

## **Discomfort Reduction for Residual Noise of Active Noise Control System using Noise Shaping Filter**

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### **ABSTRACT**

Acoustic noise problems become more and more serious. The traditional approach to acoustic noise problem uses passive noise control (PNC) such as barriers and silencers to attenuate the unwanted noise by physically shuttering or absorbing it. However, PNC systems are relatively huge and ineffective at low-frequency noise. Different from the PNC, active noise control (ANC) systems are efficiently at low-frequency noise by emitting the anti-noise with equal amplitude and opposite phase to attenuate the unwanted noise compactly with reasonable cost. However, it is impossible to attenuate the unwanted noise completely. Thus, there will be residual noise existing and may cause discomfort for human. To solve this problem, in this paper, we propose an ANC system with noise shaping filter. The noise shaping filter reshapes the spectrum of residual noise into the designated spectrum. Then, the noise control filter is updated to be both capable for reducing the unwanted noise and making the residual noise less discomfort for human. Simulation results of objective evaluation show that the proposed method successfully reshape the spectrum of residual noise.

**Keywords:** Active noise control, Residual noise, Shaping filter, Comfortable sound design

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### **1. INTRODUCTION**

Acoustic noise problems are becoming more and more serious as increased numbers of industrial equipment. Traditional methods of suppressing acoustic noise are using passive

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noise control (PNC) such as barriers and silencers to attenuate the unwanted noise by physically shuttering or absorbing it. However, PNC has a critical problem that it is difficult to attenuate low-frequency noise. This is because low-frequency noise has large wavelengths compared to the thicknesses of typical barriers, and it is not practical to make the barriers thicker since the enormous cost of space. Active noise control (ANC) [1, 2] is based on the principle of superposition and emits an anti-noise of equal amplitude and opposite phase to attenuate unwanted noise. ANC systems attenuate low-frequency noise more efficiently than PNC systems and require few spaces.

Generally, ANC systems cannot attenuate unwanted noise completely, and the remains are usually mentioned as residual noise. General ANC systems simply aim to minimize the power of residual noise regardless of the spectrum [3–5], and this is the main reason why residual noise is uncomfortable. In some applications, ANC systems considering of the spectrum of residual noise have been proposed [6, 7]. These applications modify the spectrum of residual noise based on A-weighting filters [8] represent the sound sensitivity of human’s ears. Therefore, shaping the spectrum of residual noise with A-weighting filters can improve the noise reduction performance by psychoacoustical criterion. However, in these conventional methods, the discomfort of residual noise has not been discussed.

In this paper, we proposed a novel ANC system that shapes the spectrum of residual noise using  $1/f$  fluctuation [9] in perspective of reducing the discomfort of residual noise. Results that  $1/f$  fluctuation is highly relative to human biological systems and has the effect of relaxation have been shown in [10–12]. In our proposed method, we design an adaptive noise shaping filter to shape the spectrum of residual noise into designated one satisfying  $1/f$  fluctuation. Both objective and subjective evaluations have been conducted. Results of the objective evaluation show that our proposed ANC system can shape the spectrum of residual noise successfully into the designated  $1/f$  fluctuation. Moreover, results of the subjective evaluation indicate that the residual noise with the  $1/f$  fluctuation spectrum is less uncomfortable than the residual noise of general ANC systems.

## 2. GENERAL ACTIVE NOISE CONTROL SYSTEM WITH FILTERED-X ALGORITHM

The filtered-X normalized least-mean-square (FXNLMS) algorithm is popularly used in general ANC systems [13, 14]. The block-diagram of a general ANC system using the FXNLMS is illustrated in Figure 1.

