Active Noise Control with In-Ear Headsets

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Abstract

Noise induced hearing loss (NIHL) is one of the most important recognized occupational diseases. It is often caused by permanent noise above 85 dB(A) [1]. Earmuffs are established hearing protectors to protect workers from disturbing acoustical noise, but also disturb the communication between them. Active Noise Reduction (ANR) headsets can remedy this situation. On the one hand they improve the noise protection by an out-of-phase antinoise. On the other hand it is possible to let digital communication pass through.

Previous work on ANR often investigated circum-aural headphones because the aim was to create a device with very good passive attenuation especially in very loud environments. But these devices are expensive and have a high consumption of electricity, particularly when using adaptive filters.

An inexpensive alternative offer in-ear headphones. In addition they are compact and for that reason well suited for mobile use. Mobile devices are usually powered by batteries, so the computational complexity must be kept low. The result will be a compromise between ANR and duration.

First studies with ANR headphones show that the acoustical transfer functions of the subjects vary widely, much more than with circum-aural. This paper discusses the interpersonal variances and their influences to ANR and shows a few approaches to solve these problems.

Keywords:
Active noise control, adaptive algorithm, feedback, feedforward, in-ear headset

1 INTRODUCTION

In recent years, research in ANR has been driven further and further. Circum-aural headsets were studied first because they have good passive attenuation. For people who work in noisy environments pilots for example, these hearing protection devices (HPDs) were upgraded with ANR functions. Figure 1 shows the effect of ANR for a circum-aural headset. In this case a hybrid control strategy of an adaptive feedforward and a static feedback filter was realized [2].

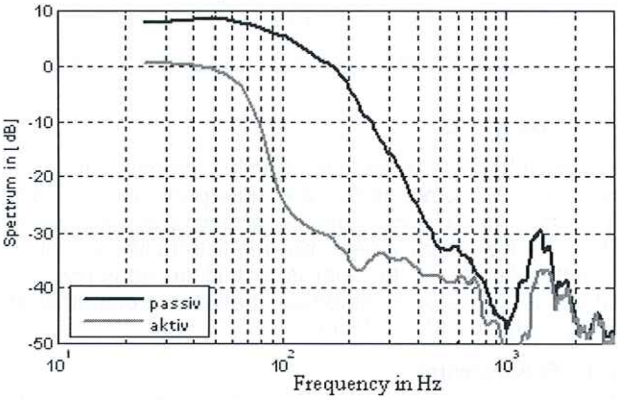

Figure 1: The broadband attenuation of a circum-aural headset with and without ANR, © IMR

But the handicap of present adaptive ANR algorithms is their computational complexity linked with high electrical power consumption. Furthermore these devices are expensive and hence not suitable for the commercial market.

That's why the aim is to develop a low priced ANR in-ear headphone. An additional benefit of these devices can be the position of the inner microphone (error microphone): The error microphone is located closer to the ear drum as illustrated in figure 2. Therefore it is possible to attenuate the noise up to higher frequencies.

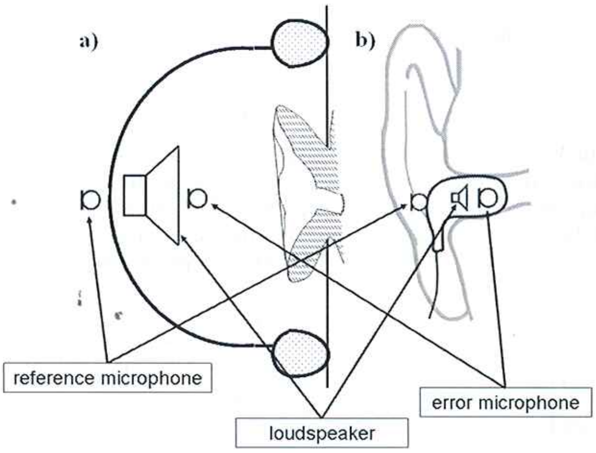

Figure 2: Schematic representation of a circum-aural (b) and an in-ear (b) headphone with ANR applications, © IMR

2 PROBLEM STATEMENT

When measuring the transfer functions P1, P2 and S2 (figure 3) of a few subjects, we notice that these have strong interpersonal variances. Therefore this chapter discusses the influences on the feedforward and feedback ANR strategies.

2.1 Feedforward

First, the influences of the variances on the feedforward filter W are discussed.

