A decoupled hybrid structure for active noise control with uncorrelated narrowband disturbances

Lifu WU[1, 2]; Xiaojun QIU[1]; Ian S. BURNETT[1]; Eva Cheng[1];Yecai GUO[2]

[1] School of Electrical and Computer Engineering, Royal Melbourne Institute of Technology, Australia

[2] Jiangsu Key Laboratory of Meteorological Observation and Information Processing, Nanjing University of Information Science and Technology, 210044, China

ABSTRACT

In real active noise control (ANC) applications, the following situations frequently occur, one is that disturbances only present at the error sensor and have low correlation with reference signal, the other is that there is no enough space or ideal position for locating the reference sensor to satisfy causality condition. Thus the residual noise after feedforward control can be seen as uncorrelated narrowband disturbances in these situations and a hybrid adaptive feedforward and feedback structure is often utilized to cope with this problem. Many efforts have been paid to improve the performance of the hybrid ANC system, nevertheless, few interests are concerned about the combination method between the feedforward and feedback structure. After investigating the conventional combination method of hybrid feedforward and feedback system, this paper introduces an alternate combination method for hybrid ANC system which features that it avoids the coupling between the feedforward and feedback structures and both structures are concatenated to attenuate the ambient noise. Simulations are carried out to validate the effectiveness of the introduced method for ANC with uncorrelated narrowband disturbances.

Keywords: Active noise control, decouple, hybrid system I-INCE Classification of Subjects Number(s): 38.5

1. INTRODUCTION

Active noise control (ANC) has attracted considerable interests in the literatures [1–2] and been utilized in real applications such as communication headsets [3–4], helmets [5] and ventilation ducts [6–7]. Feedforward structure with the filtered-x least mean square (FxLMS) algorithm is widely used in ANC systems, to achieve an effective feedforward control, the reference signal needs to provide time-advanced information (i.e., the causality condition) and have high correlation (i.e., the correlation condition) with the primary noise [2]. However, if there is no ideal position for locating the reference sensor in some real situations, feedforward structure is not satisfied with these two conditions at some narrow frequency bands, the residual noise after the feedforward control can be seen as the uncorrelated narrowband disturbance. Furthermore, the other situations also happen in real-world applications where uncorrelated disturbance only present at the error sensor, some examples are given in [8]. The problem in these situations can be considered as active control of the noise accompanied by uncorrelated narrowband disturbance [8].

Feedback structure differs from feedforward structure in that it does not require the reference sensor to give reliable reference signal and is able to control the narrowband noise. A combination of the feedforward and feedback structures is called a hybrid feedforward and feedback structure (hereinafter, called hybrid structure in short), where the secondary signal is generated based on the output summation of the feedforward and feedback structures. The hybrid structure is suitable for controlling the noise with uncorrelated narrowband disturbance since it plays a dual role: the feedforward structure attenuates primary noise that is correlated with the reference signal, while the feedback structure controls the narrowband components that are not "observed" by the reference sensor [9]. It is reported that the hybrid structure offers better performance in terms of both

[1] wulifu@nuist.edu.cn, xiaojun.qiu@rmit.edu.au, ian.burnett@rmit.edu.au, eva.cheng@rmit.edu.au
[2] guo-yecai@163.com

narrowband and broadband noise control and provides higher flexibility than either the feedforward or feedback structure [1]. In addition, the computational complexity of the hybrid structure can be reduced because a lower order FIR filter can be used to achieve the same performance as that utilizing the feedforward or feedback structure alone [9].

A hybrid ANC system is proposed by Akhtar et al. that can simultaneously control the correlated and uncorrelated noise appearing at the error sensor, it is shown that the proposed method improves noise reduction and converges at a fast speed [8]; Hybrid ANC architecture is presented and validated for a circumaural earcup and a communication earplug [10] which combines source-independent feedback structure with a Lyapunov-tuned leaky LMS filter, results in [10] show that the gain stability margins over single feedforward structure is improved. A multi-channels hybrid ANC system for infant incubators is introduced [11] which includes a feedforward structure to cancel noise generated from sources outside the incubator and a feedback structure to reduce the predictable noise inside the incubator, it is reported that the hybrid ANC system are effective in cancelling both outside and inside noises of the infant incubators in real environment. Combining analogue feedback and digital feedforward has been demonstrated for headsets by Winberg et al. and Carme [12–13] in the 1990s.