The FXNLMS algorithm aims to minimize the normalized least-mean-square (NLMS) of the residual noise  $e(n)$  by updating the noise control filter  $w(n)$  adaptively by

$$\mathbf{w}(n+1) = \mathbf{w}(n) + \frac{\alpha e(n)\mathbf{u}(n)}{\|\mathbf{u}(n)\|^2 + \beta}, \quad (1)$$

$$\mathbf{w}(n) = [w(n), w(n-1), \dots, w(n-N_w+1)]^T, \quad (2)$$

where  $\alpha$  and  $\beta$  are the step-size and regularization parameters.  $u(n)$  denotes the filtered reference signal vector expressed as follows.

$$\mathbf{u}(n) = [u(n), u(n-1), \dots, u(n-N_w+1)]^T, \quad (3)$$

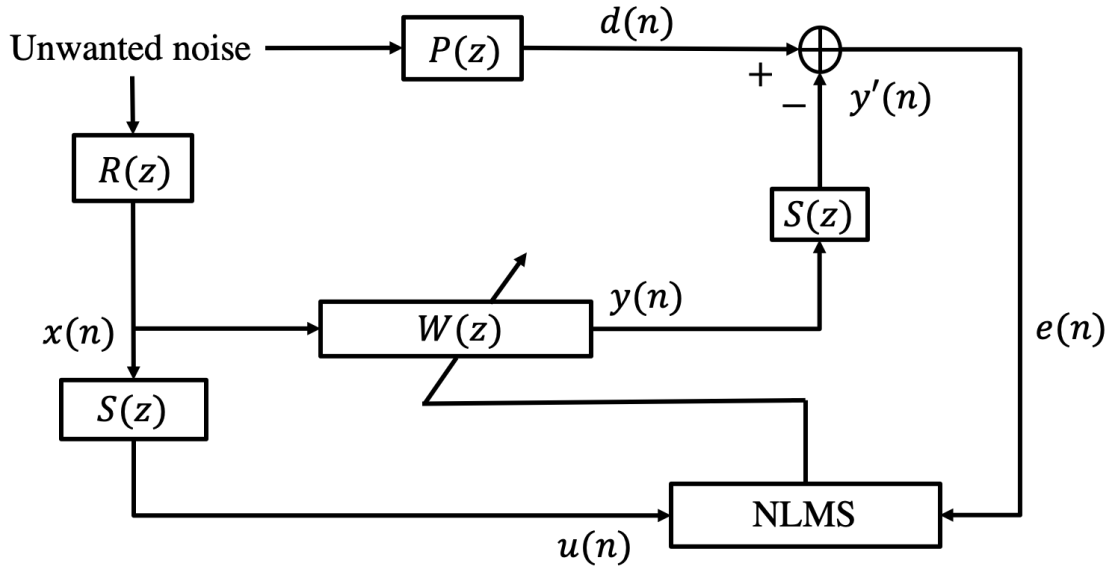


Figure 1: Block diagram of a general ANC system with FXNLMS.

$$u(n) = \hat{\mathbf{s}}^T \mathbf{x}(n), \quad (4)$$

$$\mathbf{x}(n) = [x(n), x(n-1), \dots, x(n-N_w+1)]^T, \quad (5)$$

$$\hat{\mathbf{s}} = [\hat{s}_0, \hat{s}_1, \dots, \hat{s}_{N_s-1}]^T, \quad (6)$$

where  $\mathbf{u}(n)$  and  $\hat{\mathbf{s}}$  represent the filtered reference signal vector and the impulse response of secondary path model.

General ANC systems do not consider the spectrum of residual noise, and it is the main reason why residual noise usually is uncomfortable.

### 3. PROPOSED ACTIVE NOISE CONTROL SYSTEM

To solve the problem shown in Section 2. In this paper, we propose an ANC system shaping the spectrum of residual noise into  $1/f$ -like one.  $1/f$  fluctuation has been reported in a wide variety of biological contexts [10, 11] For example, frequency analysis of the normal variability in heart rate in healthy subjects a  $1/f$ -like spectrum. As for the method to shape residual noise into desired shape, a residual noise shaping technique of importing a noise shaping filter into the general FXNMLS based system was used [6]. The block-diagram of our proposed system is shown in Figure 2.

