Effectiveness of Active Noise Control System for Nonstationary Noise in Consideration of Psychoacoustic Properties

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***Abstract*—The conventional Active noise control (ANC) system obtains the greatest noise reduction around the error microphone and minimizes the mean square error signal. However, the impression of auditory sensation may sometimes be less than the numerical value when a person actually listens to noise with ANC. This is because of the complicated characteristic of psychoacoustic properties. The noise control filter optimized based on the mean square error (conventional ANC) does not necessarily give optimal results for the human auditory system. To mitigate this problem, ANC systems considering psychoacoustic properties have been proposed and their effectiveness has also been demonstrated for magnetic resonance imaging (MRI) noise and synthesized random noise. In this ANC system, noise weighting is incorporated into the conventional ANC structure. In this paper, we examine the effectiveness of the ANC system considering psychoacoustic properties based on A weighting and ITU-R 468 noise weighting for nonstationary noise through some experimental results and a subjective evaluation.**

I. Introduction

Active noise control (ANC) is one of the techniques based on the superposition used to reduce unwanted acoustic noise[1-4]. Conventionally, an ANC system attempts to minimize the mean squared error of the error signal picked up at the error microphone. Although the sound pressure level around the error microphone becomes small, humans may not perceive sufficient noise reduction through the auditory system. This is because of complicated psychoacoustic properties. Hence, the ANC system should be adjusted to consider psychoacoustic properties. Bao and Panahi have already proposed an ANC system considering psychoacoustic properties and demonstrated its effectiveness for MRI noise and a synthesized random signal [5]. In [5], noise-weighting filters based on A-weighting defined in IEC 61672:2003 and ITU-R 468 noise weighting were incorporated into conventional ANC systems. These noise-weighting filters modify the error and reference signals, and these modified signals are used to adjust the noise control filter in the ANC structure. However, acoustic noise often has nonstationary noise. Hence, the ANC system considering psychoacoustic properties should be examined for nonstationary noise. Moreover, such ANC systems should be examined through a subjective evaluation. In this paper, we develop an ANC system integrated with noise-weighting filters and examine its effectiveness for nonstationary noise through the results of a simulation and a subjective evaluation.

This paper is organized as follows. In Section Ⅱ, the ANC system considering psychoacoustic properties is explained. The effectiveness of an A-weighting filter and ITU-R 468 noise weighting filter is examined for nonstationary noise via simulation results in Section Ⅲ. Furthermore, the results of a subjectivity evaluation are given to demonstrate the significant difference between conventional ANC and ANC based on noise-weighting filters in Section Ⅳ. Conclusions are given in Section V.

II. ANC System Considering Psychoacoustic Properties

A. Psychoacoustic Properties

The hearing sense has various characteristics such as masking, loudness and pitch. We focus on loudness in this paper. Loudness is a subjective perception, which is defined as 1 sone when the sound pressure level is 40 dB at the frequency 1 kHz. Then, the sound with n times the percieved loudness is defined as having loudness n sone. According to the definition, two sine waves with different frequencies are regarded as having equal loudness level if they are perceived as equally loud by an average young person without significant hearing impairment. The curve is called the equal-loudness contours, which are standardized in ISO 226:2003. However, acoustic noise, which is mainly a broadband signal and nonstationary, has different characteristics in terms of the hearing sense.

B. Noise-Weighting Filter

Noise weighting has been suggested as a means of quantifying the hearing sensitivity of humans to the frequency. In this paper, we use two different noise-weighting filters, i.e., the A-weighting filter and the ITU-R 468 noise-weighting filter. A-weighting, defined in IEC 61672:2003, is based on the equal-loudness contour for the 40 dB (phon) pure tone. The frequency response of A-weighting is shown in Fig. 1 [6]. In Fig. 1, the original A-weighting filter is displayed by a red line. However, we use a different characteristic in part of the frequency range because the A-weighting filter is approximated by an FIR filter with short taps in this paper,

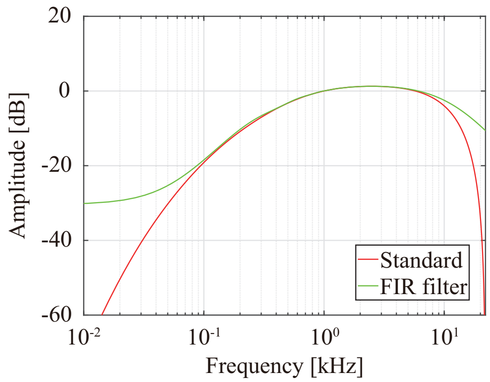


Fig. 1. Frequency response of A-weighting filter.

