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NOISE CONTROL FOR A BETTER ENVIRONMENT

A Simplified Algorithm for Hybrid Active Sound Quality Control System

LI, Shanjun[1] JIN, Guoyong[2,*] LI, Xiaobo[3] YE, Tiangui[4]
College of Power and Energy Engineering
Harbin Engineering University, Harbin, China

ABSTRACT

Active noise control system can be used to reduce the sound pressure level efficiently. In order to improve the sound quality, it is required for us to attenuate or enhance the amplitude of line-spectrum noise and to eliminate the unexpected wideband random noise. However, due to the failure of the traditional active noise control system to meet this kind of requirement，an approach named hybrid active sound quality control is proposed by Liu *et al*(7) to control sound quality of line-spectrum noise to desired target and cancel the disturbed broadband noise. To reduce the complexity of algorithm and implement it expediently, a simplified algorithm is investigated in this paper. Simulation results indicate that the simplified hybrid active sound quality control algorithm has the same ability of cancelling wideband random noise and reducing or enhancing the amplitude of line-spectrum noise.

Keywords: Simplified Algorithm, Hybrid Active Sound Quality Control, Line-spectrum Noise
I-INCE Classification of Subject Number: 30

1. INTRODUCTION

Active noise control (ANC) technology (1, 2) is mainly used to minimize the sound pressure levels at points or zones inside a listening field such as the area near human ears. This technology introduces a new acoustic field that is related to the primary acoustic field to reduce the sound levels at the controlled points and zones (3). However, it is needed to attenuate or enhance the sound levels of certain frequency bands to satisfy the requirements of the acoustic comfort in some situations.

To achieve the goal the above mentioned, the adaptive algorithm of active sound quality control was proposed by Kuo *et al* (4). It was developed on the basis of adaptive noise equalizer in which a pseudo-error noise is minimized instead of the residual noise to update the weight coefficient of controller (5-7).Besides, there is a gain factor that one can attenuate, retain and amplify noise to improve comfort by setting appropriate gain factor value in the adaptive noise equalizer structure.

Adaptive feedforward filtered-x least mean square algorithm is widely used for

[1] lishanjun98@163.com
[2] guoyongjin@ hrbeu.com
[3] lixiaobo5014@gmail .com
[4] yetiangui@ 126.com

ANC systems when reference signal can be obtained effectively by using reference sensors (8). However, if there is no suitable position to arrange the reference sensors, the causality and correlation requirement (9) may not be satisfied so that the noise can't be controlled validly by the feedforward structure. Different from the feedforward system, feedback ANC system has no reference sensor to acquire the primary noise information, the reference signal is generated by synthesizing the error signal and the secondary signal filtered with the estimation of the secondary path, and is used in actual applications where the primary noise cannot be directly observed or there are too many noise sources to economically obtain reference signal (10).

Considering that the feedforward and feedback structure have their advantages respectively, hybrid structures were developed to control both noise and uncorrelated narrowband disturbances (11-13). A decoupled hybrid algorithm was proposed by Wu *et al* (8) to improve the performance of the traditional hybrid control algorithm. However, the hybrid control algorithm above-mentioned cannot carry out the sound quality control. A traditional hybrid sound quality control algorithm was proposed by Liu *et al* (7) control sound quality of noise and reduce the disturbance. Combining the decoupled algorithm and the sound quality control algorithm, a simplified hybrid sound quality control algorithm is constructed, which decreases the complexity of algorithm and the coupling effects of the feedforward and feedback structures. This new structure excludes the secondary signals of the feedforward structure from the synthesis of the reference signal in the feedback structure and uses the summation of error signal and the output signal of line-spectrum noise control filter as the reference signal of the feedback structure. Similar to the traditional hybrid active sound quality control algorithm, the feedforward structure is used for controlling the sound quality of line-spectrum noise and the feedback structure is used for alleviating the broadband disturbed noise.