Up to now, many efforts have been paid to improve the performance of hybrid ANC system, nevertheless, the combination method between the feedforward and feedback structure in a hybrid system is not paid enough attention in the literatures. The combination method in the commonly-used hybrid systems (called traditional method) is investigated in this paper and it is found that the feedforward and feedback control filter are coupled in the traditional method and the coupling causes that one filter may affect the other and both filters must be optimized simultaneously. After analyzing the reason of the coupling effect, an alternate combination method for hybrid ANC system is presented in this paper which aims to alleviate the coupling effect between the feedforward and feedback structures and concatenate them to attenuate the ambient noise with uncorrelated narrowband disturbance. Simulations are carried out to validate the effectiveness of the introduced combination method.

2. THE DECOUPLED HYBRID ANC SYSTEM

Figure 1 is the frequently used hybrid system in ANC applications based on the traditional combination method (called tHybrid hereinafter). The feedforward structure (underlay with grey color) is composed of one reference sensor to pick up the reference noise $x(k)$, one error sensor to measure the residual noise $e(k)$ and one secondary sound source to generate the canceling signal $y_{\mathrm{ff}}(k)$ for attenuating the primary noise $d(k)$ and the uncorrelated narrowband disturbance is denoted by $v(k)$. Here the reference signal $x(k)$ is filtered through $\hat{S}(z)$, the so-called estimation of secondary path $S(z)$, The control filter $W_{\mathrm{ff}}(z)$ is often presented as tap weight vector of length L. The feedback structure consists of the control filter $W_{\mathrm{c}}(z)$ and the reference signal $x_{\mathrm{c}}(k)$ which is synthesized based on $e(k)$ and the secondary signal $y(k)$ filtered by $\hat{S}(z)$.

Assuming the existence of Z-transforms of the signals in Figure 1, the error signal in the tHybrid ANC system is derived as follows, Eqs. (1) – (2) can be read from Figure 1 directly:

$$E(z) = D(z) + V(z) + S(z)Y(z) \tag{1}$$

$$Y(z) = Y_{\mathrm{ff}}(z) + Y_{\mathrm{c}}(z) \tag{2}$$

where

$$Y_{\mathrm{ff}}(z) = X(z)W_{\mathrm{ff}}(z) \tag{3}$$

$$Y_{\mathrm{c}}(z) = X_{\mathrm{c}}(z)W_{\mathrm{c}}(z) \tag{4}$$

are the secondary signals of feedforward and feedback structure respectively.

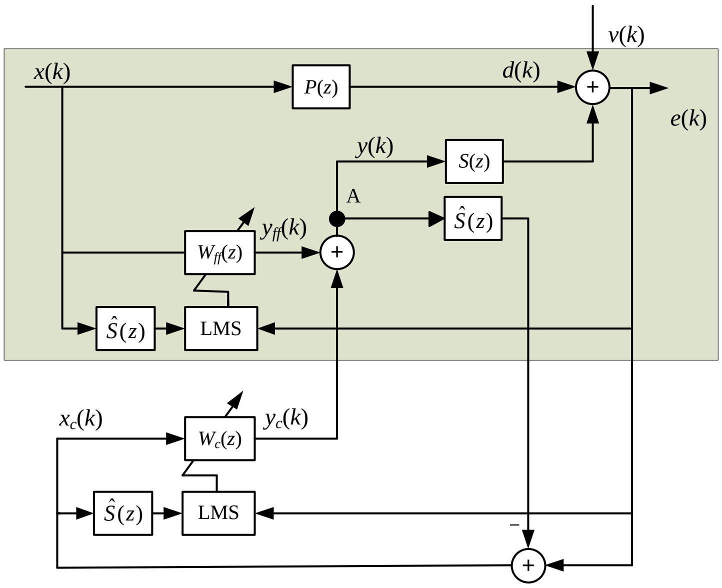


Figure 1 – Block diagram of the single channel hybrid ANC system based on traditional combination method

Inserting Eqs.(2) (3) (4) into

$$X_{\mathrm{c}}(z) = E(z) - \hat{S}(z)Y(z) \tag{5}$$

and after some arrangements, one gets

$$X_{\mathrm{c}}(z) = \frac{E(z) - \hat{S}(z)X(z)W_{\mathrm{ff}}(z)}{1 + \hat{S}(z)W_{\mathrm{c}}(z)} \tag{6}$$

