Simultaneous Variable Perturbation Method for the Active Noise Control System with a Wireless Error Microphone

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***Abstract*—This paper proposes the use of a wireless error microphone in active noise control (ANC) systems. There are several practical advantages of doing so. The target zone of quiet (ZoQ) is allowed to be reconfigured by simply moving the wireless error microphone. When the target ZoQ is large, many error microphones have to be placed. Using the wireless error microphone eases the deployment and maintenance work. However, the drawback of using wireless error microphones is due to the jitter effect of the wireless communication. The error signal samples arrive at the ANC controller at random time intervals, which sometimes are greater than the sampling interval. To solve this problem, this paper investigates the simultaneous perturbation (SP) method and proposes the simultaneous variable perturbation (SVP) method. Simulations of the ANC system with a wireless error microphone are carried out with acoustic paths measured in an actual setup. Simulation results demonstrate that when the SVP method reduces the broadband noise effectively even when the jitter effect is severe.**

I. Introduction

The ANC has gained rapid development in the last three decades to tackle problems resulting from the noise. It serves as a complementary technique to the passive noise control (PNC), which can become relatively less efficient in terms of size, weight, volume and cost when the noise frequency is lower [1], [2]. The principle of the ANC is the acoustic wave superposition. The ANC system transmits an anti-noise wave that has the same amplitude and opposite phase as the noise wave. The anti-noise wave interferes with the noise wave. Together, they result in a trivial residual noise level. This procedure is readily extended to a 3D space, where the ANC constructs an anti-noise sound field and results in a large ZoQ [3], [4], [5].

ANC systems are categorized by their control structures and number of electro-acoustic devices involved [6]. The single-channel feedforward ANC system includes a reference microphone, a control source and an error microphone, which can be imaged based on Fig. 1 by replacing the wireless channel with a connecting wire. The reference microphone provides the reference signal to the ANC controller. The error microphone inputs the error signal for the controller to adapt its control filter coefficients. The control source transmits the control signal, which is the output of the control filter. The FxLMS algorithm is widely-recognized as the standard ANC algorithm [7], [8]. In order for the FxLMS algorithm to work, the reference and error signals are fed to the ANC controller in a non-stop sample by sample manner.

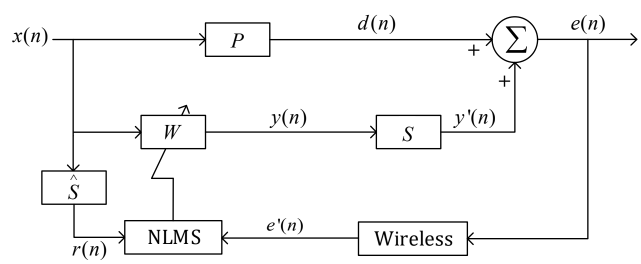

Fig. 1. Block diagram of the feedforward ANC system with a wireless error microphone.

However, the noise canceling headphone, one of the most successful ANC applications, adopts a fixed-filter structure [9]. The reference signal is still crucial to generate the control signal in real time, but the error signal is abandoned since no adaption is implemented. This fact inspires us to make the transmission of the error signal to be wireless. In Fig. 1, we propose to use a wireless error microphone in the ANC system. The proposed system design has several practical advantages. Since the ZoQ is formed around the error microphone, the target ZoQ is allowed to be reconfigured by simply moving the wireless error microphone around [10], [11], [12]. Moreover, when the target ZoQ is large, more than one error microphones have to be placed. Using the wireless error microphone eases the deployment and maintenance work.

With the emerging technology, such as 5G, latency is no longer a concern with the wireless communication [13], [14]. The drawback of the wireless error microphone lies in the jitter effect. The error signal samples arrive at the ANC controller at random time intervals, which are likely to be greater than the sampling interval. Buffering the error signal samples and adopting the delay FxLMS algorithm can only deal with a mild jitter effect. Therefore, this paper investigates the SP method and proposes the SVP method. The SP method requires no secondary path model, which is more suitable to be used with the wireless error microphone than the FxLMS algorithm [15]. By introducing a time-varying perturbation magnitude, the SVP method can converge to a lower noise level than the

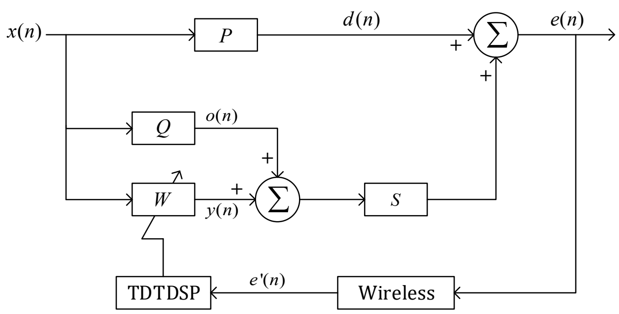

Fig. 2. Block diagram of the simultaneous perturbation method.

