An investigation of multi-channel ANC system based on different values of step-size

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ABSTRACT

Multi-channel Active Noise Control (ANC) system can effectively eliminate low-frequency noise in large scenes, received widespread attention in recent years. First, we derived the multi-channel ANC algorithm, namely the multi-channel Filtered-x Least Mean Squared (FxLMS) algorithm. Based on the multi-channel FxLMS algorithm, we analyzed the effect of the step-size parameter on the multi-channel ANC system. The simulation results show that increasing the step-size parameter can effectively improve the low-frequency noise cancellation speed. However, the system stability decreases dramatically when the step-size parameter larger than the threshold. Meanwhile, when the value of step-size is larger than the threshold, the multi-channel ANC system is very sensitive. A small change will have a drastic impact on the multi-channel ANC system.

Keywords: Active noise control, FxLMS algorithm, multi-channel system, step-size parameter, sound signal processing

1. INTRODUCTION

With the improvement of people's requirements for quality of life, noise control technology has gradually become a hot topic in recent years [1-3]. Various noise control algorithms and applications have emerged [4-6]. Noise control technology can be divided into two categories: Passive Noise Control (PNC) and Active Noise Control (ANC) [7]. Since PNC devices such as sound insulation walls and sponges are less efficient in controlling low-frequency noise, ANC is triggering a research boom.

The ANC system mainly consists of the reference microphones, the secondary loudspeakers, the error microphones, and the adaptive controllers. According to the work with or without reference microphones, the ANC system can be divided into feedforward and feedback ANC systems [8]. The adaptive controller drives the secondary loudspeaker to emit a signal of the same amplitude and opposite phase to the noise signal by referring to the noise signal, namely the anti-noise signal. The two signals in space form an interference to cancel the noise signal. The error microphone measures the amplitude of the combined noise signal and transmits it back to the adaptive controller. Subsequently, the adaptive controller generates a more efficient anti-noise until the energy received at the error microphone is minimized.

Depending on the size of the scenes to be processed, ANC systems are usually differentiated into small-scale single-channel ANC systems and large-scale multi-channel ANC systems [9]. A multichannel ANC system usually consists of I reference microphones, J secondary loudspeakers and K error microphones, abbreviated as *case(I,J,K)* where I, J, K are not all equal to 1. The structure of a multi-channel ANC system is shown in Figure 1.

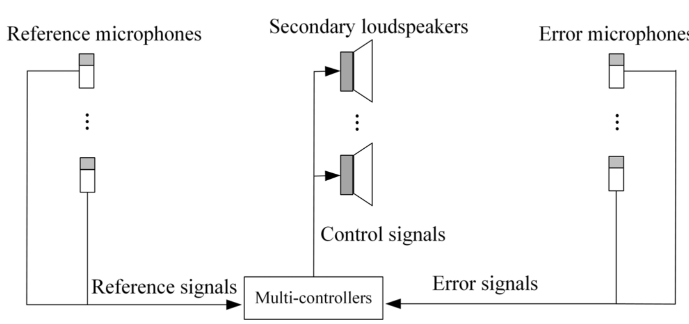

Figure 1. The structure of a multi-channel ANC system.

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In the multi-channel ANC system, I reference microphones measure spatial noise simultaneously, creating I reference signals. Meanwhile, multiple adaptive controllers process the error signals obtained from I reference signals and K error signals simultaneously to generate J control signals. Next, the control signals stimulate the secondary loudspeakers to emit J anti-noises to control the noise in large scenes, creating residual noises in the space. Finally, the error microphones transmit the residual signals back to the adaptive controllers, which generate new control signals according to the residual signals at a certain iteration speed. The above-mentioned steps keep working until the noise environment of the space is stable.

Obviously, the core of the multi-channel ANC algorithm lies in the update iteration process, which means that the selection of the step-size parameter plays an important role on the update iteration of the adaptive controller. In 2021, we have explored the effect of step-size parameter on the performance of single-channel feedforward ANC systems [9]. In order to further investigate the effect of iteration step value of multi-channel ANC system, we derive the multi-channel Filtered-x Least Mean Squared (FxLMS) algorithm in detail in this paper and analyze the relationship between the step-size parameter and multi-channel ANC system through multiple simulations.

The rest of this paper is organized as follows. In Section 2, the multi-channel ANC algorithm, multi-channel FxLMS algorithm, is introduced and derived in detail. The role of the step-size parameter in the multi-channel FxLMS algorithm is analyzed. In Section 3, the simulation results are demonstrated and analyzed. Finally, we conclude in Section 4.

2. MULTI-CHANNEL FXLMS ALGORITHM

The block diagram of the multi-channel FxLMS algorithm is shown in Figure 2.

