Combined Control for Computationally Efficient Active Noise Reduction in Aviation Headsets

J. Graf[1], E. Reithmeier[1]
[1]Leibniz Universität Hannover, Germany

Corresponding author: J. Graf, Leibniz Universität Hannover,
30167 Hannover, Nienburger Strasse 17, Germany, jens.graf@imr.uni-hannover.de

Abstract. In commercial aviation ANR-headsets (Active Noise Reduction), the simple and computationally efficient non-adaptive feedback control approach is commonly used. However, this strategy causes a limited active attenuation performance. Especially in case of aircraft noise with narrowband dominant frequencies, it is favorable to attenuate these dominants more effectively. The reduction of the dominant frequency results in an enhanced hearing protection as well as in improved speech intelligibility of the communication signal.

In this paper, a computationally efficient control approach, which permits the reduction of low frequency noise with a single dominant frequency, is presented. In the framework of the proposed control strategy, the combination of a non-adaptive feedback controller and an adaptive narrowband feedforward controller is suggested. While the non-adaptive feedback controller permits the reduction of the broadband low frequency noise, the dominant frequency is further reduced by the adaptive narrowband feedforward controller. The performance of the proposed control strategy is discussed and concluding remarks are given.

1 Introduction

In case of high level noise (above 100 dB), the passive attenuation of a headset's ear-cup is insufficient. Thus, active noise reduction methods are used to improve the overall noise reduction of the headset. Commercial ANR-headsets enhance the passive noise attenuation in the lower frequency range using a non-adaptive feedback controller [1] [2] [3]. A typical application of such an ANR-headset is the hearing protection of the cabin crew of propeller driven aircrafts [1]. The engines of such aircrafts produce high level noise with dominant single frequency components in the low frequency range.

As already stated, the feedback control strategy is commonly used in order to actively attenuate the disturbing noise. On one hand, this control approach accomplishes broadband steady-state noise reduction and guarantees an active attenuation by up to 20 dB [4]. On the other hand however, it is impossible to completely eliminate the dominant frequency component. In this paper, a computationally efficient control approach, which attenuates broadband low frequency noise as well as the dominant disturbing frequency, is presented. Since ANR-headsets use an audio signal for communication purposes, the compensation of the dominant frequency results in improved communication intelligibility.

The next section covers advantages and disadvantages of the non-adaptive feedback control approach. Especially the attenuation performance of the feedback approach in case of existing dominant frequencies in the noise spectrum is discussed. Section 3 describes the proposed noise controller that accomplishes broadband low frequency noise reduction as well as the compensation of the dominant frequency. In section 4 the noise reduction performance of the proposed control strategy is illustrated and concluding remarks are given in section 5.

2 Problem Statement

With regard to ANR-headsets, the non-adaptive feedback control technique is simple to implement, computationally efficient and thus cost-efficient to realize. This approach guarantees steady state noise reduction in a frequency range below 300 Hz [5]. However, in case of high level cabin noise of turbo propeller aircrafts, the disturbing noise is often characterized by a dominant frequency component. For example the noise spectrum of a *Dornier DO228-212* aircraft is illustrated in figure 1. In this spectrum, the dominant frequency at 102Hz exceeds the noise spectrum by $15-20$ dB. Thus this dominant is perceived as especially disturbing by passengers. However, the complete compensation of the dominant is not feasible using solely the non-adaptive feedback control approach. One reason for this is the non-adaptive controller design which is always a compromise between noise reduction bandwidth and attenuation performance. Additionally, the controller design is based on one single representative model of the plant, which is in the domain of active noise control also referred to as the secondary path. In real applications however, the secondary path may change with varying ear-cup leakage. Therefore, a non-adaptive feedback controller is usually designed suboptimally and hence the overall compensation of the dominant disturbing frequency is not possible.