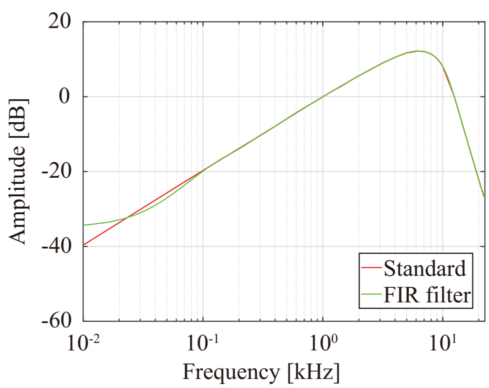


Fig. 2. Frequency response of ITU-R 468.

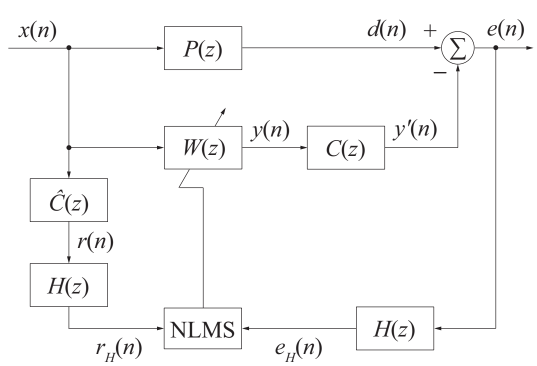


Fig. 3. Block diagram of the ANC system in consideration of psychoacoustic properties.

which is indicated by the green line. On the other hand, the ITU-R 468 noise-weighting filter, recommended by CCIR is used to evaluate random noise. The frequency response of the ITU-R 468 noise-weighting filter is shown in Fig. 2 [7]. In Fig. 2, the red line indicates the frequency response of the original ITU-R 468 noise-weighting filter and the green line indicates the approximated response by an FIR filter with short taps.

TABLE I
SIMULATION CONDITIONS.

Input signal	Factory noise
Sampling frequency	44100 Hz
Tap length of unknown system P	500
Tap length of noise control filter filter W	500
Tap length of secondary path model $\hat{C}$	500
Tap length of noise weighting filter H	500
Update algorithm	NLMS
Step size parameter α	0.01
Regularization parameter β	1.0×10^{-6}

C. Feedforward ANC System Considering of Psychoacoustic Properties

Feedforward ANC with a noise-weighting filter can effectively reduce noise over a specific frequency band by incorporating a noise-weighting filter in a conventional ANC system. A block diagram of a feedforward ANC system that considers psychoacoustic properties is shown in Fig. 3. In Fig. 3, $P(z)$ indicates the primary path from the noise source to the error microphone, $C(z)$ is the secondary path from the secondary source to the error microphone, $\hat{C}(z)$ is the model of $C(z)$, $W(z)$ is the noise control filter, and $H(z)$ is the noise-weighting filter. In this system, noise reduction in terms of acoustic impression can be expected by using the filtered reference signal $r_H(n)$ and the error signal $e_H(n)$ through the use of the noise-weighting filter to update the noise control filter $W(z)$. The update equation of the filter coefficients in the ANC system in consideration of the hearing characteristic is given by

$$\mathbf{w}(n+1) = \mathbf{w}(n) + \frac{\alpha}{\beta + \|\mathbf{r}_H(n)\|^2}\mathbf{r}_H(n)e_H(n), \quad (1)$$

where α is the step size parameter and β is the regularization parameter. $\mathbf{w}(n)$ is the noise control filter vector, $r_H(n)$ is obtained by convolution of the filtered reference signal $r(n)$ with the noise weighting filter $H(z)$, and $e_h(n)$ is obtained by convolution of the error signal $e(n)$ with $H(z)$.

III. SIMULATION RESULTS

A. Simulation Conditions and Evaluation Criteria

In this section, we examine the effectiveness of the ANC system in consideration of psychoacoustic properties by simulation. Table 1 lists the simulation conditions. In the simulations, the noise reduction performance is evaluated by

$$\text{Reduction} = 10\log_{10}\frac{\sum d^2(n)}{\sum e^2(n)}. \quad (2)$$

The primary and secondary paths are actual acoustic paths, which are estimated in advance using white noise. The impulse responses of the primary and secondary paths are shown in Figs. 4 and 5, respectively. In addition, the A-weighting filter and ITU-R 468 noise weighting filter are realized by a 500-tap FIR filter, which is designed by the window-function

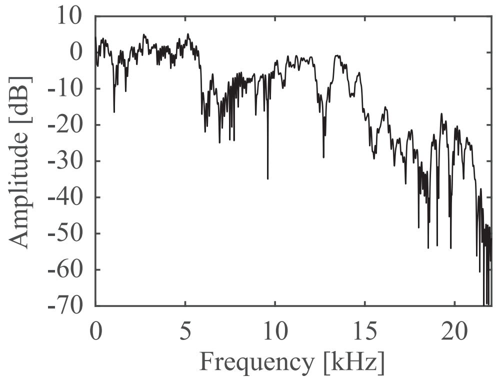


Fig. 4. Frequency spectrum of primary path.

