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A METHOD FOR RE-ESTIMATING FEEDBACK PATH UNDER ACTIVE NOISE CONTROL

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In this paper, we propose a method necessary for estimating the feedback path changed under active noise control. The feedback path is formed in the feedforward type active noise control system detecting target noise, called primary noise, with a microphone. A feedback control filter is accordingly applied to the cancellation of the feedback path and thereby the occurrence of howling is prevented. The feedback path, however, cannot be completely canceled. The cancellation error of the feedback path transforms the secondary path from a loudspeaker to an error microphone. The transformed secondary path is different from the original path estimated by feeding white noise to the loudspeaker. The simultaneous equations method permits the transformation and can successfully reduce the primary noise if the cancellation error is slight. The large error, however, increases the non-minimum phase components composing the transformed secondary path, which deteriorates the effect of reducing the primary noise. We first demonstrate using computer simulation that the cancellation error deteriorates the noise reduction effect. The deterioration can be improved by solving the simultaneous equations, however, cannot be completely restored when the cancellation error is larger than a certain level. The re-estimation of the feedback path is then required for restoring the noise reduction effect. We next show that the power gain of the auxiliary filter characterizing the simultaneous equations method corresponds to the noise reduction effect. The deterioration can be consequently recognized by monitoring the power gain. We propose to re-estimate the feedback path only after it is recognized that the noise reduction effect cannot be restored even by solving the simultaneous equations method. The recognition is available for promptly restoring the noise reduction effect.
Keywords: simultaneous equations method, auxiliary filter, feedback path, path change

1. Introduction

Feedforward type active noise control systems [1], detecting a primary noise by using a noise detection microphone, inevitably form a feedback path, which may cause howling in practical use. To prevent the occurrence of howling, an adaptive filter, called a *feedback control filter*, is generally connected in parallel to the feedback path [2]. The feedback path is previously identified by the adaptive filter, whose coefficients are fixed after the identification is completed. The feedback path is consequently cancelled by the feedback control filter; thereby the occurrence of howling is prevented. The problem is that the feedback path is supposed to change under active noise control. The change of the feedback path reduces the performance of the system, and at worst the system diverges. However, in theoretical studies, the feedback path is generally neglected [3] by the reason that it is not related to the principle of the filtered-x algorithm.

On the other hand, the simultaneous equations method [4-6] based on the different principle from the filtered-x algorithm is proposed. The method does not require the previous estimation of the secondary path. Moreover, the previous estimation of the feedback path also is unnecessary, if the feedback path does not cause howling. The simultaneous equations method can reduce the primary noise even after any path changed under active noise control. The large change of the feedback path, however, deteriorates the performance of the system. In this case, the re-estimation of the feedback path is required.

Two methods capable of re-estimating the feedback path under active noise control with the precision of more than about 20 dB are proposed. One is the method applying a linear prediction filter to the input signal of the noise control filter generating the secondary noise reducing the primary noise [7,8]. The method, however, requires that the characteristic of the primary noise is invariant until the re-estimation process is completed. Another is the method utilizing the modified secondary path estimated by the simultaneous equations method [9]. The latter method allows the change of the characteristic, however, requires sufficiently separating the loudspeaker providing the secondary noise from the noise detection microphone monitoring the noise reduction effect.

Moreover, the method radiating a weak white noise from the loudspeaker also is available for the re-estimation of the feedback path [10], if a certain deterioration of the noise reduction effect can be allowed. This method estimates the feedback path by utilizing the principle of the simultaneous equations method. However, all the three method mentioned above require a considerable amount of time for estimating the feedback path. This means that the noise reduction effect does not recover for a long period, which is supposed to be undesirable operation for practical systems.

In this paper, we propose to re-estimate the feedback path not continuously but instantly only after the noise reduction effect deteriorates, and moreover we present a method for detecting the deterioration. The duration of the low noise reduction effect can be thereby minimized. We next show that the power gain of the auxiliary filter, identifying the overall path from the noise reduction microphone to the error microphone, corresponds to the noise reduction effect, and finally we verify using computer simulation that a moment proper to re-estimate the feedback path can be clearly and exactly recognized.