In order to compensate for the dominant frequency, an adaptive broadband feedforward system could be considered

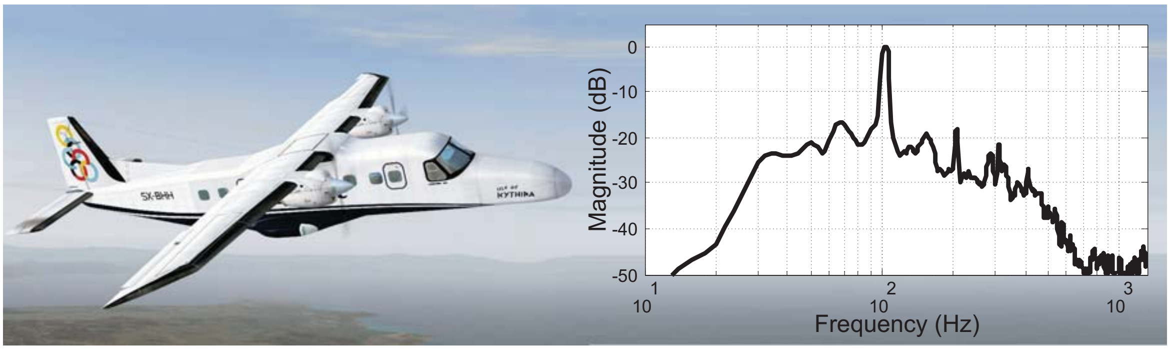

Figure 1: Left: *Dornier DO228-212* turbo prop aircraft. Right: Cabin noise spectrum of the aircraft. The dominant frequency of 102 Hz exceeds the noise spectrum by up to 20 dB.

[1] [4]. Even though such an adaptive broadband approach effectively reduces dominant frequencies, often more than 100 adaptive filter taps [4] are necessary. This amount of filter taps results in a considerable computational effort and thus in a complex and computationally expensive ANR-system. However, more promising with respect to the computational efficiency is an adaptive single frequency feedforward approach which only necessitates two adaptive parameters for the compensation of the dominant frequency. The design of this so called adaptive notch-filter is described in the following section.

3 Noise Controller Design

As previously mentioned, the noise power of turbo prop aircrafts is especially located in the low frequency range and has, in case of the *Dornier DO228-212* aircraft, a dominant frequency at 102 Hz. In the framework of the subsequently described control approach, low frequency broadband attenuation is provided by a non-adaptive feedback controller and the dominant disturbance is further reduced by an adaptive single frequency feedforward controller. Since this single frequency controller only compensates for one frequency, it is also referred to as an adaptive notch-filter [2].

3.1 Adaptive Notch-Filter

In order to compensate for the dominant frequency, the adaptive system has to generate a monofrequent wave with the same frequency as the disturbing dominant frequency, but with 180° of phase shift. According to figure 2a, the compensation signal $y(n)$ is represented by a complex vector with the angular frequency ω. The real sinusoidal signal is obtained by projecting the complex vector onto the real-axis. As depicted, the compensation signal can be synthesized by the superposition of two other sinusoidal signals which are referred to as the reference signals:

$$x_0(n) = \hat{x}_0 \cos(\omega n) \quad (1)$$
$$x_1(n) = \hat{x}_1 \cos(\omega n + \theta_1). \quad (2)$$

However, in real applications the amplidude as well as the phase of the dominant frequency varies and thus the synthesized compensation signal $y(n)$ has to be adapted to these variations. This is accomplished by the introduction of two adaptive weights w_0 and w_1 which modulate the amplitudes of the reference signals. Choosing the angle between the two reference signals as $\theta_1 = 90°$ [2], the adaptive sine synthesis results in:

$$y(n) = w_0(n)x_0(n) + w_1(n)x_1(n) \quad (3)$$

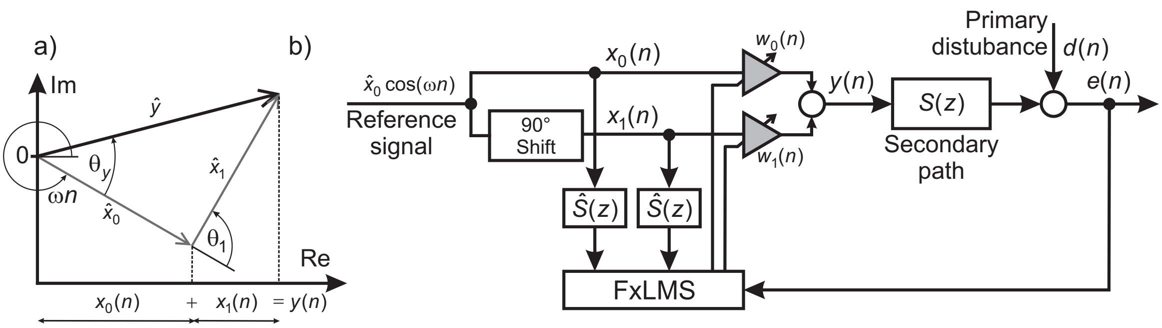

Figure 2: a) The compensating signal $y(n)$ is synthesized by two reference sines $x_0(n)$ and $x_1(n)$. b) Adaptive notch-filter with two adaptive parameters w_0 and w_1.

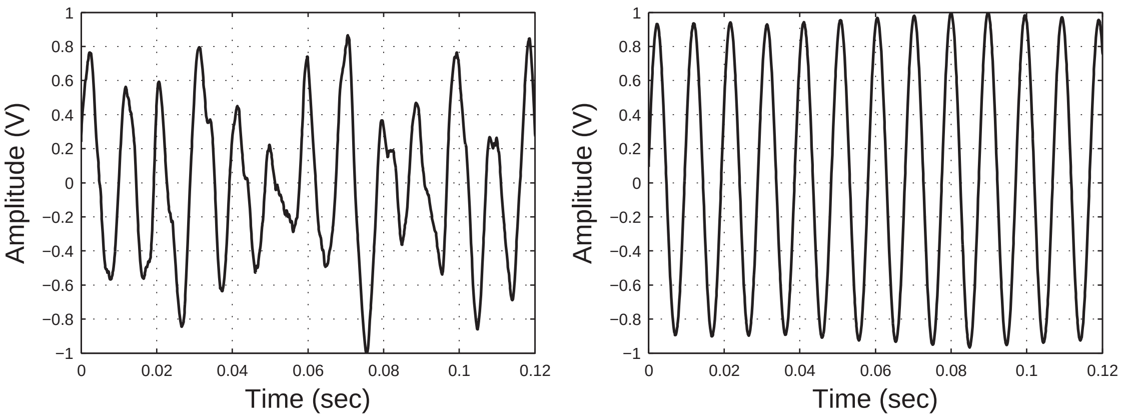

Figure 3: Left: Unfiltered reference signal. Right: Reference signal after filtering. Remark: Both signals are normalized to the amplitude of one volt.

$$\underbrace{\hat{y}\cos(\omega n+\theta_y)}_{y(n)} = w_0(n)\underbrace{\hat{x}_0\cos(\omega n)}_{x_0(n)}+w_1(n)\underbrace{\hat{x}_1\sin(\omega n)}_{x_1(n)}. \quad (4)$$

The obtained synthesis method is illustrated as a block diagram in figure 2b. The reference input of the two weight adaptive filter is formed by an undisrupted sinusoidal signal $x_0(n)$ that has the identical angular frequency ω as the disturbing dominant. However, the reference input can be abitrary regarding amplitude and phase. The update of the weights w_0 and w_1 is accomplished by the well known filtered-x least mean squares (FxLMS) algorithm:

$$w_0(n+1) = w_0(n)+\mu x_0'(n)e(n) \quad (5)$$

$$w_1(n+1) = w_1(n)+\mu x_1'(n)e(n). \quad (6)$$

3.2 Acquisition and Processing of the Reference Signal

In order to achieve reasonable attenuation of the dominant frequency, the sinusoidal reference signals $x_0(n)$ and $x_1(n)$ have to be accurate in frequency and additionally as narrowband as possible. Therefore, non-acoustic sensors such as accelerometers or tachometers are commonly used to obtain an undisturbed sinusoidal reference signals [2]. However, in conjunction with headsets the application of such non-acoustical sensors is impractical, the acquisition of the reference signal using a microphone is suggested. This microphone is located at the outside of the ear cup and thus the signal contains the complete spectrum of the disturbing noise. In order to obtain solely the dominant sine wave, the filtering with a very narrow bandpass filter is unavoidable. The bandpass filtering guarantees the pass of the dominant frequency by simultaneously suppressing peripheral noise components. The so processed reference signal is shown in the right part of figure 3. Such an undisturbed signal can be used for the reference input $x_0(n)$ of the adaptive notch-filter.

3.3 Combining the Notch-Filter and the non-adaptive Feedback Controller

The adaptive notch-filter exclusively accomplishes the compensation of the dominant frequency. Disturbing noise as depicted in figure 1 however, additionally consists of broadband noise components. In order to attenuate this broadband noise, a non-adaptive standard feedback control loop according to figure 4 is used. The feedback controller is designed as a time discrete transfer function and realized on the same digital platform as the adaptive notch-filter. On one hand, the digital implementation involves the disadvantage of an increased latency compared to an analog realization [4]. On the other hand however, a digital implementation is preferred in case of very limited volume onto the circuit board. Also, in some applications, the DSP may not operate at full computational capacity. Thus, computational resources can be used in order to calculate the actuating variable of the non-adaptive feedback controller.

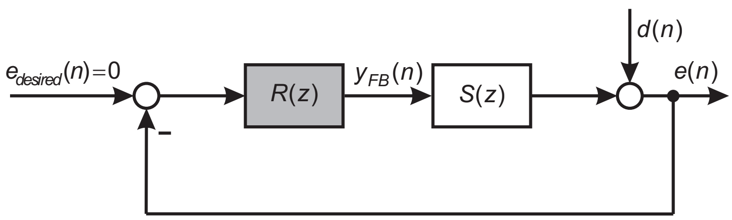

Figure 4: Standard control loop for active nose reduction. Signals: desired value $e_{desired}$, primary noise $d(n)$, actuating variable $y_{FB}(n)$ and error signal $e(n)$. Transfer functions: controller $R(z)$ and secondary path $S(z)$.

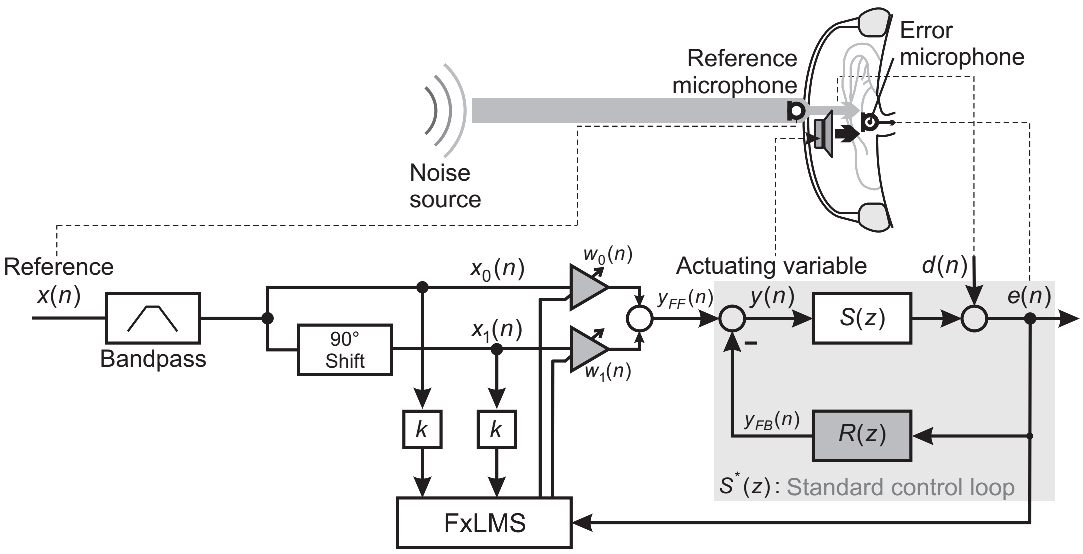

Figure 5: Combined control approach consisting of a non-adaptive feedback controller linked to an adaptive notch-filter. The upper part shows a sketch of the acoustical front-end including two microphones and the compensation loudspeaker.