2. SIMPLIFIED HYBRID ACTIVE SOUND QUALITY CONTROL SYSTEMS

2.1 Simplified Hybrid Feedforward and Feedback Control Structure

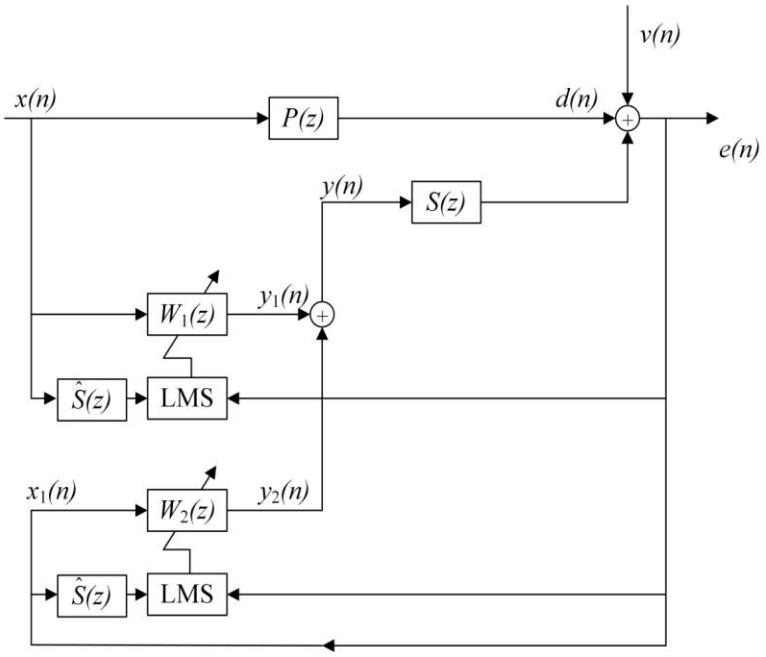


Figure 1 Schematic diagram of the simplified hybrid ANC algorithm structure first proposed by Ref.(8)

A simplified structure based on feedforward and feedback ANC systems was illustrated by Wu and Guo et al. (8). The schematic diagram of the hybrid structure is shown in Figure 1.It can be observed that the residual error signal $e(n)$ in the feedforward structure is used directly as the reference signal $x_1(n)$ for the feedback structure. The reference signal $x_1(n)$ for the feedback structure is Equation (1) instead of Equation (2) in the Ref.8.

$$x_1(n) = e(n) \tag{1}$$

$$x_1(n) = e(n) + y(n) * \hat{s}(n) \tag{2}$$

where $y(n)$ is the summation of the output signals for feedforward and feedback control filter, $\hat{s}(n)$ is the estimated model of the secondary path for feedforward structure.