Substituting Eqs. (2) (3) (4) (6) into Eq. (1), gets

$$\begin{aligned} E(z) &= D(z) + V(z) + S(z)\left[X(z)W_{\mathrm{ff}}(z) + \frac{E(z) - \hat{S}(z)X(z)W_{\mathrm{ff}}(z)}{1 + \hat{S}(z)W_{\mathrm{c}}(z)} W_{\mathrm{c}}(z) \right] \\ &= D(z) + V(z) + S(z)\frac{E(z)W_{\mathrm{c}}(z) + X(z)W_{\mathrm{ff}}(z)}{1 + \hat{S}(z)W_{\mathrm{c}}(z)} \end{aligned} \tag{7}$$

Rearranging Eq. (7), gives

$$E(z) = \frac{1 + \hat{S}(z)W_{\mathrm{c}}(z)}{1 + [\hat{S}(z) - S(z)]W_{\mathrm{c}}(z)}[D(z) + V(z)] + \frac{S(z)W_{\mathrm{ff}}(z)}{1 + [\hat{S}(z) - S(z)]W_{\mathrm{c}}(z)} X(z) \tag{8}$$

If $S(z) = \hat{S}(z)$ and $D(z) = X(z)P(z)$ are applied in Eq. (8), the error signal of the tHybrid ANC system is given by

$$E(z) = [1 + S(z)W_{\mathrm{c}}(z)]V(z) + \left\{ [1 + S(z)W_{\mathrm{c}}(z)]\, P(z) + S(z)W_{\mathrm{ff}}(z) \right\} X(z) \tag{9}$$

Eq. (9) shows that the feedforward control filter $W_{\mathrm{ff}}(z)$ and the feedback control filter $W_{\mathrm{c}}(z)$ are coupled in the traditional method, that is, in order to control the noise $d(k)$, the term $[1+ S(z)W_{\mathrm{c}}(z)]P(z)+ S(z)W_{\mathrm{ff}}(z)$ should approach zero, then the feedforward control filter $W_{\mathrm{ff}}(z)$ = –[1+

$S(z)W_c(z)]P(z)/S(z) = -P(z)/\{S(z)/[1+S(z)W_c(z)]\}$. It is known that in the single feedforward structure ANC system, the feedforward control filter $W_{ff}(z)) = -P(z)/S(z)$ [1], thus in the traditional method the effects of the coupling is that the feedback control filter $W_c(z)$ will influence the feedforward control filter $W_{ff}(z)$ by change the secondary path from $S(z)$ to a time-varying $S(z)/[1+S(z)W_c(z)]$. At some moments, when the updating $W_c(z)$ cause the results that the phase difference between $S(z)$ and $S(z)/[1+S(z)W_c(z)]$ is larger than $\pi/2$ radians, the feedforward structure will diverge. The reason for coupling between $W_c(z)$ and $W_{ff}(z)$ can be found at point A in Figure 1, the reference signal $x_c(k)$ is synthesized using $y_{ff}(k)$ and $y_c(k)$, i.e., both the secondary signal of feedforward and feedback structure. Thus the reference signal $x_c(k)$ is expressed as Eqs. (5) (6) which involves $W_{ff}(z)$ and $W_c(z)$ simultaneously.

