FEEDBACK ACTIVE NOISE CONTROL SYSTEM COMBINING LINEAR PREDICTION FILTER

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ABSTRACT

In this paper, we propose a feedback active noise control (ANC) system including a linear prediction filter. The proposed ANC system can reduce narrowband noise while suppressing disturbance having broadband components. The disturbance makes the conventional feedback ANC system unstable or divergent because the disturbance corrupts the input signal to the system. In the proposed ANC system, a linear prediction filter is combined with the feedback ANC system in order to suppress the disturbance. Simulation results demonstrate that the proposed feedback ANC system is superior to the conventional feedback ANC system on the stability while maintaining the same noise reduction ability.

1. INTRODUCTION

Acoustic noise problems become more and more serious with increasing use of industrial equipment. Active noise control (ANC) [1] has been studied in order to solve such acoustic noise problems. ANC is a technique based on the principle of superposition, i.e., an antinoise with the same amplitude and opposite phase is generated and combined with an unwanted noise, thus resulting in the cancellation of both noises. The control structure of the ANC is classified into two groups. One is a feedforward structure and the other is a feedback one. The feedforward ANC is very popular and can reduce all classes of noise, but the system scale is likely to be large one. On the other hand, the feedback ANC system [2] has small system scale in comparison with the feedforward ANC system. The feedback ANC system is effective for narrowband noise and widely used for headset applications [3, 4] because of the small system scale. However, the feedback ANC system becomes unstable or divergent due to broadband noise mixed into the narrowband noise because of the control scheme. We call this broadband noise “disturbance” in this paper. We therefore propose a novel feedback ANC system which can suppress the effect of the disturbance to the control scheme. The proposed feedback ANC system exploits a linear prediction filter [5] in order to remove the broadband noise because the linear prediction filter can convey only predictable narrowband noise. Hence, the proposed feedback ANC system has robust control ability compared to the ordinary ones.

The organization of this paper is as follows. First, the principle and problem of the conventional feedback ANC system are introduced. Next, the proposed feedback ANC system utilizing the linear prediction filter is explained and the effectiveness is demonstrated through some simulation results. Finally, the conclusions and future works are presented.

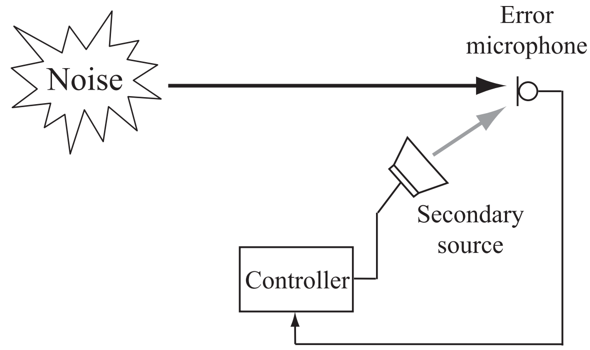


Figure 1: Conceptual diagram of the feedback ANC system.

2. FEEDBACK ANC SYSTEM

Figure 1 shows the conceptual diagram of the feedback ANC system. The feedback ANC system consists of a secondary source which radiates an antinoise and an error microphone which measures a residual error. The controller attempts to minimize the residual error using the past unwanted noise, that is, predicting the present unwanted noise. Hence, the feedback ANC system can reduce only predictable noise (e.g. multi-sinusoidal and narrowband noises). The feedback ANC system is on a small scale compared with the feedforward ANC system because the latter one needs a reference microphone to obtain a reference input. However, the feedback ANC system cannot cancel the broadband noises. Hence, the broadband noise behaves as an uncontrollable disturbance in the feedback ANC system.

2.1 Basic Principle and Algorithm

Figure 2 shows the block diagram of the ordinary feedback ANC system using the Filtered-X LMS (FXLMS) algorithm, where W is the noise control filter, C is the secondary path from the output of W to the error microphone, $\hat{C}$ is the estimated model of C called a secondary path model, and n denotes sample time. d_n is the narrowband noise which is the control target, v_n is the disturbance which is an uncontrollable broadband noise, e_n is the error signal measured at the error microphone, $\hat{d}_n$ is the input signal for the system, r_n is the filtered reference signal, y_n is the output signal of the noise control filter, and y'_n is the anti-noise originating from y_n. The basic idea of the feedback ANC system is to estimate the narrowband noise d_n and use it as an input signal $\hat{d}_n$. In other words, it is desirable for d_n and $\hat{d}_n$ to become equal.