According to figure 5, both described ANR-methods (the adaptive notch-filter and the standard feedback control loop) are linked to a combined ANR-controller. The control law of the combined controller is given by:

$$y(n) = w_0(n)x_0(n) + w_1(n)x_1(n) - \mathscr{Z}^{-1}\{R(z)E(z)\}. \quad (7)$$

In case of a combined controller, attention has to be paid to the modelling of the secondary path. The secondary path influences the convergence behavior of the FxLMS-algorithm and has to be modeled in order to filter the reference signals $x_0(n)$ and $x_1(n)$. In contrast to figure 2, the secondary path of the combined control system includes the closed feedback loop:

$$S^*(z) = \frac{E(z)}{Y_{ff}(z)} = \frac{S(z)}{1+S(z)R(z).} \quad (8)$$

In case of broadband adaptive feedforward ANR-systems, the secondary path $S^*(z)$ has to be modeled over a wide frequency range in order to filter the reference signals $x_0(n)$ and $x_1(n)$:

$$x_0'(n) = \mathscr{Z}^{-1}\{X_0(z)\hat{S}^*(z)\} \quad (9)$$

$$x_1'(n) = \mathscr{Z}^{-1}\{X_1(z)\hat{S}^*(z)\}. \quad (10)$$

However, in this paper only one single frequency, the dominant, is compensated. Therefore, a simplification compared to the filtering of equation 10 is suggested. In contrast to a filtering with $\hat{S}^*(z)$, the secondary path is modeled at only one single frequency which is the frequency of the dominant sine wave. Thus, the filtering with closed feedback loop model $\hat{S}^*(z)$ reduces to a simple multiplication:

$$x_0'(n) = k \cdot x_0(n) \quad (11)$$

$$x_1'(n) = k \cdot x_1(n). \quad (12)$$

In order to account for variations of the signal power, the normalized FxLMS-algorithm is used for the parameter update [2]. Signal distortion due to a limited actuating variable is prevented by the implementation of an adaptive leakage factor as proposed in [1].

The suggested combined control strategy efficiently guarantees the compensation of the dominant frequency as well as the attenuation of broadband low frequency noise. The noise reduction performance is discussed in the following section.

4 Noise Reduction Performance

The combined control strategy is implemented on a C-programmable digital platform including a digital signal processor and an A/D- and D/A-converter board. The non-adaptive feedback controller is realized as a ten order transfer function and the adaptive notch-filter merely necessitates two adaptive parameters. The acoustical front-end is identical to the ear-cups of the commercial product *HMEC 350*.

In order to validate the active noise attenuation performance, a test-head with an integrated ear simulator is used. In order to conduct the experiments under realistic conditions, an average ear-cup leakage is reproduced and the