SP method [16]. The SVP method is also proven to be more robust than the FxLMS algorithm when coping with the jitter effect.

II. Theory and Method

In Fig. 1, $x(n)$ denotes the reference signal sample at the time n. A vector form of the reference signal is written as

$$\mathbf{x}_N(n) = [x(n), x(n-1), \ldots, x(n-N+1)]^T, \quad (1)$$

where N is the memory size, depending on the length of the control filter N_w and the length of the secondary path model $N_{\hat{s}}$; ^{T} denotes the transpose.

The error signal $e(n)$ is resultant from the acoustic wave superposition of the noise and anti-noise wave, *i.e.*

$$e(n) = d(n) + y'(n), \quad (2)$$

where $d(n)$ is the disturbance signal; and $y'(n)$ is the anti-noise signal. The imaginary system taking the reference signal as the input and generating the disturbance signal as the output is modeled as the primary path $\mathbf{p}$. Another imaginary system taking the control signal as the input and generating the anti-noise signal as the output is modeled as the secondary path $\mathbf{s}$. Both the primary and secondary paths are not just the acoustic paths. They also include the effects of the electro-acoustic devices. In order for the ANC controller to implement the FxLMS algorithm, a secondary path model $\hat{\mathbf{s}}$ is trained either off-line or on-line [17], [18]. The adaption of the control filter coefficients $\mathbf{w}(n)$ is written as

$$\mathbf{w}(n+1) = \mathbf{w}(n) - \mu\frac{\mathbf{r}(n)e(n)}{\mathbf{r}^T(n)\mathbf{r}(n)}, \quad (3)$$

where μ is the step size; the filtered reference signal vector is provided by

$$\mathbf{r}(n) = [r(n), r(n-1), \ldots, r(n-N_w+1)]^T, \quad (4)$$

in which

$$r(n) = \hat{\mathbf{s}} * \mathbf{x}_{N_{\hat{s}}}(n) \quad (5)$$

and $*$ denotes the convolution.

Figure 2 shows an alternative adaptation, namely the time-domain time-difference SP (TDTDSP) method [19]. The SP method adds perturbation to the control filter coefficients and update the control filter coefficients in a block by block manner. Supposing the block size is given by the length of the control filter N_w, the updating equation is written as

$$\mathbf{w}(n+N_w) = \mathbf{w}(n) - \mu\frac{J(n+N_w) - J(n)}{c}\mathbf{q}(n), \quad (6)$$

where

$$J(n) = \sum_{k=n-N_w+1}^{n} e^2(k); \quad (7)$$

$$\mathbf{q}(n) = [q(n), q(n-1), \ldots, q(n-N_w+1)]^T \quad (8)$$

and $q(n)$ is generated by the M sequence. $\mathbf{q}(n)$ serves as the perturbation filter coefficients, which are changing in every block. The output of the perturbation filter is denoted as $o(n)$, which is further written as

$$o(n) = c\mathbf{q}(n) * \mathbf{x}(n). \quad (9)$$

c is the perturbation magnitude in both (6) and (9).

Previous studies show that the convergence speed becomes slower as the perturbation is made smaller. Therefore, in this paper, we propose the SVP method, whereby the constant c in (4) and (7) is replaced by a time-varying $c(n)$ as

$$c(n+N_w) = \alpha c(n) + \gamma J^2(n). \quad (10)$$

α and γ are two hyper parameters to ensure that the perturbation magnitude decreases as the noise level reduces. Last but

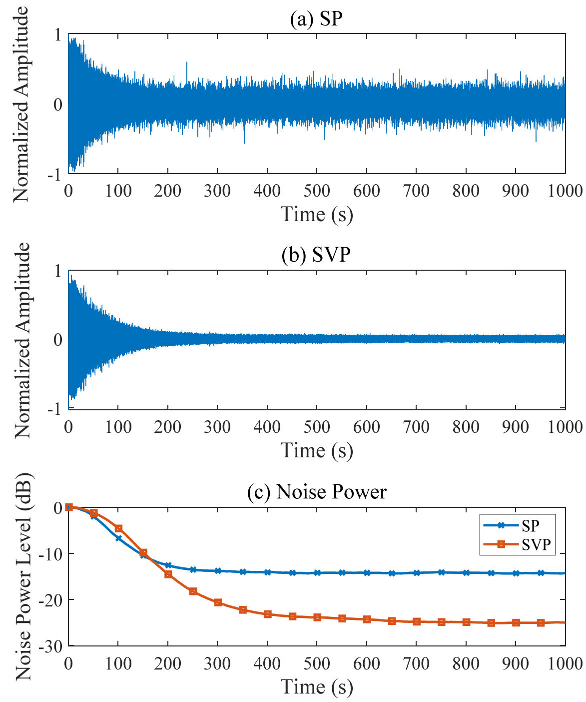

Fig. 3. Comparison of the SP and SVP methods when $\mu = 1.0 \times 10^{-6}$, $\alpha = 0.9965$ and $\gamma = 5.0 \times 10^{-9}$.