The narrowband noise d_n is not available during the operation of ANC because of being canceled by the antinoise y'_n. Hence, the error signal e_n and the output signal y_n filtered by $\hat{C}$ are combined with each other in order to reconstruct d_n as follows:

$$\begin{aligned}
\hat{d}_n &= e_n + \hat{\mathbf{c}}^T \mathbf{y}_n \qquad (1)\\
e_n &= d_n - y'_n + v_n\\
\hat{\mathbf{c}} &= [\hat{c}(1)\ \hat{c}(2) \cdots \hat{c}(i) \cdots \hat{c}(M)]^T\\
\mathbf{y}_n &= [y_n\ y_{n-1} \cdots y_{n-i+1} \cdots y_{n-M+1}]^T
\end{aligned}$$

where $\hat{\mathbf{c}}$ is the coefficient vector of the secondary path model and M is the tap length. T denotes transpose. The output signal y_n is generated as

$$\begin{aligned}
y_n &= \mathbf{w}_n^T \hat{\mathbf{d}}_{n-1} \qquad (2)\\
\mathbf{w}_n &= [w_n(1)\ w_n(2) \cdots w_n(i) \cdots w_n(N)]^T\\
\hat{\mathbf{d}}_n &= [\hat{d}_n\ \hat{d}_{n-1} \cdots \hat{d}_{n-i+1} \cdots \hat{d}_{n-N+1}]^T
\end{aligned}$$

where $\mathbf{w}_n$ is the coefficient vector of the noise control filter and N is the tap length. The coefficients of the noise control filter are updated by FXLMS algorithm as follows:

$$\begin{aligned}
\mathbf{w}_{n+1} &= \mathbf{w}_n + \mu_w \mathbf{r}_n e_n \qquad (3)\\
\mathbf{r}_n &= [r_n\ r_{n-1} \cdots r_{n-i+1} \cdots r_{n-N+1}]^T
\end{aligned}$$

where μ_w is the step-size parameter and the filtered reference signal r_n is expressed as follows:

$$r_n = \hat{\mathbf{c}}^T \hat{\mathbf{d}}_{n-1} \qquad (4)$$

The algorithm for the feedback ANC system is summarized in (1) to (4). By the way, in real application, the power normalized version of FXLMS algorithm called as FXNLMS algorithm is commonly used because of giving a better convergence property. FXNLMS algorithm is expressed as follows:

$$\mathbf{w}_{n+1} = \mathbf{w}_n + \frac{\alpha_w}{\|\mathbf{r}_n\|^2 + \beta_w} \mathbf{r}_n e_n \qquad (5)$$

where α_w and β_w are the step-size and the regularization parameters, respectively.

2.2 Effect of Broadband Noise

As stated above, the error and the output signals are combined with each other in order to generate the input signal $\hat{d}_n$ to the noise control filter. However, the uncontrollable broadband noise v_n such as background noise is always included in the error signal e_n. The broadband noise v_n consequently corrupts the input signal $\hat{d}_n$ as the disturbance at all times. If the disturbance increases, the ANC system becomes unstable and divergent. Hence, it is desirable to remove the disturbance components from the input signal $\hat{d}_n$.

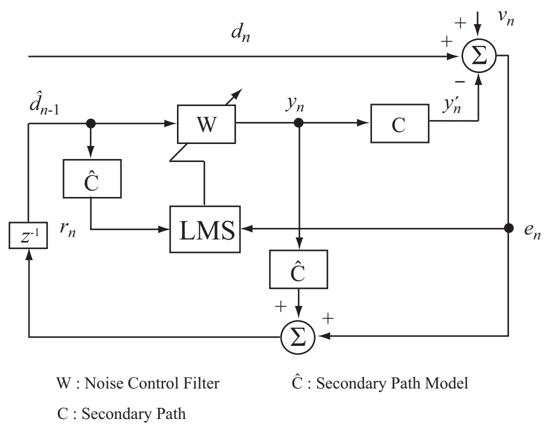


Figure 2: Block diagram of the conventional feedback ANC system using FXLMS algorithm.