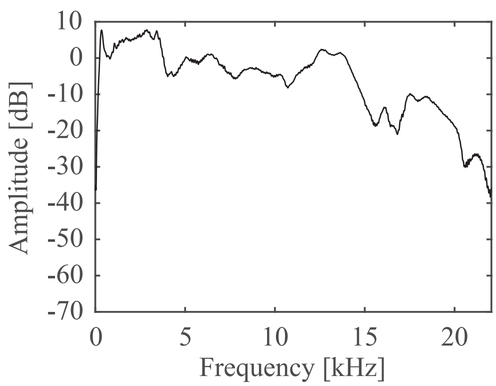
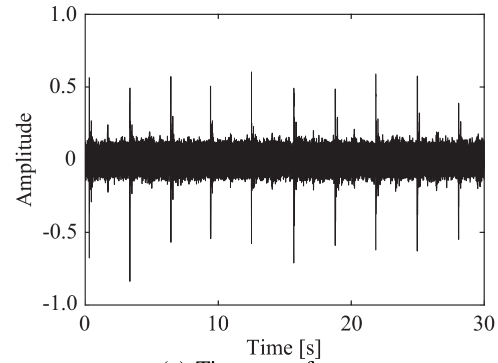
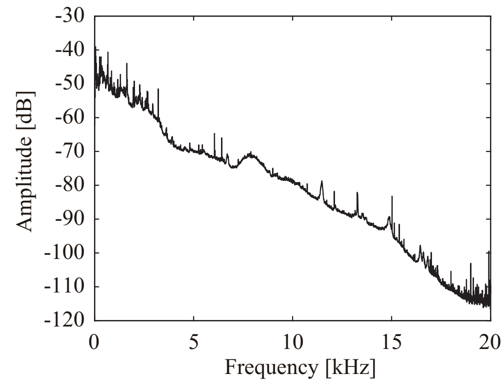


Fig. 5. Frequency spectrum of secondary path.



(a) Time waveform.



(b) Frequency spectrum.

Fig. 6. Factory noise.

method, where the sampling frequency is 44,100 Hz and the number of points in the FFT is 8,192. Furthermore, the time waveform and frequency spectrum of the factory noise used as nonstationary noise are shown in Fig. 6. As can be seen from Fig. 6, the factory noise is broadband noise. In the simulations, we compare the noise reduction between the ANC systems with and without the noise-weighting filter. Moreover, the secondary path estimate $\hat{C}(z)$ is the same as the actual secondary path $C(z)$.

B. Simulation Results

The time waveforms, the corresponding frequency spectra, the reductions in noise, and the spectrograms of the error signal in the ANC systems with and without the noise-weighting filter are shown in Figs. 7, 8, 9, and 10, respectively. From Fig. 7, all ANC systems work stably. From Figs. 7 and 9, it can be seen that the ANC systems with the noise-weighting filter have a lower convergence speed than the ANC system without the noise-weighting filter, but the steady-state performance is almost the same. The ANC system with the noise-weighting filter can reduce the noise by 4 to 9 kHz compared with the conventional system as shown in Fig. 8. The reason for the lower convergence is that the reference and error signals are modified by the noise-weighting filter, and the autocorrelation consequently becomes strong. Moreover, the noise reduction performance becomes larger in the frequency band where the error and reference signals are largely weighted by the noise weighting filter, whereas the noise reduction performance deteriorates in the other frequency bands as shown in Figs. 7 and 10. Therefore, there is no significant difference between the steady-state values of the reduction for the ANC systems with and without the noise-weighting filter.

