THE JOURNAL OF THE ACOUSTICAL SOCIETY OF KOREA Vol.21, No.2E 2002. 6. pp. 56~62

Stability Evaluation for Estimated Impulse Response with a Feedforward Adaptive Control System

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(Received 31 May 2001; revised 24 October 2001; accepted 11 March 2002)

Abstract

This paper describes a new method of stability evaluation for an estimated impulse response of a plant. It is difficult for the conventional stability evaluation equation to be used in an adaptive feedforward control system which uses an immeasurable acoustic transfer system of a real plant, because the equation requires an exact true impulse response of the plant. Therefore, the usefulness of the conventional equation is limited in a computer simulation. The proposed method is applicable to not only a computer simulation but also a real feedforward adaptive control system. It is found that the system is stable when the value of misadjustment is below -10 dB through computer simulations and experiments. And also, it is proved that the error signal is stable through the verification using filtered reference and filtered error LMS methods.

***Keywords:** Stability evalution, Feedforward adaptive control system, Adaptive control system*

I. Introduction

A feedforward adaptive control system can be used for the purpose of noise cancellation in an acoustic transfer plant. In this case it is necessary to find a filter factor, which is related to the generation of a signal for the cancellation. The factor is calculated from the error signal between an output and a desired response signal of a plant. The calculation process for the filter factor requires an impulse response of a plant. Therefore, the impulse response should be measured before the adaptive control system implementation. And a stability of an estimated impulse response also should be evaluated before the implementation[1,2]. Usually, it is required for the adaptive control system to be simple and small-sized in the hardware implementation, and the minimized calculation time is demanded to achieve a real time processing system. One of the solutions to meet the requirement is the reduction of the length of an estimated impulse response as short as possible without the loss of the system stability.

Ren and Kumar have reported a stability evaluation equation for an estimated impulse response[3]. Elliott used the equation for an active control of sound[4]. The stability of the equation is evaluated by the phase characteristics of the impulse response of a real plant and an estimated impulse response. However, it is impossible to measure the exact impulse response of a real plant. Therefore, the stability evaluation equation can

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be used only in a computer simulation. The equation cannot be applied to a real feedforword adaptive control system.

This paper proposes a new method for the stability evaluation of an estimated impulse response in a plant. The proposed method can be applied to not only computer simulation but also real feedforward adaptive control system, and has the merit of reduced length of an estimated impulse response. Computer simulations and experimental results show the usefulness of the proposed method. And the validity of the proposed method is verified by the well-known filtered reference and filtered error LMS (Least Mean Square) methods. The methods are widely used to reduce noise or to cancel some specific frequency components of noise[6].

II. Adaptive Control System and Stability Evaluation Equation

In order to cancel undesirable noises in a plant, usually, adaptive control system is employed. The minimization of an error between output and desired response signal depends on a used adaptive algorithm. The ultimate aim of the adaptive control system is to obtain an optimum condition with minimized error signal. Fig. 1 shows the basic block diagram of a feedforward adaptive control system[1].

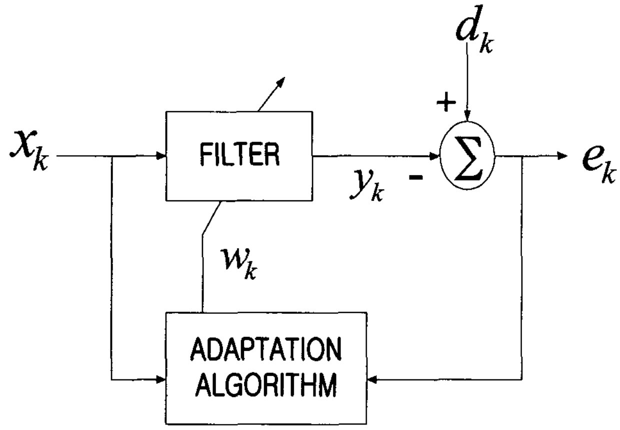

Figure 1. Block diagram of a feedforward adaptive control system.

