Real-Time Implementation of The Active Adaptive Noise Controller Considering the Reflected Noise

(반사 소음을 고려한 능동 적응 소음 제어기의 실시간 구현)

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ABSTRACT

Real-time implementations of the active adaptive noise controller are proposed and tested. There are three problems in active noise control such as real-time processing, an acoustic feedback of secondary signal and a time-delay of control system elements.

For real-time processing, the DSP56001 (Digital Signal Processor) was used. To avoid acoustic feedback, the secondary signal (control signal) was excluded from prediction. And for compensation of time delay, the ahead prediction was applied. As the primary noise (source noise) is reflected in space, the reflected noise should be controlled for perfect noise control. But in this case, the controller might be unstable. For solving the problem, it is proposed that the source noise and the reflected noise are predicted separately. Some experimental results show the stability and effectiveness of the proposed controller.

I. Introduction

As the industry and economy grow, we are more concerned about environments, specially about noise.
This problem has been studied in two classes. The one is how to lessen the noise from the primary source (passive control), the other is how to cancel the noise using secondary source (active control). Active control has been actively studied in America, Japan and Europe since 1970.

Active methods are the best at low-frequency noise, which complements more conventional passive methods since these tend to work best at higher frequency.

The basic ideas of active noise control are as follows. The controller detects source noise by a microphone, changes its phase (180°) and generates the control signal through the speaker. It is desirable to make the controller adaptive. Because the frequency or spatial distribution of the primary noise changes with time, and the controller is required to track these changes. A more difficult adaptive task has to be performed when the response of the system to be controlled to a given secondary excitation also varies with time. In this case, an algorithm must be able to perform identification and control simultaneously. So far, the active noise control in a duct is mainly studied. In this paper, the control problem in a free space was studied.

In section 2, the basic concepts of active adaptive noise control are introduced. The problems of the active control in a free space and its solutions are presented in Section 3, 4. The real-time controller is implemented in Section 5, and conclusions are presented in Section 6.

II. Basic Concepts of Active Adaptive Noise Control.

In general, noise signals are nearly periodic, so it can be written as sum of sinusoidal signals,

\[ s(t) = b_0 + \sum_{n=1}^{\infty} a_n \sin(n\omega t + \theta_n) \]  

If we know the factors \((b_0, a_n, \omega, \theta_n)\), noise signal \(s(t)\) can be canceled by the control signal \(s_c(t)\) which has 180° phase shift. But in many cases, the factors are time-varying, so controller must contain predictor as shown in Fig. 2.2.

Let the noise signal \(s(t)\) be approximated by AR model,

\[ s(t) = \sum_{n=1}^{\infty} a_n s(t-n) + e(t) \]

(2.2)

Estimating the coefficient vector \(a_n\) by adaptive filter, we can make the control signal \(s_c(t)\) as (2.3), (2.4).

\[ \hat{s}(t) = \sum_{n=1}^{\infty} \hat{a}_n s(t-n) \]

(2.3)

\[ s_c(t) = -\hat{s}(t) \]

(2.4)
III. Problems on Active Noise Control and Solutions.

There are problems on active noise control such as

- Real-Time Processing
- Time Delay of Control System Elements
- Acoustic Feedback of Secondary Signal

3.1. Real-Time Processing

It is well known that

$$2f_0 f_s$$ (3.1)

$$f_0$$: maximum frequency of signal
$$f_s$$: sampling frequency

In processing low-frequency noise signal (lower than 1KHz), sampling frequency $$f_s$$ should be much higher than 2 KHz. So sampling interval $$T_s$$ is,

$$T_s(1/(2 \text{KHz}) = 0.5 \times 10^{-3} \text{sec} \quad (3.2)$$

The prediction should be finished in the sampling interval. But general processors (80286 or 80386 based personal computer) can not perform the computations (prediction) within that interval.

For real-time processing, we adopt the DSP chip and apply the pipe-lining technique°:

- Pipe-Lining.
  perform the calculation and fetch the next data in single instruction cycle.

(Ex)

<table>
<thead>
<tr>
<th>noise source (a) to (d)</th>
<th>(c)</th>
</tr>
</thead>
<tbody>
<tr>
<td>controller (d) to (e)</td>
<td>(c)</td>
</tr>
</tbody>
</table>

- DSP56001.

