SELECTIVE VIRTUAL SENSING TECHNIQUE FOR MULTI-CHANNEL FEEDFORWARD ACTIVE NOISE CONTROL SYSTEMS

Chuang Shi[1], *Rong Xie*[1], *Nan Jiang*[1], *Huiyong Li*[1], *Yoshinobu Kajikawa*[2]

1. School of Information and Communication Engineering,
University of Electronic Science and Technology of China, Chengdu, China
2. Faculty of Engineering Science, Kansai University, Osaka, Japan

ABSTRACT

The virtual sensing technique allows the active noise control (ANC) system to work with error microphones that are placed far from the desired zone of quietness (ZoQ). Conventionally, a training stage is required to obtain the auxiliary filters with the temporary error microphones placed in the ZoQ. When the characteristics of the primary noise changes, the auxiliary filters have to be retrained. As a result, the conventional virtual sensing technique can only be used when the frequency band of the primary noise remains unchanged. In order to solve this limitation, this paper proposes a selective virtual sensing technique for the multi-channel feedforward ANC system. The selective virtual sensing technique obtains a bank of auxiliary filters in the subband structure. Based on the frequency-band-matching mechanism, a linear combination of the auxiliary filters is calculated and used in the real-time control stage. Experimental results show that the selective virtual sensing technique achieves better noise reduction performance than the conventional virtual sensing technique when the frequency band of the primary noise fluctuates.

Index Terms— Multi-channel active noise control, virtual sensing technique, FxLMS algorithm, adaptive filtering

1. INTRODUCTION

ANC systems generate a secondary sound to suppress the undesirable noise [1,2]. Based on the principle of wave superposition, the secondary sound should have the same amplitude and the opposite phase of the undesirable noise. The generation of the secondary sound can be implemented by an adaptive control filter, of which the coefficients are updated by the filtered-x least mean squares (FxLMS) algorithm [3,4]. In the adaptation, error signals are provided by error microphones placed in the desired ZoQ, where the acoustic summation of the secondary sound and the unwanted noise gradually approaches the minimum power [5].

When error microphones are not placed in the ZoQ, accurate estimates of the error signals are necessary to ensure the effectiveness of the ANC system. For example, in the ANC headset, the desired ZoQ should be formed in the eardrum. However, error microphones can only be placed at the entrance of the ear canal [6]. An intuitive solution to this problem is the remote sensing method that models the acoustic paths between the physical microphones outside the ZoQ and the virtual microphones in the ZoQ [7–12]. The acoustic path models are then used to calculate the estimates of the virtual error signals. The model accuracy greatly impacts the noise reduction performance and stability of the remote sensing method, requiring deliberate arrangement of the physical error microphones.

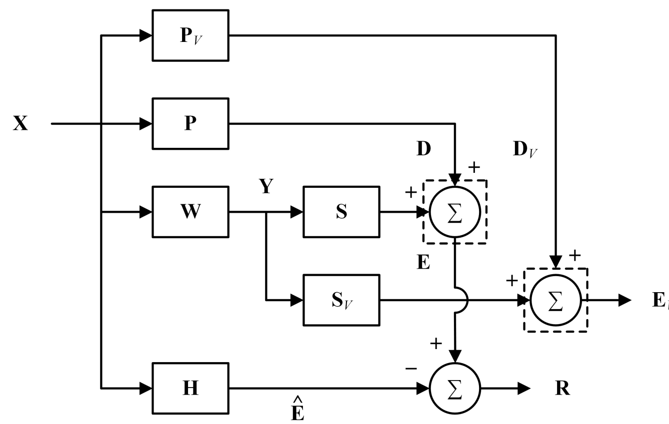

Fig. 1. Block diagram of the multi-channel virtual sensing technique in the frequency domain, where all notations of (ω) have been abbreviated.

