In this paper, we propose a frequency domain active noise control (ANC) system without a secondary path model. The proposed system is based on the frequency domain simultaneous perturbation (FDSP) method we have proposed. In this system, the coefficients of the adaptive filter are updated only by error signals. The conventional ANC system using the filtered-x algorithm becomes unstable due to the error between the secondary path, from secondary source to error sensor, and its model. In contrast, the proposed ANC system has the advantage that it does not use a model. In this paper, we show the principle of the proposed ANC system, and examine its efficiency by means of computer simulations.

2 ANC SYSTEM AND PROBLEMS OF CONVENTIONAL METHODS

2.1 ANC System in an Air Duct

Figure 1 shows an active noise control system in a duct. In this figure, $x_k$, etc., are time sequences at sample $k$, and $P(z)$, etc., are transfer functions.

Primary noise $x_k$ reaches the error sensor through the primary path $P(z)$. $x_k$ is also detected at the detection sensor and is input to the noise control filter $H(z)$. The corresponding output $u_k$ is fed to the secondary path, and the control signal $y_k$ is generated. $d_k$ then interferes with the control signal $y_k$ at the error sensor, and the error signal $e_k$ is detected. The coefficients of the noise control filter $H(z)$ are adaptively updated so that the error signal $e_k$ becomes 0.

2.2 Filtered-x LMS Algorithm

If the coefficients of the noise control filter $H(z)$ in Fig. 1 are updated by the filtered-x algorithm, Fig. 1 can then be ex-
pressed by the block diagram in Fig. 2. From Fig. 2, we can see that the filtered-x algorithm updates the filter coefficients by using the error signal $e_k$ and the reference signal $r_k$ generated by filtering $x_k$ with the secondary path model $\hat{C}$ in order to update the coefficients of the noise control filter. In Fig. 2, $v_k$ is the additive noise detected at the error sensor shown in Fig. 1. The filtered-x LMS algorithm is expressed as follows.

$$h_{k+1} = h_k + \mu e_k r_k$$

(1)

where,

$$h_k = [h_k(1), h_k(2), \ldots, h_k(i), \ldots, h_k(N)]^T$$

$$r_k = [r_k, r_{k-1}, \ldots, r_{k-N+1}]^T$$

$$e_k = d_k + y_k + v_k$$

$\mu$ is a positive constant called the step-size parameter to control the speed and the accuracy of convergence, and $h_k$ and $\hat{c}$ are the coefficient vectors of the noise control filter and the secondary path model, respectively. Moreover, $N$ and $M$ are the tap lengths of the noise control filter and the secondary path model, respectively. Finally, $T$ denotes transportation.

### 2.3 A Problem of the Filtered-x Algorithm

From equation (1), the filtered-x algorithm needs the error signal $e_k$ and the reference signal $r_k$ generated by filtering $x_k$ with the secondary path model $\hat{C}$ in order to update the coefficients of the noise control filter. It is clear, therefore, that the modeling error of the secondary path model affects the updating algorithm. Some researchers have already discussed the effect of this modeling error, and all have reported that if the phase error between the secondary path and the corresponding model is within $-\pi/2 \sim \pi/2$, then the ANC system becomes stable. The filtered-x algorithm, however, has the fatal problem that we cannot know whether the ANC system operates stably until the system starts operating. That is, we cannot examine the above stability condition because we cannot obtain the accurate transfer function of the secondary path. Consequently, an algorithm to avoid the secondary path model is required in order to solve this problem.

### 3 FREQUENCY DOMAIN ANC SYSTEM WITHOUT SECONDARY PATH MODEL

The proposed system uses the FDSP method. This method requires two simultaneous error signals, one from an adaptive filter with a little perturbation, and another without perturbation. These error signals cannot be obtained simultaneously in the ANC system because the output of the noise control filter, with and without perturbation, cannot propagate the secondary path at the same time. The FDSP method, however, is a kind of block type algorithms. Hence, if the input signal $x_k$ and the additive noise $v_k$ are stationary for a short time, the FDSP method can be applied to the ANC system.

The actual system arrangement is shown in Fig. 3. In the proposed ANC system, the filtering operates according to the time domain, and the adaptive algorithm operates according to the frequency domain, as the ANC system reduces noise in real time. In Fig. 3, one of the perturbation vectors(PV1~4) is added to the time-domain control filter (TDCF) within a half period of a given block and not during the block's rest period. The error signals within each period are transformed to two different error vectors. Moreover, the vectors are transformed into the frequency domain by means of the FFT algorithm. If the input signal $x_k$ and the additive noise are stationary within the block, then those transformed vectors are nearly equal to the simultaneously obtained transformed error vectors. Consequently, the FDSP method is applicable to the ANC system.