In Fig. 1, x_k and y_k are the input and output signals of a filter, respectively, and d_k and w_k mean a desired response and an adaptive factor, respectively. The difference between d_k and y_k generates an error signal of e_k.

In this paper the stability of an estimated impulse response for a linear single input and single output in an adaptive control system shown in Fig. 1 is evaluated.

The conventional stability evaluation equation[3] for an estimated impulse response is represented in equation (1).

$$Re\left[\frac{\hat{P}(e^{j\omega T})}{P(e^{j\omega T})}\right]>0 \qquad \text{for } all\ \omega T \tag{1}$$

In the equation $P(e^{j\omega T})$ and $\hat{P}(e^{j\omega T})$ are the frequency characteristics of a real impulse response and an estimated one, respectively. The equation implies that the system is stable if the ratio of an estimated real impulse response to a real impulse response keeps a positive real value. The adaptive control system is stable as long as phase responses of $P(e^{j\omega T})$ are within 90_0 of those of $\hat{P}(e^{j\omega T})$ for all frequency components. However, the equation needs an exact real impulse response. Accordingly, the usefulness of the equation is restricted only to computer simulation. It is difficult to apply the equation to a feedforward adaptive control system using an acoustic transfer system of a real plant because exact real impulse responses are immeasurable.

To overcome the problem this paper suggests a new method of stability evaluation. The proposed method introduces a well-known equation[5] that is widely used in the measurement of estimated impulse. The introduced equation can be used as a good one of the stability evaluation. Furthermore, the equation is applicable to a real feedforward adaptive control system, and is described as follows.

$$\text{Misadjustment} = 10\log_{10}\left[\frac{\sum e(n)^2}{\sum y(n)^2}\right] \tag{2}$$

Equation (2) means that the stability is evaluated by the ratio of $e(n)^2$ to $y(n)^2$. Fig. 2 shows the plant for a stability evaluation.

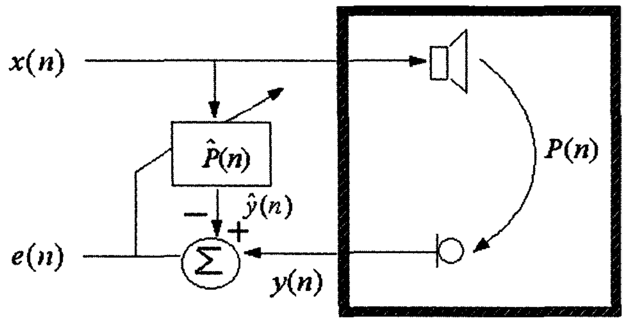

Figure 2. A plant for a stability evaluation.

The meaning of each signal in Fig. 2 is as follows:

$x(n)$: plant input signal

$y(n)$: plant output signal

$e(n)$: error signal of $y(n)$ and $\hat{y}(n)$

$\hat{y}(n)$: convolution signal of $x(n)$ and $\hat{P}(n)$

$\hat{P}(n)$: estimated impulse response of a plant

III. Computer Simulations

The input and output signals used in simulation are used with the output signal of a 500 Hz LPF (Low Pass Filter), where the input signal of the LPF is white noise. The distance between speaker and microphone is 68 cm, and

Table 1. Misadjustment values according to the variation of impulse response length.

Estimated Impulse Response	Length of Impulse Response	Misadjustment
$\hat{P}1$	128	-17.4648
$\hat{P}2$	96	-16.5480
$\hat{P}3$	80	-14.6969
$\hat{P}4$	64	-15.0737
$\hat{P}5$	48	-12.4619
$\hat{P}6$	32	-8.2363
$\hat{P}7$	24	-7.5646

