Proceedings of 20th International Congress on Acoustics, ICA 2010

23-27 August 2010, Sydney, Australia

Noise suppression method for a high-realistic reproduction system with active noise control

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PACS: 43.50.KI

ABSTRACT

A "semi-transaural" system, which can realize a highly realistic sensation comparable to that possible with a transaural system, was proposed and experimentally verified. This system reduces spatial crosstalk because the loudspeakers for the left ear are located near the left ear and those for the right ear are located near the right ear. However, it more easily picks up the environmental noises than a binaural system, so the realistic sound sensation is distorted. The N-1-1 ANC system, which has already been proposed as a noise-suppression method, can effectively suppress non-directional noise by using several reference microphones; this method was thus applied in our proposed semi-transaural system. In the experimental evaluation of the system, white noise, pink noise and PC server noise were used as environmental noises. The experimental results showed that on average the noises are suppressed by 3.79 dB in the frequency of 50–1000 Hz.

INTRODUCTION

A lot of sound field reproduction systems for creating highly realistic sensations have been proposed. A transaural system is one such system. It can realize highly realistic sensations by employing several loudspeakers. However, its performance is limited by spatial crosstalk and the fluctuation of the transfer function between the loudspeakers and the listener. Spatial crosstalk means that the signal for the right ear interfuses into the left ear or the signal for the left ear interfuses into the right ear. In addition, with a conventional transaural system, there is a long distance between the loudspeakers and the listener, so the transfer function between them fluctuates easily. As a result, the realistic sensation is distorted by these problems. On the other hand, a "binaural" system easily suppresses the crosstalk because the listener wears headphones. The system also realizes a highly realistic sound sensation by considering the head-related transfer function (HRTF) [1] of them. However, compared with the transaural system, the binaural system has poor performancein terms of realistic sensation. In addition, it gives the listener an oppressive feeling because they must wear headphones.

Fig. 1. Semi-transaural system

To solve the above-described problems, we therefore proposed a "semi-transaural" system [2]. This system is shown in Figure 1. It can reduce the spatial crosstalk because the loudspeakers for the left ear are located near the left ear, and those for the right ear are located near the right ear. It can effectively reduce the spatial crosstalk while simultaneously avoiding an oppressive feeling because the loudspeakers are not touching the ears. However, it is more sensitive to environmental noises than the binaural system; that is, environmental noises are easily picked up by the listener and distort the realistic sensation.

In the present study, we tried to suppress the noises around the proposed system to realize a more-realistic sensation. In the case of a conventional noise-suppression method, passive noise control (PNC) [3][4][5] and active noise control (ANC) [6][7] have been demonstrated. PNC suppresses noise by means of insulation or absorption of sound waves. PNC is more effective for suppressing high-frequency noises. ANC suppresses noise by means of secondary sources generated by loudspeakers. It is more effective for suppressing low-frequency noise. In this study, we employed ANC because PNC needs walls or sound absorbers, which give the listener an oppressive feeling. In addition, ANC is effective for suppressing environmental noises. One ANC system, a N-1-1 ANC [3], which has already been proposed as a noise-suppression method, can effectively suppress non-directional noises by means of several reference microphones. The authors therefore employed this noise-suppression method to suppress the environmental noise around the proposed semi-transaural system.

CONVENTIONAL METHODS

ANC (active noise control)

ANC is a noise-suppression method with offsets of noises and secondary sources. An overview of an ANC system is shown in Figure 2. In this system, n represents a time index, $x(n)$ represents a reference signal, $y(n)$ represents a secondary source that suppresses the noises, $e(n)$ represents an error signal, $P(z)$ represents a primary path and $S(z)$ represents a secondary path. The spectra of $x(n)$, $y(n)$ and $e(n)$ are shown as $X(z)$, $Y(z)$ and $E(z)$. The signal captured by the error microphone is thus given as

$$E(z) = P(z)X(z) - S(z)Y(z). \tag{1}$$

The ANC controller renews the adaptive filter to fulfil Eq. (2).

$$E(z) = 0. \tag{2}$$

Generally, a least mean square (LMS) algorithm or a filtered-X LMS algorithm is used to renew the adaptive filter that is used for calculating $y(n)$.