  DSP56001 calculates about $$10^7$$ instructions in a second.

3.2. Time Delay of the Control System Elements.

  During noise signals are transmitted to the predictor, the control system elements (microphone, amplifier, A / D conveter, etc) have time delay ($$T_d$$) as shown in Fig. 3.1.

$$T_d = d_{ac} + d_{ab} + d_{ba}$$

where, Sampling Interval :
$$d_{ac}$$
Time Delay of Mic, Amp, A / D :
$$d_{ab}$$
Time Delay of D / A, Amp, Sp :
$$d_{ba}$$
Total Time Delay :
$$T_d = d_{ac} + d_{ab} + d_{ba}$$

Fig. 3.1. Time Delay of Control System Elements

Though the controller predicts precise $$s(t)$$ and generates the control signal $$s_c(t)$$, noise signals can not be canceled because of the time delay $$T_d$$.

at time to

$$s_c(t_o) = -s(t_o - T_d) + s(t_o) \quad (3.3)$$

For solving this problem, it is necessary that the ahead prediction considering the delay time is applied.

- Ahead Prediction

  The ahead step can be found as follows.

  (ex)

  | mac X0, Y0, A | X:(R0)+,X0|Y:(R4)−,Y0 |
  |---------------|------------|
  | multiply data X0, Y0 | fetch next data |

  and accumulate it to A

  controller to (d) to (e) (c)

  $$d_{ac}+d_{ab}+d_{ba}+d_{da}$$

Fig. 3.2 n step Ahead Prediction
(a) \((t_0+d_{ab}):\) noise source generates 
\(s(t_0+d_{ab}),\) predictor receives 
\(s(t_0).\)

(b) \((t_0+d_{ab}+d_{bc}):\) predictor estimates 
\(s(t_0+d_{ab}+d_{bc}+d_{bc})\)

(c) \((t_0+d_{ab}+d_{bc}+d_{cd}):\) noise source generates 
\(s(t_0+d_{ab}+d_{bc}+d_{cd}),\)
controller generates 
\(s_c(t_0+d_{ab}+d_{bc}+d_{cd}).\)

Hence, suitable steps of ahead prediction is

\[
\text{# of ahead steps} = \frac{d_{bc} + d_{cd}}{d_{bc}} = T_d / d_{bc} \quad (3.4)
\]


This problem is related to the reflected noise, so it is considered in next section.

IV. Reflected Noise.

A general active noise controller is shown in Fig. 4.1.

The microphone is located very close to the primary source in order to take the source noise only. Hence, the controller predicts and controls the source noise only.

![Fig. 4.1. Control Scheme for Source Noise only](image)

Even though \(s(t)\) is precisely estimated, the noise can not be perfectly canceled for the effects of reflected noise signals \((s_r(t), s_r'(t)).\)

Hence, the reflected noise signals should be considered.

4.1. Consideration of reflected noise.

The microphone takes both noise and the secondary signal (control signal), as shown in Fig. 4.3. Therefore, the secondary signal returns to the predictor, which disturbs next prediction (Acoustic feedback).

The error signal detected by the microphone is,

\[
e(t) = s(t) + s_r(t) + s_r'(t) \quad (4.1)
\]

To avoid the acoustic feedback, \(s_c(t)\) should be excluded.

Actually, \(s_r'(t),\) detected by the microphone, is slightly different from \(s_c(t).\) But if the microphone were close enough to speaker, then

\[
s_c(t) = s_c'(t) \quad (4.2)
\]

Hence,

\[
s_c(t) = e(t) - s_c(t) = s(t) + s_r(t) \quad (4.3)
\]
where the reflected noise $s_r(t)$ is,

$$s_r(t) = s_n(t) + s_{r2}(t) + \cdots$$  \hspace{1cm} (4.4)\text{  }

The reflected noise $s_n(t)$, $s_r(t)$ differs from source noise in phase respectively.

$$s_n(t) = s(t - t_n)$$ \hspace{1cm} (4.5)\text{  }

$$s_{r1}(t) = s(t - t_{r1})$$

This method has much error in initial states, specially at ahead prediction. (See following simulations) Because of the poor prediction, the reflected noise is generated by not only source noise but also control error.

$$s_r(t) = s_n(t) + s_{n2}(t) + \cdots$$ \hspace{1cm} (4.6)

where,

$$e_n(t) = e(t - t_n)$$ \hspace{1cm} (4.7)

$$e_{r1}(t) = e(t - t_{r1})$$

Thus, the control error $e(t)$ can not converge.