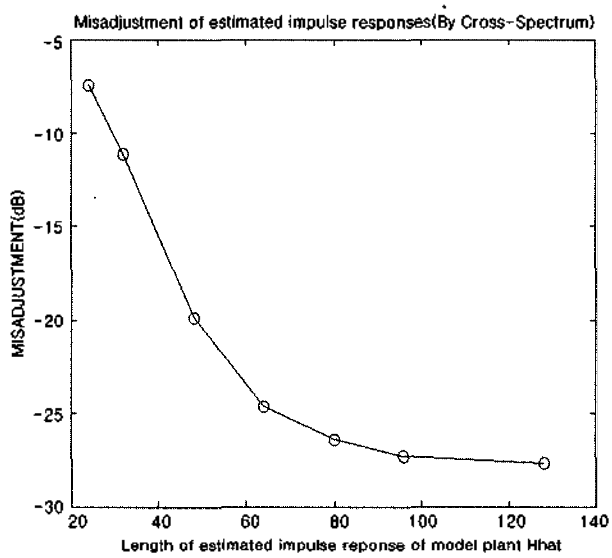

Figure 3. Misadjustment values according to the variation of impulse response length.

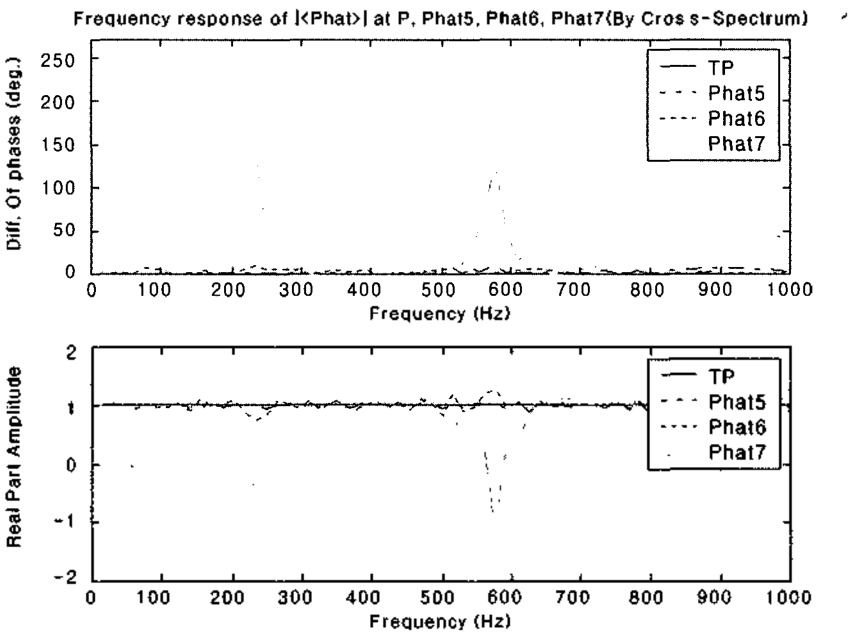

Figure 4. Phase characteristics of the real and estimated impulse response.

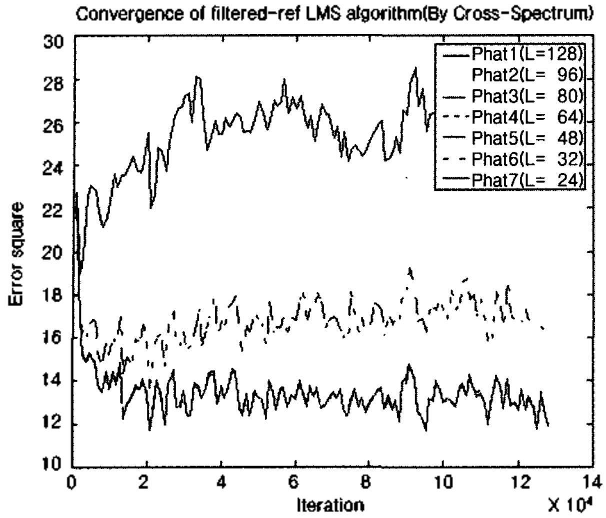

Figure 5. Convergence characteristics by a filtered reference-LMS method.