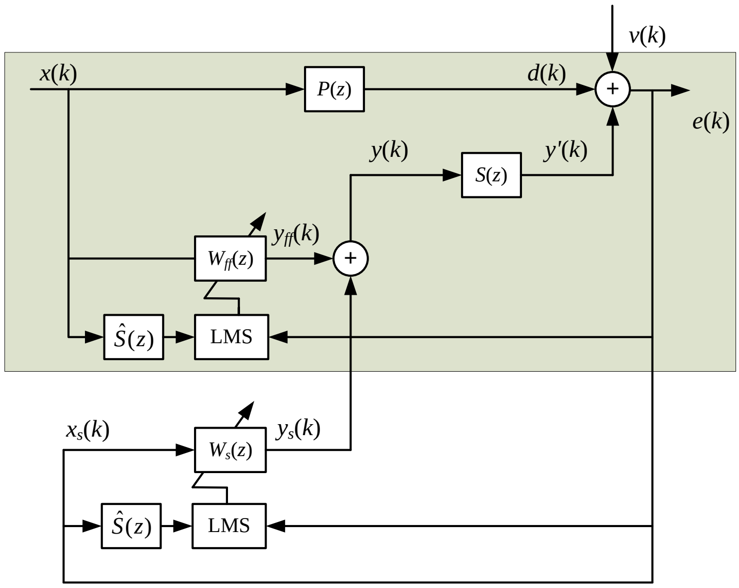


Figure 2 – Block diagram of the single channel hybrid ANC system based on simplified combination method

Since the coupling happens at the point A in Figure 1, an intuitive method to emigrate the coupling effects is to remove the connection between point A to the feedback structure, which results in the simplified combination method based system (sHybrid) shown in Figure 2. The feedback structure is a simplification of that in tHybrid system, where the reference signal $x_s(k)$ comes from the error signal directly, i.e.,

$$X_s(z) = E(z) \tag{10}$$

Repeating the similar derivation of Eq. (9) by replacing Eq. (5) with Eq. (10), the error signal in the sHybrid ANC system can be derived as (also assuming $S(z) = \hat{S}(z)$ and $D(z) = X(z)P(z)$)

$$E_s(z) = \frac{1}{1-S(z)W_s(z)}V(z) + \frac{1}{1-S(z)W_s(z)}[P(z)+S(z)W_{ff}(z)]\,X(z) \tag{11}$$

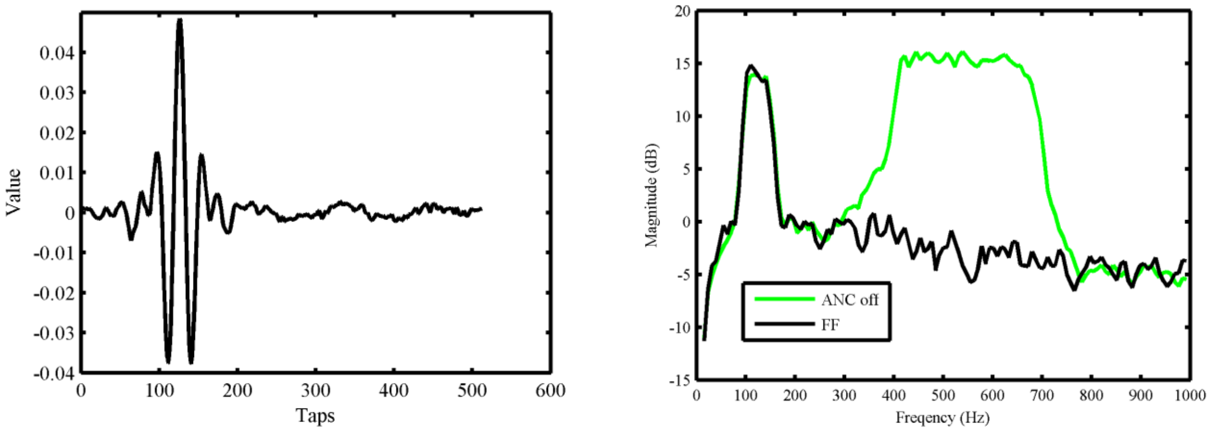
The system in Figure 2 features in low computational load and ease of implementation due to the elimination of the convolution operation required in the tHybrid ANC system. The simplification on the feedback structure is validated in the work [14] presented recently. What's more, the simplification decouples the feedforward and feedback structures and the feedforward structure does not impact feedback structure directly. The benefits of the decoupled structure can be found from Eq. (11): firstly the feedforward and feedback structure can be updated independently, the feedback structure aims to control the uncorrelated disturbance $v(k)$ and its ideal solution is to update the controller $W_s(z)$ to have a large gain over the frequency of interest and make the term $1/[1-S(z)\,W_s(z)]$ as small as possible [14]. The feedforward control filter $W_{ff}(z)$ approximates $-P(z)/S(z)$ to attenuate $d(k)$; secondly, the feedforward and feedback structures are cascaded, i.e., The term $[P(z)+S(z)W_{ff}(z)]/[1-S(z)W_s(z)]$ in Eq. (11) is a product of the feedforward and feedback structure, as a result, both structures may contribute to the overall attenuation of the noise with uncorrelated disturbance.

