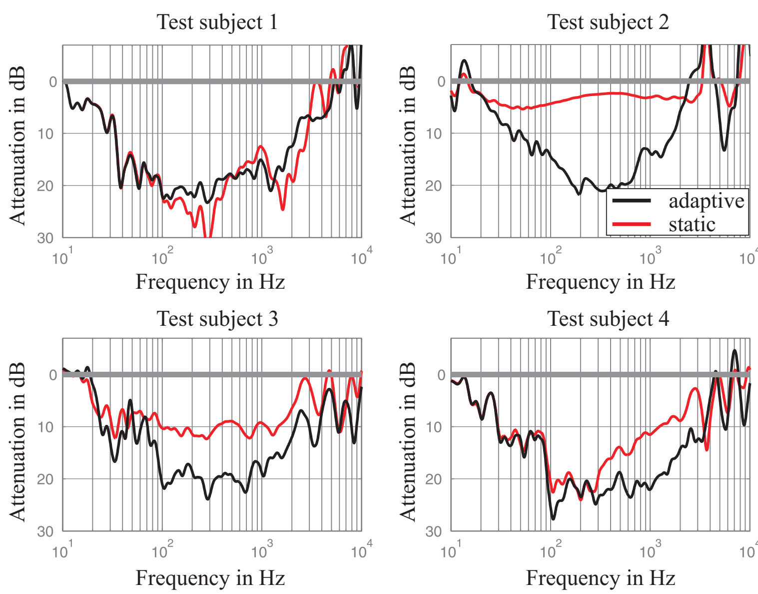

FIGURE 5. Comparison of active attenuation of the adaptive and static feedforward for different test subjects. The adaptive attenuation is plotted in black and the static attenuation in red.

Figure 5 displays the active attenuation of four selected test subjects. These results are also representative for the ones not shown. The attenuation of the adaptive and the static filter are compared for each person. For the chosen noise spectrum with high output power between 50 Hz and 2000 Hz the adaptive filter always achieves about 20 dB attenuation in the frequency range between 100 Hz and 1000 Hz. In contrast the attenuation of the static filter varies a lot. For some test subjects adaptive and static filters achieve quite similar results, such as in the case of subject 1. Then again for other test persons the static filter generates almost no attenuation as can be seen at subject 2. In general the static filter does not achieve a comparable high performance as the adaptive one (subject 3 and 4). Even though a static attenuation is well recognizable by the test persons, the results of the adaptive control cannot be reached. The average attenuation of the static filter over all test subjects is just about 10 dB between 100 Hz and 1000 Hz. Therefore, the adaptive feedforward filter outperforms the static one.

In addition to the ability to compensate interpersonal and intrapersonal variances, adaptive filters have the advantage to adapt to changing disturbing noises. The algorithm finds the optimal filter for any disturbance automatically and so always achieves the best attenuation. In particular, dominant frequencies can easily be eliminated in this way.

SUMMARY

Static filters which are normally used for in-ear noise cancelling headphones show large variances in attenuation depending on the user. Digital semi-adaptive headphones can compensate some of the interpersonal differences with the help of adjustable parameters. Furthermore, different ANC filters are available for different noise spectra. A fully adaptive control, such as the one presented above, automatically adjusts to the user and finds the optimal filter for every kind of the outside noise, not only for the predesigned ones. In general, adaptive filters achieve much better attenuation then static filters. Furthermore, it is no longer necessary to manually adapt the headphone to the user, which makes it much more user-friendly.

ACKNOWLEDGMENTS

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