A New Hybrid Active Noise Control System with Residual Error Separation Structure

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Abstract—The conventional broadband active noise control (ANC) system may not be able to function well when the target noise contains both wideband and narrowband components simultaneously. Feed-forward hybrid active control has attracted quite a lot attention recently, as it can effectively suppress both components at the same time. Such hybrid ANC system consists of three tightly integrated subsystems, namely, the sinusoidal noise canceller (SNC), broadband ANC (BANC) system and narrowband ANC (NANC). The BANC and NANC subsystems are placed in a parallel form, such that a good performance can be achieved. What’s more, the update formulas of the two subsystems depend on the overall residual noise of the whole system, which is a combined measurement of two individual errors that correspond to the wideband and narrowband noise reduction, respectively. Using this “global” residual error may make both subsystems unable to reach their best performance. In this paper, a new hybrid ANC system is proposed to tackle this problem, by adding a new residual error separation (RES) subsystem to the conventional hybrid ANC system such that the two subsystems can update themselves based on their own residual errors. In this way, the two subsystems can work more effectively and make the whole system more capable. Extensive simulations show that the new system enjoys improved performance.

I. INTRODUCTION

Generally speaking, noise can be divided as broadband noise and narrowband noise according to their frequency distribution. Broadband noise features wide frequency distribution and randomness, such as noise produced by jet engines or impulsive noise emitted by explosion. Concentrating on some discrete frequencies, narrowband noise is periodic or nearly periodic, such as low-frequency noise produced by rotating machinery or reciprocating equipment [1, 2].

Previously ANC system for broadband noise and narrowband noise was usually studied independently, and have been developed a number of practical structures and algorithms [1-8]. However, environmental noise usually exhibits a hybrid characteristic with both broadband and narrowband components. While conventional broadband systems can cancel wideband noise effectively and dealing with narrow-band noise well, but usually a large step size has to be used to achieve fast convergence. However, if a large step size is adopted, the so-called "firework" noise will appear, leading to the system performance deterioration [9,10].

Recently, Xiao proposed a new feed-forward hybrid ANC system capable of dealing with broadband and narrowband noise simultaneously [9]. The structure of Xiao’s method is shown in Fig. 1(a), where a non-acoustic sensor is used to obtain narrowband reference signals, meanwhile an acoustic sensor is used to obtain a reference that contains both broadband and narrowband noise signals. The system consists of three subsystems, broadband ANC (BANC), narrowband ANC (NANC) and a sinusoidal noise canceller (SNC). The SNC subsystem is introduced to remove the sinusoids from the acoustic reference signal to let the BANC subsystem do what it is good at, and then place an NANC subsystem parallel to the BANC to cancel the sinusoids in the primary noise. The hybrid system is very effective in reducing both wideband and narrowband components in the primary noise signal.

However, the coefficients update equations are derived from the residual noise, which contains errors of both the narrowband and broadband subsystems. The coupling of the error signals of each ANC subsystem may make both of them unable to achieve their best performance. To this end, we propose a new hybrid ANC system by adding a residual error separation (RES) subsystem to decouple the error signals for BANC and NANC. In this way, the controller update formula of BANC and NANC use their portion of residual error, so that they can perform more effectively, thereby improving system performance. Compared with conventional broadband and narrowband hybrid systems, the new system proposed in this paper only adds a small amount of computation but achieve better performance. We will validate the effectiveness of the proposed system by simulations.

The remainder of this paper is as follows. In section II, a new hybrid ANC system is proposed; in section III, simulations and discussions on the results are given. The conclusions and future topics are provided in section IV.

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II. THE NEW HYBRID ANC SYSTEM

A. The Overview of Conventional Hybrid System

In conventional feed-forward hybrid ANC system of [9], the primary path, secondary path and its estimate are separately expressed by $P(z), S(z)$ and $\hat{S}(z)$, where $M_p-1, M-1, \hat{M}-1$ are their FIR model orders, and $c_j, s_m, \hat{s}_m$ are their model coefficients.

The primary signals are expressed as

$$p_b(n) = \sum_{i=1}^{N} [a_{pi} x_i(n) + b_{pi} x_h(n)] + p_s(n) \tag{1}$$

The reference noise signals are expressed as

$$x_h(n) = x_f(n) + x_s(n) \tag{2}$$

$$x_h(n) = \sum_{i=1}^{q} [a_{pi} \cos(\omega_i n) + b_{pi} \sin(\omega_i n)] + x_s(n) \tag{2}$$

where $q$ is the number of frequencies of sinusoids and $x_h(n) = \cos(\omega_i n), x_h(n) = \sin(\omega_i n), \{a_{pi}, b_{pi}\}_{i=1}^{q}$ are the discrete Fourier coefficients (DFC) of $x_p(n), x_s(n)$ is a wideband primary noise component which is white or colored noise with zero mean and variance $\sigma^2_w$. Update formulas for discrete Fourier coefficients of SNC subsystem are expressed as

$$\hat{a}_{ci}(n+1) = \hat{a}_{ci}(n) + \mu(t) x_h(n) x_{ci}(n) \tag{3}$$

$$\hat{b}_{ci}(n+1) = \hat{b}_{ci}(n) + \mu(t) x_h(n) x_{ci}(n) \tag{4}$$

The error signal of adaptive filter is used as the BANC subsystem, and its expression is

$$x(n) = x_s(n) - \sum_{i=1}^{q} [\hat{a}_{ci} x_{ci}(n) + \hat{b}_{ci} x_{ci}(n)] \tag{5}$$

The FIR filter $H(z)$ of the BANC subsystem is updated by an FXLMS algorithm

$$\hat{c}_{j}(n+1) = \hat{c}_{j}(n) + \mu(t) e(n) \hat{x}(n-j) \tag{6}$$

$$y(n) = y_s(n) + y_f(n) \tag{7}$$

$$y_s(n) = \sum_{j=0}^{M-1} b_{j} x(n-j) \tag{8}$$

$$y_f(n) = \sum_{i=1}^{q} [\hat{a}_{ci} x_{ci}(n) + \hat{b}_{ci} x_{ci}(n)] \tag{9}$$

Because the interference of sinusoids is canceled by SNC subsystem, the BANC subsystem can work effectively in a way similar to the traditional broadband system.

