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A FEEDFORWARD ACTIVE NOISE CONTROL SYSTEM FOR DUCTS USING A PASSIVE SILENCER TO REDUCE ACOUSTIC FEEDBACK

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Abstract

Ventilation systems installed in buildings usually generate low-frequency noise because the passive silencers commonly used to attenuate the ventilation noise are not effective in the low-frequency range. A method proven to effectively reduce low-frequency noise in a wide variety of applications is active noise control (ANC). A feedforward ANC system applied to duct noise normally uses a reference microphone, a control unit, a loudspeaker to generate the secondary noise created by the controller, and an error microphone. The secondary noise generated by the loudspeaker will travel both downstream canceling the primary noise, and upstream to the reference microphone, i.e. acoustic feedback. The acoustic feedback may result in performance reduction and stability problems of the control system. Common approaches to solve the feedback problem result in more complex controller structures and/or system configurations than the simple feedforward controller, e.g. introducing a feedback cancellation filter in the controller in parallel with the acoustic feedback path, or using a dual-microphone reference sensing system. This paper presents a simple approach to reduce the acoustic feedback by using a basic feedforward controller in combination with a passive silencer. Simulations show that efficient acoustic feedback cancellation is achieved by using a passive silencer. In the experimental setup another advantage with using a passive silencer is that the frequency response function of the forward path, which is to be estimated, is smoother, i.e. most of the dominant frequency peaks in the frequency response function when *not* using a passive silencer is reduced. This in turn results in an acoustic path that is less complex to estimate with high accuracy using an adaptive FIR filter steered with the LMS algorithm.

1. INTRODUCTION

Normally, an acoustic single-channel feedforward ANC system applied to duct noise consists of a reference microphone to pick up the noise propagating through the duct, a controller in which an adaptive algorithm is implemented, a loudspeaker to generate the secondary noise created by the controller and an error microphone to monitor the residual noise after control [1]. The reference microphone generates a reference signal which is fed to the controller. In the controller the reference signal is filtered with an adaptive FIR filter to create an output sent to the loudspeaker which is in anti-phase with the primary noise by the time it reaches the placement of the error microphone. Primary noise that correlates with the reference signal will be attenuated downstream of the loudspeaker and a high correlation is required to obtain a high noise attenuation. The error microphone in turn generates an error signal to the controller where the adaptive algorithm uses it to update the filter coefficients of the adaptive filter with the purpose of continuously minimizing the noise sensed by the error microphone in the mean-squared sense. A common problem when applying feedforward ANC to attenuate ventilation noise, is the fact that the secondary noise produced by the loudspeaker not only travels downstream attenuating the primary noise, but also upstream to the reference microphone. This is often referred to as acoustic feedback [1, 2]. The acoustic feedback corrupts the reference signal and may, depending on the gain in the feedback loop, result in an instability of the controller [1]. Accordingly, it is of highest importance to reduce the acoustic feedback to utilize the full noise reduction potential of the ANC system. Many approaches to reduce the acoustic feedback have been proposed, e.g. using a feedback neutralization filter in parallel with the feedback path [1], and dual-microphone sensing [3]. However, these solutions implies an increased complexity of the controller structure and/or system configuration.

The passive silencers commonly used to attenuate ventilation noise [4] are relatively ineffective in the low frequency range but have high attenuation in the higher frequency range where ANC is not very efficient. Therefore, combining these two, forming a hybrid passive/active silencer, is often an attractive solution resulting in attenuation over a broad frequency range. In this paper simulations of a hybrid passive/active silencer are presented. The simulations show that with the proper choosing and placement of the passive silencer, it can be used to attenuate the acoustic feedback, preserving the simple configuration of a single-channel feedforward ANC system. The method of using a passive silencer to attenuate the acoustic feedback is also compared to using a feedback neutralization filter in parallel with the acoustic feedback path. Furthermore, it is shown that when using the passive silencer the standing waves in the duct are less pronounced for the actual frequency range, resulting in an increased coherence between the reference- and error microphones which in turn leads to an increased performance of the ANC system.