An alternative approach is the virtual sensing technique, which is first demonstrated in the single-channel feedback ANC system and then extended for the single-channel and multi-channel feedforward ANC systems [13–15]. In the virtual sensing technique, estimates of the virtual error signals are calculated by the auxiliary filters implicitly. As illustrated in Fig. 1, a multi-channel feedforward ANC system receives the reference signal $\mathbf{X}^{(I\times1)}$ and the error signal $\mathbf{E}^{(K\times1)}$ to generate the control signal $\mathbf{Y}^{(J\times1)}$ that minimizes the power of the virtual error signal $\mathbf{E}_v^{(K\times1)}$. All notations of (ω) are

This research is supported by the National Science Foundation of China (Grant No. 61701090 and Grant No. 61671137).

abbreviated.

There are two stages in the virtual sensing technique. In the training stage, temporary error microphones are placed in the ZoQ to provide the virtual error signal, which is expressed by

$$\mathbf{E}_v^{(K\times 1)} = \mathbf{P}_v^{(K\times I)}\mathbf{X}^{(I\times 1)} + \mathbf{S}_v^{(K\times J)}\mathbf{W}^{(J\times I)}\mathbf{X}^{(I\times 1)}, \quad (1)$$

where $\mathbf{W}^{(J\times I)}$ is the control filter; $\mathbf{P}_v^{(K\times I)}$ and $\mathbf{S}_v^{(K\times J)}$ are the combined primary path and the secondary path to virtual error microphone, respectively. The optimum control filter is written by

$$\mathbf{W}_{opt}^{(J\times I)} = -\mathbf{S}_+^{(J\times K)}\mathbf{P}_v^{(K\times I)}, \quad (2)$$

where $\mathbf{S}_+^{(J\times K)}$ denotes the pseudo inverse of $\mathbf{S}_v^{(K\times J)}$.

With the optimum control filter in the training stage, the virtual error signal is no longer coherent with the reference signal. However, the error signal is still coherent with the reference signal, i.e.

$$\begin{aligned}\mathbf{E}^{(K\times 1)} &= \mathbf{P}^{(K\times I)}\mathbf{X}^{(I\times 1)} + \mathbf{S}^{(K\times J)}\mathbf{W}_{opt}^{(J\times I)}\mathbf{X}^{(I\times 1)} \\ &= \left[\mathbf{P}^{(K\times I)} + \mathbf{S}^{(K\times J)}\mathbf{W}_{opt}^{(J\times I)}\right]\mathbf{X}^{(I\times 1)}, \quad (3)\end{aligned}$$

where $\mathbf{P}^{(K\times I)}$ and $\mathbf{S}^{(K\times J)}$ are the combined primary path and the secondary path to the error microphones.

Therefore, the auxiliary filter $\mathbf{H}^{(K\times I)}$ can be obtained by the adaptive system identification, which treats $\mathbf{X}^{(I\times 1)}$ as the system input and $\mathbf{E}^{(K\times 1)}$ as the system output. The optimum auxiliary filter is written as

$$\mathbf{H}_{opt}^{(K\times I)} = \mathbf{P}^{(K\times I)} + \mathbf{S}^{(K\times J)}\mathbf{W}_{opt}^{(J\times I)}. \quad (4)$$

It is clear that the virtual sensing technique embeds the optimum control filter in the auxiliary filter, rather than simply estimating the virtual error signal. A previous study has demonstrated that moderate disturbances to the primary and secondary paths can be neutralized by the adaptive control filter while the auxiliary filter does not require retraining [16].