Finally, we perform an objective evaluation of the noise reduction for humans using the average power of the residual error and the error weighted by the ITU-R 468 noise-weighting filter. Here, the average power of the residual error is normalized by the maximum power of the signal before noise reduction. The weighted average power is expressed as

$$L_{\mathrm{ITUeq}} = 10\log_{10}\left(\frac{1}{N_{\mathrm{av}}}\sum_{n=N_0}^{N_0+N_{\mathrm{av}}-1} e_{\mathrm{ITU}}^2(n)\right), \qquad (3)$$

where $e_{ITU}(n)$ is the error signal weighted by the ITU-R 468 filter, N_0 is the initial sample time, and N_{av} is the number of measured samples, which is 882,000. The average power of the residual error and the error weighted by the ITU-R 468 noise-weighting filter are shown in Table II. It can be seen that there is no significant difference between the average power level of

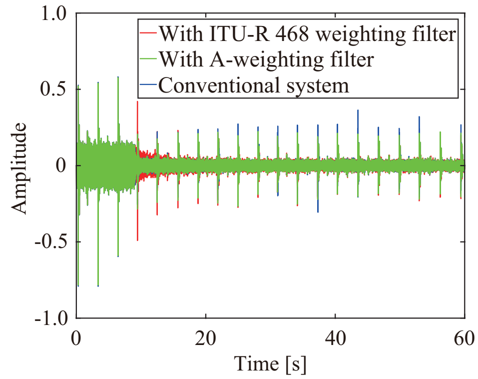


Fig. 7. Comparison of error signal $e(n)$.

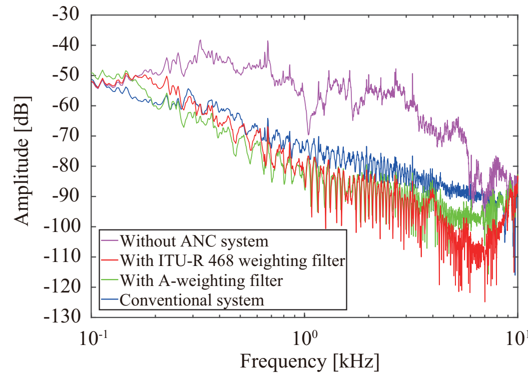


Fig. 8. Comparison of error spectrum.

TABLE II
AVERAGE POWER OF RESIDUAL ERROR AND THE AVERAGE POWER WEIGHTED BY ITU-R 468 WEIGHTING FILTER.

	Average power level of residual noise [dB]	Average power level of residual noise weighted by ITU-R 468 filter [dB]
ANC off	-21.002	-19.647
Without noise weighting filter	-29.929	-40.198
With A-weighting filter	-29.747	-44.396
With ITU-R 468 filter	-29.569	-44.528

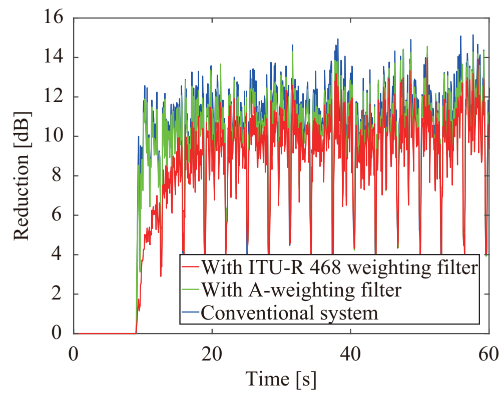


Fig. 9. Comparison of reduction.

the residual error for the ANC systems with and without the noise-weighting filter. On the other hand, the weighted average power of the ANC system with the noise-weighting filter is smaller than that for the conventional system. Therefore, it can be seen that the noise reduction in the hearing sense can be improved by incorporating the noise weighting filter. However, there is no difference between the results for the A-weighting filter and ITU-R 468 noise-weighting filter. From Fig. 8, it is found that the ANC system using the ITU-R 468 noise-weighting filter can improve the noise reduction performance in the frequency band from 4 to 9 kHz, but the noise reduction performance in the frequency band below 1 kHz is degraded compared with that for the ANC system using the A-weighting filter. On the other hand, the factory noise used in the simulation has larger components in the frequency band below 1 kHz than from 4 to 9 kHz. Therefore, it appears that the effect of noise reduction for high- and low-frequency components is almost the same in the hearing sense.

IV. SUBJECTIVE EVALUATION

A. Method of Paired Comparisons

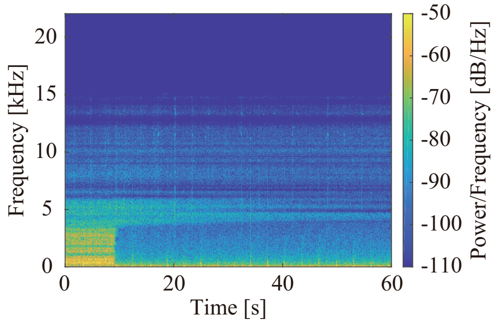
The method of paired comparisons [8] is used for the measure individuals' preference orderings of items presented to them as discrete binary choices. Because the judgment is simple, the reliability of the result is high. However, the data obtained from the method are on an ordinal scale. Therefore, we need a procedure to convert them into an interval scale. Although there are many analysis methods, we applied Scheffe's paired comparison to indicate results as scores.