The approach of the optimal feedforward filter is based on the following model (figure 3):

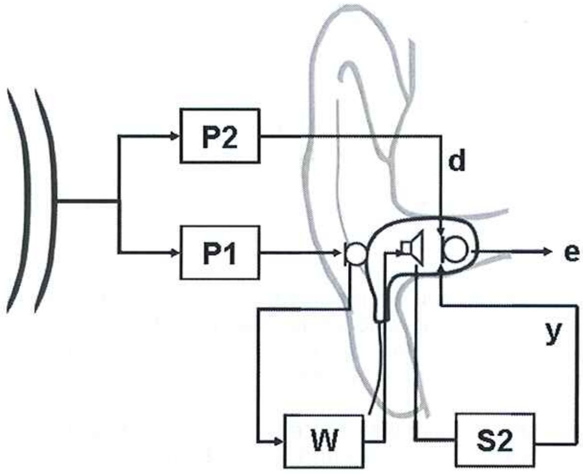

Figure 3: Representation of an in-ear ANR headphone with the acoustical transfer functions P1, P2 and S2 and the electrical feedforward filter W, © IMR

To use the model in this case, it is necessary that the transfer functions are linear and time invariant. That has been proven by measuring the coherence in the relevant frequency range.

The optimal feedforward filter W_{opt} results in minimizing the noise level *e* at the error microphone:

$$e=d+y\rightarrow 0 \tag{1}$$

This results in:

$$W_{opt}=-\frac{P2}{P1\cdot S2} \tag{2}$$

But W_{opt} can be unstable and / or not causal. To avoid this problem we used the FxLMS algorithm [4]. This algorithm produces an optimal FIR filter W_{opt}^* by minimizing the quadratic error. The frequency responses of the optimal filters W_{opt}^* of a few subjects are shown in figure 4:

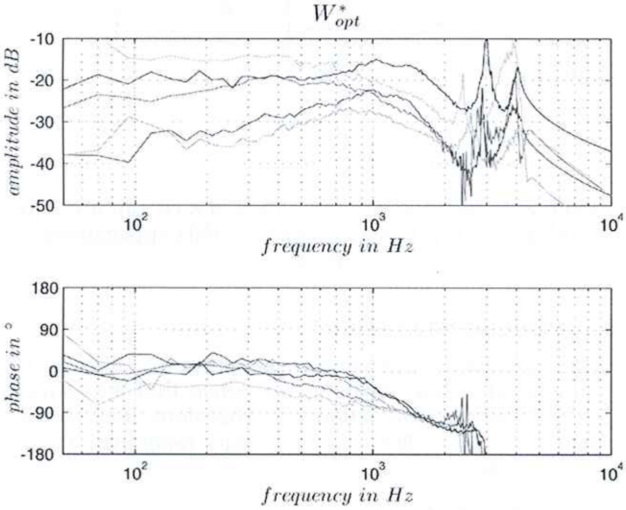

Figure 4: Bode plot of optimal FIR feedforward filters, ©IMR

It is noticeable that the interpersonal variances have a strong effect on the optimal feedforward filter. Hence it is not possible to use the same static feedforward filter for all subjects to achieve a good broadband attenuation of disturbing acoustical noise.

So an adaptive feedforward filter with low computational complexity has to be developed.

2.2 Feedback

The feedback ANR controller is a disturbance variable controller. The closed loop block diagram can be considered as follows:

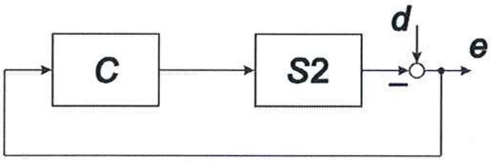

Figure 5: Block diagram of the standard feedback noise controller, © IMR

Obviously the design of the controller C is just affected by the plant S2. The interpersonal variances are illustrated in figure 6. Because of these variances it is not possible to design a controller with a good noise attenuation performance in a given frequency range and a small amplification apart from that for any subject.

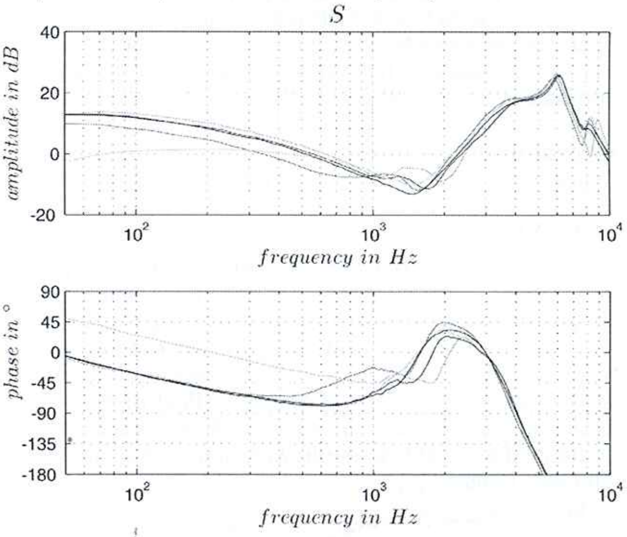

Figure 6: Plant S2 of different subjects, © IMR

3 APPROACH

As described in the second chapter, adaptive filters are needed to compensate the interpersonal spreads. Thereby the devices must be cheep and low-current. Hence a full adaptive filter, like the listed LMS algorithm, is not suitable. So the aim is to find an adaptive filter, which is a good compromise between computational complexity and ANR effects.