Referring to Figure 2,  $H(z)$  denotes the response of noise shaping filter  $\mathbf{h}$  given as

$$\begin{aligned} \mathbf{h} &= \mathcal{Z}^{-1}\{H(z)\} \\ &= [h_0, h_1, \dots, h_{N_h-1}]^T, \end{aligned} \quad (7)$$

where  $\mathcal{Z}^{-1}\{*\}$  is defined as inverse  $z$  transform operator. The relation between  $H(z)$  and  $1/f$  fluctuation can be represented as

$$G(z) = \frac{1}{H(z)}, \quad (8)$$

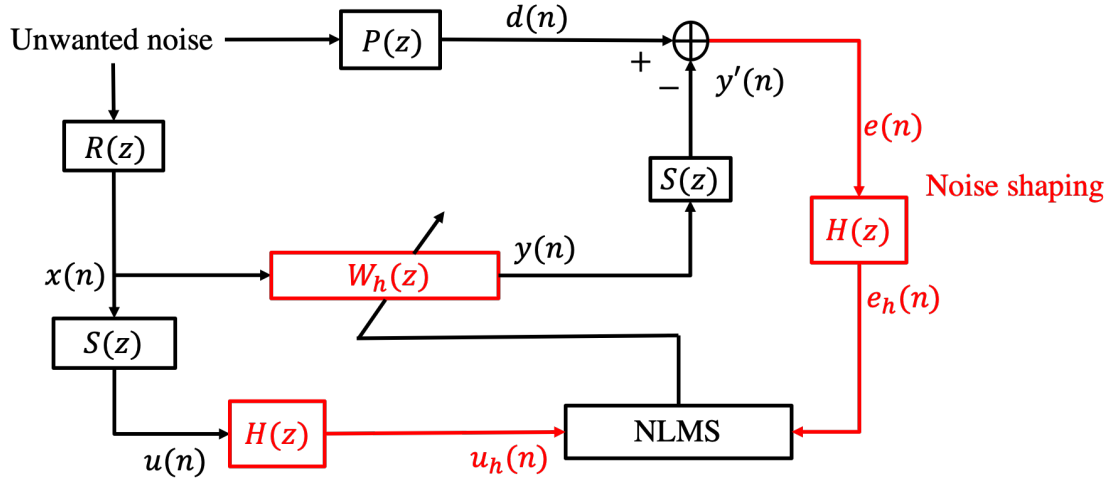


Figure 2: Block-diagram of proposed ANC system with noise shaping filtering, where the parts of noise shaping are marked in red.

where  $G(z)$  is the designated  $1/f$ -like spectrum. And the noise shaping is shown as

$$e_h(n) = \mathbf{h}^T \mathbf{e}(n), \quad (9)$$

$$\mathbf{e}_h(n) = [e_h(n), e_h(n-1), \dots, e_h(n-N_h+1)]^T, \quad (10)$$

where  $\mathbf{h}$  denotes the noise shaping filter. Therefore, the noise control filter  $\mathbf{w}_h(n)$  of the proposed ANC system is expressed as

$$\mathbf{w}_h(n+1) = \mathbf{w}_h(n) + \frac{\alpha e_h(n) \mathbf{u}_h(n)}{\|\mathbf{u}_h(n)\|^2 + \beta}, \quad (11)$$

$$\mathbf{u}_h(n) = [u_h(n), u_h(n-1), \dots, u_h(n-N_h+1)]^T, \quad (12)$$

$$u_h(n) = \mathbf{h}^T \mathbf{u}(n). \quad (13)$$

As Equation (8) illustrated, the noise shaping filter has an inverse response of the desired residual noise magnitude. This is because that the filtered residual noise  $e_h(n)$  will be minimized instead of the real residual noise  $e(n)$  and  $e(n)$  will have a  $1/f$ -like spectrum after the convergence.