2. EFFECTS OF ACOUSTIC FEEDBACK

In Fig. 1 a block diagram of a feedforward ANC system *without* acoustic feedback, using the filtered-x LMS algorithm is illustrated. In the figure, the primary path is denoted $P(z)$, the forward path $F(z)$, the estimate of the forward path $\hat{F}(z)$, the adaptive filter $W(z)$, the reference signal $x(n)$, the output from the adaptive filter $y(n)$, the primary noise signal $d(n)$, and the error signal $e(n)$. Assuming that the adaptive filter is time invariant, the error signal of the system in Fig. 1 may in the z-domain be written as

$$E(z) = P(z)\,X(z) + F(z)\,Y(z) = [P(z) + F(z)\,W(z)]\,X(z) \tag{1}$$

The goal of the adaptive filter, $W(z)$, is to minimize the error, $E(z)$, which in an ideal case will equal zero after the convergence of $W(z)$. Hence, setting $E(z) = 0$ in Eq. 1 gives the optimal

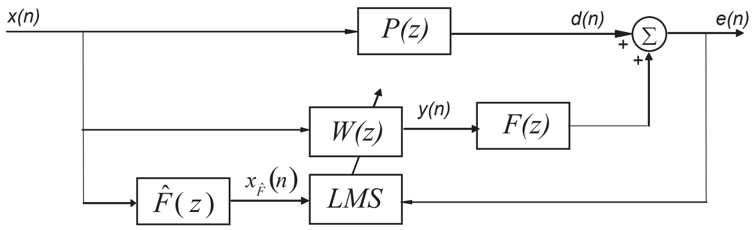


Figure 1. Block diagram of a feedforward ANC system without acoustic feedback using the filtered-x LMS algorithm.

filter as

$$W_o(z) = -\frac{P(z)}{F(z)} \tag{2}$$

Note, if the adaptive filter is realized as a FIR filter, to enable an accurate approximation of the optimal filter a FIR filter of sufficient order is required.
In Fig. 2 a block diagram of an ANC system *with* acoustic feedback, using the filtered-x LMS algorithm is illustrated. In the figure the feedback path is denoted $B(z)$, and the transfer function of the feedback loop is denoted $H(z)$.

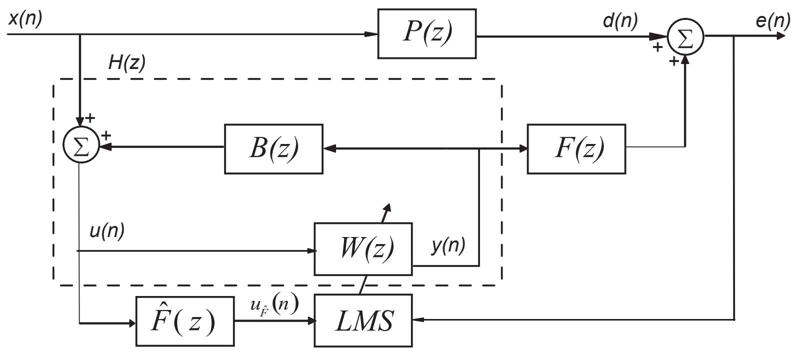


Figure 2. Block diagram of an ANC system with acoustic feedback using the filtered-x algorithm. The signal $x(n)$ is the reference signal related to the primary noise source and the signal $u(n)$ is the reference microphone signal including the contribution based on the acoustic feedback.

Assuming that the adaptive filter is time invariant, the output from the adaptive filter in Fig. 2 is given in z-domain by

$$Y(z) = W(z)\left[X(z) + B(z)Y(z)\right] \Leftrightarrow Y(z) = \frac{W(z)}{1 - W(z)B(z)}X(z) \tag{3}$$