2.2 Simplified Hybrid Active Sound Quality Control Systems

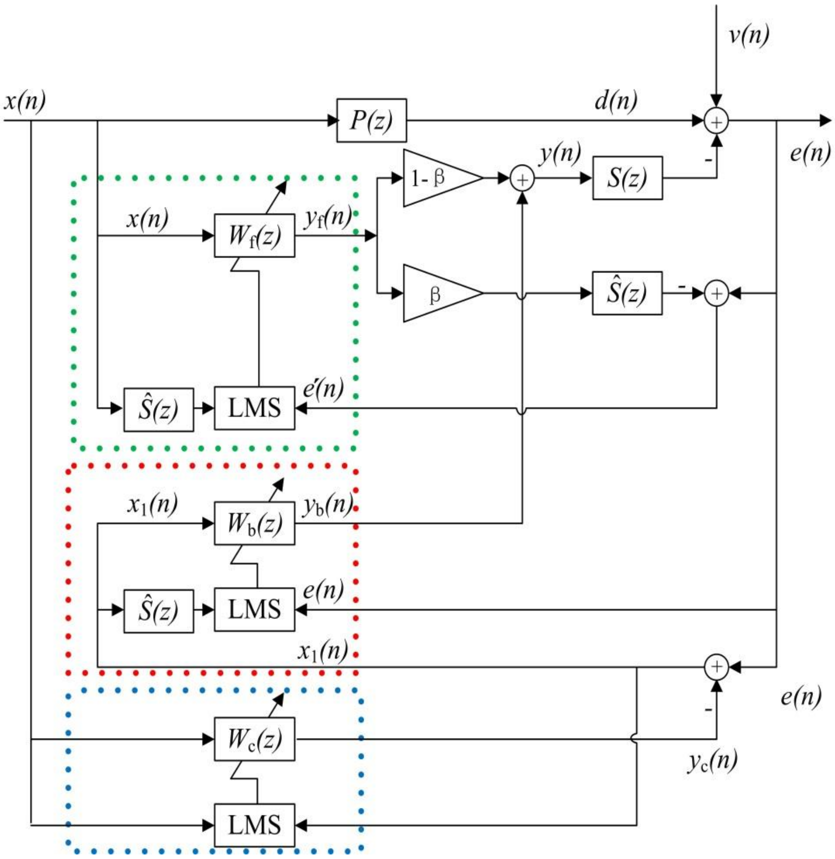


Figure 2 Schematic diagram of the proposed simplified HSQC system

In the practical application, the model of the secondary path needs be estimated, so the simplified hybrid active sound quality control system is proposed for the ease of implementation and less complexity of system. The schematic diagram is presented in Figure 2. The simplified system has three parts, the feedforward control structure, the feedback control structure and the line-spectrum noise control structure respectively, which correspond to the green, red and blue rectangle boxes in Figure 2. The feedforward control structure is used to control sound quality of line-spectrum noise such as the gearbox noise. The feedback control structure is used to control the broadband noise whose reference signal can be synthesised easily. And the line-spectrum noise control structure is used to cancel the line-spectrum noise that is residual noise in the sound quality control structure.

To study coupling effect of this structure, some formulas are derived as follows. By using the Z transforms of the signals in Figure 2, the residual error signal in the feedforward can be written as

$$E(z) = D(z) + V(z) - Y(z)S(z) \tag{3}$$

where $D(z)$ is the desired signal of line-spectrum noise, $V(z)$ is the broadband noise signal uncorrelated with the narrowband noise signal, $S(z)$ is the model of the secondary path from secondary loudspeakers to error sensors, and $Y(z)$ is the total output of the control system

$$Y(z) = (1-\beta)Y_f(z) + Y_b(z) \tag{4}$$

where β is the gain factor which can be selected on the basis of the control target of sound quality, $Y_f(z)$ and $Y_b(z)$ are the secondary signals of the feedforward and feedback structures respectively

$$Y_f(z) = X(z)W_f(z) \tag{5}$$

$$Y_b(z) = X_1(z)W_b(z) \tag{6}$$

where $W_f(z)$ and $W_b(z)$ are the feedforward control filter and the feedback control filters, respectively, $X(z)$ is the reference signal of the feedforward control structure, and $X_1(z)$ is the reference signal of the feedback structure synthesized by

$$X_1(z) = E(z) - Y_c(z) \tag{7}$$

where $Y_c(z)$ is the output of the line-spectrum noise controller, which can be obtained by

$$Y_c(z) = X(z)W_c(z) \tag{8}$$

where $W_c(z)$ is the line-spectrum noise control filter.

Substituting Equation (4-6) into Equation (3) gives

$$E(z) = D(z) + V(z) - S(z)[(1-\beta)X(z)W_f(z) + X_1(z)W_b(z)] \tag{9}$$

Substituting Equation 7-8 into Equation (9) and rearranging Equation (9), one has

$$E(z) = D(z) + V(z) - S(z)[(1-\beta)X(z)W_f(z) + (E(z) - X(z)W_c(z))W_b(z)] \tag{10}$$

After further derivation, one yields

$$E(z) = \frac{1}{1+S(z)W_b(z)}\left[D(z)+V(z)\right] - \frac{(1-\beta)W_f(z) - W_c(z))W_b(z)}{1+S(z)W_b(z)}S(z)X(z)] \tag{11}$$

where $D(z) = X(z)P(z)$, $P(z)$ is the model of the main path from reference sensors to error sensors.

Then the error signal in this simplified system is given by

$$E(z) = \frac{1}{1+S(z)W_b(z)}V(z) - \frac{\mathrm{P(z)} + [(1-\beta)W_f(z) - W_c(z)W_b(z)]S(z)}{1+S(z)W_b(z)}X(z) \tag{12}$$

From Equation (12) it can be known that the feedforward controller and the feedback controller has less coupling effect compared with the traditional hybrid active sound quality control system. When the gain facter β is set to zero, the sound quality control system becomes the common ANC system. In the moment, the term $\mathrm{P(z)} + [(1-\beta)W_f(z) - W_c(z)W_b(z)]S(z)$ can be seen as zeros in order to reduce the line-spectrum noise, then the feedforward controller becomes

$$W_f(z) = W_c(z)W_b(z) - \frac{P(z)}{S(z)} \tag{13}$$

Based on the Equation (13), it can be seen that the feedback controller and the line-spectrum noise controller influence the iteration of the feedforward controller.