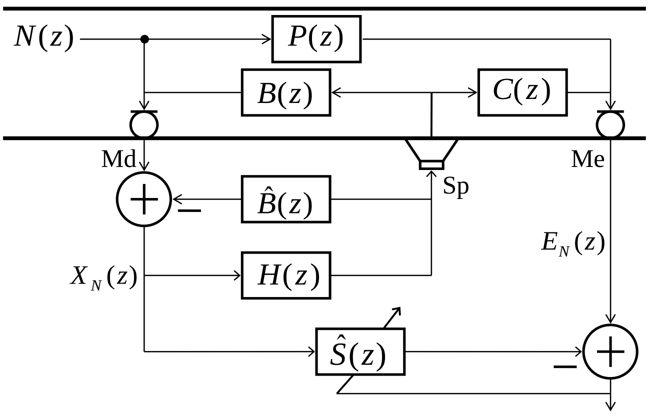


Figure 1: Configuration of active noise control system using simultaneous equations method.

2. Simultaneous equations method

Figure 1 shows the configuration of the active noise control system using the simultaneous equations method, where $N(z)$ is the primary noise detected by noise detection microphone Md, $P(z)$ is the primary path from the noise detection microphone to error microphone Me, $B(z)$ is the feedback path from loudspeaker Sp to the noise detection microphone, $C(z)$ is the secondary path from the loudspeaker to the error microphone, and $\hat{B}(z)$ is the feedback control filter used for cancelling the feedback path. The simultaneous equations method uses auxiliary filter $\hat{S}(z)$ for deriving noise control filter $H(z)$ cancelling the primary noise. The auxiliary filter works as an adaptive filter, and estimates the overall path from the input of the noise control filter to the error microphone as

$$S(z) = P(z) + H(z)\{C(z) - \Delta B(z)P(z)\} \tag{1}$$

by using the input signal of the noise control filter,

$$X_N(z) = \frac{N(z)}{1 - \Delta B(z)H(z)}, \tag{2}$$

and the error microphone output , $E_N(z)$, as a reference signal and a desired signal, respectively, where

$$\Delta(z) = B(z) - \hat{B}(z) \tag{3}$$

is the cancellation error corresponding to the difference between the impulse responses of the feed-back path and the feedback control filter.

In the active noise control system shown in Fig.1, the optimum noise control filter, $H_{opt}(z)$, completely cancelling the primary noise, satisfies the following relation,

$$S(z) = P(z) + H_{opt}(z)\{C(z) - \Delta B(z)P(z)\} = 0, \tag{4}$$

which can be arranged as

$$H_{opt}(z) = -\frac{P(z)}{C(z) - \Delta B(z)P(z)} = -\frac{P(z)}{\tilde{C}(z)}, \tag{5}$$

where

$$\tilde{C}(z) = C(z) - \Delta B(z)P(z), \tag{6}$$

which is called *modified secondary path* in this study. Equation (5) states that the secondary, the feedback and the primary paths need to be constantly estimated for reducing the primary noise. In practical systems, the paths are assumed to change under noise control.

The simultaneous equations method does not require individually estimating the paths. They are totally estimated by the auxiliary filter. Concretely, the simultaneous equations method gives two different coefficients to the noise control filter, whose transfer functions are expressed in this study as $H_1(z)$ and $H_2(z)$, and thereby derives two independent equations as

$$\hat{S}_1(z) \approx P(z) + H_1(z)\tilde{C}(z) \tag{7}$$

and

$$\hat{S}_2(z) \approx P(z) + H_2(z)\tilde{C}(z), \tag{8}$$

respectively, by using the auxiliary filter estimating the overall path. From Eqs. (7) and (8) consist-ing of the two unknowns, $P(z)$ and $\tilde{C}(z)$, the optimum noise control filter can be estimated as