In the control stage, there are no physical error microphones in the ZoQ. The estimate of the error signal is computed as

$$\hat{\mathbf{E}}^{(K\times 1)} = \mathbf{H}_{opt}^{(K\times I)}\mathbf{X}^{(I\times 1)}. \quad (5)$$

The control filter is updated by minimizing the difference between the measured and estimated error signals, i.e.

$$\begin{aligned}\mathbf{R}^{(K\times 1)} &= \mathbf{E}^{(K\times 1)} - \hat{\mathbf{E}}^{(K\times 1)} \\ &= \mathbf{S}^{(K\times J)}\left[\mathbf{W}^{(J\times I)} - \mathbf{W}_{opt}^{(J\times I)}\right]\mathbf{X}^{(I\times 1)}. \quad (6)\end{aligned}$$

The optimum control filters in (2) should eventually be recovered. However, (6) also demonstrates that the control filter is affected by the frequency band of the reference signal. When the frequency band of the primary noise changes in the control stage, the auxiliary filter has to be retrained. As a result, the conventional virtual sensing technique can only be used when the frequency band of the primary noise is consistent in the training and control stages. In order to solve this limitation, this paper proposes a selective virtual sensing technique that obtains a bank of subband auxiliary filters in the training stage. Based on the frequency-band-matching mechanism, a linear combination of the subband auxiliary filters can be calculated and used in the control stage.

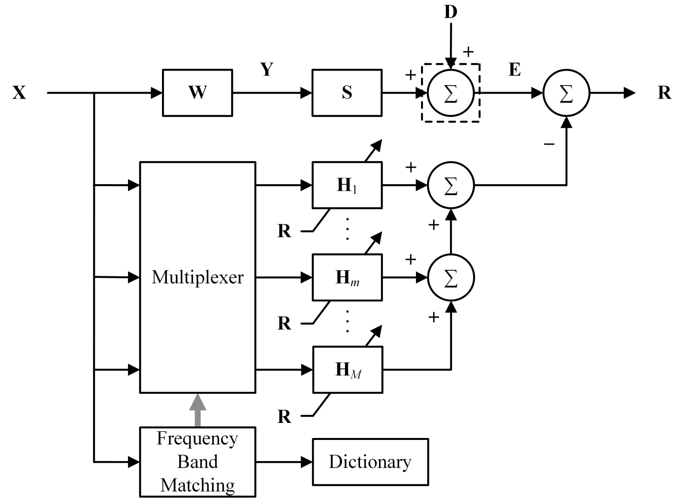

Fig. 2. Proposed training stage of the selective virtual sensing technique.

2. SELECTIVE VIRTUAL SENSING TECHNIQUE

The training stage of the selective virtual sensing technique is proposed in Fig. 2. The frequency-band-matching mechanism classifies the reference signal by its frequency band. When the frequency band is not found in the dictionary, the multiplexer is switched to an untrained set of auxiliary filters and the adaptation is activated.

Consider an ideal bandpass filter, of which the frequency response is written as

$$B_{\omega_1,\omega_2}(\omega) = u(\omega-\omega_1) - u(\omega-\omega_2), \quad (7)$$

where $u(\omega)$ is a Heaviside step function; ω_1 and ω_2 denotes the cut-off frequencies.

A band-limited reference signal is thus expressed by

$$\mathbf{X}_0^{(I\times 1)} = \mathbf{T}_0^{(I\times 1)} \circ \mathbf{B}_{\omega_1,\omega_2}^{(I\times 1)}, \quad (8)$$

where $\mathbf{T}_0^{(I\times 1)}$ is a univalent and conjugate symmetry functions of ω; $\circ$ denotes the Hadamard product; every element of $\mathbf{B}_{\omega_1,\omega_2}$ is determined by $B_{\omega_1,\omega_2}(\omega)$ and the size of $\mathbf{B}_{\omega_1,\omega_2}$ is indicted by its superscript.