3. SIMULATIONS AND DISCUSSIONS

3.1 Simulation Parameters

The simulation parameters of the simplified hybrid active sound quality control algorithm are set up to study their performances. The mathematic model of the main path $P(z)$ and the secondary path $S(z)$ are the same as Ref.7 for convenience of comparison

$$P(z) = 0.0167 + 0.4833z^{-1} + 0.4833z^{-2} + 0.0167z^{-3} \tag{14}$$

$$\mathrm{S}(z) = 0.2037z^{-1} + 0.5926z^{-2} + 0.2037z^{-3} \tag{15}$$

At the same time, it is assumed that the estimated model of the secondary path $\hat{S}(z)$ is equal to the actual model of the secondary path $S(z)$.

In the simulation, the noise signal has two parts, first part is the line-spectrum noise $d(n)$ and the second one is the wideband random noise $v(n)$. The line-spectrum noise $d(n)$ can be acquired by filtering the reference signal $x(n)$ via the main path $P(z)$. The frequency of the reference signal is 56 Hz and the amplitude of the reference signal is 1. The wideband random noise $v(n)$ can be set to a bandlimited random noise that is received by filtering a zero mean normally distributed pseudorandom signal with a 128th order lowpass filter with cut off frequency of 100Hz. And the length of the feedforward control filter $W_f(z)$, the feedback control filter $W_b(z)$ and the line-spectrum noise control filter $W_c(z)$ is 512, the step size μ_1, μ_2 and μ_3 are 0.0005, 0.0005 and 0.005, respectively. Besides, the sampling frequency is 10240 Hz, the length of the simulation is 4s.

3.2 Simulation Results and Discussions

Figures 1, 3, 5 and 7 present the waveforms of the residual and pseudo-error noise when the gain factor β is set to 0, 0.5, 1 and 2 respectively. These pictures show that the present algorithm can achieve the control goal for sound quality. In other word, it can attenuate, retain and enhance the amplitude of line-spectrum noise. However, it can be noticed that only harmonic noise signal is used to validate the algorithm performance. The reference noise signal with multiple frequencies can be controlled by configuring multiple feedforward sound quality controllers in parallel.

In addition, both the residual error signal and the pseudo-error signal can converge rapidly. The waveform of residual error signal is the same as the one of pseudo-error signal because the residual error signal is equal to the pseudo-error signal when the gain

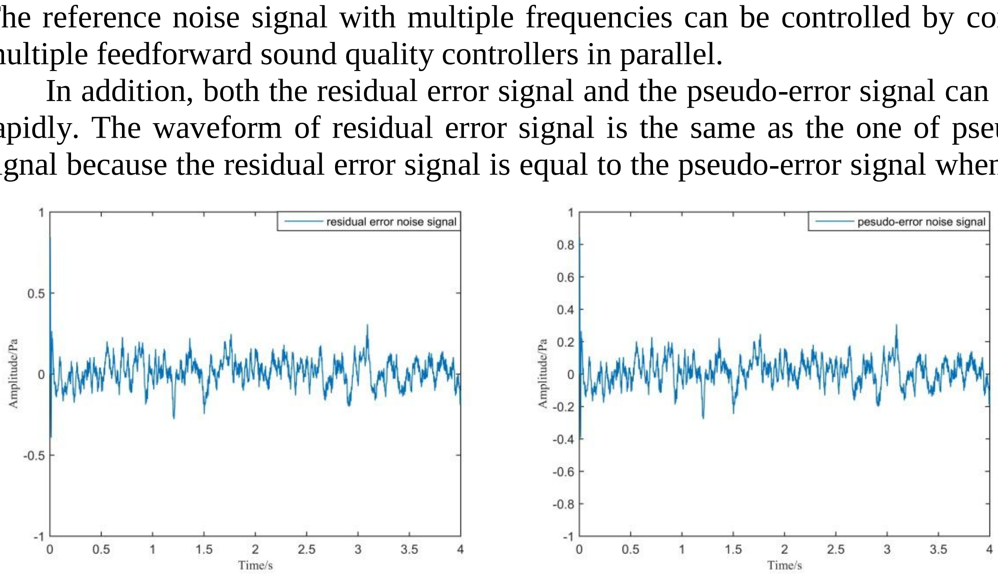


Figure 3 Waveforms of the residual error noise signal and pseudo-error noise signal (β =0)