3. SIMULATIONS AND DISCUSSIONS

Simulations were carried out to compare the properties of the tHybrid and sHybrid ANC systems. The sample rate is 16000 Hz and the primary path $P(z)$ is a 320~720 Hz band-pass filter modeled with 256 taps FIR structure. The secondary path $S(z)$ is selected as a pure delay $S(z) = z^{-3}$ and here the estimation of secondary path is assumed to be idea, i.e., $\hat{S}(z) = S(z)$.The primary noise $d(k)$ is a 400~700 Hz wideband noise and the uncorrelated narrowband disturbances $v(k)$ is a 100~150 Hz narrowband noise. The feedforward control filter $W_{\mathrm{ff}}(z)$ was selected to be FIR filter with 512 taps and the feedback control filters (including $W_c(z)$ and $W_s(z)$) in Figures 1~2 were selected to be FIR filters with 256 taps. The power spectrum is used to evaluate the noise reduction performance. In the next Figures legends, following abbreviations are defined: "ANC off" denotes without ANC; "FF" denotes single feedforward structure; "tFB" and "sFB" denote traditional and simplified feedback structure shown in Figures 1 and 2 respectively; "itHybrid" means inserting the "FF" and "tFB" control filter coefficients into the tHybrid system directly to control the noise, likewise, "isHybrid" means inserting the "FF" and "sFB" control filter coefficients into the sHybrid system directly; "FF-tHybrid" and "FB-tHybrid" denote the feedforward and feedback structure in the tHybrid system respectively, likewise, "FF-sHybrid", "FB-sHybrid" are abbreviated.

3.1 Control by feedforward or feedback structure alone

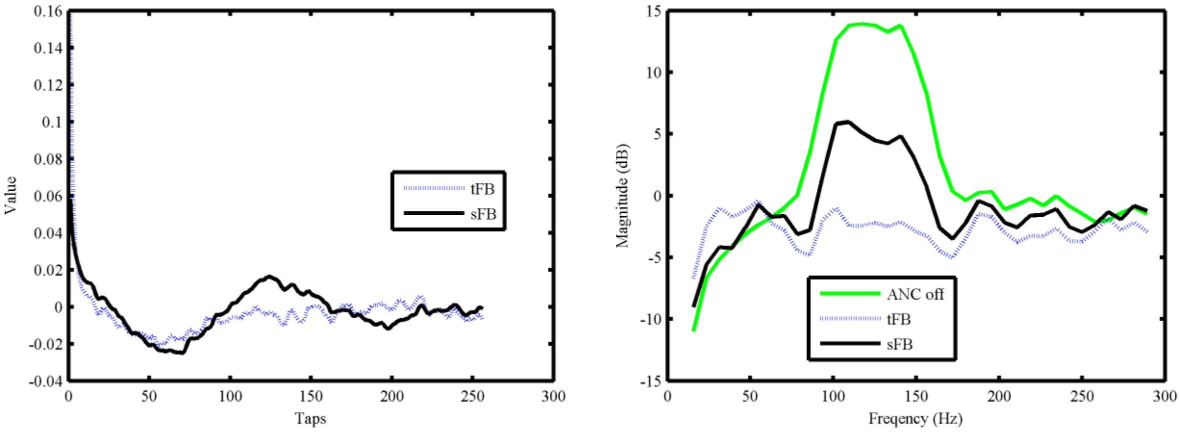
Firstly, single feedforward structure is used to control the noise with uncorrelated narrowband disturbance, the FxLMS algorithm [1–2] is employed to update the control filter and the step size is 0.005. The converged feedforward control filter coefficients are plotted in Figure 3 (a) and the power spectra of the residual error signal at steady state is shown in Figure 3 (b). It is shown from Figure 3 (b) that the noise within 400~700 Hz frequency band is reduced about 15 dB while the uncorrelated disturbance within 100~150 Hz frequency band cannot be controlled by single feedforward structure.