#### 4. EVALUATIONS

The objective evaluation based on simulations aimed to confirm whether the proposed ANC system can successfully attenuate the residual noise and shape its spectrum into  $1/f$  fluctuation. Experimental environment of the simulations is shown in Figure 3. Table 1 consists the parameters and equipment of simulations. Figure 6 illustrates impulse responses and magnitude spectra of the noise shaping filter, the reference path, the primary path and the secondary path respectively.

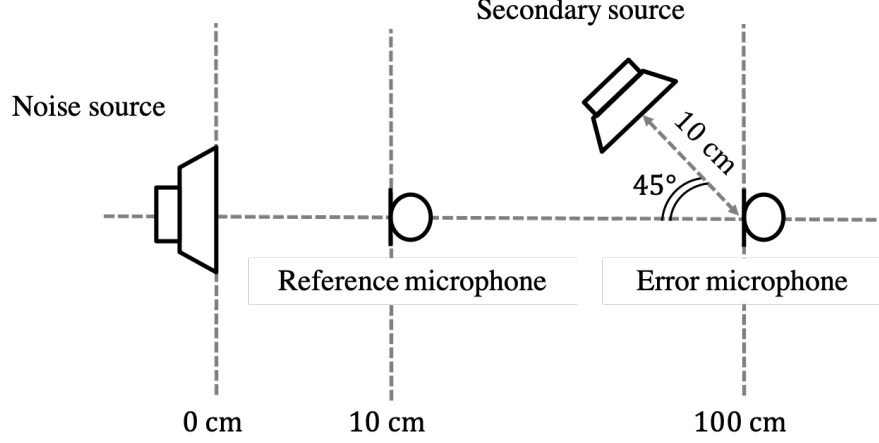


Figure 3: Experimental environment.

Table 1: Simulation conditions.

Sampling-rate	8 kHz
Ambient environment	Sound proof room ( $L_A = 22$ dB)
Noise source	White gaussian noise
Duration	60 s (ANC on at 5 s)
Length of noise control filter $w(n)$	512
Step-size parameter $\alpha$	$1.0 \times 10^{-2}$
Regularization parameter $\beta$	$1.0 \times 10^{-5}$

Noise attenuation performance is evaluated by reduction defined as follows,

$$\text{Reduction}(n, I) = 10 \log_{10} \frac{\sum_{i=0}^{I-1} d^2(n-i)}{\sum_{i=0}^{I-1} e^2(n-i)}, \quad (14)$$

where  $\text{Reduction}(n, I)$  denotes the noise reduction of at  $n$ th sample referring its former  $I$  samples. Spectral convergence of the residual noise is defined as

$$\text{Spectral Convergence} = 10 \log_{10} \left\| |G(z)| - |E(z)| \right\|_2, \quad (15)$$

where  $E(z)$  and  $G(z)$  are the frequency spectra of the residual noise and desired  $1/f$  fluctuation. Note that we did the simulations for 100 times and performed the objective evaluation with the average spectrum.

Reduction( $n, I$ ) of a general ANC and our proposed ANC with the noise shaping filter are shown in Figure 5. Comparison of spectral convergence is shown in Table 2. The spectra of the residual noise of ANC OFF, general ANC, as well as proposed ANC are shown in Figure 4

Table 2: Comparison of spectral convergence.