Hence, the transfer function of the feedback loop, dashed and denoted $H(z)$ in Fig. 2, is given by

$$H(z) = \frac{W(z)}{1 - W(z)B(z)} \tag{4}$$

Eq. 4 indicates that the acoustic feedback is a source for instability. The open-loop transfer function associated with the feedback loop is given by $W(z)B(z)$, which is related both to the

control filter and the acoustic feedback path. According to Nyquist stability criterion instability will occur when the open-loop gain is greater than unity while the open-loop phase lag reaches $180°$ [5]. The system can be stabilized by restricting the magnitude of the coefficients in the control filter by using the leaky filtered-x LMS algorithm, if required with a high leakage [1]. This results in reduced noise attenuation since the controller does not converge to the optimum solution. If $H(z)$ becomes unstable it will result in an instability of the ANC system [1].
The error signal $E(z)$ in Fig. 2 is given by

$$E\left(z\right) = P\left(z\right) X\left(z\right) + F\left(z\right) Y\left(z\right) = X\left(z\right)\left[P\left(z\right) + \frac{F\left(z\right) W\left(z\right)}{1 - W\left(z\right) B\left(z\right)}\right] \tag{5}$$

Setting $E(z) = 0$ in Eq. 5 gives the optimal filter for the case with acoustic feedback as

$$W_o\left(z\right) = -\frac{P\left(z\right)}{F\left(z\right) - P\left(z\right) B\left(z\right)} \tag{6}$$

In comparing Eq. 6 and the optimal filter for feedforward control given by Eq. 2, the optimal filter coefficients for the system with acoustic feedback differ from the case with without acoustic feedback.

2.1. Feedback neutralization filter

In this method, a filter which is an estimate of the feedback path, $\hat{B}(z)$, is introduced in parallel with the actual feedback path, $B(z)$, as illustrated in Fig. 3. If $\hat{B}(z) = B(z)$ the contribution from the feedback is removed and hence the optimal filter of Eq. 6 becomes equal to Eq. 2. Hence a stable feedforward system without feedback is achieved.

2.2. Effects of introducing a passive silencer

When installing a passive silencer so that it is a part of the feedback- and primary paths, the primary path can be written as $P_{S_P}(z) = S_P(z)P(z)$ where $S_P(z)$ is the transfer path modification introduced in the primary path by the passive silencer and $P(z)$ is the primary path excluding the passive silencer. Consequently, the feedback path may be written as $B_{S_B}(z) = S_B(z)B(z)$ where $S_B(z)$ is the transfer path modification introduced in the feedback path by the passive silencer and $B(z)$ is the feedback path excluding the passive silencer. Rewriting Eq. 6 in terms of these expressions results in

$$W_o\left(z\right) = -\frac{S_P\left(z\right) P\left(z\right)}{F\left(z\right) - S_P\left(z\right) S_B\left(z\right) P\left(z\right) B\left(z\right)} \tag{7}$$

The passive silencer affects the paths $P_{S_P}(z)$ and $B_{S_B}(z)$. Accordingly, installing a passive silencer that produces high enough attenuation can remove the effects of the acoustic feedback, resulting in a stable feedforward system. Compare Eq. 7 with the pure feedforward controller given in Eq. 2. The standing waves in the duct become less pronounced when installing the passive silencer. As shown in Fig. 5 this leads to an increased coherence between the reference signal and the primary noise. The attenuation of the propagating sound can be related to the coherence between these two signals [1, 2]. For example, a simple estimate of the noise reduction achievable by an ANC system at frequency f is given by $-10\log_{10}\left(1 - \gamma_{dx}^2\left(f\right)\right)\ dB$, where

$\gamma^2_{dx}(f)$ is the coherence function between the primary noise signal and the reference signal in absence of control [1, 2]. Accordingly, the noise attenuation produced by the ANC system is likely to be increased if installing a passive silencer even if a feedback neutralization filter is used to remove the acoustic feedback, as illustrated in Fig. 4.

3. SIMULATION

The simulation of an ANC system in operation was performed in matlab using the time-domain leaky filtered-x LMS algorithm [1, 2]. Figure 3 is a block diagram illustrating the construction of the ANC system used in the simulations including both the acoustic- and electric domain. In the feedback through the filters $B(z)$ and $\hat{B}(z)$ there is included one sample delay, because when calculating the signal $u(n)$ the output $y(n)$ has not yet been calculated. The feedback path $B(z)$, and forward path $F(z)$, were measured in a real duct system. These were then estimated off-line using the LMS algorithm which gave the estimates of the feedback path $\hat{B}(z)$, and forward path $\hat{F}(z)$. The reference signal $x(n)$, and the primary noise signal $d(n)$, were also measured in the duct system. The measured impulse responses of the feedback- and forward paths were then used in the simulation to filter the signals as they would in the real duct system. In Fig. 3 the primary path is denoted $P(z)$, the adaptive FIR filter $W(z)$, and the error signal is denoted $e(n)$. The reference- and primary noise signals as well as the forward- and feedback paths were measured both with- and without a passive silencer installed near the duct outlet. The simulations were conducted both including and excluding the passive silencer. Also the simulations were performed with- and without the feedback neutralization filter $\hat{B}(z)$.