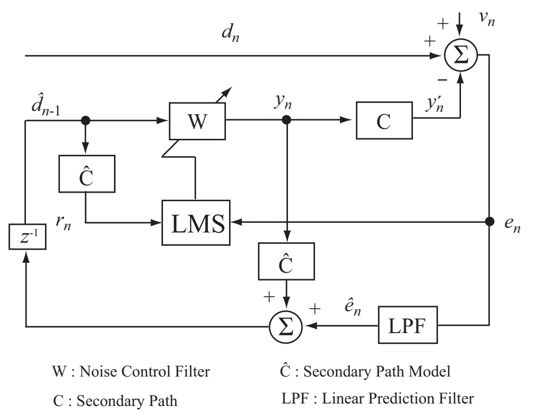


Figure 3: Block diagram of the proposed feedback ANC system using FXLMS algorithm.

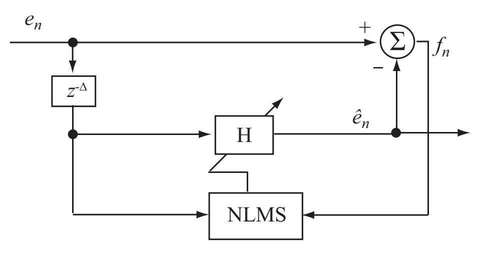


Figure 4: Block diagram of the linear prediction filter using LMS algorithm.

3. PROPOSED FEEDBACK ANC SYSTEM

We propose a novel feedback ANC system which can remove the disturbance from input signal in order to improve the stability. Figure 3 shows the block diagram of the proposed feedback ANC system. In the proposed feedback ANC system, the linear prediction filter whose input is the error signal e_n is incorporated. Figure 4 shows the block diagram of the linear prediction filter using NLMS algorithm. The linear prediction filter prevents unpredictable broadband signals and passes only predictable narrowband signals. The update algorithm of the linear prediction filter at sample time n is

Table 1: Simulation conditions

Sampling frequency	6000Hz
N	300
M	250
K	300
α_w	0.01
α_h	0.05
β_w	10^{-6}
β_h	10^{-6}
Δ	5

expressed as follows:

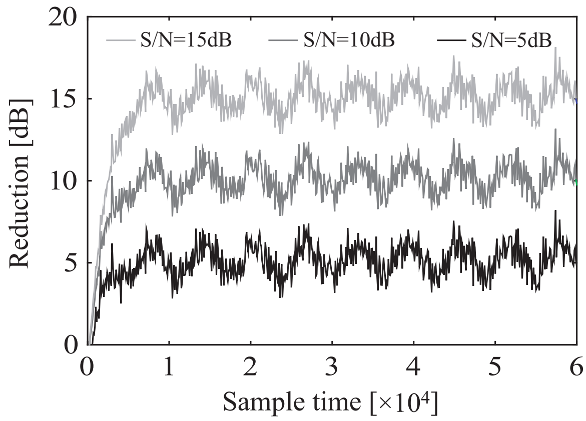
$$\mathbf{h}_{n+1} = \mathbf{h}_n + \frac{\alpha_h}{\|\mathbf{f}_n\|^2 + \beta_h}\mathbf{e}_{n-\Delta} f_n \tag{6}$$
$$\hat{e}_n = \mathbf{h}_n^T \mathbf{e}_{n-\Delta}$$
$$f_n = e_n - \hat{e}_n$$
$$\mathbf{h}_n = [h_n(1)\ h_n(2) \cdots h_n(i) \cdots h_n(K)]^T$$
$$\mathbf{e}_n = [e_n\ e_{n-1} \cdots e_{n-i+1} \cdots e_{n-K+1}]^T$$

where μ_h is the step size parameter, β_h is the regularization parameter, $\mathbf{h}_n$ is the coefficient vector of the linear prediction filter, f_n is the prediction error, and K is the tap length of the linear prediction filter. Δ is the delay of the input signal to the linear prediction filter and is determined according to the auto-correlation characteristic of the removing signal. That is, Δ is set to a small value for white noise and pink noise and to a large value for speech signal because the speech signal has stronger auto-correlation characteristic than the white and the ping noises. In the early stages of the convergence, the linear prediction filter passes only the narrowband noise d_n while removing the disturbance v_n. In this case, the disturbance v_n is removed from the original error signal e_n and then the new error signal $\hat{e}_n$ is output from the linear prediction filter. On the other hand, the original error signal e_n contains only the disturbance v_n in the steady state, and then $\hat{e}_n$ becomes equal to zero because the narrowband noise d_n is canceled due to the original function of ANC . Hence, the proposed feedback ANC system can improve the stability because the disturbance v_n corrupting the input signal x_n is removed. The update algorithm of the proposed feedback ANC system is the almost same as the conventional one except for Eq. (1) to generate the input signal $\hat{d_n}$, that is, Eq. (1) is rewritten as follows;