ANC utilizes secondary sources generated by loudspeakers. The secondary sources are noise signals with reversed phase. ANC is effective for low-frequency noises because those noises have long wave length, so the phases of the noises and secondary sources can be easily synchronized. On the other hand, ANC is weak in regard to suppressing high-frequency noises because it is difficult to synchronize the phases of those noises and secondary sources.

Filtered-X LMS algorithm

A filtered-X LMS algorithm is a training algorithm, and ANC generally applies it for real-time transfer-function training. It is expressed as

$$w(n+1) = w(n) + 2\mu e(n)r(n), \tag{3}$$

n is a time index, $w(n)$ is a filter coefficient, μ is a step size parameter, $e(n)$ is an error signal and $r(n)$ is a reference signal filtered by the characteristic between the loudspeaker and the error microphone. This algorithm renews the filter coefficients on the basis of the filter coefficients of the previous one clock. It is therefore efficient for real-time filter-coefficient training such as ANC.

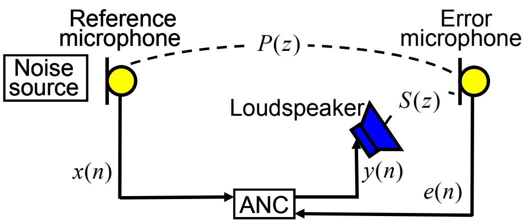

Fig. 2. Overview of ANC system

SUPPRESSION OF ENVIRONMENTAL NOISES AROUND A "SEMI-TRANSAURAL" SYSTEM

Noises around the proposed "semi-transaural" system were suppressed in order to realize a more-realistic sound sensation. Generally, environmental noise is generated by many different sound sources, for example, air ducts, air–conditioners and PC servers. The N-1-1 filtered-X LMS ANC system is employed to reduce such noise. This system can effectively suppress non-directional noises by using several reference microphones, so we applied it to our proposed "semi-transaural" system. It consists of three reference microphones, one cancelling loudspeaker and one error microphone. The reference microphones capture non-directional noises in the room, the left and right loudspeakers of the semi-transaural system are used as a cancelling loudspeaker, and the error microphone is located at the listening point. The proposed system captures non-directional noises with reference microphones, and it calculates the cancelling signal for the noises based on captured signals and emits it with the cancelling loudspeaker. Finally, it suppresses the noises in the point of the error microphone. The secondary path, namely, the transfer function between the cancelling loudspeaker and the error microphone, can be simply estimated due to the short distance between them.

An overview of the N-1-1 filtered-X LMS system is shown in Figure 3, where n is a time index, $x_{1\sim3}(n)$ represents reference signals, $y(n)$ represents the secondary source, and $e(n)$ represents the error signal. $P_{1\sim3}(z)$ shows the primary paths, and $S(z)$ shows the secondary path. The spectra of $x_{1\sim3}(n)$, $y(n)$ and $e(n)$ are shown as $X_{1\sim3}(z)$, $Y(z)$ and $E(z)$. The signal captured by the error microphone is represented as

$$\begin{aligned} E(z) &= P_1(z)X_1(z) + P_2(z)X_2(z) \\ &\quad + P_3(z)X_3(z) - S(z)Y(z). \end{aligned} \tag{4}$$

The ANC controller renews the adaptive filter to fulfil Eq. (5).

$$E(z) = 0. \tag{5}$$

In this system, $S(z)$ is easily estimated because the cancelling loudspeakers are located near the listner's ears, and the required control area is small because the listener's movement is lightly constrained.