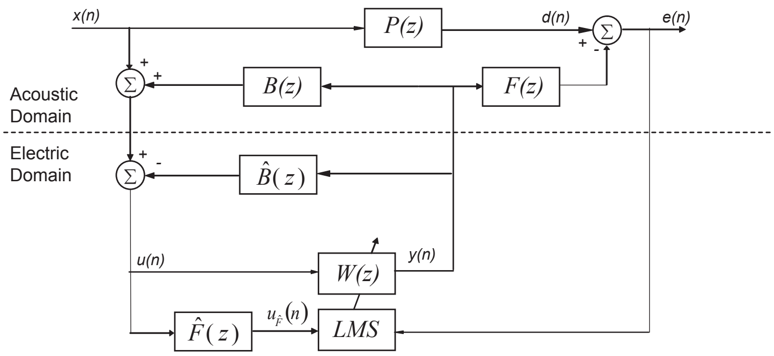


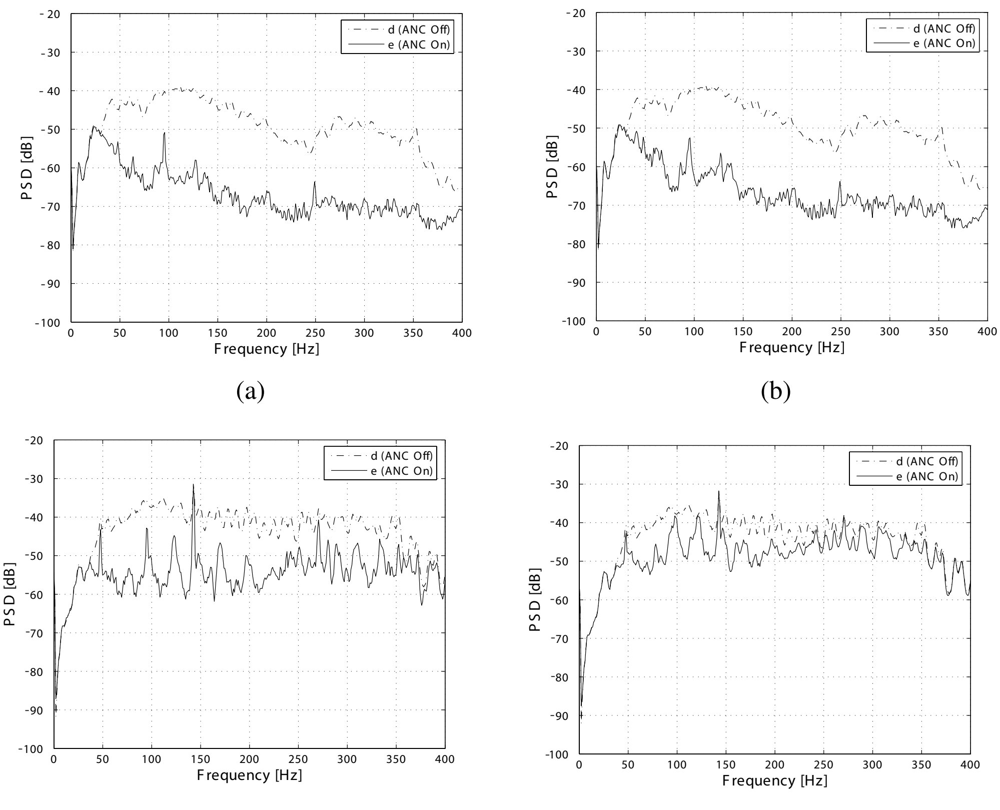
Figure 3. Block diagram illustrating the construction of the ANC system used in the simulations.