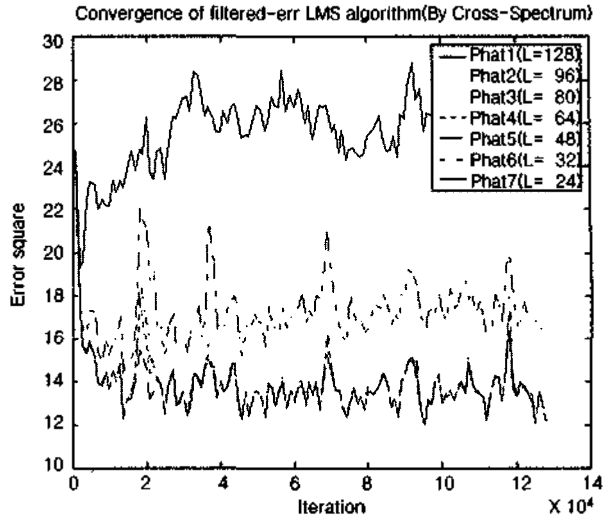

Figure 6. Convergence characteristics by a filtered error-LMS method.

the sampling frequency is 2 kHz. The Impulse responses of 128 points are estimated by the method of cross-spectrum.

The response are classified into 7 cases according to the length of the impulse response. Table 1 and Fig. 3 show the misadjustment values of each estimated impulse response, where impulse response is zero faded from the end of the length.

Equation (1) is used to investigate the convergence characteristics of the estimated impulse responses shown in table 1 and Fig. 3. Fig. 4 shows the phase characteristics of real and estimated impulse responses. The phase differences of $\hat{P}1$, $\hat{P}2$, $\hat{P}3$, $\hat{P}4$, $\hat{P}5$, and $\hat{P}6$ are within 90_o, which results in convergence of the error signals. However, the phase difference of $\hat{P}7$ is greater than 90_o, and hence, the error signal of $\hat{P}7$ has the characteristics of a divergence. Fig. 5 and Fig. 6 show the convergence characteristics of the estimated impulse responses in table 1 and Fig. 3, and the characteristics are tested by filtered reference and filtered error-LMS methods, respectively.

The figures show that $\hat{P}1$, $\hat{P}2$, $\hat{P}3$, $\hat{P}4$, $\hat{P}5$, and $\hat{P}6$ have the characteristic of convergence and $\hat{P}7$ has that of divergence. Therefore, it can be concluded that the estimated impulse response, which is estimated by a Cross-spectrum method is stable as long as the misadjustment value of the introduced equation keeps below -10 dB.

IV. Experimental Results

Fig. 7 shows the overall system block diagram for an experiment. The output signal of white noise from the function generator is filtered by a 500 Hz LPF. The filtered signal is amplified to drive the speaker. The output signal of a microphone is also filtered by a 500 Hz LPF. The distance between the speaker and microphone is 68cm. The sampling frequency is 2 kHz. A room is used as an acoustic transfer system of a plant. The room sizes of width, depth, and height are 8.6, 4.6, and 2.6 m, respectively.

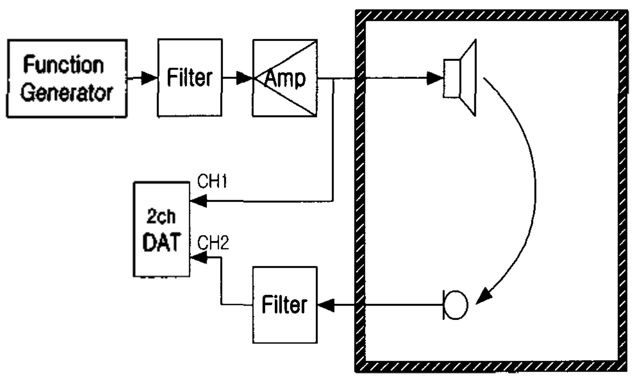

Figure 7. Overall system for an experiment.

Table 2. Misadjustment values according to the length of the impulse response.