The residual error of the whole system is expressed as

$$e(n) = \sum_{m=0}^{M-1} s_m e_p(n-m) + v_p(n) \tag{10}$$

$$e_p(n) = p_h(n) - y(n) \tag{11}$$

B. Residual Error Separation Subsystem

In-depth study of the hybrid ANC system structure, refinement and improvement of a sinusoidal noise canceller (SNC) subsystem, as well as broadband and narrowband ANC subsystems is expected to play a crucial role to improve the overall performance of the system. Here, we provide an idea to improve the original system.

Since the controller update formula of the aforementioned broadband and narrowband subsystems in the hybrid ANC system directly make use of the system’s overall residual error, the subsystem that contributes less to overall residual error will definitely be influenced by residual error resulted from the other subsystem, downgrading the system performance. To this end, we add a RES subsystem that enables the controller update formula of both subsystems to use residual error arising from their own, so that the whole
system can work more effectively. The new hybrid ANC system is in Fig. 1.

Here we adopt an approach similar to SNC subsystem: extract residual error of the narrowband subsystem by the LMS-based discrete Fourier analyzer. Residual error signal produced by narrowband subsystem can be expressed by

\[
e_n(n) = \sum_{i=1}^{n} \left[ \hat{a}_{en}(n)x_e(n) + \hat{b}_{en}(n)x_b(n) \right]
\]

Through (8)and(10), the residual error signal produced by wide-band subsystem is expressed by

\[
e_p(n) = e(n) - e_n(n)
\]

The update formulas for RES subsystem are expressed as

\[
\hat{a}_{en}(n+1) = \hat{a}_{en}(n) + \mu e_p(n)x_e(n)
\]

\[
\hat{b}_{en}(n+1) = \hat{b}_{en}(n) + \mu e_p(n)x_b(n)
\]

III. SIMULATIONS

To verify the effectiveness of the new hybrid ANC system, extensive simulations have been conducted.

Primary and secondary paths are generated by the MATLAB function (FIR low-pass filter), whose cut-off frequency is 0.4 \(\pi\). Through the classical LMS algorithm, we can obtain the estimate of the secondary path. The conditions of the simulation are shown in TABLE I.

<table>
<thead>
<tr>
<th>Parameters</th>
<th>Parameter value</th>
</tr>
</thead>
<tbody>
<tr>
<td>The order of primary path</td>
<td>40(Mp=41)</td>
</tr>
<tr>
<td>The order of secondary path</td>
<td>20(M=21)</td>
</tr>
<tr>
<td>The estimate of the secondary path</td>
<td>30((\hat{M} = 31))</td>
</tr>
<tr>
<td>Step size</td>
<td>(\mu_s = 0.001)</td>
</tr>
<tr>
<td>Input white noise variance</td>
<td>(\sigma_w^2(n) = 0.1)</td>
</tr>
<tr>
<td>Observation additive noise variance</td>
<td>(\sigma_n^2(n) = 0.1)</td>
</tr>
<tr>
<td>Iteration number</td>
<td>(N_s = 3.0 \times 10^4)</td>
</tr>
<tr>
<td>Low-frequency sinusoids</td>
<td>(\omega_\ell = [0.03 0.06 0.09]\pi)</td>
</tr>
<tr>
<td>DFCs of low-frequency sinusoids</td>
<td>(a_{en} = [2.0 1.0 0.5], b_{en} = [-1.0 -0.5 0.1])</td>
</tr>
<tr>
<td>Additive noise variance</td>
<td>(\sigma_p^2(n) = 0.01)</td>
</tr>
</tbody>
</table>

We import a residual error separation subsystem on the basis of the conventional system. Extensive simulations have been conducted to compare with the performance of conventional system. In the simulations, the update step size for the Fourier coefficient of the RES subsystem is \(\mu_s = 0.007\). One hundred (100) independent runs are performed for each case. Other conditions are same as in [9].

The representative results are shown for two situations. The MSE convergence curves of the conventional hybrid system and proposed hybrid system, with white noise variance \(\sigma_w^2 = 1\), are given in Fig. 2. We can find the two systems exhibit comparable convergence, but the new one has better steady-state performance. The results, which present similar tendency as in Fig. 2, are provided in Fig. 3, with white noise variance \(\sigma_w^2 = 0.25\).
The updating of coefficients of the subsystems in the hybrid ANC system directly utilizes the system’s overall residual error, making both subsystems influence each other, resulting in declined overall performance. Focusing on this issue, we propose a new hybrid ANC system by adding a residual error separation subsystem, which is capable of separating residual errors arising from broadband and narrowband subsystems, so that the coefficients of the broadband and narrowband subsystems can be updated independently. Simulations reveal that the new hybrid ANC system with RES subsystem has better steady-state performance compared with conventional ones under comparable convergence rates. Performance analysis of the new hybrid ANC system and improvements of algorithms to better the system performance are future topics.

REFERENCES