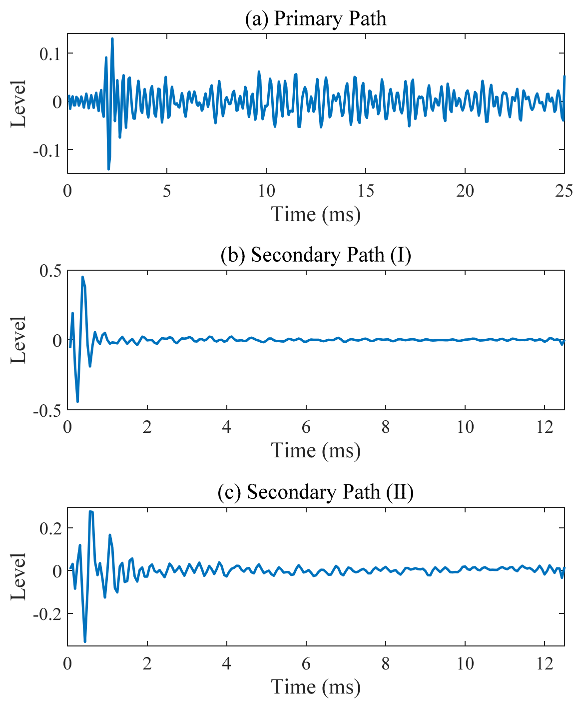

Fig. 4. Primary and secondary paths measured in a single-channel feedforward ANC system setup.

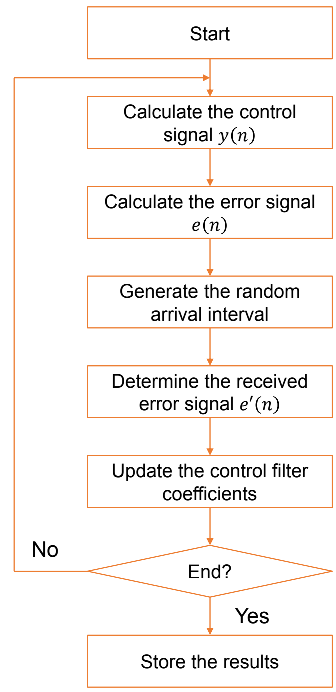

Fig. 5. Simulation flow of the single-channel feedforward ANC system with a wireless error microphone.

Table 1. Simulation parameters.

Primary Noise Type	White Noise
Primary Noise Frequency	500Hz-1000Hz
Sample Rate	1.6×10^4Hz
Step Size of the FxLMS Algorithm	1.0×10^{-4}
Step Size of the SP and the SVP Method	1.0×10^{-6}
Constant Perturbation Magnitude of the SP Method	3.7×10^{-3}
Length of the Primary Path	400 Taps
Length of the Secondary Path	200 Taps
Length of the Control Filter	400 Taps

not the least, when considering the effect of the wireless error microphone, we can substitute $e(n)$ by $e'(n)$ in (3) and (4). $e'(n)$ is the error signal sample that is received by the ANC controller after the wireless communication.

III. Simulation Results

Simulations are carried out with a single-channel feedforward ANC system setup. The primary and secondary paths are measured in advance. They are shown in Fig. 4. The secondary path is measured in two times. The secondary path II is mainly used to validate the effectiveness of the SVP method when there is a change in the secondary path. The secondary path model in the FxLMS algorithm is the same as the secondary path I. The rest of simulation settings are listed in Table 1.

Figure 3 firstly compares the SP and SVP methods with a conventional error microphone. As the constant perturbation magnitude is large in the SP method, it converges faster in the beginning. However, the residual noise level of the SP method is much higher than the SVP method. Both the SP and SVP methods take few minutes to reach the steady state.

The jitter effect is carried out by the simulation flow shown in Fig. 5. A random variable obeying with the Poisson distribution is adopted as the time interval between two error signal samples. λ denotes the expected value in terms of the integer multiple of the sampling interval. When the arrival interval of the error signal samples is shorter than the sampling interval, the error signal sample arrives at the ANC controller on time and can be used immediately in the adaptation [20]. When the arrival interval of the error signal samples is greater than the sampling interval, the error signal sample does not arrive at the ANC controller on time. The ANC controller has to run the adaptation with the last error signal sample in the memory, until the wireless communication catches up.