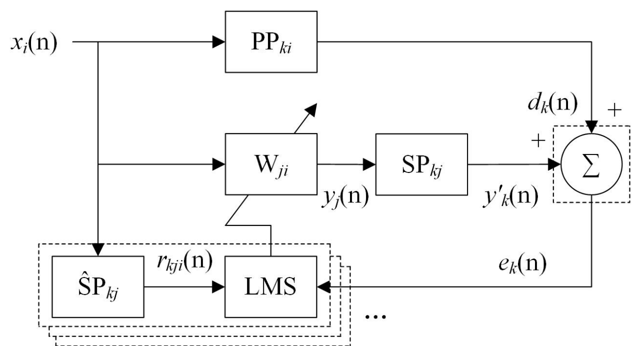

Figure 2. The block diagram of the multi-channel FxLMS algorithm.

In the multi-channel FxLMS algorithm, the k-th error signal is shown as

$$e_k(n) = d_k(n) + y'_k(n) \tag{1}$$

where $d_k(n)$ is the signal passed through the primary path to the k-th error microphone, which is expressed as

$$d_k(n) = \sum_{i=1}^{I} \boldsymbol{x_i}^T(n) PP_{ki} \tag{2}$$

$\boldsymbol{x_i}$ is the i-th reference signal. PP_{ki} represents the primary path sequence between the i-th reference microphone and the k-th error microphone, which can be defined as

$$PP_{ki} = \left[pp_{ki}^{(0)}, pp_{ki}^{(1)}, \cdots, pp_{ki}^{(L_p-1)} \right]^T \tag{3}$$

where L_p denotes the length of primary path sequence.

On the other hand, $y'_k(n)$ in equation (1) is the signal passed through the secondary path to the *k*-th error microphone, which can be expressed as

$$y'_k(n) = \sum_{j=1}^{J} \boldsymbol{y_j}^T(n) SP_{kj} \tag{4}$$

where SP_{kj} represents the secondary path sequence between the *j*-th secondary loudspeaker and the *k*-th error microphone, which can be defined as

$$SP_{kj} = \left[sp_{kj}^{(0)}, sp_{kj}^{(1)}, \cdots, sp_{kj}^{(L_s-1)} \right]^T \tag{5}$$

$y_j(n)$ in equation (4) represents the *j*-th control signal transmitted by *j*-th secondary loudspeaker, and it is demonstrated as

$$y_j(n) = \sum_{i=1}^{I} \boldsymbol{x_i}^T(n) \boldsymbol{w_{ji}}(n) \tag{6}$$

where $\boldsymbol{w_{ji}}(n)$ denotes the control filter coefficient sequence.

Then, the objective function $G(n)$ is set to the sum of the squares of the error signals received by each error microphone at each moment,

$$G(n) = \sum_{k=1}^{K} e_k^2(n) \tag{7}$$

According to equation (1) and (4), the *k*-th error signal $e_k(n)$ can be expressed as

$$e_k(n) = d_k(n) + \sum_{j=1}^{J} \boldsymbol{y_j^T}(n) SP_{kj} \tag{8}$$

Hence, the final updated iterative expression of the filter coefficients is illustrated as

$$\boldsymbol{w_{ji}}(n+1) = \boldsymbol{w_{ji}}(n) - 2\mu \sum_{k=1}^{K} e_k(n) \boldsymbol{r_{kji}}(n) \tag{9}$$

where μ denotes the step-size parameter and $\boldsymbol{r_{kji}}(n)$ is the filtered signal sequence, which is defined as

$$\boldsymbol{r_{kji}}(n) = \boldsymbol{x_i}^T(n) \hat{S}P_{kj} \tag{10}$$

Obviously, $\hat{S}P_{kj}$ represents the estimated value of kj-th secondary path.

By observing equation (9), we can easily find that the update iteration speed of the adaptive control filter coefficients is controlled by the value of the step-size parameter. Literature [9] discovered a larger step-size will speed up the convergence of the single-channel ANC system. However, when it exceeds the threshold, the system will no longer converge, which indicates that the low-frequency noise cannot be suppressed at this point.

3. SIMULATION RESULTS AND ANALYSIS

Next, we use a publicly available data of a case(1,4,4) multi-channel ANC system to investigate the effect of the step-size parameter on the performance of the multi-channel ANC system.

In the simulations, the reference signal is set as white noise from 300 Hz to 1300 Hz. Due to the spatial coupling of the multi-channel ANC system, there are 4 primary paths and 16 secondary paths in a case (1, 4, 4) ANC system. The length of primary and secondary path equals 400 and 200, respectively. The sampling frequency of the adaptive controller is 16 kHz and the length is 400. The number of simulation iterations was set to 100,000. The true value of the primary and secondary path are shown in Figure 3 and Figure 4, respectively.