Based on (6), when the optimum auxiliary filter is considered to be trained for unlimited bandwidth, the control filter

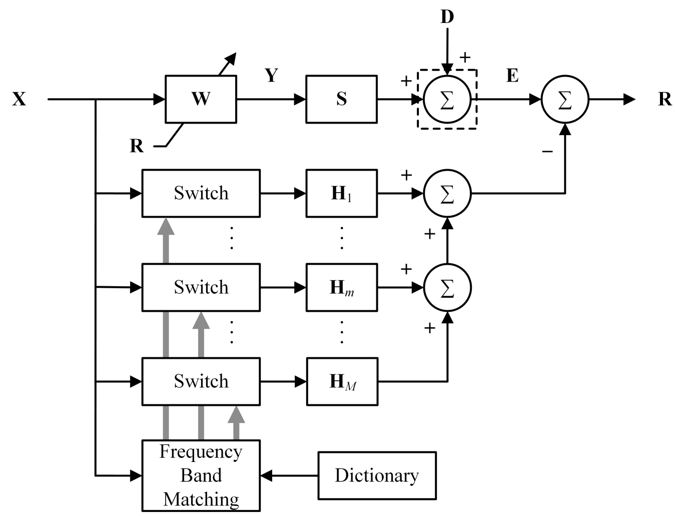

Fig. 3. Proposed control stage of the selective virtual sensing technique.

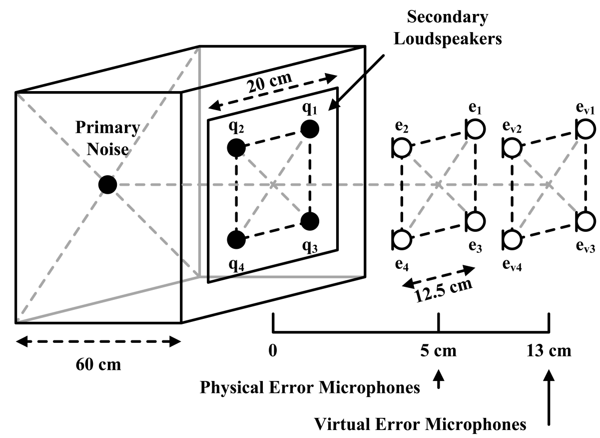

Fig. 4. Experiment setup.

obtained for the band-limited reference signal becomes

$$\left[\mathbf{W}_{\omega_1,\omega_2}^{(J\times I)} - \mathbf{W}_{opt}^{(J\times I)}\right]\mathbf{X}_0^{(J\times I)} = 0, \tag{9}$$

which can be further expressed as

$$\mathbf{W}_{\omega_1,\omega_2}^{(J\times I)} \circ \mathbf{B}_{\omega_1,\omega_2}^{(J\times I)} = \mathbf{W}_{opt}^{(J\times I)} \circ \mathbf{B}_{\omega_1,\omega_2}^{(J\times I)}. \tag{10}$$

Equation (10) shows that the control filter can only match its optimum solution within the frequency band of the reference signal. The control filter trained by one primary noise remains effective to another primary noise with a narrower frequency band. A similar study on the selective ANC system without considering the virtual sensing technique suggests that many primary noises are necessary in order for the reference signals to obtain a variety of frequency bands [17].

Furthermore, when the band-limited reference signal is used in the training stage, based on (3), the auxiliary filter becomes

$$\mathbf{H}_{\omega_1,\omega_2}^{(K\times I)} \circ \mathbf{B}_{\omega_1,\omega_2}^{(K\times I)} = \mathbf{H}_{opt}^{(K\times I)} \circ \mathbf{B}_{\omega_1,\omega_2}^{(K\times I)}. \tag{11}$$

Consequently, the control filter is affected by the frequency band of the reference signal and leads to the same solution in (10).