For stable noise controller, it is proposed that the source noise and the reflected noise are estimated separately.

In Fig. 4.4,

$$e(t) = s(t) + s_r(t) + s_c(t)$$ \hspace{1cm} (4.6)\text{  }

$$e'(t) = e(t) - s(t)$$ \hspace{1cm} (4.7)

$$= s_r(t) + s_c(t)$$

To avoid acoustic feedback,

$$s_r'(t) = e'(t) - s_c(t) = s_r(t)$$ \hspace{1cm} (4.8)\text{  }

Thus, the reflected noise $s_r(t)$ can be obtained from (4.8). $s(t)$ and $s_r(t)$ can be predicted as (4.9), (4.10) respectively.

$$s_n(t) = \sum_{i=1}^{N} a_i s(t - i)$$ \hspace{1cm} (4.9)\text{  }

$$s_{r1}(t) = \sum_{j=1}^{N} b_j s(t - j)$$ \hspace{1cm} (4.10)\text{  }

then, the control signal is,

$$s_c(t + T_d) = s_n(t + T_a) + s_r(t + T_d)$$ \hspace{1cm} (4.11)\text{  }

If $s_r(t)$ is badly estimated or there are sudden disturbances, then the controller generates control signal $s_c(t + T_d)$ using $s_n(t + T_a)$ only. Then, overall controller can be stable.

$$s_c(t + T_d) > \alpha$$ \hspace{1cm} (4.12)\text{  }

where, $\alpha$ is maximum error bound

○ Simulations.

Source Noise :

$$s(t) = 4.12 \times \sin \ (2 \times \pi \times 0.32 \times t) + 2.94 \times \sin \ (2 \times \pi \times 0.99 \times t)$$

Reflected Noise ;
Fig. (a) Prediction Source Noise only.

Fig. (b) Prediction Source Noise and Reflected Noise
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Fig. (c) Prediction Source Noise and Reflected Noise separately.

\[ r(t) = \sum_{i} (a_i + 0.412) \sin (2 \pi (0.32 - b_i) + c_i) + \sum_{j} (a_j + 0.294) \sin (2 \pi (0.99 - b_j) + c_j) + w(t) \]

where, \( w(t) \) is (0, 0.1) White Noise

\( 0 < a_i, b_i < 0.1 \quad 0 < a_j, b_j < 0.1 \)
\( 0 < c_i < 10 \quad 0 < c_j < 10 \)
\# of ahead step : 16 step

V. Implementation of Active Noise Controller.

5.1. Specification

• Primary Noise
  sinusoidal signal (120 Hz)
• A/ D, D/ A Conveter
  56ADC16\(^{oc}\).
  resolution : 16 bit
  containing a reconstruction filter and an anti-
  aliasing filter
• Processor
  DSP56001:
  programmable real-time digital signal processor
  (10 MIPS)
• Interfacing
  IBM PC (AT)
• System Constants

Sampling time : 0.25 msec
Delay Time : about 4 msec
\# of Ahead Step : 16 step

• Algorithm
  Recursive Least Squares

Fig. 5.1. Block diagram of the Active Adaptive Noise Control Experiment

5.2. Experimental Results.

Fig. 5.2. Prediction Source Noise only.

Fig. 5.3. Prediction Source Noise and Reflected Noise,
VI. Conclusion

The active adaptive noise controller is introduced and implemented. Using the ahead prediction and the pipe-lining technique and the DSP56001, the controller can be real-time implemented. The experimental results show that the separate prediction method improves efficiency by canceling the reflected noise, which agree well with computer simulations. Applying this method, 40 dB noise can be attenuated below 20 dB, and proposed controller is assured the stability.

For the modifications to noise control of broad space, a study for parallel processing is needed.

References


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