General ANC	<b>41.4 dB</b>
Proposed ANC	63.2 dB

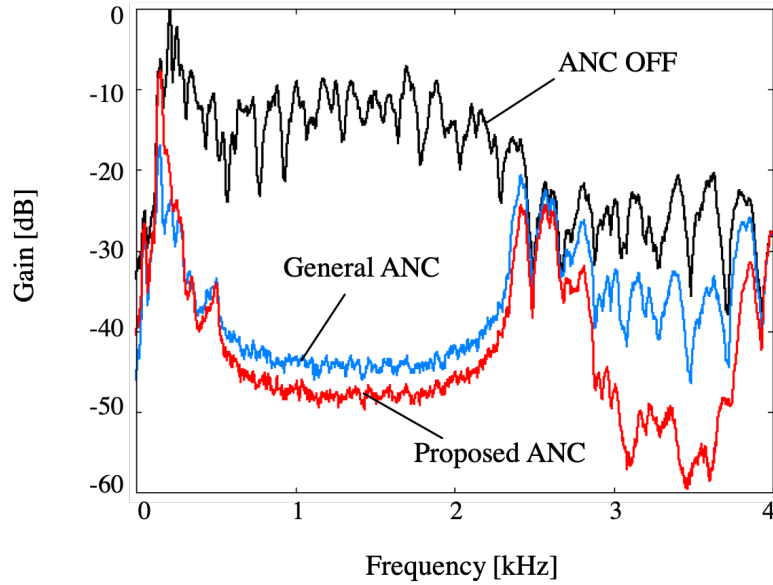


Figure 4: Magnitude spectra of ANC OFF, general ANC, and proposed  $1/f$  ANC.

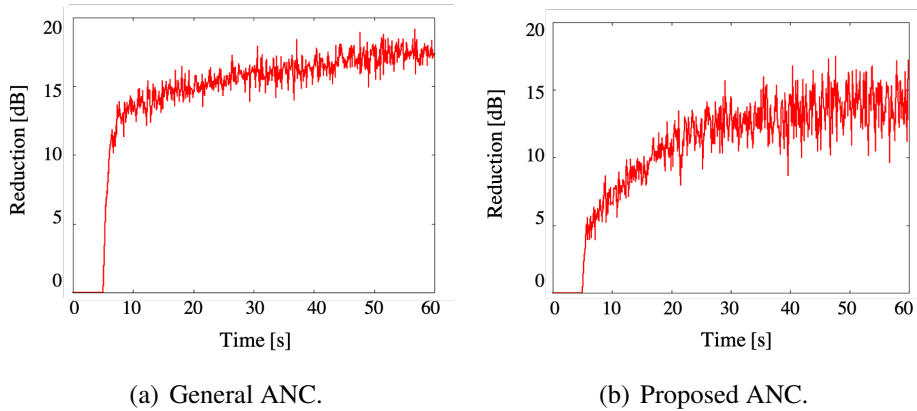
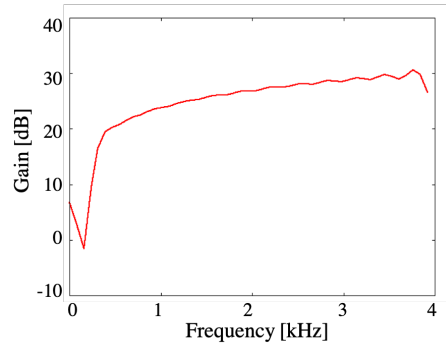
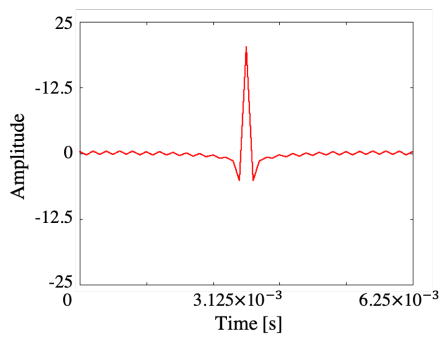
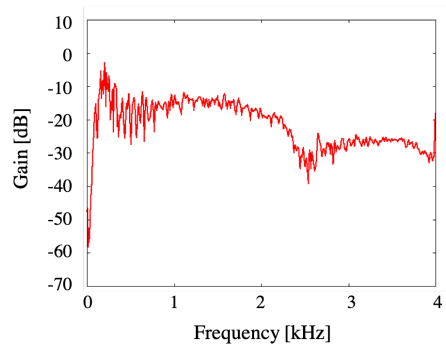
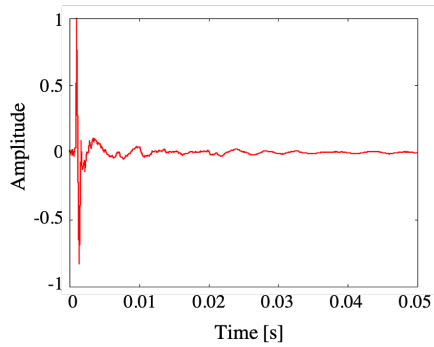


Figure 5: Comparison of noise reduction performances between general and proposed ANC.