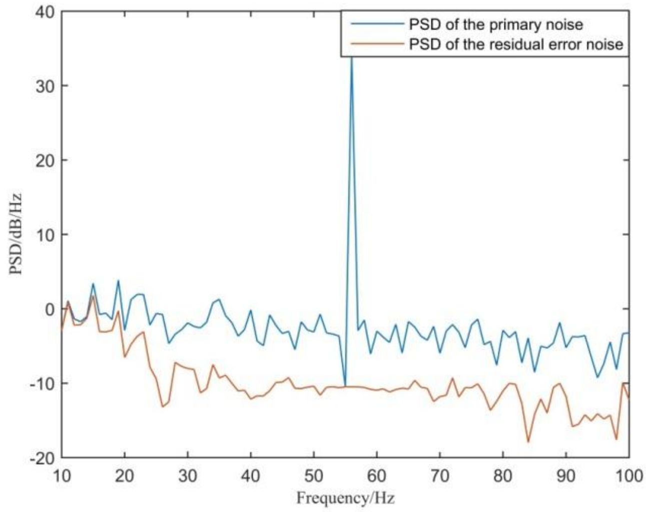


Figure 4 PSD of the primary noise signal and the residual noise signal(β =0)

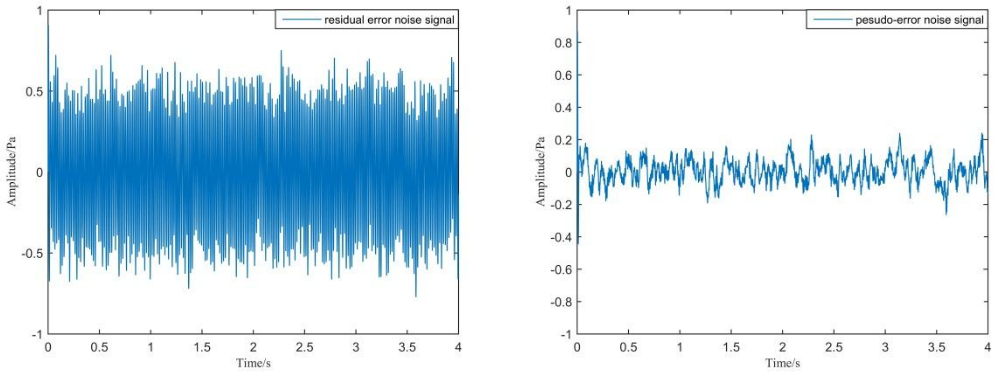


Figure 5 Waveforms of the residual error noise signal and pseudo-error noise signal (β =0.5)

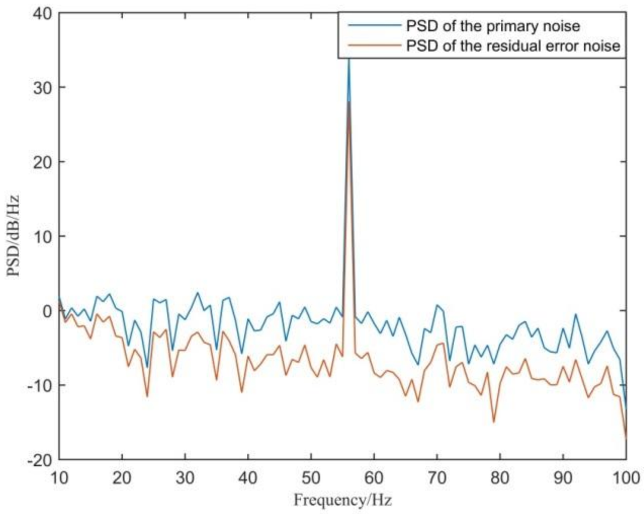


Figure 6 PSD of the primary noise signal and the residual noise signal(β =0.5)

factor β is set to zero. And the pseudo-error signals cannot be minimized to zero because of the existence of random noise in the primary noise.