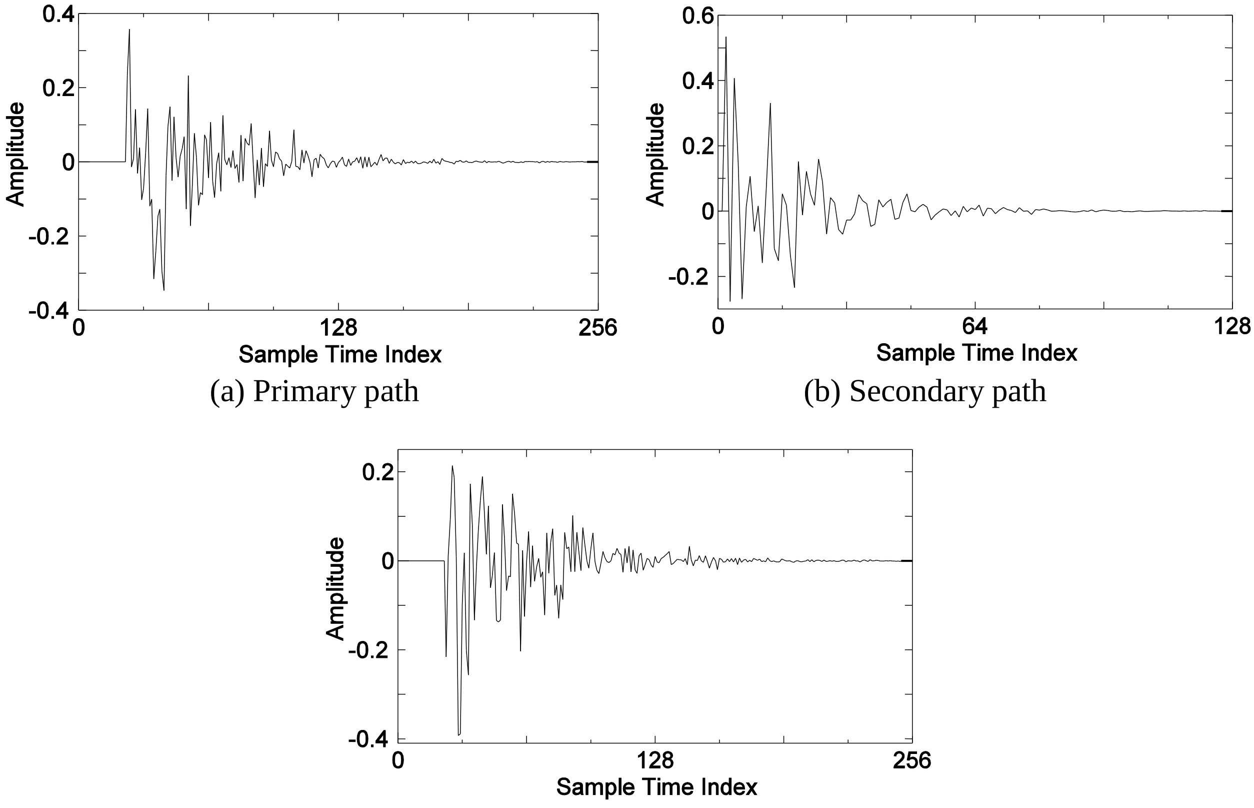
$$H_{opt}(z) = \frac{S_1(z)H_2(z) - S_2(z)H_1(z)}{S_1(z) - S_2(z)}. \tag{9}$$

Thus, the simultaneous equations method drives the optimum noise control filter, and thereby re-duces the primary noise stably if the cancellation error of the feedback path does not cause howling. However, as seen from Eq. (5), the increase of the cancellation error of the feedback path enlarges the non-minimum phase components composing the modified secondary path, which enhances the potential deteriorating the noise reduction effect. The primary path involved in the denominator of

Eq. (5) moreover increases the potential. This means that the simultaneous equations method also needs to reduce the cancellation error for restoring the deteriorated noise reduction effect.