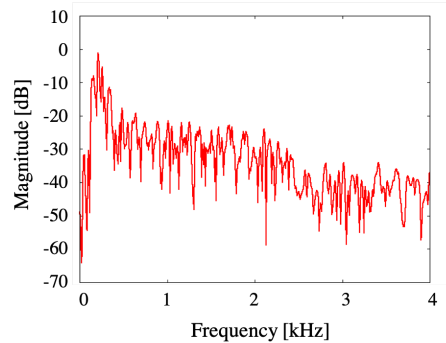
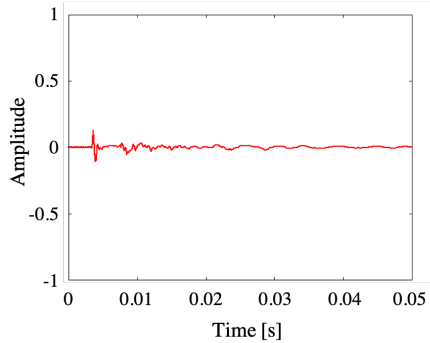
Results in Figure 5 and Table 2 indicate that the proposed ANC can shape the spectrum of the residual noise and make it closer to  $1/f$  fluctuation. Meanwhile, Figure 4 demonstrates that the proposed method may lead to a degradation of noise reduction performance approximately 3 dB, which results from the noise shaping filtering.



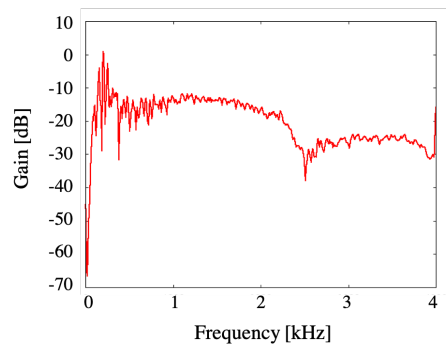
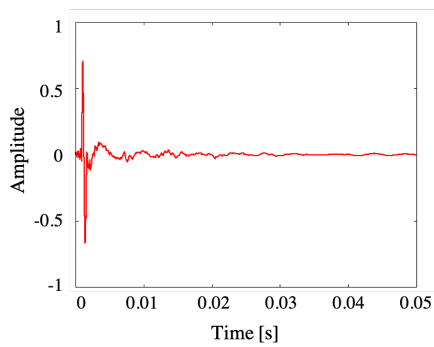
(a) Impulse response of the noise shaping (b) Magnitude spectrum of the noise shaping filter.



(c) Impulse response of the reference path. (d) Magnitude spectrum of the reference path.



(e) Impulse response of the primary path. (f) Magnitude spectrum of the primary path.



(g) Impulse response of the secondary path. (h) Magnitude spectrum of the secondary path.

Figure 6: Impulse responses and magnitude spectra.

## 5. CONCLUSIONS & FUTURE WORKS

In this paper, we proposed a novel ANC system that shapes the spectrum of residual noise using noise shaping filter in perspective of reducing the discomfort. Objective evaluations show that noise shaping filter can shape the residual noise spectrum into desired  $1/f$  fluctuation. However, the proposed method requires on sacrifice of noise reduction performance by about 3 dB.

As for future works, we consider to compare the comfort between conventional ANC systems that shape the residual noise with A-weighting filter [6, 7] and our proposed ANC system by subjective evaluations.

## 6. ACKNOWLEDGEMENTS

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