The impulse responses of the forward- and feedback paths were estimated using cross-correlation in the duct-system using a HP 35670A dynamic signal analyzer. The duct system consisted of approximately 21 meters of circular duct having a diameter 315 mm. The noise source was a standard axial fan (Lindab CK315) and a draught valve was placed near the fan to regulate the airflow. The forward path was measured between the source output sent to the loudspeaker, and the error microphone. The feedback path was measured between the source output sent to the loudspeaker, and the reference microphone. In both paths two anti-aliasing filters, one amplifier and the loudspeaker were included as well. Broadband noise with constant spectral density level within the analysis bandwidth was used as identification signal. Both the forward- and feedback paths were estimated based on cross-correlation and recalculated to FIR filters having the lengths of 256 coefficients. The reference- and primary noise signals used in the simulation were simultaneously measured in the reference microphone and error microphone respectively, using the fan as source for an airflow of 3,2 m/s. Both the acoustic paths and the reference- and primary noise signals were measured with- and without a passive silencer (Lindab SLU 100) installed near the duct outlet.

4. RESULTS

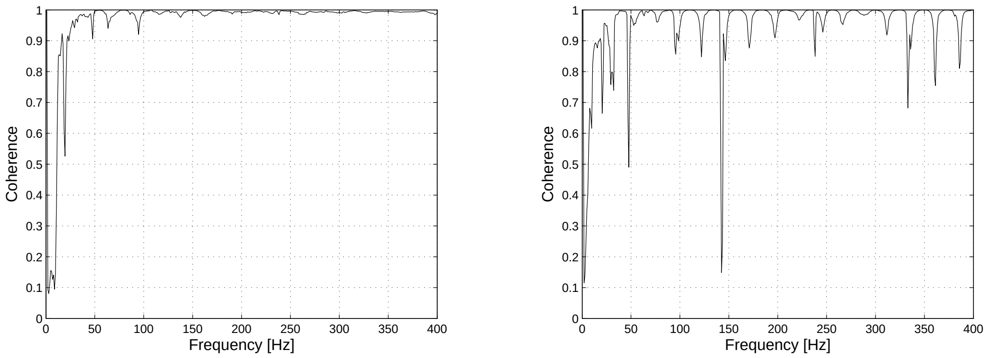
The measurements and simulations were carried out in the frequency range 0-400 Hz which is well below the cut-on frequency for the first higher order mode of the ducts in use. In Fig. 4 the power spectral density (PSD) of the primary noise signal and the error signal for different configurations is illustrated. The measurements of the reference- and desired signals were not calibrated hence the unit of the PSD:s are only specified in dB.

In Fig. 5 the coherence between the reference- and the primary noise signal is illustrated both with and without the passive silencer installed in the duct system. In Fig. 6 (a) the learning curves, i.e. mean square error as a function of number of iterations with the ANC system in operation, are plotted for the different configurations. In Fig. 6 (b) the mean square error is plotted as a function of the filter length of $\hat{F}(z)$ when estimating the forward path using the LMS algorithm. In Fig. 7 the frequency response functions of $F(z)$ and $\hat{F}(z)$ with and without passive silencer are illustrated.



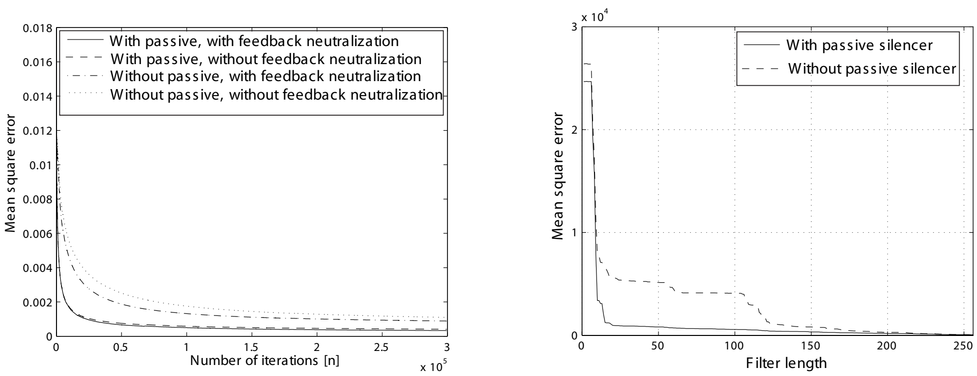
(a) (b) (c) (d)

