Combination of non-Adaptive and Adaptive Control Strategies for Active Noise Reduction in Headsets

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Abstract ANR (Active Noise Reduction) Headsets are hearing protection devices which cancel disturbing acoustical noise by an out-of-phase antinoise. To generate antinoise, commercial ANR Headsets typically use a non-adaptive feedback controller. In academic research, the use of adaptive controllers in active noise reduction has been increasingly investigated during the last two decades. In some approaches the combination of non-adaptive and adaptive control strategies is proposed. The non-adaptive controller guarantees a minimal steady-state noise attenuation in a bounded frequency range, whereas the adaptive controller is able to adapt its behaviour to changing conditions, and hence to augment the overall noise reduction. Even though combination strategies of non-adaptive and adaptive controllers perform well in academic research, no commercial ANR headset based on this approach is yet on the market. One major reason for this fact is the high computational complexity linked to the adaptive algorithms used. In this paper, a computationally effective combination of non-adaptive and adaptive controllers is proposed. The implemented algorithm results in a similar noise reduction performance as existing approaches while limiting the computational effort. The developed algorithm is implemented on a DSP platform and the noise reduction is verified in conjunction with a prototype headset.

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1 Introduction

Nowadays, commercial active noise reduction headsets usually use either feedback control or feedforward control strategies to actively attenuate noise in a headset's ear cups [1]. In supra-aural headsets where the ear is not enclosed by the ear cups, feedforward control is applicable. In case of circum-aural headsets, the feedback control strategy is more suitable. Recently, adaptive control strategies are increasingly being proposed in ANC applications. However, the computational complexity linked with adaptive control algorithms is a burden to dead with when developing commercial headsets. Thus, most products use exclusively non-adaptive feedback control techniques to attenuate disturbing noise. In the last two decades the processing power of commercial digital signal processors grew immensely and thus researchers developed more complex adaptive active noise control techniques and combined them with non-adaptive controllers. Different approaches are published to combine non-adaptive feedback with adaptive feedforward controllers. Concerning the feedback controller, in many applications the internal model control technique (IMC) is used as to provide attenuation at low frequencies [2]. Even though this approach produces promising results under laboratory conditions, the attenuation is limited in realistic surroundings. In contrast to the IMC approach, the standard feedback controller combined with an adaptive feedforward controller [3], results in better attenuation performance under realistic conditions. However, this combination strategy still suffers from high computational demand.

In this paper we suggest a combination of a continuous time non-adaptive feedback controller combined with a discrete time adaptive feedforward controller. The continuous time feedback controller of this combination strategy permits to reduce computational complexity. A further advantage of this combination method lies in less dead time of the continuous time control loop. In case of a discrete time feedback controller the dead time is introduced by the sample based processing as well as the latency linked to the data conversion. Since the dead time produces a considerable phase lag of the open loop control system, in less dead time results a larger stability margin. The proposed control strategy is implemented on a digital signal processor platform. A commercial headset, the PXC 450 of Sennheiser electronic, provided the acoustical platform for the new prototype.

2 Problem Statement

Three interlinked critical issues are identified in conjunction with discrete time feedback controllers: Controller stability, noise attenuation performance and computational complexity.

Obtaining significant noise attenuation in conjunction with reduced computational complexity is the ultimate objective in active noise control. The following section describes advantages of the continuous time feedback control approach compared to a discrete time feedback implementation and highlights the restrictions regarding

controller design by maintaining the stability of the closed control loop.
For convenience, in the following sections the term continuous time controller is replaced by analogue controller and in case of a discrete time controller the term digital controller is used.

2.1 Digital Feedback Control Versus Analogue Feedback Control

The standard closed loop block diagram of a feedback noise control system is shown in figure 1. Related to the depicted control structure, the feedback controller $R(z)$ has to be designed in terms of minimizing the residual error $e(n)$ and thus minimizing the disturbing noise $d(n)$. To find a capable controller, several redesigns of the controller are necessary. Accordingly, due to its flexibility, the use of digital feedback controllers is better suited during the development phase.
Usually, the controller design is based on a plant model $S(z)$ of the secondary path. Because the plant is subject to only minor changes, it can be assumed to be nearly constant. This constant plant enables the design of a stable non-adaptive feedback controller. In case the non-adaptive controller is implemented digitally, the closed loop control suffers from increased dead time. One component of the introduced dead time results from time delay of A/D and D/A-conversions. Further dead time is induced due to the calculation time that is needed to compute the controllers output.
Even a larger dead time than the calculation time is caused by some digital platforms. This larger dead time occurs when signals are outputted strictly at the end of the sample interval, while input signals are picked up at the beginning. In this case, a fixed dead time which is linked to the length of the sample interval is added to the plant. Figure 2 illustrates the above problematic by opposing an analogue plant with

