A NARROWBAND ACTIVE NOISE CONTROL SYSTEM WITH SIMULTANEOUS ONLINE SECONDARY- AND FEEDBACK-PATH MODELING USING ADAPTIVE IIR NOTCH FILTER

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In this paper, a new narrowband active noise control (NANC) system with a single frequency channel is proposed which consists of an online secondary-path modeling (SPM) subsystem and an online feedback-path modeling (FBPM) subsystem. The online SPM and FBPM subsystems are simultaneously adjusted in harmony in the hope of effectively suppressing the target sinusoidal noise, with the former aiming at obtaining a reasonably good SP estimate for updating the ANC controller and the latter trying to remove the FBP influence on the system performance. An auxiliary white Gaussian noise scaled by a nonlinear function of the residual noise is injected into the secondary source to implement the online SPM and FBPM. An adaptive second-order IIR notch filter is placed in front of the controller to reduce the coupling between the FBPM subsystem and the controller. A first-order FIR filter or magnitude and phase adjuster (MPA) is adopted as the controller. The FXLMS and LMS algorithms are applied to the ANC controller, the FBPM and the SPM subsystems, respectively. Extensive simulations reveal the effectiveness and computational advantage of the proposed ANC system.

Keywords: Active noise control (ANC), narrowband ANC (NANC), feedback-path modeling (FBPM), secondary-path modeling (SPM), auxiliary white Gaussian noise (AWGN).

1. Introduction

Active noise control (ANC) has become a high-technology, and has been paid considerable attention in recent years, see [1]-[18] and references therein. It may be used to help or even replace the conventional passive noise control technology, because if well implemented and calibrated it is capable of reducing the low-frequency components in various hostile noises in an efficient and effective way [1]-[4].

The ANC systems may be divided into two types according to the frequency characteristics of the target noise [1]. The first type takes care of the noise that is of broadband nature, while the second type is proposed for the narrowband noise that contains one or multiple discrete frequencies [1],[2]. The first type is called broadband ANC (BANC) that may be used to deal with the broadband and / or narrowband noise. The second type is called narrowband ANC (NANC) that is designated to solely cope with the narrowband noise.
There are three physical paths that are very important in ANC systems. The first one is the primary path that the noise source flows through. It starts from the reference microphone and ends at the error or residual noise microphone. An FIR-type controller is set long enough in the BANC or NANC to approximate the primary path [1], [4].

The second one is the secondary path (SP) that includes the cancelling speaker, the error microphone, and the space between them. Usually, the SP is estimated in advance by virtue of the typical system identification configuration, and then used to filter the reference noise signal to facilitate the so-called filtered-x LMS (FXLMS) algorithm that updates the ANC controller [1]-[4]. If the SP presents a significant drift during operation, its estimate has to be obtained from time to time and copied to the ANC system to maintain the system performance. The online SP modeling (SPM) technique has been proposed and modified to overcome the difficulties posed by the SP drift or time-varying property [16]-[18].

The third one is the feedback path (FBP) that consists of the cancelling speaker, the reference microphone and the space between both [2], [5]. Similar to the situation with the SP, the FBP also significantly affects the ANC performance and its nonstationarity may render the ANC useless or even divergent. The online FBP modeling (FBPM) was proposed to mitigate the destructive influence of the FBP for the first time by Eriksson [5].

In [6], Kuo and Luan proposed an FBPM technique that an auxiliary white Gaussian noise (AWGN) is injected into the ANC system to facilitate the FBPM. However, the noise source in the reference noise signal affects the FBPM as an additive noise, and the remaining AWGN in the input signal to the controller poses negative influence on the controller performance. This implies that the FBPM subsystem and the controller is coupled, possibly making the entire ANC system less effective. Furthermore, the AWGN is unattended in the ANC system and it contributes to the residual noise on its own. Kuo obtained a patent [7] in 2002, where an FIR prediction filter is placed right in front of the FBPM system to reduce the influence of the noise source on the FBPM, but the AWGN is still unattended. In [8]-[14], many researchers tried to modify Kuo’s system. Their aim is twofold: reducing the influence of the noise source on the FBPM and minimizing the contribution of the AWGN to the residual noise by using of an auxiliary noise power scheduling scheme. Recently, an effective gain scheduling scheme and variable step sizes have been proposed to further improve the performance of the NANC system that operates in the presence of a narrowband noise [14]. However, the gain scheduling is done by using of “local” information from the FBPM subsystem rather than “global” information from the residual noise. And, a long FIR-based prediction filter is still required.

Recently, an NANC system with FBPM has been proposed for a single frequency case [15]. An adaptive IIR notch filter [19] is introduced as the prediction filter and the AWGN gain scheduling is performed based on the “global” residual noise power. The NANC system has two advantages over the previous systems. First, computational cost is considerably less because the IIR notch filter is used as the prediction filter and the first-order FIR filter or magnitude and phase adjuster (MPA) is adopted as the controller. Second, the AWGN gain scheduling is implemented by a nonlinear function of the “global” residual noise, which minimizes the AWGN contribution to the residual noise in a seamless way.