Figure 6 shows the comparison between the FxLMS algorithm and the SVP method under different settings of λ. When $\lambda = 1$, most of the error signal samples arrive at the ANC controller on time. In this case, due to the existence of the perturbation, the SVP method results in a higher residual noise level than the FxLMS algorithm. The step size of the FxLMS algorithm is set to have a similar convergence speed as that of the SVP method. However, when $\lambda = 6$ and the rest of the settings are unchanged, the FxLMS algorithm is more severely affected by the jitter effect of the wireless communication. The SVP method demonstrates better performance than the FxLMS algorithm. When $\lambda = 7$, the FxLMS algorithm starts

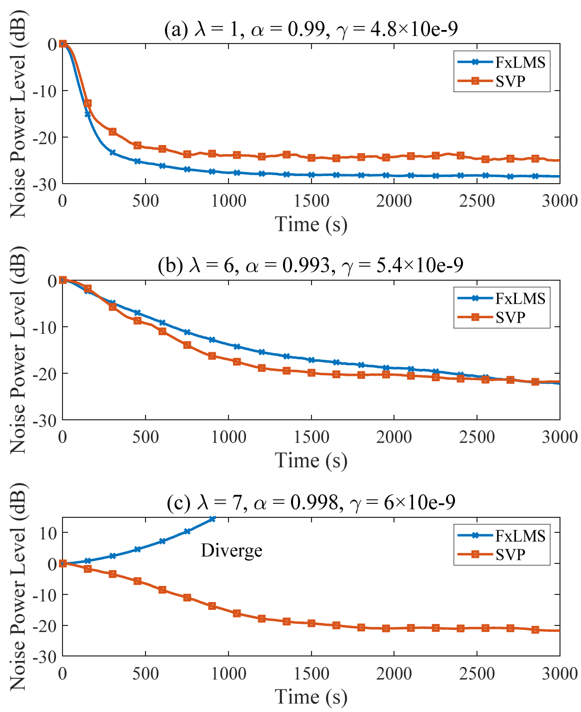

Fig. 6. Comparison of the FxLMS and SVP methods using the wireless error microphone and perfect secondary path model.

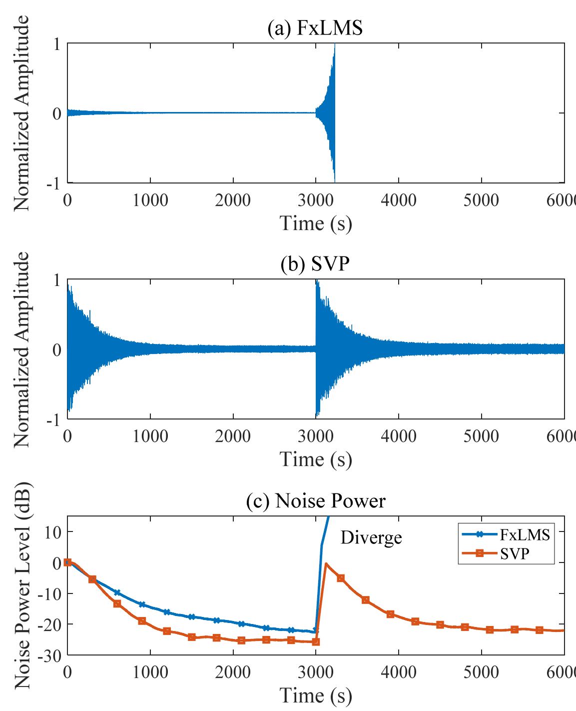

Fig. 7. Comparison of the FxLMS and SVP methods under the jitter effect $(\lambda = 6)$ when there is a sudden change of the secondary path.

to diverge. It is worth noting that the perfect secondary path model in the FxLMS algorithm cannot take the jitter effect into account. On the other hand, the SVP method stores the error signal samples in the block.

In Fig. 7, a sudden change of the secondary path is simulated. Since there is no on-line modeling of the secondary path, the SVP method outperforms the FxLMS algorithm.

IV. Conclusions

This paper proposes the use of a wireless error microphone in the ANC system. The jitter effect of the wireless communication is highlighted in ANC applications for the first time. The constant perturbation magnitude in the SP method is modified to be time-varying, leading to the SVP method. The SVP method decreases the perturbation magnitude when the noise level is reducing. Thus, it results in reduced residual noise levels than the SP method. Simulations of the ANC system with a wireless error microphone are carried out with primary and secondary paths measured in an actual setup. Simulation results demonstrate that when the jitter effect is severe, the FxLMS algorithm becomes difficult to converge, even when the perfect secondary path model is available. Moreover, when there is a sudden change of the secondary path, the SVP method converges steadily due to its advantage in not requiring the secondary path model.

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