3. Influence of feedback path cancellation error

The simultaneous equations method allows a certain cancellation error. However, the cancellation error over a certain limit deteriorates the noise reduction effect. We first present an example that the cancellation error deteriorates the noise reduction effect though not causing howling. Figure 2 shows the impulse responses of the primary, the secondary and the feedback paths applied to the computer simulations used for examining the performance of the methods presented in this study, which are expressed by exponentially decayed regular random numbers. In general, acoustic paths and loudspeakers are supposed to involve some non-minimum phase components, which require distancing the loudspeaker from the noise detection microphone. Oppositely, the error microphone is needed to be placed close to the loudspeaker. Under these reasons, the propagation delays of the three acoustic paths shown in Fig. 2 were determined to be 24, 24 and two sample times, respectively.



(a) Primary path (b) Secondary path

(c) Secondary path

Figure 2: Impulse responses of acoustic paths applied to computer simulations.

The other conditions are as follows.

- Number of taps of feedback and noise control filters: 256 and 512, respectively.
- Number of taps of auxiliary filter: 1024.
- Adaptive algorithm applied to estimation of coefficient of auxiliary filter: Normalized least mean (NLMS) algorithm whose step size is 0.001.
- Number of times of updating coefficients of auxiliary filter: $2{,}000 \times 5{,}000$.
- Initial coefficient given to noise control filter: ± 0.5 ($H_1(z) = 0.5$ and $H_2(z) = -0.5$).
- Primary noise and disturbance whose power ratio is 30 dB: White noise.
- Estimation method of optimum noise control filter: adaptive filter system [4].

- Execution condition of above estimation: square difference between $S_1(z)$ and $S_2(z)$ is more than 0.1.

Figure 3 shows the transitions of the noise reduction effects calculated on the above conditions, where the cancellation errors of the feedback path are fixed at -30 dB, -20 dB and -10 dB, respectively. In this result, we can see that the noise reduction effect deteriorates where the cancellation error is fixed at -10 dB. This example indicates that the reduction of the cancellation error to less than about -20 dB is necessary for removing the influence of the feedback path even where the simultaneous equations method is applied. This inversely means that the simultaneous equations method can potentially restore the noise reduction effect deteriorated by the change of the acoustic path change when the cancellation error of the feedback path is less than about -20 dB.

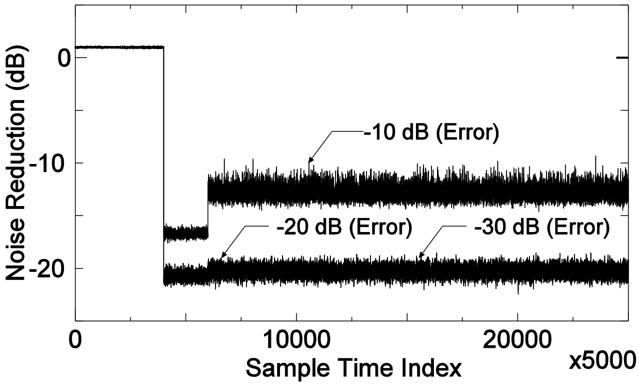


Figure 3: Influence of cancellation error of feedback path on noise reduction effect.

In practical use, not only the feedback path but also the other paths are supposed to change simultaneously. Figure 4 shows an example that the simultaneous equations method could not automatically recover the noise reduction effect deteriorated by the path change, where "path change (-10 dB)" and "path change (-20 dB)" denote 31% and 10% percent changes of the impulse responses of the acoustic paths, respectively. In this example, the coefficients of the noise control filter are not updated when the square difference between $S_1(z)$ and $S_2(z)$ is less than 0.1. Accordingly, the noise reduction effects do not recover after the path change.