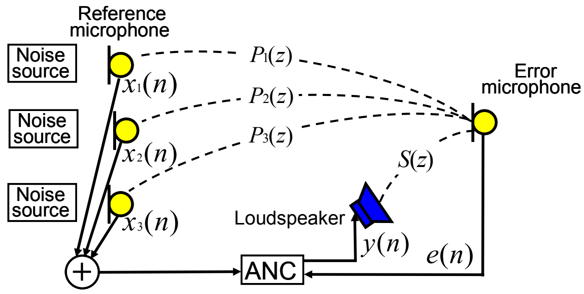

Fig. 3. N-1-1(3-1-1) filtered-X LMS ANC system

EVALUATION EXPERIMENTS

"White noise", "Pink noise" and "PC server noise", which are limited to frequencies from zero to 1000Hz, are employed as environmental noises. Figure 4 shows the pre-limited spectrum of the PC server noise. Figure 5 shows the experimental measurement locations, where "+" indicates an addition by using a mixer. Figure 6 shows the experimental environment. Here, an error microphone is located near the lisner's left ear, and we conducted the noise-suppression experiment. Table 1 lists the experimental conditions. The experimental flow is as follows.

1. All noises are continuously emitted by the loudspeakers.
2. The switches of the reference microphones are turned on and off according to all patterns.
3. The suppression results during all patterns are capututed by the error microphone.

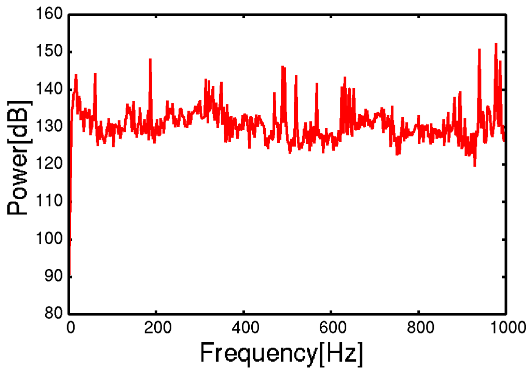

Fig. 4. Power spectrum of the PC server noise

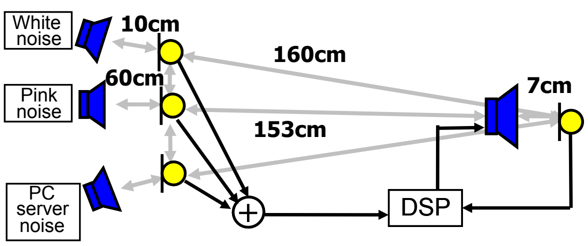

Fig. 5. Experimental locations

Fig. 6. Experimental environment

Table 1. Experimental conditions

Microphone	HOSHIDEN, KUC-1333
Noise source loudspeaker	MITSUBISHI, DIATONE DS-7
Cancelling loudspeaker	PROTRO, NCFR
DSP	Analog Devices, ADSP-2181
Adaptive filter length	128
Sampling frequency	16kHz

EXPERIMENTAL RESULTS

The average suppression levels from 50 to 1000 Hz are shown in Figure. 7. Letters "P", "W" and "S" mean that the noise suppression experiment was conducted with reference to pink noise, white noise or PC server noise. As for "P+W+S", which indicates all noises are referred to, the suppression level is highest. This result means that it is efficient to refer to a number of noise sound sources. Figure 8 shows the power spectrum for P+W+S. This result shows that the proposed method suppress the noises at 10-20 dB from the range of 50-1000 Hz. Figure 9 shows the power spectrum with reference to pink noise. This result shows that the noises are well suppressed at 300, 520 and 800 Hz. Figure 10 shows power spectrum with reference to white noise. This result shows that the noises are well suppressed at 420 and 800 Hz. Figure 11 shows the power spectrum with reference to PC server noise.

In reference to pink noise, the system could suppress the noises more effectively than white noise or PC server noise. The reason for that is that the microphone for pink noise could also caputure white noise and PC server noise. The secondary source could be actually realized to the noise. It will thus be possible to locate the reference microphones so as to attain a higher suppression effect.

It is confirmed by Figure 4 that the server noise has several peaks in its frequency characteristic. It therefore does not have much correlation with the white noise and the pink noise. As a result, it was not possible to achieve a storong suppression effect in reference to PC server noise only.