B. Experimental Conditions

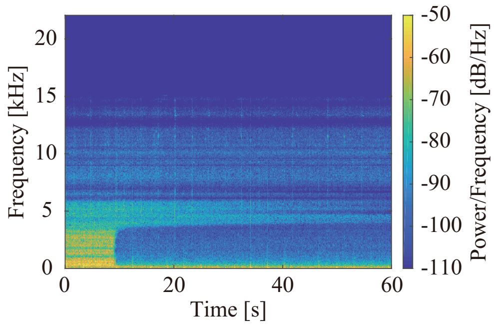
The subjective evaluation using Scheffe's paired comparison was conducted in a general room to examine the effectiveness of the feedforward ANC system in consideration of psychoacoustic properties. In this test, the participants judged whether one system could cancel noise better than another system. The experimental conditions were the same as the simulation conditions listed in Table I. Pairs of residual noise generated by simulation were evaluated by three possible responses, namely, the former was better, the latter was better, and the participant could not decide. The samples used in this subjective evaluation are shown in Table III. This experiment was conducted on 17 participants without significant hearing impairment whose ages are between 22 and 31.

C. Results of Subjective Evaluation

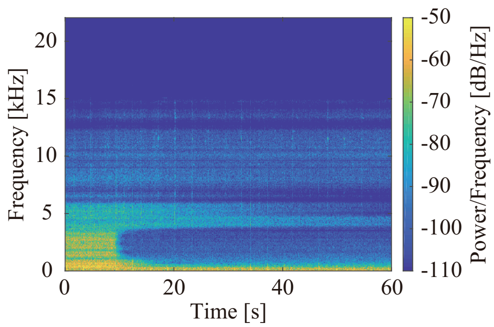
The results of the subjective evaluation are shown in Fig. 11, where the ordinate represents the interval scale. The filled diamond for each sample represents the average and the



(a) For the conventional system



(b) For the system using A-weighting filter



(c) For the system using ITU-R 468 weighting filter

Fig. 10. Spectrograms of error signal.

vertical line from the filled diamond indicates the confidence interval. When a filled diamond (average) is outside of the other confidence interval, there is a significant difference at a 5% probability between the samples. According to Fig. 11, the ANC systems using the noise-weighting filter have significantly different performance from the conventional system because the filled diamonds of Samples 3 and 4 are outside of the confidence interval of Sample 2. On the other hand, the system using the ITU-R 468 noise-weighting filter does not have a significant difference from the system using the A-weighting filter because the filled diamond of Sample 4 is in the confidence interval of Sample 3. This is for the same reason as that given for the previous simulation results shown in Fig. 8.

TABLE III
SAMPLES FOR SUBJECTIVE EVALUATION.

Sample 1	Only factory noise
Sample 2	Factory noise + Conventional system
Sample 3	Factory noise + A-weighting system
Sample 4	Factory noise + ITU-R 468 weighting system

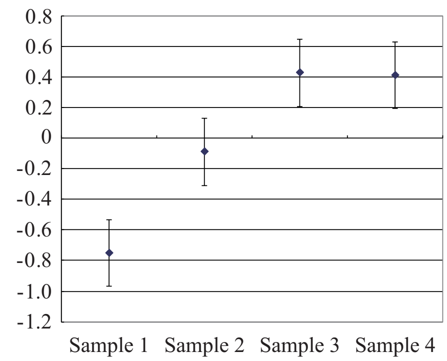


Fig. 11. Subjective evaluation results using Scheffe's paired comparison.

V. CONCLUSIONS

The conventional ANC system minimizes the mean squared error. However, the effect on the hearing sense is sometimes smaller than that of the numerical value when a person actually hears the sound with ANC. To solve this problem, we examined ANC systems with an A-weighting filter and ITU-R 468 noise-weighting filter in consideration of psychoacoustic properties. In this paper, the ANC systems using the noise-weighting filter were compared with the conventionall system for nonstationary broadband noise.

According to the simulation results, the weighted average power of the ANC systems using the noise-weighting filter is smaller than that of the conventional ANC system. Therefore, it can be concluded that the noise reduction for the hearing sense can be improved. We also conducted a subjective evaluation using Scheffe's paired comparison. It was found that the ANC systems with the noise-weighting filter have significantly improved noise reduction performance with the conventional ANC system.

ACKNOWLEDGMENT

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