However, it is not straightforward to combine two auxiliary filters to cope with a broader frequency band. The subband auxiliary filter trained with the band-limited reference signal is thereafter post-processed to ensure

$$\mathbf{H}_{\omega_1,\omega_2}^{(K\times I)} = \mathbf{H}_{\omega_1,\omega_2}^{(K\times I)} \circ \mathbf{B}_{\omega_1,\omega_2}^{(K\times I)} = \mathbf{H}_{opt}^{(K\times I)} \circ \mathbf{B}_{\omega_1,\omega_2}^{(K\times I)}. \tag{12}$$

Under this condition, the linear combination of auxiliary filters achieves a new auxiliary filter that can represent the optimum filter within the combined frequency band, e.g.

$$\mathbf{H}_{\omega_1,\omega_2}^{(K\times I)} + \mathbf{H}_{\omega_2,\omega_3}^{(K\times I)} = \mathbf{H}_{\omega_1,\omega_3}^{(K\times I)} = \mathbf{H}_{opt}^{(K\times I)} \circ \mathbf{B}_{\omega_1,\omega_3}^{(K\times I)}. \tag{13}$$

The control stage of the selective virtual sensing technique is shown in Fig. 3. The frequency band of the reference signal is detected. The frequency-band-matching mechanism looks for the best combination of frequency bands in the dictionary. A broader frequency band is used instead of a narrower frequency band when the frequency band of the reference signal could not be matched perfectly. The selected auxiliary filters are then switched on, while the adaptive control filter is updating.

3. EXPERIMENTAL VALIDATION

The primary noise source is enclosed in a cube ($60 \times 60 \times 60$ cm^3). There is an opening on one side of the cube. The size of the opening is 20×20 cm^2. Four secondary loudspeakers are distributed on the opening. The spacing between the secondary loudspeakers is 12.5 cm. Four error microphones are placed in the experiment room. They are 5 cm away from the opening. Another four microphones are temporarily arranged as the virtual error microphones, which are 13 cm away from the opening. The task of the virtual sensing technique is to use the four error microphones to implement active noise control at the locations of the four virtual error microphones.

A case $(1, 4, 4)$ feedforward ANC controller is deployed. The sampling frequency is set at 48 kHz. The secondary path models, control filters and auxiliary filters have the lengths of 200, 400 and 400 taps, respectively. In the training stage of the selective virtual sensing technique, the primary noises are generated as the band-limited white noises. The identified subband auxiliary filters are referred to as $\mathbf{H}_{300,500}$, $\mathbf{H}_{500,700}$, $\mathbf{H}_{700,900}$, $\mathbf{H}_{900,1100}$ and $\mathbf{H}_{1100,1300}$, where the subscript indicates the frequency band. Two other auxiliary filters $\mathbf{H}_{500,1100}$ and $\mathbf{H}_{300,1300}$ are trained with the conventional virtual sensing technique with broader frequency bands. In the latter comparison, these two auxiliary filters are referred to as the "conventional virtual sensing technique I" and "conven-

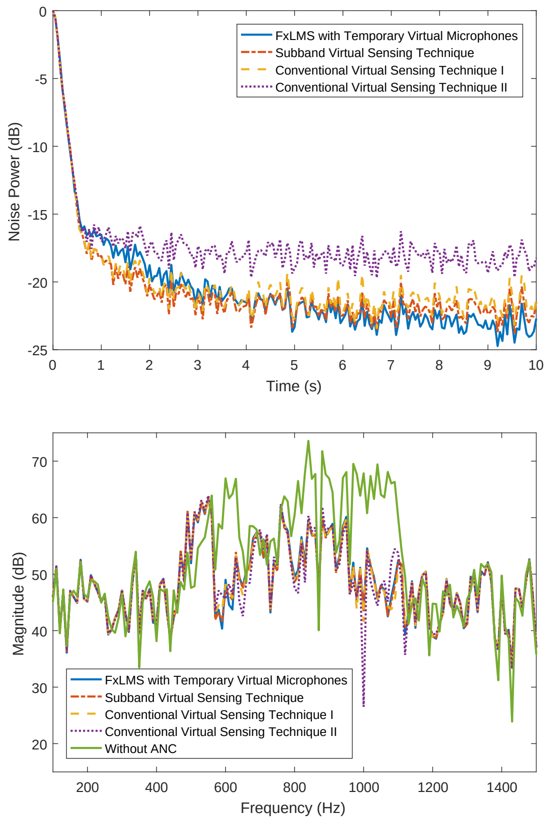

Fig. 5. The primary noise ranges from 500 Hz to 1100 Hz.