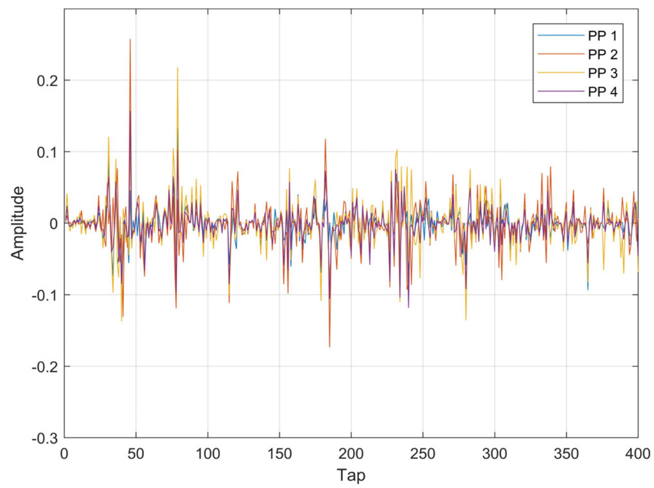

Figure 3. The true value of primary path PP1-PP4.

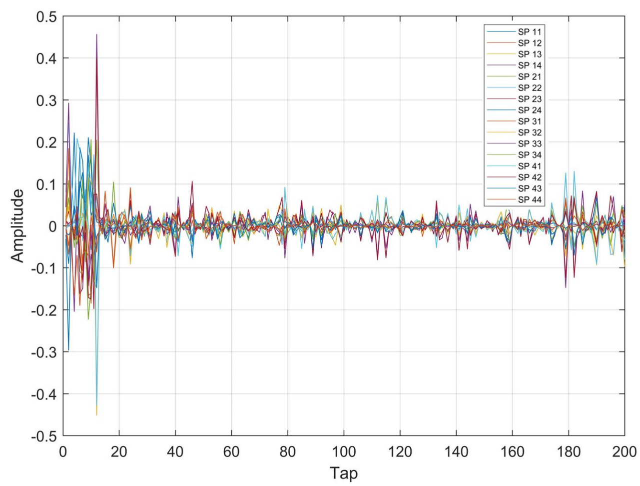

Figure 4. The true value of secondary path SP11-SP44.

In order to clearly demonstrate the effect of the step-size parameter, we assume $\mu = 2e^{-6}$ and $\mu = 2e^{-5}$ in the first simulation, respectively. The convergence of the noise signals for the four error microphones at different step-size are shown in Figure 5.

By observing Figure 5 we can see that when the ANC off, the noise signal measured at each error microphone position cannot be reduced and is unacceptable as time grows. When the ANC system is turned on and $\mu = 2e^{-6}$, the white noise at all microphone positions is significantly suppressed. The system gradually stabilizes after about 50,000 iterations. We increase the step-size to $\mu = 2e^{-5}$, at which time the noise suppression of the multi-channel ANC system is significantly accelerated, and the system can achieve stable noise reduction after about 20,000 iterations. Therefore, we find that a reasonable increase in the range of the step-size parameter can effectively improve the noise rejection speed of the multi-channel ANC system.

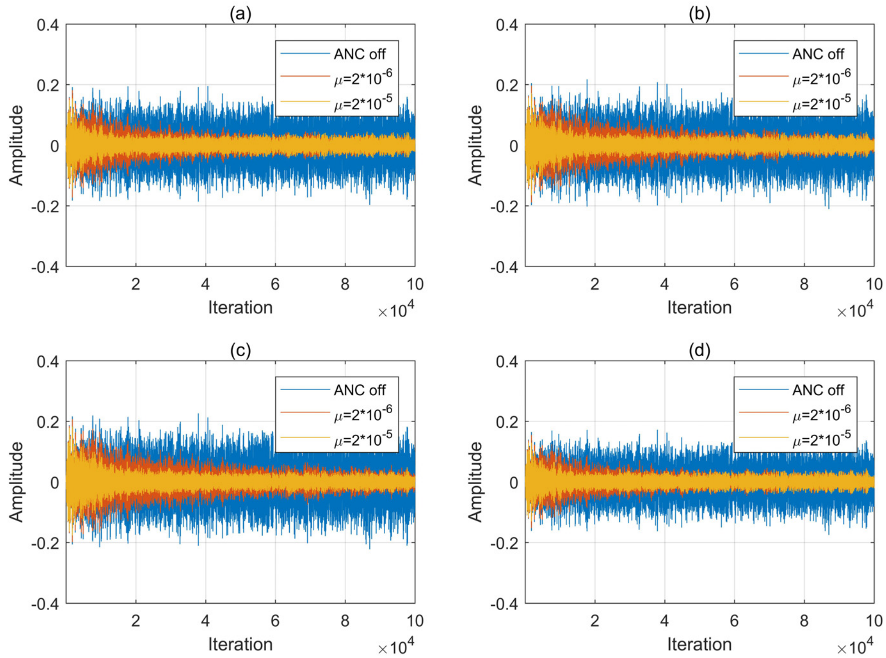

Figure 5. Residual noise amplitude of 4 error microphones when ANC off, ANC on with $\mu = 2e^{-6}$, and with $\mu = 2e^{-5}$