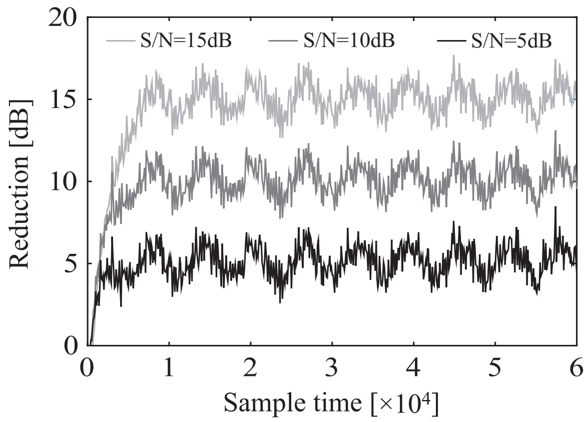
$$\hat{d_n} = \hat{e}_n + \hat{\mathbf{c}}^T \mathbf{y}_n \tag{7}$$

4. COMPUTER SIMULATION

In this section, we demonstrate the effectiveness of the proposed feedback ANC system through some simulation results. First, we compare the proposed feedback ANC system with the conventional one on the convergence property. In this simulation, the disturbance is white noise and the magnitude is changed. We assume that the secondary path model has the same impulse response as the secondary path. The simulation conditions are shown in Table 1. We use the multi-sinusoidal whose fundamental frequency is



(a) Conventional feedback ANC system



(b) Proposed feedback ANC system

Figure 5: Comparison of convergence properties within 6×10^4 iterations.

$f_0 = 200$Hz as the narrowband noise d_n:

$$d_n = a_n \left\{ \sum_{k=1}^{5} \sin(2\pi k f_0 n) \right\} \tag{8}$$

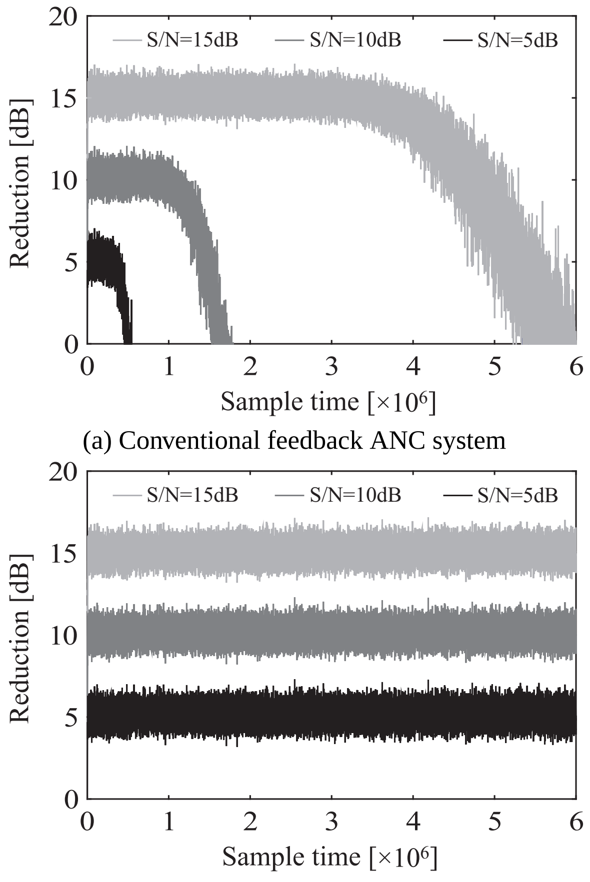
where a_n is the amplitude of the multi-sinusoidal wave and changes with time according to

$$a_n = 6000 + 600\sin(0.001n) \tag{9}$$

In the convergence property, the vertical axis indicates the reduction of the unwanted noise (Reduction) which is defined as follows:

$$\text{Reduction} = 10\log_{10}\frac{\sum d_n^2}{\sum e_n^2} \tag{10}$$

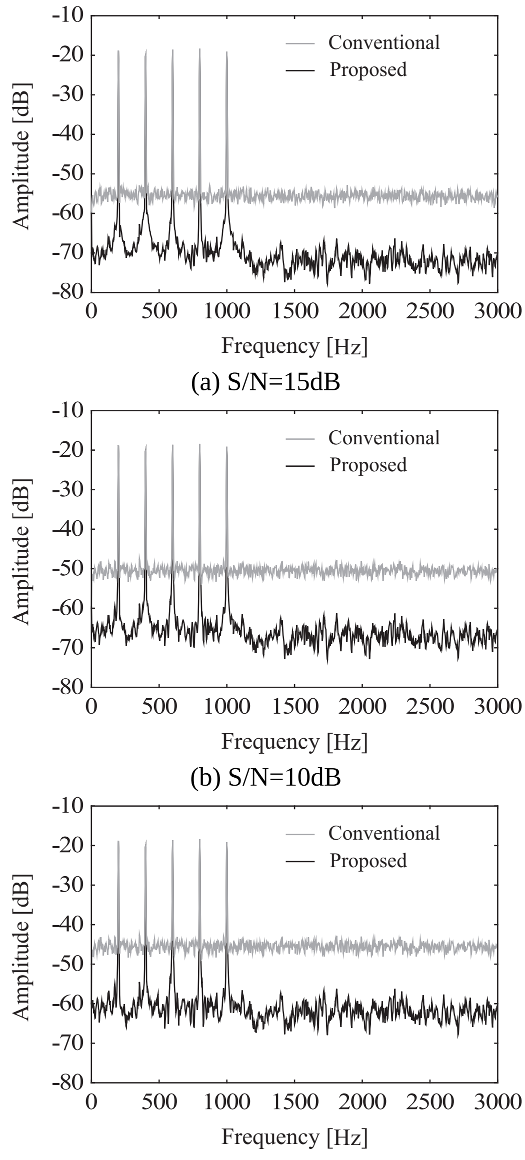
Figures 5 and 6 show the convergence property with 6×10^4 and 6×10^6 iterations, respectively. In these cases, the SNR (narrowband noise-to-disturbance power ratio) is changed to 15, 10 and 5dB. It can be seen from Fig. 5 that the proposed feedback ANC system has the same convergence property as the conventional one in early stages of convergence. On the other hand, it can be seen from Fig. 6 that the proposed feedback ANC system shows the different convergence property from the conventional one. Fig. 6(a) shows that the conventional one tends to diverge after the convergence. The disturbance causes the instability of the system because the divergent speed varies as the SNR varies. On the other hand, Fig.



(a) Conventional feedback ANC system

(b) Proposed feedback ANC system

Figure 6: Comparison of convergence properties within 6×10^6 iterations.



(a) S/N=15dB

(b) S/N=10dB

(c) S/N=5dB

Figure 7: Comparison of input spectra between the proposed and the conventional feedback ANC systems.

6(b) demonstrates that the proposed feedback ANC system can converge stably for a long time regardless of the magnitude of the disturbance. Figure 7 shows the spectra of the input signal $\hat{d}_n$ in the proposed and the conventional ANC systems. It can be seen from Fig. 7 that the disturbance (broadband noise) included in the input signal $\hat{d}_n$ is reduced about 15dB within the frequency range from 0 to 3000Hz. Hence, the proposed feedback ANC system can effectively remove the disturbance and improve the system stability.

Next, we compare the proposed and the conventional feedback ANC systems in case where the disturbance is colored noise. Other simulation conditions are the same as the previous ones. Figure 8 shows the comparison of the convergence properties where the disturbance is pink noise. Fig. 8 demonstrates that the proposed ANC system can converge stably while reducing the narrowband (predictable) noise. Figure 9 shows the spectra of the input signal $\hat{d}_n$ in the proposed and the conventional ANC systems. It can be seen from Fig. 9 that the proposed ANC system can accurately estimate the narrowband noise and reduce the colored broadband noise about 15dB. Hence, the proposed feedback ANC system is effective for the colored broadband noise.

Finally, we compare the performance of the proposed and the conventional feedback ANC systems for narrowband noise superimposed with speech signal. Speech signal can be predicted by the linear prediction filter but the auto-correlation is weaker than that of the narrowband noise. Accordingly, the delay Δ of the linear prediction filter is set to a large value in order to prevent the linear prediction filter from predicting the speech signal. In the simulation, we empirically set the delay Δ to 40. Figure 10 shows the comparison of the convergence properties where the disturbance is speech signal. Fig. 10 demonstrates that the proposed ANC system can converge stably for the speech disturbance while reducing the narrowband (predictable) noise. Figure 11 shows the spectra of the input signal $\hat{d}_n$ in the proposed and the conventional ANC systems. It can be seen from Fig. 11 that the proposed ANC system can accurately estimate the narrowband noise and reduce the speech disturbance about 10dB. Hence, the proposed feedback ANC system is also effective for the speech disturbance.