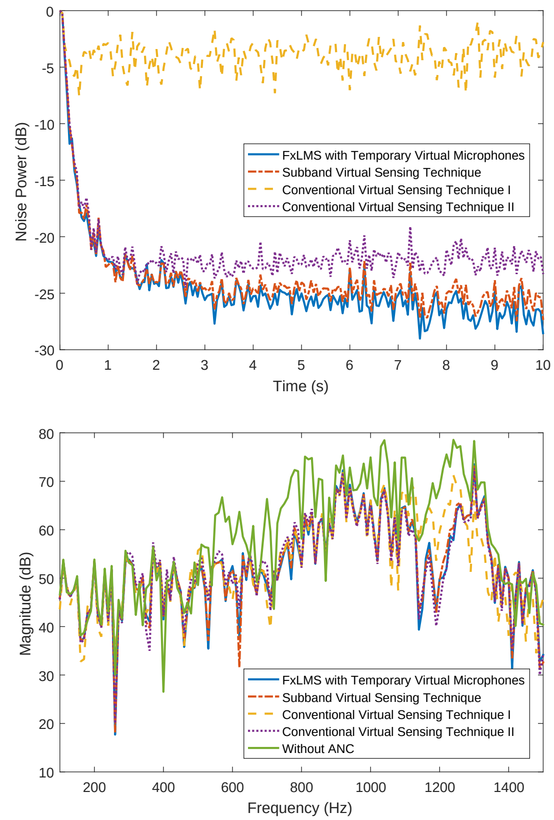

Fig. 6. The primary noise ranges from 300 Hz to 1300Hz.

tional virtual sensing technique II", respectively. The results of the selective virtual sensing technique are labeled as the "subband virtual sensing technique".

Figure 5 demonstrates the noise reduction performance when the primary noise possesses the frequency band from 500 Hz to 1100 Hz. This primary noise has uneven power in each frequency band. The selective virtual sensing technique switches $\mathbf{H}_{500,700}$, $\mathbf{H}_{700,900}$ and $\mathbf{H}_{900,1100}$ on in the control stage. The experimental results confirm the effectiveness of all the methods in comparison. The selective virtual sensing technique and the conventional virtual sensing technique I achieve almost identical noise reduction performance to the FxLMS algorithm. With the temporary error microphones placed in the ZoQ, the FxLMS algorithm no doubt achieves the maximum noise reduction performance.

Figure 6 shows the noise reduction performance when the primary noise possesses the frequency band from 300 Hz to 1300 Hz. This primary noise is generated with higher power for higher frequency band. The selective virtual sensing technique selects all the five subband auxiliary filters in the control stage. In this comparison, the conventional virtual sensing technique I fails to provide noise reduction because its auxiliary filter has been trained by a narrower frequency band than that of the primary noise. The selective virtual sensing technique still achieves the closest noise reduction performance to the FxLMS algorithm. The conventional virtual sensing technique II leads to similar noise reduction performance in Figs. 5 and 6. The performance gap between the conventional virtual sensing technique II and the FxLMS algorithm is likely due to an insufficient length of the auxiliary filter that results in a loss of the model precision.

4. CONCLUSIONS

This paper proposes a selective virtual sensing technique that obtains a bank of auxiliary filters in the subband structure during the training stage. The frequency-band-matching mechanism selects several auxiliary filters to form the best approximation of the frequency band of the primary noise. Those selected auxiliary filters are then switched on in the control stage. The experimental validation carried out with a case (1,4,4) ANC system demonstrates that the proposed selective virtual sensing technique achieves the closest noise reduction performance to the FxLMS algorithm with temporary error microphones placed in the ZoQ. The conventional virtual sensing technique fails to reduce the noise when the primary noise possesses a broader frequency band in the control stage.