Figure 4. Power spectral density of the primary noise signal $d(n)$ (dash-dotted), and the error signal $e(n)$ (solid), when using (a) the passive silencer and a feedback neutralization filter, (b) the passive silencer and no feedback neutralization filter, (c) no passive silencer and a feedback neutralization filter, and (d) no passive silencer and no feedback neutralization filter.



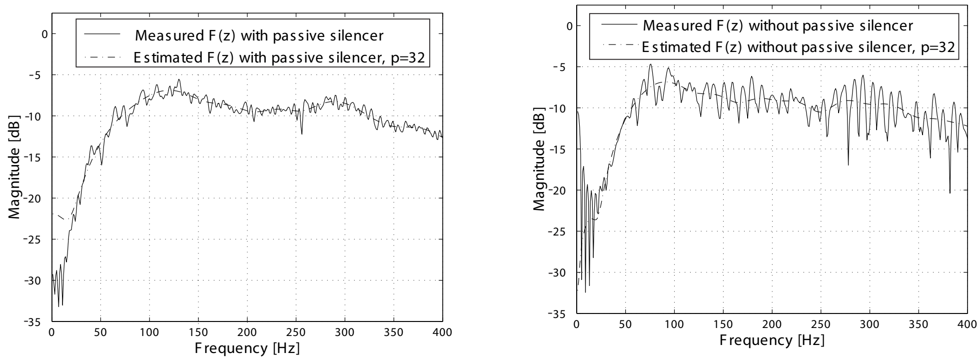
(a) (b)

Figure 5. Coherence between the reference signal $x(n)$, and the primary noise signal $d(n)$, in (a) when using the passive silencer and in (b) when *not* using the passive silencer.



(a) (b)

Figure 6. In (a) mean square error as a function of number of iterations with the ANC system in operation. In (b) mean square error as a function of filter length when estimating the forward path using the LMS algorithm.



(a) (b)

Figure 7. Frequency response functions of the measured (solid line) forward path $F(z)$ with 256 coefficients and the estimated (dash-dotted line) forward path $\hat{F}(z)$ with 32 coefficients in (a) with passive silencer and in (b) without passive silencer.

5. SUMMARY AND CONCLUSIONS

When using a passive silencer in combination with the filtered-x LMS algorithm, the ANC results in a similar level of noise attenuation as in the case of using a feedback neutralization filter in combination with the filtered-x LMS algorithm (see Figs. 4(a) and 4(b)). This indicates that the passive silencer may cause the use of a feedback neutralization filter to be superfluous. Without passive silencer the ANC noise attenuation is increased by using a feedback neutralization filter (see Figs. 4(c) and 4(d)). Also, the noise attenuation is approximately 5-10 dB higher between 50-350 Hz when using a passive silencer as compared to using only a feedback neutralization filter and no passive silencer (see Fig. 4). This is probably because of the increased coherence between the reference- and error microphone signals when using the passive silencer (see Fig. 5). The adaptive algorithm converges faster when using the passive silencer as compared to when not using it (see Fig. 6(a)). Furthermore, using a feedback neutralization filter does not influence the convergence rate significantly in combination with a passive silencer, which it on the other hand does when not using a passive silencer. Also, when estimating the forward path the filter used as an estimate of the forward path may have a lower order when using a passive silencer as compared to the cases without passive silencer (see Fig. 6 (b) and Fig. 7). The standing waves in the duct are less pronounced when using a passive silencer which leads to an increased coherence between the reference- and primary noise signals and hence to an increased performance of the ANC system. Finally, the adaptive algorithm display highest convergence rate in combination with passive silencer plus feedback neutralization filter. However, the improvement in convergence rate introduced by the feedback neutralization filter is negligible.

6. ACKNOWLEDGMENT

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