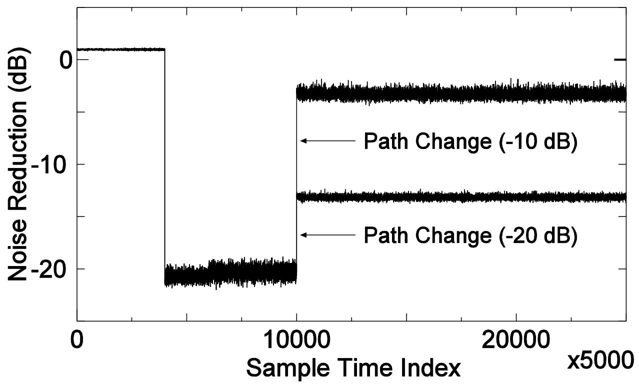


Figure 4: deterioration of noise reduction effect caused by path change.

On the other hand, the result shown in Fig. 3 indicates the potential of restoring the noise reduction effect deteriorated by the path change where the cancellation error of the feedback path is less than -20 dB. The effect is expected to be improved by solving the simultaneous equations, which can be restored to the former state, especially where the cancellation error is less than about -20 dB. A method restoring the noise reduction effect is to update the coefficients of the noise control filter artificially when the deterioration is recognized. Inversely, the feedback path should be quickly re-estimated when the effect does not recover nevertheless.

4. Method for recognizing deterioration of noise reduction effect

The deterioration of the noise reduction effect can be basically recognized by monitoring the power ratio of the error microphone output to the primary noise. However, various disturbances arrive at the error microphone from the outside of the active noise control system in practical use, which causes the false recognition. In this paper, we propose to utilize the power gain of the auxiliary filter for detecting the deterioration. Practically, the auxiliary filter works as the adaptive filter identifying the overall path from the input of the noise control filter to the error microphone, whose power gain is equal to that of the overall path. Moreover, the power gain corresponds to the noise reduction effect. In practical use, the disturbance impedes the identification by the auxiliary filter. The precision of the identification thereby deteriorates, which causes the false recognition. The deterioration of the precision, however, can be prevented by applying the step size control [11] to the adaptive algorithm.

Figure 5 shows the transition of the power gain of the auxiliary filter used for updating the coefficients of the noise control filter providing the noise reduction effect shown in Fig. 4, where the power of the disturbance is supposed to be static, for simplification, on the premise of applying the step size control to the identification of the overall path. The two results shown in Figs. 4 and 5 demonstrate that the deterioration of the noise reduction effect can be recognized by calculating the power gain of the auxiliary filter.

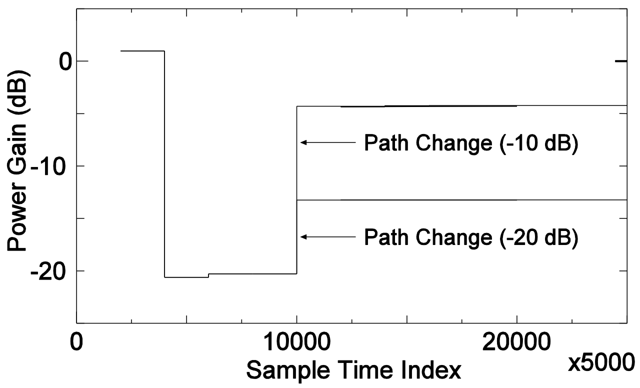


Figure 5: Transition of power gain of auxiliary filter.

On the other hand, although the result shown in Fig. 3 indicates that the deterioration can be improved by solving the simultaneous equations, the noise reduction effect deteriorated by path change of -20 dB does not recover. As mentioned above, since the square difference between $S_1(z)$ and $S_2(z)$ is less than 0.1, the coefficients of the noise control filter are not updated. However, the noise reduction effect result deteriorated by the path change of -20 dB is expected to be improved by solving the simultaneous equations artificially. The re-estimation of the feedback path is not too late even after it is confirmed that the noise reduction effect was not restored by updating the coefficients of the noise control filter.