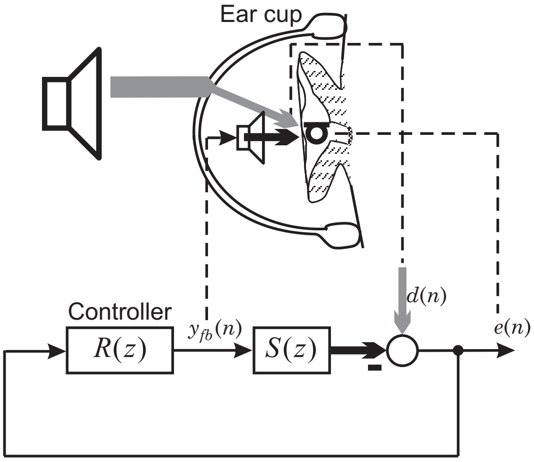
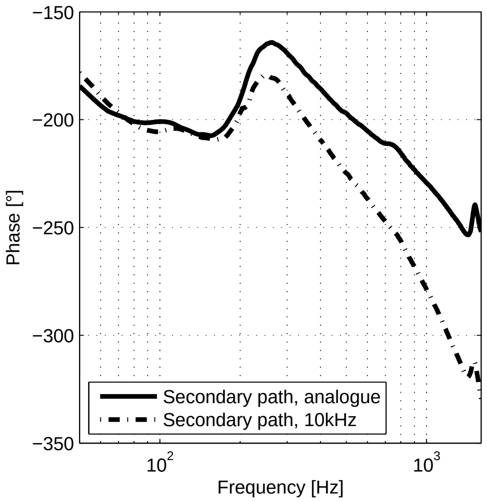


Fig. 1 The block diagram of the standard closed loop feedback noise controller is shown. $S(z)$ is the transfer function of the plant. The control loudspeaker which is located inside the ear cup, is involved in the plant model. The plant is also called secondary path in active noise control. $y_{fb}(n)$ denotes the actuating variable of the feedback controller and $d(n)$ represents the disturbing noise.

Fig. 2 Bode plot of two different plants. The plant which contains exclusively of analogue components shows less phase lag than the secondary path containing digital components. Thus, regarding feedback controller design, the analogue plant guarantees better stability margins.



a digital plant. Obviously, the phase lag increases when the plant involves digital components. The larger phase lag results in a smaller phase margin of the closed loop control system. Consequently, a worse attenuation performance of the digital implemented feedback controller is measured.

A further crucial issue related to digital feedback controllers is the limited computational performance of digital signal processors. Usually, in addition to the feedback controller other computations have to be accomplished. Thus, in case the signal processor operates at full capacity, no further computation time is available for feedback controller. This is especially a problem when the controller is a high-order system.

All the above mentioned problems related to digital controllers can be avoided by using an analogue instead of a digital feedback controller.

2.2 *Advantages of Analogue Feedback Controllers in Combination with Adaptive Feedforward Controllers*

In order to achieve broadband noise attenuation, some research works suggest active ANR systems in which different control strategies are combined. One approach is to combine a non-adaptive feedback controller with an adaptive feedforward controller. In the framework of such an ANR system, the non-adaptive feedback controller often is implemented digitally which causes several disadvantages compared to an analogue realisation. In the following, the advantages of an analogue feedback controller in combined with an adaptive feedforward controller are discussed.

As mentioned in section 2.1, analogue closed control loops suffer less from dead time than digital closed control loops. Because of this, a larger phase margin and hence a better stability is achieved with an analogue implementation. The larger phase margin can be used to enhance control performance. This results in better noise attenuation of the closed control loop. Thus, better attenuation discharges the adaptive feedforward controller in the corresponding frequency range.

In case of digital adaptive feedforward controllers, the processing power to adapt the controller's parameters is limited. Discharging the processor by the analogue feedback implementation makes it feasible to use digital signal processors with less processing power. Alternatively, the released processing power can be used to realise an adaptive feedforward controller with more filter coefficients.