3.1 Feedforward

First, the following adaptive feedforward filters will be analyzed [3]. They are a composition of a static IIR filter W_{stat} and an adaptive FIR filter W_{adap}:

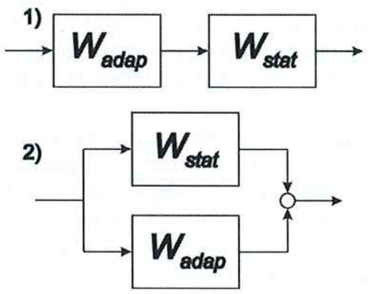

Figure 7: Two possible compositions of a static and an adaptive filter, © IMR

Afterwards the replacement of W_{adap} by an adaptive IIR filter will be investigated. These filters have two main advantages compared to FIR filters: It is possible to emulate every given linear system exactly. And they need fewer parameters linked with a low computational complexity to do this. The disadvantages of adaptive IIR filters are:

- potential instability
- local minima
- slow convergence rate

A possibility to assure stability is presented in [6] but anyhow with a slow convergence rate.

3.2 Feedback

The plant S2 always has an acoustical delay which corresponds to a system dead time. Because of that, ANR controllers are generally that way designed that the disturbance variable (3) has a good damping in the lower frequency range and nevertheless a small amplification apart from that. Most important for every feedback controller in ANR is to minimize the disturbance variable:

$$\frac{E}{D}=\frac{1}{1+C\cdot S2} \qquad (3)$$

This equation shows that both the zeros and poles of the controller affect the poles of the closed loop. For that reason the system can be instable by using an adaptive controller even when the controller is stable.

Therefore the internal model control technique (IMC) is used to design an adaptive feedback controller [5]:

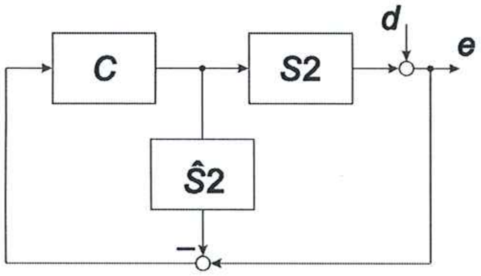

Figure 8: Block diagram of the IMC feedback controller, © IMR

This results in:

$$\frac{E}{D}=\frac{1+C\cdot\hat{S}2}{1+C\cdot(\hat{S}2-S2)} \qquad (4)$$

Is $\hat{S}2\approx S2$ than (4) comes to the following simplification:

$$\frac{E}{D}\approx 1+C\cdot\hat{S}2 \qquad (5)$$

Now the poles of the system match the poles of the controller C. If C is stable and $\hat{S}2\approx S2$ than the system is also stable. In addition the theoretical optimal controller results in:

$$C=-\frac{1}{\hat{S}2} \qquad (6)$$

The plant and consequently the model are not minimum-phase because of the dead time. Hence equation 6 leads to an instable controller. It remains to be seen how to design a controller which is stable and has a good performance.

Yet aside from that the effects of the deviation between $S2$ and $\hat{S}2$ to the closed loop have to be discussed later on.

4 CONCLUSION

Interpersonal variances in in-ear ANR headphones and their effects to the feedforward and feedback strategies were shown. The result is that it is not suitable to use a static feedforward filter. A few possible approaches to develop an adaptive one were demonstrated in Chapter 3.1.

The influences even make it hard to design a strong feedback controller. In Chapter 3.2 the IMC technique was presented to use an adaptive feedback controller. But also in this method the interpersonal spread of the plant becomes more important.

In future work the described approaches have to be investigated.

5 REFERENCES

[1] Feldmann H.: Das Gutachten des Hals-Nasen-Ohren-Arztes. G. Thieme Verlag Stuttgart, 6. Aufl. 2006

[2] Foudhaili H.: Kombinierte Feedback- und adaptive Feedforward-Regelung für die aktive Lärmreduktion in einem Kommunikations-Headset. Shaker Verlag, Aachen 2008

[3] Graf J.: Berechnungseffiziente Regelstrategien zur aktiven Lärmreduktion in Headsets. Shaker Verlag, Aachen 2009

[4] Kuo, S. M.; Morgan D. R.: Active Noise Control in Systems Algorithms and DSP Implementations. Wilex-Interscience Publication, New York 1996

[5] Kuo, S. M.; Morgan D. R.: Active Noise Control System for Headphone Applications. IEEE Transactions on Control Systems Technology, Vol. 14, No. 2, pp. 331-5, MARCH 2006

[6] Larimore M. G.; Treichler J. R.; Johnson C. R. Jr.: SHARF: An Algorithm for Adapting IIR Digital Filters. IEEE Transactions on Acoustics, Speech, and Signal Processing, Vol. ASSP-28, No. 4, pp. 428-40, August 1980.