In this paper, a new narrowband active noise control (NANC) system with a single frequency channel is proposed to further extend and improve the NANC system that was provided in [15]. The proposed system consists of an online SPM subsystem and an online FBPM subsystem. Both subsystems are adjusted simultaneously, making the entire NANC system more flexible, more efficient and more effective for real-life applications. Extensive simulations are provided to show the effectiveness of the proposed NANC system.
2. The proposed NANC system

The ANC system proposed in [6] is shown in Fig. 1. The noise source \( x_s(n) \) is a sinusoid contaminated by an additive noise:

\[
x_s(n) = A_s \cos(\omega_s n + \theta_s) + v_s(n)
\]

(1)

where \( A_s \) and \( \theta_s \) are the amplitude and phase of the sinusoid, respectively, \( v_s(n) \) is a zero-mean additive white noise with variance \( \sigma_{v_s}^2 \) which is much smaller than \( 0.5A_s^2 \), and \( n \) is the time instant. \( P(z) \), \( S(z) \), and \( F(z) \) are the transfer functions of the three important paths. They are FIR filters with lengths \( L_p \), \( M \), and \( L_f \), respectively. Their impulse responses are \( \{ s_{pj} \}_{j=0}^{L_p-1} \), \( \{ s_{m} \}_{m=0}^{M-1} \), and \( \{ s_{fi} \}_{i=0}^{L_f-1} \), respectively. The estimates of the SP and FBP are \( \hat{S}(z) \) and \( \hat{F}_n(z) \) with lengths \( \hat{M} \), \( \hat{L}_f \), and impulse responses \( \{ \hat{s}_{m} \}_{m=0}^{\hat{M}-1} \) and \( \{ \hat{s}_{fi}(n) \}_{i=0}^{\hat{L}_f-1} \), respectively. The controller \( W(z) \) is an FIR filter of length \( L_w \). Its weights are \( \{ w_i(n) \}_{i=0}^{L_w-1} \). The controller and the FBPM subsystem are updated by virtue of the FXLMS and the LMS algorithm, respectively.

\[
\begin{align*}
\sum & x_s(n) P(z) y_p(n) = y_p(n) + v_p(n) \\
\sum & x_s(n) F(z) y_p(n) = y_p(n) + v(n) \\
\sum & x_s(n) S(z) y_p(n) = y_p(n) + v(n) \\
\sum & x_s(n) W(z) y_p(n) = y_p(n) + v(n)
\end{align*}
\]

![Fig. 1. An ANC system with online FBPM proposed by Kuo & Luan [6].](image)

Fig. 2 depicts a NANC system that was recently proposed in [15]. The output of \( \hat{F}_n(z) \) is calculated by

\[
\begin{align*}
\hat{y}_f(n) &= \sum_{i=0}^{\hat{L}_f-1} \hat{s}_{fi}(n)y(n - i) \\
y(n) &= y_0(n) + v(n) \\
v(n) &= g(n)v_a(n)
\end{align*}
\]

(2) \hspace{1cm} (3) \hspace{1cm} (4)

where \( y_0(n) \) is the output of the MPA, \( v(n) \) is the auxiliary noise scaled by a function \( g(n) \) of the residual error signal \( e(n) \) [17]. \( v_a(n) \) is the AWGN with zero-mean and variance \( \sigma_{v_a}^2 \). The gain \( g(n) \) can be set to \( |e(n-1)| \) or

\[
g(n) = \lambda_1 g(n - 1) + (1 - \lambda_1)|e(n-1)|^\gamma \hspace{1cm} (\gamma = 1 \text{ or } 2)
\]

(5)
and $\lambda_1$ is a positive user parameter close to unit, say, 0.98, 0.99, etc. The adaptive IIR notch filter input is expressed as

$$\hat{x}_r(n) = x_r(n) - \hat{y}_f(n)$$  \hspace{1cm} (6)

$$x_r(n) = x_s(n) + \sum_{i=0}^{L_f-1} s_{fi} y(n-i).$$  \hspace{1cm} (7)

The output of the adaptive IIR notch filter [19] is then given by

$$u_x(n) = -\rho c(n) u_x(n-1) - \rho^2 u_x(n-2) + \hat{x}_r(n) + c(n) \hat{x}_s(n-1) + \hat{x}_r(n-2)$$  \hspace{1cm} (8)

where $\rho$ is called pole attraction parameter $\in [0, 1]$ that takes a number close to unit, like 0.90, 0.95, etc. and defines the bandwidth of the notch filter, $c(n)$ is the notch filter coefficient which converges to $-2 \cos \omega_s$ if properly updated. The output of the MPA turns out to be

$$y_0(n) = h_0(n) \hat{x}_s(n) + h_1(n) \hat{x}_s(n-1)$$  \hspace{1cm} (9)

$$\hat{x}_s(n) = \hat{x}_r(n) - u_x(n)$$  \hspace{1cm} (10)

where \{ $h_0(n), h_1(n)$ \} are the MPA coefficients.