The updating algorithm at the $n$'th block in the proposed ANC system can be given as follows.
where probability variables that are zero-mean and uncorrelated

Moreover, all the elements at the same block take the same value because each frequency is orthogonalized. Consequently, we only have to prepare four kinds of perturbation vectors, which are selected randomly at each block. More specifically, the M sequence is generated by two bits at each block, and the perturbation vector corresponding to the two bits is selected in order to satisfy Eq. (5), that is, \(00 \rightarrow PV1(1+j), 01 \rightarrow PV2(1-j), 10 \rightarrow PV3(-1+j), 11 \rightarrow PV4(-1-j)\).

From the above, we can establish the frequency domain ANC system without the secondary path model. This system has two advantages. One is simply that the secondary path model is not needed, and the other is that this system can suppress additional noise caused by the perturbation in comparison with the system using the TDSP method because of changing the only gain in anti-noise, as all perturbation elements are the same on the frequency domain. Moreover, the proposed system can converge faster than the conventional system using the TDSP method.

## 4 RESULTS AND DISCUSSIONS

We show our simulation results here in order to demonstrate the effectiveness of the proposed system. Common conditions in all simulations are shown in Table 1. The vertical axis for the convergence properties below indicates the reduction in noise (Reduction) defined as follows.

\[ \text{(Reduction)} = 10 \log_{10} \frac{\sum_{k=1}^{L} d_k^2}{\sum_{k=1}^{L} (d_k + v_k - y_k)^2} \]  

### Table 1 Common conditions in all simulations

<table>
<thead>
<tr>
<th>Tap length of primary path</th>
<th>128</th>
</tr>
</thead>
<tbody>
<tr>
<td>Tap length of error path</td>
<td>128</td>
</tr>
<tr>
<td>Tap length of adaptive filter</td>
<td>128</td>
</tr>
<tr>
<td>Block length</td>
<td>512</td>
</tr>
<tr>
<td>Noise source</td>
<td>White noise (Power 1)</td>
</tr>
</tbody>
</table>

### 4.1 The Results of Changing the Step-Size Parameter

Consider the convergence properties in cases where the step-size parameter \(\mu\) is changed. The conditions of this computer simulation are as follows: perturbation \(c=0.01\) and S/N=20dB. Figure 4 shows the convergence properties.

It can be seen from Fig. 4 that noise is reduced by the proposed system. Moreover, the step-size parameter \(\mu=1.0 \times 10^{-6}\) converges the fastest of all step-size parameters, with the convergence speed slows if the step-size parameter is made smaller. On the other hand, the convergence speed also slows if the step-size parameter is made larger, and the adaptive filter cannot converge, which under the present simulation conditions occurred in the case where the step-size parameter was greater than \(1.7 \times 10^{-6}\). From the above, it appears that the selection of the step-size parameter,
similar to the filtered-x algorithm affects the stability of the ANC system. However, deriving an exact boundary for the step-size parameter to provide stable operation of the proposed ANC system is a very difficult problem, as difficult as in the conventional ANC system using the filtered-x algorithm. Consequently, deriving a boundary for the step-size parameter is beyond the scope of this paper.

4.2 Comparison between the proposed method and the Filtered-x algorithm

Next, we compare the convergence property between the ANC systems using the FDSP method and the Filtered-x algorithm. Comparing the proposed ANC system and the conventional ANC system using the filtered-x LMS algorithm is very difficult because the conventional system requires a secondary path model. That is, the convergence property of the conventional ANC system is affected by the modeling error of the secondary path model. Hence, we compared two systems with the following experiment. First, each parameter in both systems is selected so that the fastest convergence speed is obtained. Next, the secondary path model in the filtered-x algorithm is made equal to the secondary path. Finally, the secondary path is changed at 500×51200 sample. The results of this experiment, which are shown in Fig. 5, illustrate the robustness of the proposed ANC system with the secondary path variation.

It can be seen in Fig. 5 that the proposed ANC system can re-converge after the secondary path changes. On the other hand, the conventional ANC system cannot re-converge, although the first convergence speed is faster than that of the proposed ANC system. Hence, with a path variation, the proposed ANC system has superior robustness in comparison with the conventional ANC system.

5 Conclusion

In this paper, we have proposed a novel frequency domain ANC system to solve the problem of conventional ANC systems that employ a filtered-x algorithm, and have examined the effectiveness of this system. The proposed system is advantageous in that, due to updates to the adaptive filter coefficients through the sole use of error signals, the secondary path model is not needed. The proposed system, therefore, is very simple and avoids the modeling errors that can be introduced by the secondary path model. In addition, the proposed ANC system has robustness on the secondary path variation where the conventional ANC system cannot re-converge.

Acknowledgement

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References