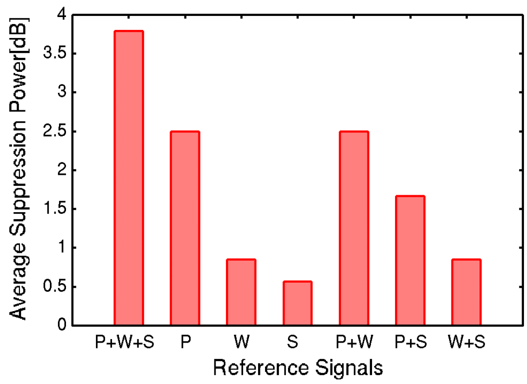

Fig. 7. Average suppression levels

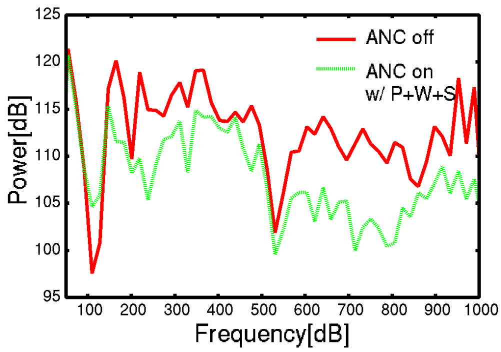

Fig. 8. Experimental result with P+W+S

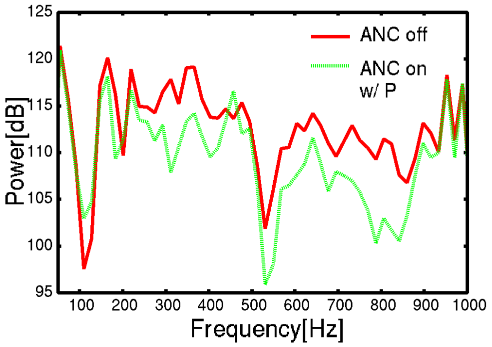

Fig. 9. Experimental result with reference to P (pink noise)

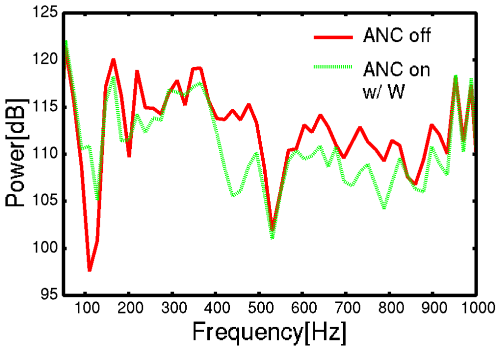

Fig. 10. Experimental result with reference to W (white noise)

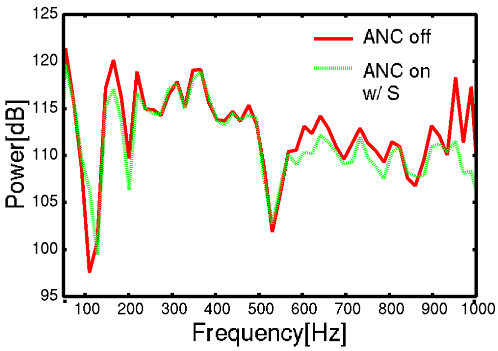

Fig. 11. Experimental result with reference to S (PC server noise)

CONCLUSIONS

A "semi-transaural" system, which realizes a highly realistic sound sensation by suppressing the spatial crosstalk by locating cancelling loudspeakers near the listener, was proposed as experimentally tested. To realize this higher-realistic sensation, environmental noises around the system are suppressed. The 3-1-1 filtered-X LMS ANC system is used to suppress non-directional noises. The system was experimentally evaluated with white noise, pink noise, and servers noise as the environmental noises, the suppression levels for these noises at the location of an error microphone were evaluated. The experiment confirmed the effect of refering a number of noise sound sources. Results showed that on average the noises were suppressed by 3.79 dB in the frequency range of 50-1000 Hz. In our future works, we will try to suppress diffused sound sources, and estimate the relation between the suppression level and the realistic sensation.

ACKNOULEDGEMENTS

This work was partly supported by Grants-in-Aid for Sci entific Research funded by The Ministry of Education, Culture, Sports, Science and Technology of Japan.

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