Then, the step-size is enlarged to $2e^{-4}$, the noise convergence results is shown in Figure 6.

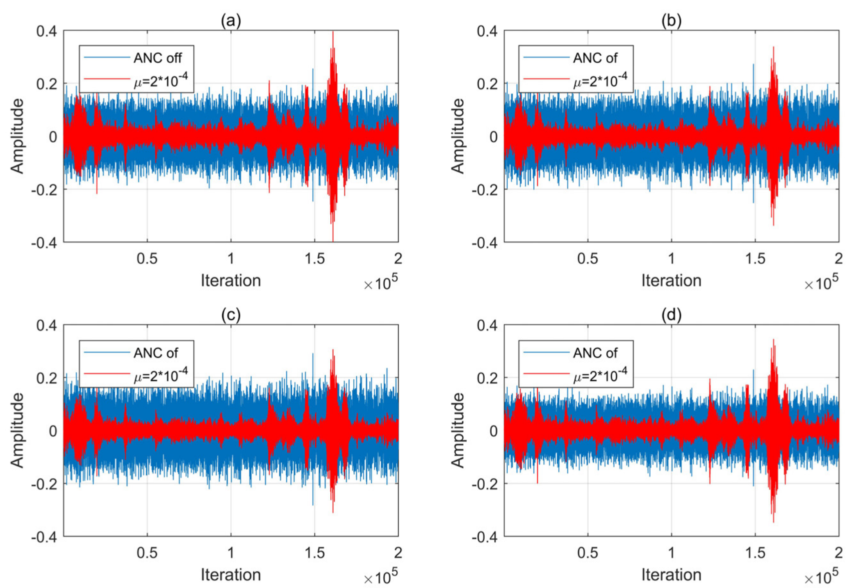

Figure 6. Residual noise amplitude of 4 error microphones when ANC off and ANC on with $\mu = 2e^{-4}$

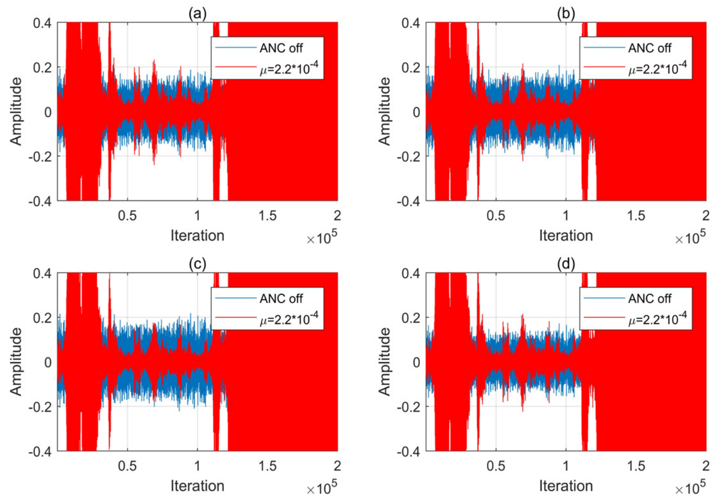

Figure 7. Residual noise amplitude of 4 error microphones when ANC off and ANC on with $\mu = 2.2e^{-4}$

When $\mu = 2e^{-4}$, the whole multi-channel ANC system becomes unstable and the system will fail at some point. Obviously, this value of step-size parameter is already larger than the system threshold, which indicates that an excessive step-size will be detrimental to the stability of the multi-channel ANC system.

Finally, we set $\mu = 2.2e^{-4}$ and the noise convergence results is demonstrated in Figure 7. It is clear that the system has completely failed at this point. Therefore, we found that the multi-channel ANC system will be very sensitive to the step-size parameter when it is larger than threshold. A small change will drastically affect its noise reduction performance.

4. CONCLUSION

In this paper, the effect of the step-size parameter in the multi-channel FxLMS algorithm is analytically explored. A reasonable increase can significantly improve the convergence speed of the multi-channel ANC system. However, a too large step-size is not conducive to the stability of the system. When the step-size is larger than the threshold, the system will fail directly and is very sensitive to it.

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