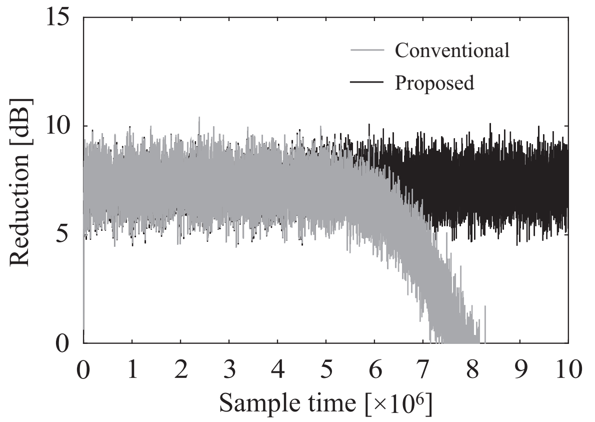


Figure 8: Comparison of convergence properties in case where the disturbance is pink noise.

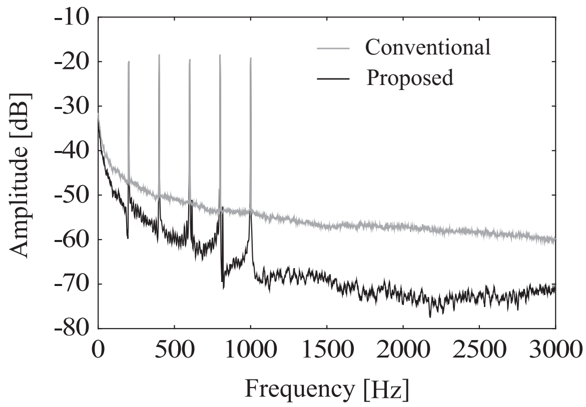


Figure 9: Comparison of input spectra between the proposed and the conventional feedback ANC systems in case where the disturbance is pink noise.

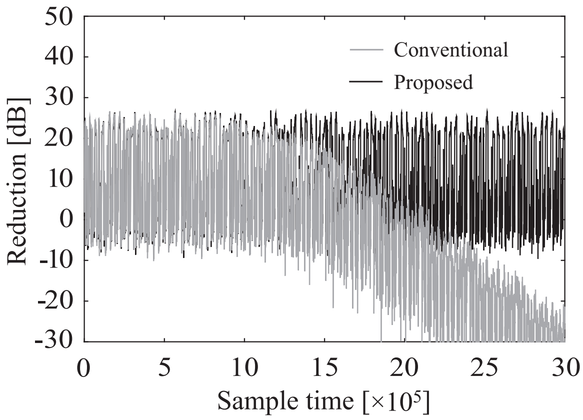


Figure 10: Comparison of convergence properties in case where the disturbance is speech signal.

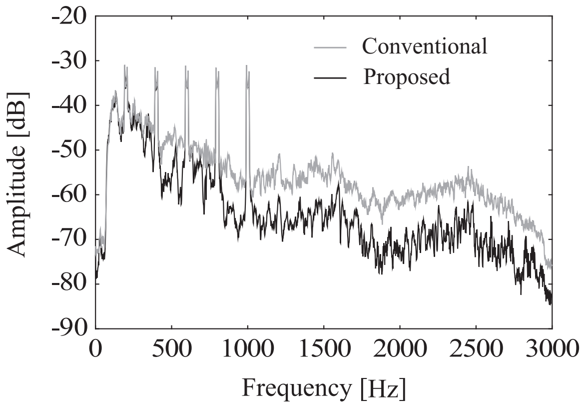


Figure 11: Comparison of input spectra between the proposed and the conventional feedback ANC systems in case where the disturbance is speech signal.

5. CONCLUSIONS

In this paper, we have proposed a novel feedback ANC system utilizing the linear prediction filter in order to remove the disturbance such as uncontrollable broadband noise. The simulation results have demonstrated that the proposed feedback ANC system can reduce narrowband noise stably for various disturbances regardless of the magnitude of the disturbance. In the future, we will implement the proposed feedback ANC system on DSP.

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