(a) (b)

Figure 3 – Active control of noise with uncorrelated narrowband disturbance using single feedforward structure: (a) converged feedforward filter coefficients, (b) power spectra of the error signal

Secondly, the tFB and sFB structures are utilized to control uncorrelated disturbance within 100~150 Hz frequency band respectively. The FxLMS algorithm is also employed to update the control filter in tFB structure and the step size is 0.005, but the leaky FxLMS algorithm (with leakage coefficient 0.9999) is employed to adapt the control filter in sFB structure as suggested in [14] and the step size is also 0.005. The converged control filter coefficients in tFB and sFB structures are plotted in Figure 4 (a) and the power spectra of the residual error signal at steady state is shown in Figure 4 (b). It is found from Figure 4 (b) that the uncorrelated disturbance within 100~150 Hz frequency band is attenuated about 15 dB and 10 dB by tFB and sFB structure respectively, which is in accordance with the observation in [14] that sFB structure may have lower noise reduction performance than tFB structure.



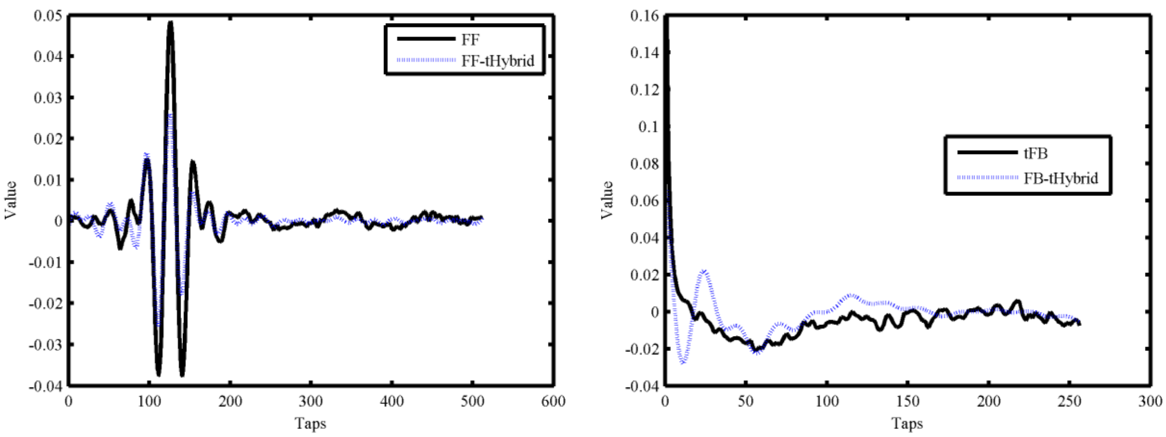
(a) (b)

Figure 4 – Active control of uncorrelated narrowband disturbance using single feedback structure: (a) converged feedback filter coefficients, (b) power spectra of the error signal

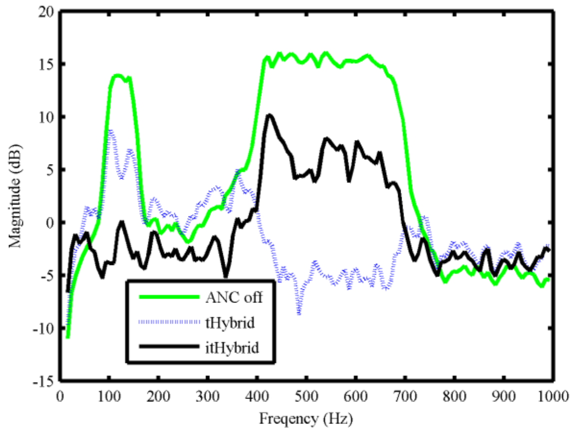
3.2 Control by tHybrid system

The simulation results of the tHybrid ANC system are illustrated in Figure 5. The feedforward control filter coefficients between FF and FF-tHybrid are compared in Figure 5 (a), it is obvious that the coefficients of FF-tHybrid do not match that of FF, and the Euclidean norm of the mismatch normalized by the Euclidean norm of FF coefficients is 0.4866. Likewise, Figure 5 (b) compares the feedback control filter coefficients between tFB and FB-tHybrid, it is shown that the coefficients of FB-tHybrid do not match that of tFB, either. The Euclidean norm of the mismatch normalized by the Euclidean norm of tFB coefficients is 0.7608.