Figures 4, 6, 8 and 10 illustrate the power spectrum density (PSD) of the primary noise signal and the residual noise signal. The primary noise signal includes the line-spectrum noise signal and the random noise signal. From these photos, it can be known that the simplified hybrid sound quality control system can control sound quality of line-spectrum noise by setting different the gain factors to control the noise amplitude. And the simulation results are in accord with theoretical calculations in Ref.7.

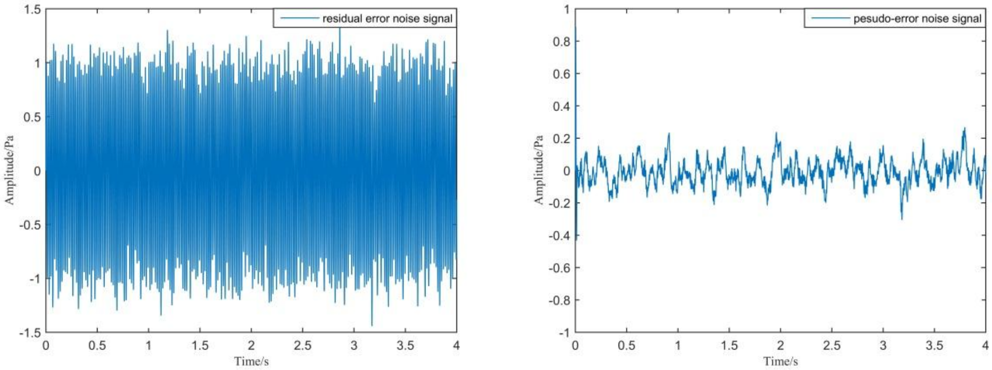


Figure 7 Waveforms of the residual error noise signal and pseudo-error noise signal (β =1)

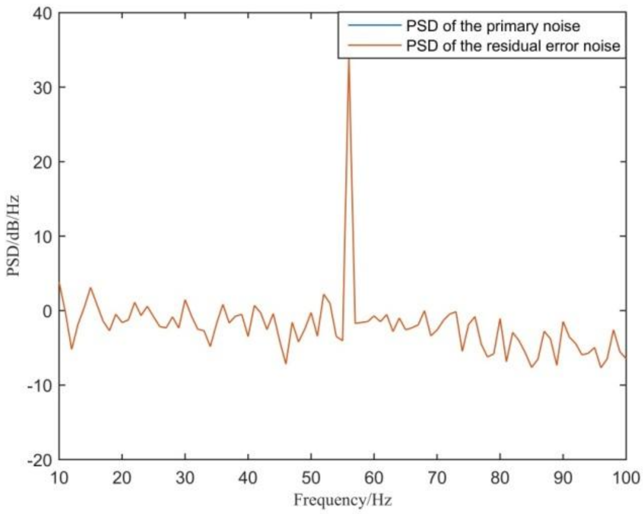


Figure 8 PSD of the primary noise signal and the residual noise signal (β =1)

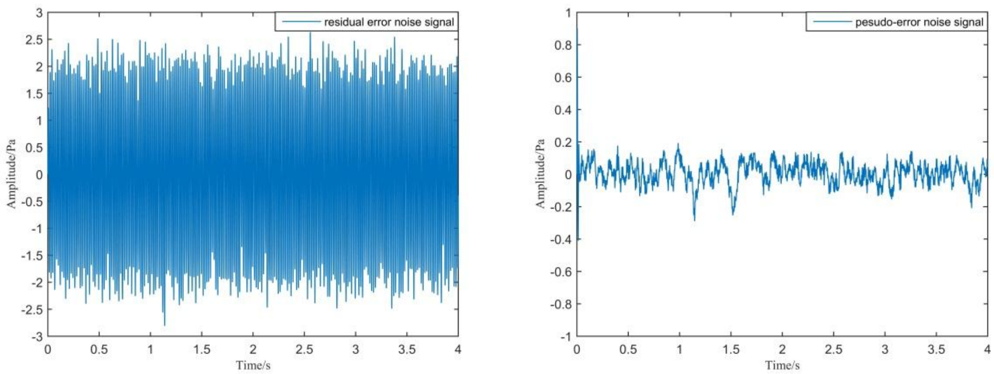


Figure 9 Waveforms of the residual error noise signal and pseudo-error noise signal (β =2)