5. Confirmation trial for feedback path re-estimation

A simple method for enabling to the solution of the simultaneous equations is to add a slight constant to one of the coefficients of the noise control filter so as to increase the square difference between $S_1(z)$ and $S_2(z)$ to more than 0.1. Figure 6 shows the simulation result for verifying that the addition of a slight constant can restore the noise reduction effect deteriorated by the path change, where two constants, $+0.2$ and -0.2, are added to the first coefficient of the noise control filter, whose transfer functions are then expressed by $H_1(z) = 0.2$ and $H_2(z) = -0.2$, respectively.

As seen from the result shown in Fig. 6, the noise reduction effect recovers in the case of -20 dB path change, however, which does not decrease to -20 dB in the case of -10 dB path change. In the latter case, the re-estimation of the feedback path is required.

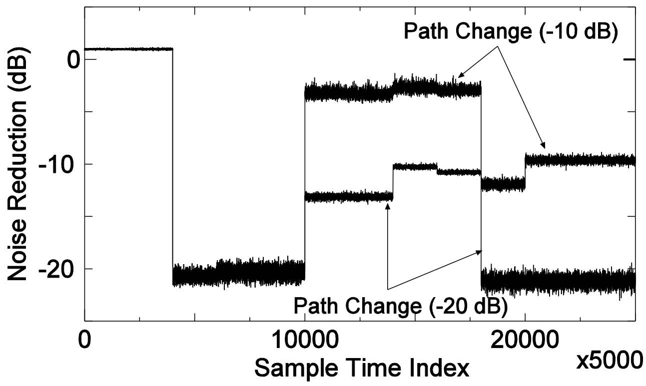


Figure 6: Configuration of active noise control system using simultaneous equations method.

Figure 7 shows the transition of the power gain of the auxiliary filter used for the calculation of the noise reduction effect shown in Fig. 6. The comparison of the two results shown in Figs. 6 and 7 demonstrates that the deterioration of the noise reduction effect can be recognized by calculating the power gain of the auxiliary filter. In this example, the re-estimation of the feedback path is unnecessary in the case of -20 dB path change. On the other hand, the result calculated in the case of -10 dB path change states that the feedback path should be re-estimated for reducing the primary noise to less than -20 dB.

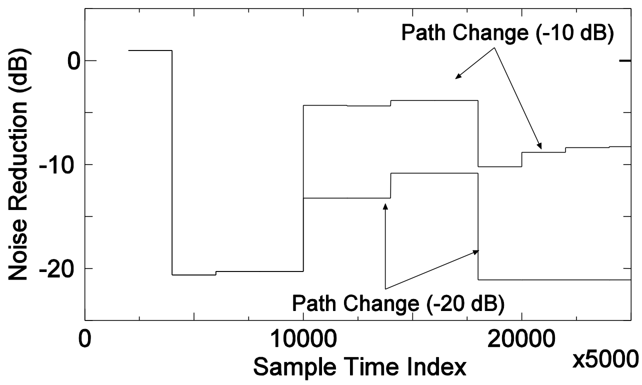


Figure 7: Transition of power gain of auxiliary filter.

It should be noted here that the period necessary for re-estimating the feedback path under noise control without significantly deteriorating the noise reduction effect is several hours [7,8,10]. Contrarily, the period is several minutes if the restart of the active noise control can be allowed. In either case, the recognition of the deterioration of the noise reduction effect is required.

6. Summary

In this paper, we have presented the method for recognizing the deterioration of the noise reduction effect and then have verified using computer simulation that the presented method can successfully express the transition of the noise reduction effect. The noise reduction effect deteriorated by the path change can be restored by solving the simultaneous equation. Re-estimating the feedback path under active noise control or restarting the system can be determined after that. In the near future, we will reduce the period of the identification of the overall path by applying the frequency domain adaptive algorithm to updating the coefficients of the auxiliary filter.

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