The issues mentioned above motivate the implementation of an analogue feedback controller combined with a digital adaptive feedforward noise controller.

3 Combination of non-Adaptive Feedback with Adaptive Feedforward Control

By exclusively using a feedback controller, an active noise control system is obtained, that is especially able to attenuate low frequency components of the disturbing noise spectrum [5]. Higher frequencies are not affected due to the phase shift introduced by the dead time of the secondary path. Unlike feedback controllers, feedforward control systems do not suffer from dead time and thus are able to attenuate disturbances of higher frequency. Therefore, several active noise control systems are developed, which link the feedback control and the feedforward control approach to accomplish attenuation in a wider frequency range [2],[3],[4].

3.1 Analogue Feedback Controller Design

Before the combination of the analogue feedback controller and the digital adaptive feedforward controller is discussed, some considerations of feedback controller design are stated in this paragraph.

Under steady-state conditions, the primary noise $d(n)$ is transmitted to the error microphone via the plant which can be modeled as

$$\frac{E(z)}{D(z)} = \frac{1}{1+S(z)R(z)} \tag{1}$$

In order to minimize the error signal $e(n)$, a feedback controller $R(z)$ has to be designed that maximizes the term $1+S(z)R(z)$. Additionally, the controller design of $R(z)$ needs to be accomplished to guarantee robust stability. Therefore, it is essential to maximize the gain of $S(z)R(z)$ at low frequencies, while the phase shift has to be within the interval

$$-180^\circ < \phi < 180^\circ. \tag{2}$$

In consideration of the stability condition, a plant with increasing dead time directly results in less controller gain and thus less noise attenuation [5].

3.2 Combined Control Strategy for Broadband Active Noise Control

As already mentioned, the feedback controller guarantees noise attenuation in the lower frequency domain. In contrast, the feedforward control strategy permits to attenuate noise of higher frequencies. Hence, a combined control strategy is suggested which provides broadband noise attenuation.

The simplified block diagram of the combined ANR system is illustrated in figure 3. As the figure shows, the adaptive feedforward controller is linked to a subordinated standard feedback control loop [3]. The resulting actuating variable $y(n)$ is the sum composed of the actuating variable of the feedforward controller and the actuating variable of the subordinated feedback controller. It has to be emphasised, that the feedback controller is only realised with analogue components. Hence, the digital output of the feedforward controller has to be D/A-converted prior to the combina-

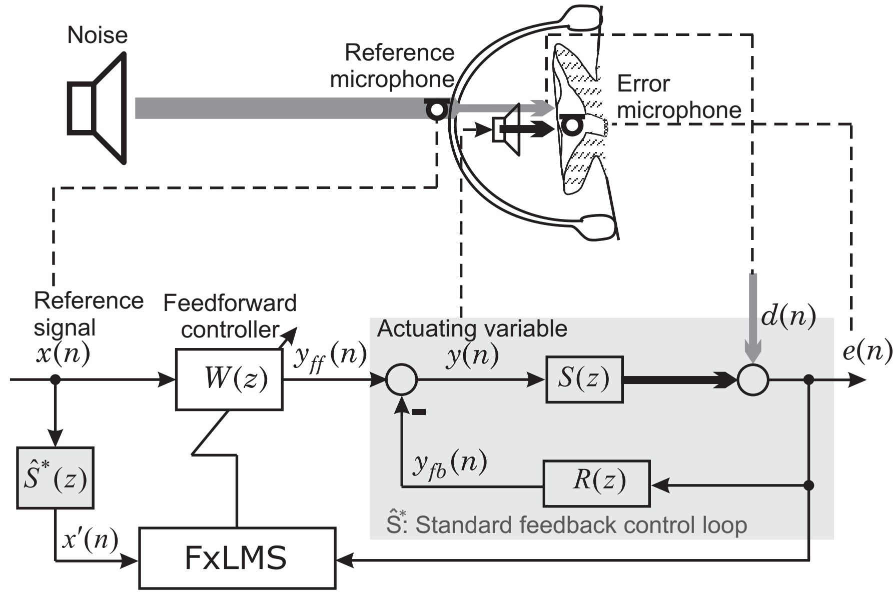


Fig. 3 Simplified ANR system consisting of a digital adaptive feedforward controller linked to a subordinated non-adaptive analogue feedforward controller. While the upper part illustrates the acoustical scheme, the lower part shows the block diagram of the control structure.

tion with the analogue output of the feedback control loop.