Figure 11, It is indicated that the waveforms of output signal for feedback control filter when the step size of feedback control filter is 0.005 and the gain factor is 0.5. In this figure, it can be understand that the feedback control filter used different control algorithm, FXLMS and Leaky-FXLMS algorithm (14). It can be drawn that the output signal for feedback control filter using Leaky-FXLMS algorithm is more stable compared to the one using FXLMS algorithm because some iterations of the feedback control filter in feedback control structure are unstable.

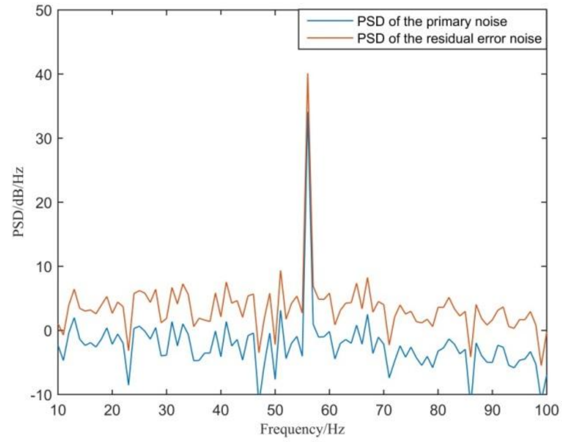
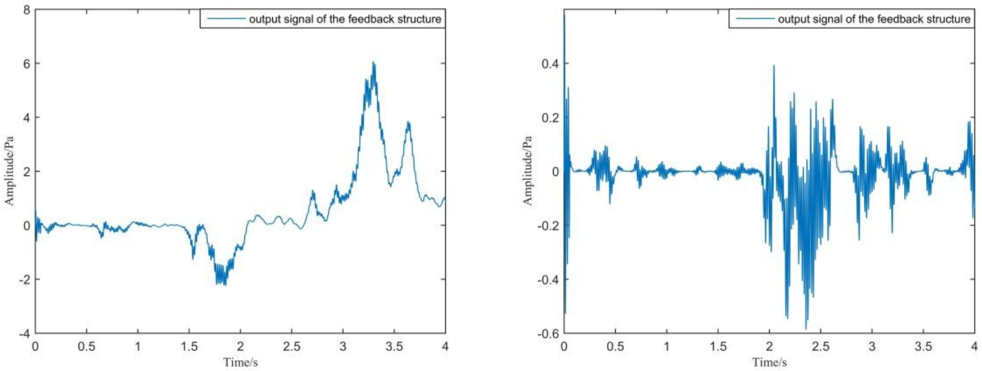


Figure 10 PSD of the primary and the residual noise (β =2)



a.) The FXLMS algorithm *b.) The leaky-FXLMS algorithm*

Figure 11 Waveforms of the output for feedback control filter

4. CONCLUSIONS

The traditional hybrid active sound quality control algorithm not only has a complicated schematic diagram, but also it exists the coupling effect of feedforward and feedback structures. To decrease the complexity of system and the coupling effect, a simplified hybrid active sound quality control system is constructed to control the sound quality of line-spectrum noise in this paper. This new structure excludes the secondary signals of the feedforward structure from the synthesis of the reference signal and uses summation of the error signal and the output signal of line-spectrum noise control filter as the reference signal of the feedback structure. The advantages of the system are low complexity and ease of implementation. Simulation results verify the validity of the algorithm. In other word, the simplified hybrid active sound quality control algorithm has the same ability of cancelling wideband random noise and reducing or enhancing the amplitude of line-spectrum noise compared with the traditional hybrid active sound quality control algorithm. In addition, the feedback control filter in the simplified algorithm can be unstable in some iterations, it can be solved by using a leaky-FXLMS algorithm in the feedback control filter.

5. ACKNOWLEDGEMENTS

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