In order to demonstrate the coupling effects in the tHybrid system, the FF coefficients plotted in Figure 3 (a) and tFB coefficients plotted in Figure 4 (a) are used directly as the converged ones in tHybrid system to control the noise, results are shown with "itHybrid" curve in Figure 5 (c). Comparing the tHybrid curve with itHybrid curve, it is found that for 400~700 Hz frequency range, tHybrid achieves about 17 dB noise reduction and that of itHybrid is about 8 dB, the reason is that FF coefficients of itHybrid is obtained by only regarding secondary path as S(z), however, as mentioned in section 2, the true secondary path is changed to the time-varying $S(z)/[1+S(z)W_c(z)]$ due to the coupling. On the other hand, for 100~150 Hz frequency range, itHybrid achieves about 15 dB noise reduction and that of tHybrid is about 5 dB. As a result, Figure 5 confirms that the FF and tFB structures are coupled in the tHybrid system, and one structure may affect the other and both structures must be updated simultaneously.



(a) (b)



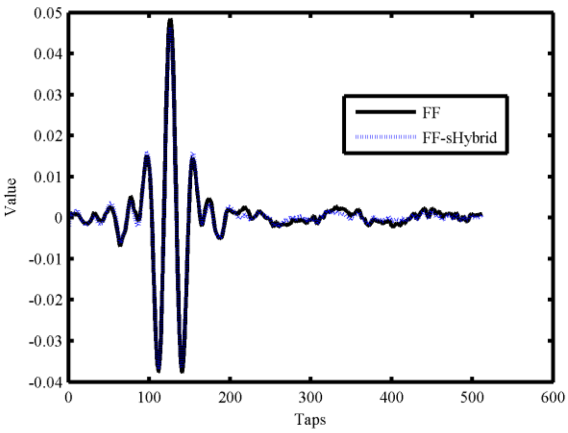
(c)

Figure 5 – Simulation results of the traditional combination method based hybrid system: (a) the feedforward control filters coefficients, (b) the feedback control filters coefficients, (c) power spectra of the error signal

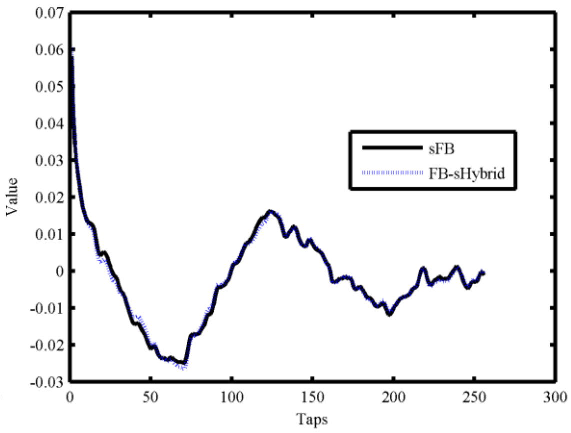
3.3 Control by sHybrid system

The simulation results of the sHybrid ANC system are exhibited in Figure 6. Comparison of the feedforward control filter coefficients between FF and FF-sHybrid is given Figure 6 (a), the Euclidean norm of the mismatch normalized by the Euclidean norm of FF coefficients is 0.0895, as indicate that the coefficients of FF-sHybrid match that of FF well. Likewise, Figure 6 (b) compares the feedback control filter coefficients between sFB and FB-sHybrid, the Euclidean norm of the mismatch normalized by the Euclidean norm of sFB coefficients is 0.0691, as show that the coefficients of FB-sHybrid match that of sFB, too.

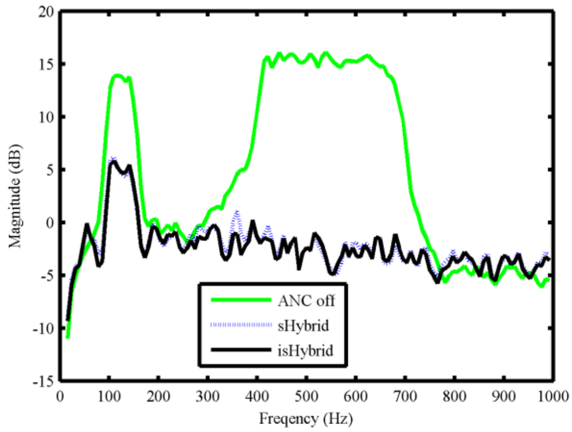
The FF coefficients plotted in Figure 3 (a) and sFB coefficients plotted in Figure 4 (a) are inserted directly into the sHybrid system to control the noise, results are shown with “isHybrid” curve in Figure 6 (c). It is found that the sHybrid curve is very close to the isHybrid curve, in more detail, for 400~700 Hz frequency range, both isHybrid and sHybrid can achieve about 15 dB noise reduction, for 100~150 Hz frequency range, the noise reduction of sHybrid and isHybrid is about 10 dB. As a result, Figure 6 confirms that the coupling between FF and FB structures is alleviated in the sHybrid system, and one structure does not affect heavily the other and both structures can be designed individually. Especially, for the low cost hybrid system using analog circuits [12–13], the ability to separately optimize the FF and FB parts brings much convenience for the practical ANC design.