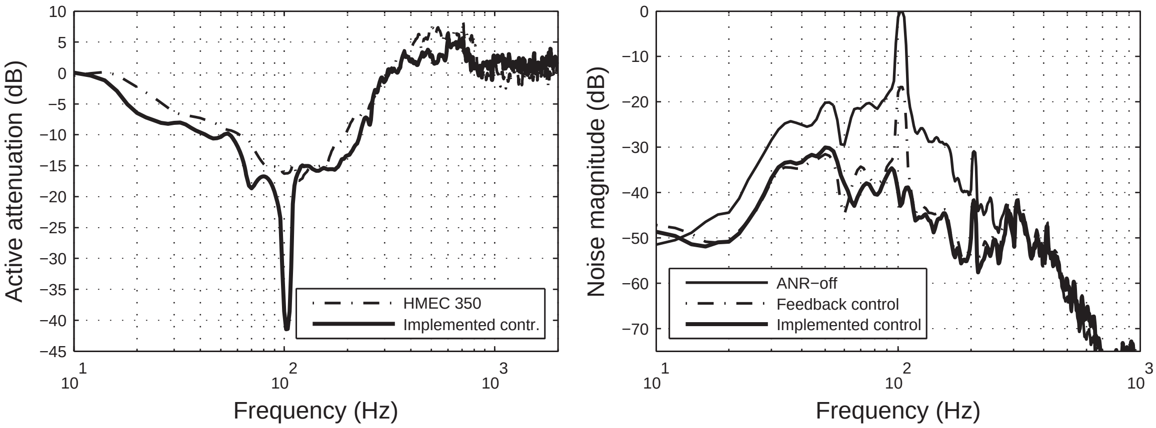

Figure 6: Left: Active noise reduction performance: Commercial product *HMEC 350* vs. the implemented combined controller. Right: Normalized noise spectra measured at the ear microphone of the test-head.

noise reduction is measured at the ear simulator's microphone rather than at the controller's error microphone. As the disturbing noise, the cabin noise of a *Dornier DO228-212* turbo prop aircraft with the frequency spectrum as depicted in figure 1 is used.

In the left part of figure 6, the active noise reduction performance of the proposed combined controller is compared to the commercial product *HMEC 350*. The illustrated attenuation curves are obtained on the basis of two measurements. The first measurement is conduced with an inactive noise controller and the second measurement is accomplished with activated control. However, the left diagram shows the difference between these measurements for the commercial product in comparison with the proposed combined control strategy. It can be seen that in case of the commercial product *HMEC 350* the broadband low frequency noise is attenuated by up to 15 dB. Approximately equal broadband noise reduction shows the proposed combined control approach. However, additionally the dominant frequency at 102 Hz is reduced by further 25 dB. Considering the sprectra depicted in the right part of figure 6, apparently a overall compensation of the dominant frequency is accomplished (bold solid line). In contrast, the dominant frequency is still present in the noise spectrum in case of using a single non-adaptive feedback controller (dashed line).
Remark: In the right part of the figure the spectra are normalized relative to the maximal amplitude of the dominant frequency.

5 Conclusion

In order to reduce high level cabin noise of aircrafts, commercial aviation ANR-headsets commonly use the non-adaptive feedback control approach. In case of turbo prop aircrafts, the noise spectrum produced by the engines consists of broadband low frequency noise with a dominant frequency of high signal power. This dominant is perceived as especially disturbing by passengers and is insufficiently attenuated using solely a non-adaptive feedback controller. Therefore, a combined control approach that reduces the broadband low frequency noise and additionally the dominant frequency is proposed. The broadband noise is attenuated using a non-adaptive feedback controller, whereas the dominant frequency is compensated by an adaptive notch-filter. The realization of this approach results in a simple and efficient algorithm that does not require a fast and expensive digital signal processor. The design of the combined control approach is described and the attenuation performance is compared to a commercial aviation ANR-headset. It is shown that the attenuation of the dominant frequency is improved by up to 25 dB compared to the commercial product.

6 References

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

[2] Kuo, S.M., Morgan, D.R.: *Active Noise Control Systems - Algorithms and DSP Implementations*. Wiley-Interscience Publication, New York, 1996.

[3] Elliott, S.J.: *Signal processing for active control*. Academic Press, San Diego, 2001.

[4] Reithmeier, E., Graf, J.: *Combination of non-Adaptive and Adaptive Control Strategies for Active Noise Reduction in Headsets*. Proc. 9th International Conference on Motion and Vibration Control, Munich, 2008.

[5] Wolter, B., Peissig, J., Foudhaili, H., Reithmeier, E.: *Combined feedback and adaptive feedforward active noise control in headsets*. Proc. 36th International Congress and Exhibition on Noise Control Engineering, Internoise, Istanbul, 2007.