5. REFERENCES

[1] S. M. Kuo, D. R. Morgan, *Active Noise Control Systems: Algorithms and DSP Implementations*. Wiley: New York, 1996.

[2] C. H. Hansen, *Understanding active noise cancellation*. Spon Press: London, 2001.

[3] S. J. Elliott, I. M. Stothers, P. A. Nelson, "A multiple error LMS algorithm and its application to the active control of sound and vibration," *IEEE Trans. Acoust. Speech Sig. Process.*, vol. ASSP-35, no. 10, pp.1423–1434, 1987.

[4] A. Gonzales, A. Albiol, S. J. Elliott, "Minimization of the maximum error signal in active control," *IEEE Trans. Speech Audio Process.*, vol. 6, no. 3, pp. 268-281, 1998.

[5] Y. Kajikawa, W. S. Gan, S. M. Kuo, "Recent advances on active noise control: Open issues and innovative applications," *APSIPA Trans. Sig. Inf. Process.*, vol. 1, no. e3, pp. 1–21, 2012.

[6] M. Pawelczyk, "Adaptive noise control algorithms for active headrest system," *Control Eng. Practice*, vol. 12, pp. 1101–1112, 2004.

[7] J. Garcia-Bonito, S. J. Elliott, C. C. Boucher, "Generation of zones of quiet using a virtual microphone arrangement," *J. Acoust. Soc. Amer.*, vol. 101, no. 6, pp. 3498–3516, 1997.

[8] C. D. Kestell, B. S. Cazzolato, C. H. Hansen, "Active noise control in a free field with virtual sensors," *J. Acoust. Soc. Amer.*, vol. 109, no. 1, pp. 232–243, 2001.

[9] D. Moreau, B. S. Cazzolato, A. Zander, C. Petersen, "A review of virtual sensing algorithms for active noise control," *Algorithms*, vol. 1, no. 2, pp. 69–99, 2008.

[10] C. Petersen, R. Fraanje, B. S. Cazzolato, A. C. Zander, C. H. Hansen, "A Kalman filter approach to virtual sensing for active noise control," *Mech. Sys. Sig. Process.*, vol. 22, no. 2, pp. 490–508, 2008.

[11] S. J. Elliott, J. Cheer, "Modeling local active sound control with remote sensors in spatially random pressure fields," *J. Acoust. Soc. Amer.*, vol. 137, no. 4, pp. 1936–1946, 2015.

[12] W. Jung, S. J. Elliott, J. Cheer, "Combining the remote microphone technique with head-tracking for local active sound control," *J. Acoust. Soc. Amer.*, vol. 142, no. 1, pp. 298–307, 2017.

[13] N. Miyazaki, Y. Kajikawa, "Head-mounted active noise control system with virtual sensing technique," *J. Sound Vib.*, vol. 339, pp. 65–83 (2015).

[14] S. Edamoto, C. Shi, Y. Kajikawa, " Directional feedforward ANC system with virtual sensing technique," *Proc. 2016 Int. Workshop Smart Info Media Sys. in Asia*, Ayutthaya, Thailand, 2016.

[15] N. Jiang, C. Shi, H. Li, Y. Kajikawa, "Near-field error sensing of multi-channel active noise control using virtual sensing technique," *Proc. 25th Int. Congr. Sound Vib.*, Hiroshima, Japan, 2018.

[16] S. Edamoto, C. Shi, Y. Kajikawa, " Directional feedforward ANC system with virtual sensing technique," *Proc. POMA*, Honolulu, Hawaii, 2017.

[17] D. Shi, B. Lam, W. S. Gan, "A novel selective active noise control algorithm to overcome practical implementation issue," *Proc. 44th Int. Conf. Acoust. Speech Sig. Process.*, Calgary, Canada, 2018.