(a)



(b)



(c)

Figure 6 – Simulation results of the simplified combination method based hybrid system: (a) the feedforward control filters coefficients, (b) the feedback control filters coefficients, (c) power spectra of the error signal

4. CONCLUSIONS

The noise with uncorrelated narrowband disturbance can be controlled using hybrid ANC system but the traditional method to combine the feedforward and feedback structure in the widely used hybrid ANC system brings the coupling effects. In order to mitigate the coupling, the simplified combination method is presented in this paper which features in low computational load and ease of implementation while its control performance is moderate. The simplified method can alleviate the coupling between the feedforward and feedback structures, as facilitate that both structures can be designed individually, on the other hand, the cascade of the feedforward and feedback structures in the simplified method may contribute to the overall attenuation of the noise. All these remarks are supported by simulations.

ACKNOWLEDGEMENTS

Project funded by Natural Science Foundation of Jiangsu Higher Education Institutions (13KJB510018), the Priority Academic Program Development of Jiangsu Higher Education Institutions, NUIST research project (2012X046, KHYS1302), China, and RMIT Project (Welding sound identification), Australia.

REFERENCES

1. Kuo SM, Morgan DR. Active noise control systems: algorithms and DSP implementations. New York, Wiley; 1996.
2. Elliott SJ. Signal processing for active control. London (UK), Academic Press; 2001.
3. Kuo SM, Song Y, Gong Y. A robust hybrid feedback active noise cancellation headset. IEEE Transactions on Speech and Audio Processing. 2005; 13: 607–617.
4. Chang CY, Li ST. Active noise control in headsets by using a low-cost microcontroller. IEEE Transactions on industrial electronics. 2011; 58: 1936–1942.
5. Castae-Selga R, Pena R. Active noise hybrid time-varying control for motorcycle helmets. IEEE Transactions on Control Systems Technology. 2010; 18: 602–612.
6. Zhou Y, Zhang Q, Li X, Gan W. On the use of an SPSA-based model-free feedback controller in active noise control for periodic disturbances in a duct. Journal of Sound and Vibration. 2008; 317: 456–472.
7. Romeu J. Salueña X, Jiménez S, Capdevila R, Coll LI. Active noise control in ducts in presence of standing waves, its influence on feedback effect. Applied Acoustics. 2001; 62: 3–14.
8. Akhtar M, Mitsuhashi W. Improving performance of hybrid active noise control systems for uncorrelated narrowband disturbances. IEEE Transactions on Audio Speech and Language Processing. 2011; 19: 2058–2066.
9. Kajikawa Y, Gan WS, Kuo SM. Recent advances on active noise control: open issues and innovative applications. APSIPA Transactions on Signal and Information Processing. 2012; 1: 1–21.

10. Ray LR, Solbeck JA, Streeter AD, Collier RD. Hybrid feedforward-feedback active noise reduction for hearing protection and communication. Journal of the Acoustical Society of America. 2006; 120: 2026–2036.
11. Liu L, Beemanpally K, Kuo SM. Application of multi-channel hybrid active noise control systems for infant incubators. Noise Control Engineering Journal. 2013; 61: 169–179.
12. Winberg M, Johansson S, Lago T, Claesson I. A new passive/active hybrid for a helicopter application. International Journal of Acoustics and Vibration. 1999; 4: 51–58.
13. Carme C. The third principle of active control: the feed forback. ACTIVE99 conference. 1999; 885-896.
14. Wu L, Qiu X, Guo Y. A simplified adaptive feedback active noise control system. Applied Acoustics. 2014; 81: 40–46.