The LMS algorithm is used to update $F_n(z)$

$$\dot{s}_{fi}(n+1) = \dot{s}_{fi}(n) + \mu_f u_x(n) v(n-i)$$  \hspace{1cm} (11)

where $\mu_f$ is a positive step size that controls the pace of the update. A normalized gradient (NG) algorithm is adopted to update the notch filter coefficient

$$c(n+1) = c(n) - \mu_n \frac{u_x(n) g_x(n)}{\epsilon + G_x(n)}$$  \hspace{1cm} (12)

$$g_x(n) = -\rho u_x(n-1) + \hat{x}_s(n-1)$$  \hspace{1cm} (13)

$$G_x(n) = \lambda_2 G_x(n-1) + (1 - \lambda_2) g_x^2(n)$$  \hspace{1cm} (14)

where $\mu_n$ is another step size similar to $\mu_f$, $\epsilon$ is a very small positive number that is put into the denominator to prevent division by zero, $\lambda_2$ is a user parameter similar to $\lambda_1$. The two-weight controller or MPA is updated by a typical FXLMS algorithm

$$h_0(n+1) = h_0(n) + \mu_h e(n) \hat{x}_s(n)$$  \hspace{1cm} (15)

$$h_1(n+1) = h_1(n) + \mu_h e(n) \hat{x}_s(n-1)$$  \hspace{1cm} (16)

where $\mu_h$ is the third step size similar to the above two, and $\hat{x}_s(n)$ is a $\hat{S}(z)$-filtered version of $\hat{x}_s(n)$.

Our proposed NANC system with simultaneous SPM and FBPM is shown in Fig. 3. The output of the online SPM subsystem $\hat{S}_n(z)$ is given by

$$y_s(n) = \sum_{m=0}^{M-1} \hat{s}_m(n) v(n-m).$$  \hspace{1cm} (17)

The $\hat{S}_n(z)$ is updated by an LMS algorithm, as follows:

$$\dot{s}_m(n+1) = \dot{s}_m(n) - \mu_m e_s(n) v(n-m)$$  \hspace{1cm} (18)

$$e_s(n) = e(n) + y_s(n)$$  \hspace{1cm} (19)

where $\mu_m$ is a positive step size for the SPM.

Now, we have the following remarks regarding the proposed NANC system:
Fig. 2. An ANC system with online FBPM using adaptive IIR notch filter and MPA [15].

Fig. 3. Proposed NANC system with simultaneous online FBPM and SPM.
1. The MPA with only two weights is used as the controller, and thus the cost to be spent on the controller is significantly reduced.
2. The scaling factor or gain used to scale the AWGN in the proposed system is a function of the residual noise $e(n - 1)$ rather than signals related to the online FBPM subsystem. As the ultimate goal of the ANC system is the primary noise reduction, it is natural to use a function of the residual noise to scale the AWGN.
3. As the residual noise becomes smaller, the input to the online SPM and FBPM subsystems $\hat{S}_n(z), \hat{F}_n(z)$ will also become smaller, which will significantly reduce the convergence of both subsystems. A variable step-size LMS (VSS-LMS) may be introduced, just like what is done in \[9\] \[10\] \[14\], to speed up the convergence and improve the accuracy of the online SPM and FBPM, at the expense of more computational cost. However, the VSS is intentionally not adopted here, because the ultimate goal is not the modeling accuracy of $S(z)$ and $F(z)$. As long as the NRP of the proposed system is improved, one does not need to care much about the online SPM and FBPM accuracy.

3. Simulations

Extensive simulations have been performed to verify the effectiveness of the proposed NANC system. The user parameters for the SPM are set to $M = 31, \mu_m = 5.0 \times 10^{-4}$. Other simulation conditions are the same as those given in \[15\]. A hundred (100) independent runs are performed to evaluate the proposed ANC system performance. A set of typical simulation results are provided in Fig. 4. As noted from this figure, our proposed system does indicate excellent performance: 1) the notch filter captures the sinusoid very well, making the prediction filter extremely cheaper as compared to the FIR prediction filters that are used in previous ANC systems \[6\]-\[14\], 2) the MPA with two weights is much shorter than the FIR controllers used in \[6\]-\[14\], and 3) both the SPM and the FBPM work well even though their accuracy is not very good, but the proposed system is still very effective in mitigating the target sinusoid as the ultimate goal of the NANC is the noise reduction rather than the SP and FBP estimation accuracy.

4. Conclusions

In this paper, a new NANC system with both online FBPM and online SPM is proposed for a target noise having a single frequency. The online FBPM and the SPM are simultaneously adjusted. The AWGN is scaled by a gain factor that is a low-passed version of the residual noise power. Extensive simulations have been performed to confirm the effectiveness of the proposed NANC system. Future work includes 1) extension to multi-frequency target noise, 2) in-depth analysis of the proposed NANC system, and 3) application to real noises that are generated by rotating components.

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Fig. 4. Simulation results of the proposed NANC system with simultaneous online FBPM and SPM.