Estimated Impulse Response	Length of Impulse Response	Misadjustment
$\hat{P}1$	128	-17.4648
$\hat{P}2$	96	-16.5480
$\hat{P}3$	80	-14.6969
$\hat{P}4$	64	-15.0737
$\hat{P}5$	48	-12.4619
$\hat{P}6$	32	-8.2363
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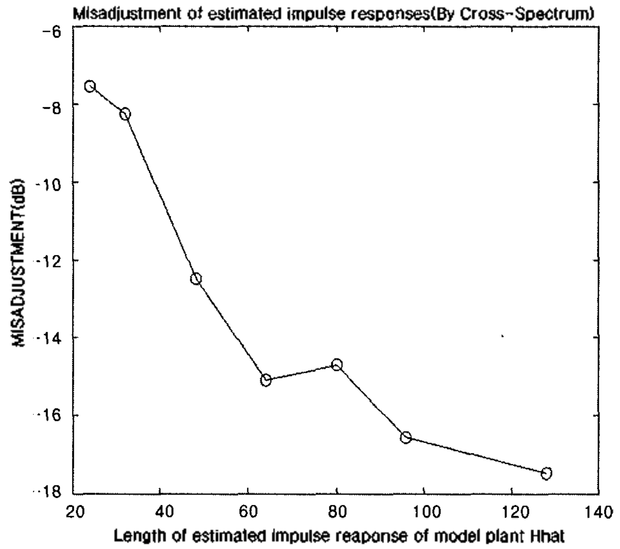

Figure 8. Misadjustment values according to the variation of impulse responses length.

In order to confirm whether the introduced equation is applicable to the stability evaluation of an estimated impulse response or not, experiments are carried out with the system shown in Fig. 7. To get a real impulse response, 128 points of impulse responses estimated with cross-spectrum method are used. The estimated impulse response is obtained from the zero faded impulse responses of 128 points, which are estimated by cross-spectrum method. Table 2 shows corresponding misadjustment values in 7 cases.

Fig. 8 shows the misadjustment values with the variation of the impulse response length obtained through experiments. Fig. 9 shows that the error signals of $\hat{P}1$, $\hat{P}2$, $\hat{P}3$, $\hat{P}4$, and $\hat{P}5$ are converge because the phase differences between real and estimated impulse responses are within 90_0 according to the equation (1).

However, the error signals of $\hat{P}6$ and $\hat{P}7$ are diverge because the difference is over 90_0. Fig. 10 and Fig. 11 show the convergence characteristics of the impulse responses by filtered reference and filtered error LMS methods, respectively. Each result in Fig. 8~11 is the same. It can be concluded that the error signals become stable as long as the misadjustment values keep below -10 dB.

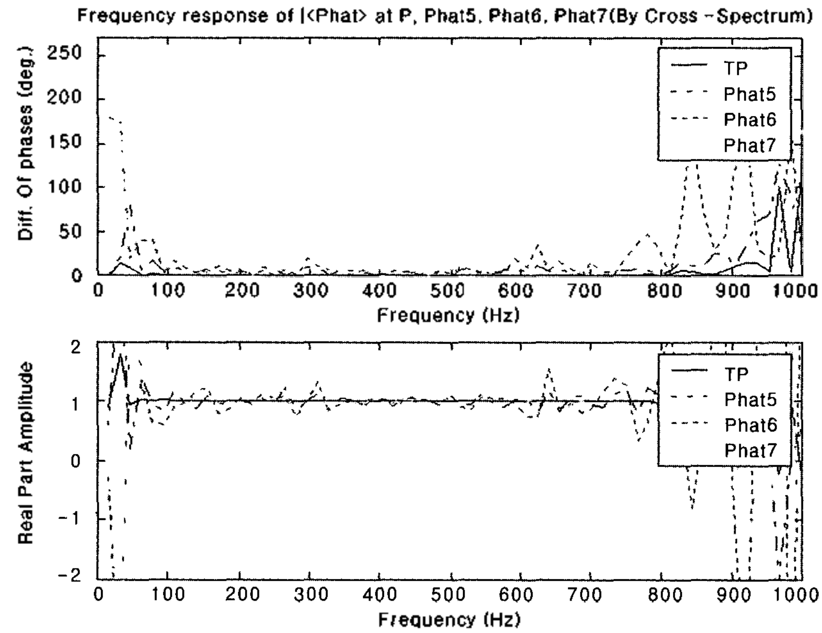

Figure 9. Phase characteristics of real and estimated impulse responses.