To guarantee stability, the feedforward controller is designed as a FIR-filter. The adaption of this filter is accomplished by the well known Filtered-x Least Mean Square (FxLMS) algorithm [6],[5]. The adaption equation to obtain the updated parameter vector $\mathbf{w(n+1)}$ is given by:

$$\begin{aligned} \mathbf{w(n+1)} &= \mathbf{w(n)} + \mu \cdot \mathbf{e(n)} \cdot \mathbf{x'(n)} \\ \mathbf{w(n)} &: \text{ Parameter vector} \\ \mathbf{x'(n)} &: \text{ Filtered reference} \\ e(n) &: \text{ Current error sample} \\ \mu &: \text{ Adaption step} \end{aligned} \tag{3}$$

In this update equation, $\mathbf{x'(n)}$ represents a time series vector of the filtered reference signal. To obtain $\mathbf{x'(n)}$, the reference signal $x(n)$ is filtered with the transfer function $\hat{S}^*(z)$ [3]. This transfer function models the system behaviour between the feedforward output $y_{ff}(n)$ and the error signal $e(n)$. $\hat{S}^*(z)$ can be expressed as:

$$\hat{S}^*(z) = \frac{E(z)}{Y_{ff}(z)} = \frac{S(z)}{1+S(z)R(z)} \tag{4}$$

The proposed combined control strategy results in a more efficient algorithm related to the computational effort as well as significant noise attenuation performance while maintaining robust stability.

4 Performance of the Combined ANR System

The presented combined ANR system is realised in conjunction with a headset based on the Sennheiser series product PXC 450, which already integrates an analogue feedback controller. In combination with the adaptive feedforward controller, this integrated feedback controller is used.

The digital adaptive feedforward controller is implemented on a `Sharc` digital signal processor with a 32 bit floating point unit. Figure 4 opposes the attenuation results of the analogue feedback controller to the combined ANR system with a feedforward filter implementing 140 coefficients. As the disturbing signal, a pink noise with a bandwidth of approximately 2500Hz is used. It should be noticed, that in real applications the disturbing noise mostly is narrowband. Since, the feedforward controller is able to adapt to those signals, this results in better attenuation performance compared to broadband noise excitation.

To verify the noise attenuation, a self constructed artificial dummy head with an ear simulator is used. The results presented in figure 4 were achieved under conditions reproducing average ear cup leakage.

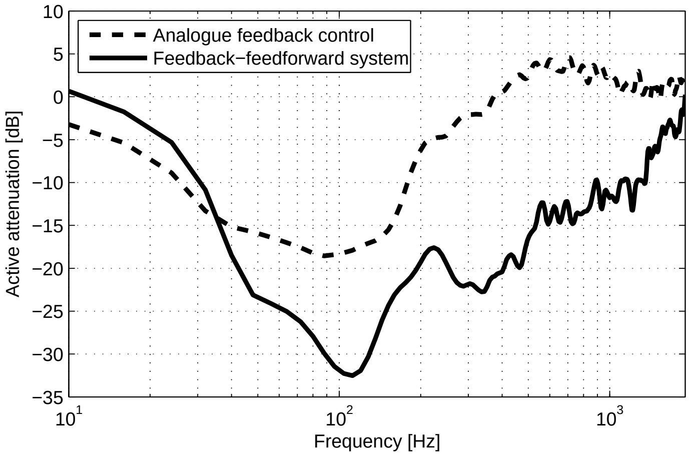


Fig. 4 Both curves represent a relative measurement between the passive attenuation and the active attenuation performance of the according ANR system. Zero dB of attenuation denotes that only passive attenuation of the headset's ear cup is available. The dashed line shows the noise attenuation at the dummy head's ear-microphone if only the analogue feedback controller operates while the solid line represents the attenuation performance of the combined ANR system .

5 Conclusion

In active noise control, digital feedback controllers usually suffer from dead time. An additional problem in conjunction with a digital implementation results from the computational effort. In case the DSP platform operates to full capacity this is always a problem. On account of the computational effort as well as the plant's dead time, an analogue feedback controller instead of a digital feedback controller is used. The analogue feedback control loop is combined with an adaptive feedforward controller to accomplish broadband noise attenuation.

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