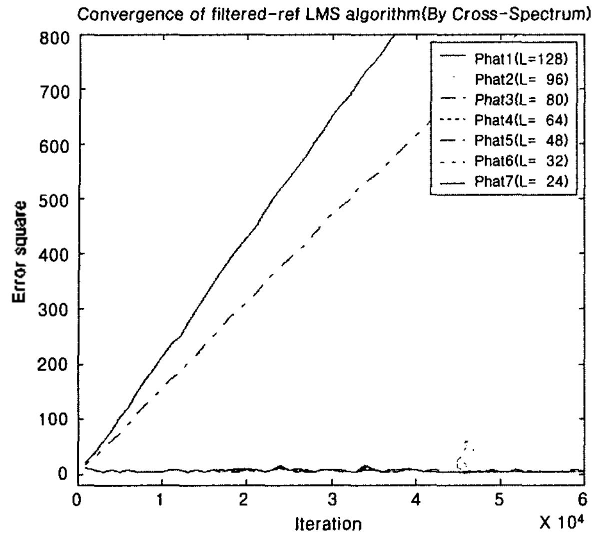

Figure 10. Convergence characteristics of filtered reference method.

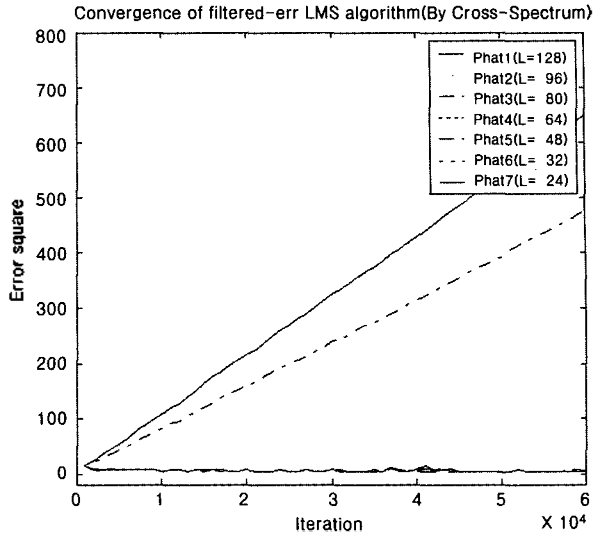

Figure 11. Convergence characteristics of filtered error method.

V. Conclusions

This paper proposes a new method for stability evaluation of estimated impulse response in a plant, which is constructed with feedforward adaptive control system. The proposed method is applicable to not only computer simulations but also real feedforward adaptive control system. It is investigated that the error signals become stable as long as the misadjustment values keep below -10 dB through simulations and experiments. There are little differences in the characteristics of convergence and divergence between the results of simulations and experiments according to the impulse response length. However, the misadjustment values are independent on the length.

The usefulness of the proposed method is verified through the conventional well-known stability evaluation equation reported by W. Ren and P. R. Kumar. And the filtered reference and filtered error LMS methods are also used to prove the validity of the proposed method, which is applicable to real feedforward adaptive control system as well as computer simulations. Furthermore, the employment of cross spectrum method in a real feedforward adaptive control system results in the reduction of the length of an estimated impulse response. As a result, the processing time of a microprocessor can be reduced. Therefore, the method has merit in the implementation of a real time processing system. It is also expected that the proposed method can reduce the processing time considerably in case of a multi-input multi-output adaptive control system which requires lots of processing steps.

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[Profile]

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The Journal of the Acoustical Society of Korea Vol. 15, No. 3, 1996.