APSIPA Transactions on Signal and Information Processing, 2023, 12, e48

Original Paper

Feedforward Active Noise Control System Using Optical Laser Microphone to Overcome Causality Constraint

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ABSTRACT

In this paper, a feedforward active noise control (ANC) system with an optical laser microphone is proposed and the effectiveness of the proposed system is introduced through real-world experiments. The main problem with the feedforward ANC system is the degradation of its noise reduction performance due to the causality constraint, that is, the ANC system should update the noise control filter and emit the anti-noise until unwanted noise reaches the error microphone. As a solution, the proposed ANC system utilizes the optical laser microphone as the reference microphone. The optical laser microphone picks up the vibration of the noise source by emitting an optical laser beam to the surface of the vibrating object. Since the reference signal obtained by the optical laser microphone is different from the unwanted noise obtained by the ordinary microphone as the error sensor, the proposed system utilizes the first-order differentiator to convert the vibration velocity into the acceleration for the improvement of the coherence between the unwanted noises obtained by the reference and error microphones. Simulation and experimental results show that the proposed system can reduce the unwanted noise by almost the same amount as the conventional system while the causality constraint is relaxed.

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Received 08 June 2023; Revised 22 September 2023
ISSN 2048-7703; DOI 10.1561/116.00000240

Keywords: Feedforward active noise control system, causality constraint, optical laser microphone, differentiator.

1 Introduction

Acoustic noise is one of the serious problems due to the increase in the number of industrial equipment components, such as engines and manufacturing plant systems. In recent years, active noise control (ANC) systems [3, 4, 13, 15, 16, 21] have been developed and implemented in real environments [17]. For example, an active soft edge is adopted in the roads in Japan, which reduces car noise by 4 dB on pavements [22–24]. Moreover, the ANC systems are applied to construction equipment [1, 7], power transformers [31], and so forth. In consumer products, noise cancelling headphones have become popular and shown to reduce noise significantly [17]. Miyake *et al.* studied the head-mounted ANC system with multiple reference microphones to reduce the unwanted noise arriving from various directions [19]. Shi *et al.* proposed the selective fixed filter ANC system based on CNN[27].

ANC systems utilize an adaptive digital filter [6, 30] to track the time-varying characteristics of noise sources, acoustic environments, and unknown plants. The ANC systems are equipped with by the feedforward [13, 15, 16, 21] or feedback [14, 18, 26] control systems. In this paper, we focus on the feedforward ANC system shown in Figure 1. The feedforward ANC system consists of a reference microphone, an error microphone, and a secondary loudspeaker. In the feedforward ANC system, the placements of the reference and error microphones are important for satisfying the causality constraint [12, 14]. That is, the noise reduction performance degrades when the anti-noise reaches the error microphone after the unwanted noise firstly reaches it. Hence, the computational time and propagation delays of anti-noise from the secondary loudspeaker to the error microphone should be smaller than

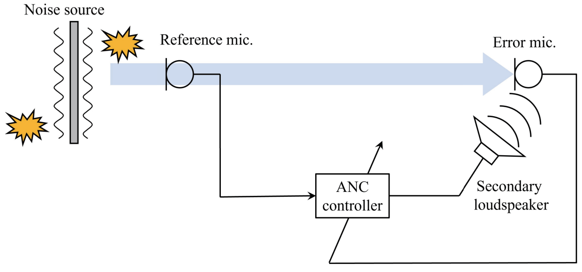

Figure 1: Structure of basic feedforward ANC system.

the propagation delay of the unwanted noise from the reference microphone to the error microphone.

To solve this problem, in this paper, the feedforward ANC system equipped with an optical laser microphone [11] is proposed. this system utilizes the optical laser microphone [5, 25] as the reference microphone. The optical laser microphone uses an optical laser beam to pick up the sound as the vibration of an object. Although the optical laser microphone cannot pick up the sound at high frequencies owing to the vibration being small, it can detect the sound at low frequencies with high accuracy. Moreover, the propagation delay from the noise source to the reference microphone is smaller than that of an ordinary microphone because of its measurement principle. Thus, the proposed feedforward ANC system is effective and can relax the causality constraint.

However, the reference signal picked up by the optical laser microphone is the vibration velocity of the noise source and the characteristic of the reference signal is different from that of the unwanted noise obtained at the error microphone, which is an ordinary microphone such as an electret condenser microphone. In general, if the coherence between the reference signal and the unwanted noise obtained at the error microphone becomes small, then the noise reduction performance of the feedforward ANC system degrades [16]. To solve this problem, in the proposed feedforward ANC system, a differentiator is applied to adjust the reference signal obtained as the vibration velocity of the noise source, considering the relationship between the sound pressure and the volume velocity. To evaluate the effectiveness of the proposed feedforward ANC system, computer simulations and experiments were conducted.

This paper is organized as follows. In Section 2, we explain the principle and problem with the feedforward ANC system. Then, the proposed ANC system with the optical laser microphone is explained in Section 3, and simulation and experimental results are shown in Sections 4 and 5, respectively. Finally, conclusions and future works are shown in Section 6.

2 Feedforward Active Noise Control System and Its Problem

In this section, the principle of the feedforward ANC system and its problem about the causality constraint [12, 14] are described.

2.1 Principle of Feedforward Active Noise Control System

The feedforward ANC system uses a noise control filter to minimize the error signal obtained at the error microphone. A block diagram of the feedforward ANC system is shown in Figure 2. In Figure 2, P is the primary path between the noise source and the error microphone, R is the reference path between the noise source and the reference microphone, S is the secondary path between the secondary loudspeaker and the error microphone, W is the noise control filter, and $\hat{S}$ is the secondary path model.

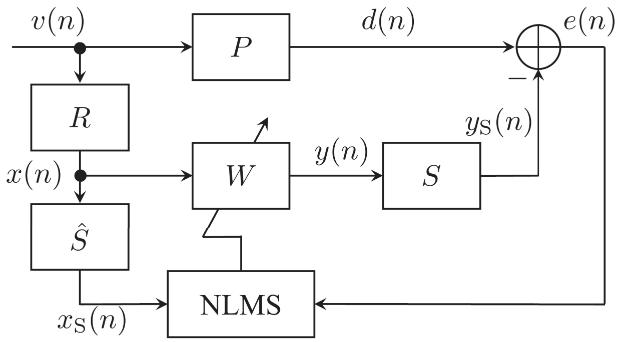

Figure 2: Block diagram of basic feedforward ANC system.

The ANC system generates the anti-noise that cancels the unwanted noise on the basis of the superposition of sound. The control signal $y(n)$ is generated by convolving the reference signal $x(n)$ and the noise control filter $w(n)$ as

$$y(n) = \mathbf{w}^{\mathrm{T}}(n)\mathbf{x}(n), \tag{1}$$

where $\mathbf{w}(n)$ is the coefficient vector of the noise control filter, $\mathbf{x}$(n) is the reference signal vector, T is the transpose operator, and n is the time index. Then, the control signal $y(n)$ is emitted from the secondary loudspeaker and reaches the error microphone. The anti-noise picked up by the error microphone is represented by

$$y_{\mathrm{S}}(n) = \mathbf{s}^{\mathrm{T}}(n)\mathbf{y}(n), \tag{2}$$

where $\mathbf{s}(n)$ is the impulse response of the secondary path. The unwanted noise passing through the primary path $d(n)$ is cancelled by the anti-noise $y_{\mathrm{S}}(n)$. Here, the error signal $e(n)$ is picked up by the error microphone and represented by

$$e(n) = d(n) - y_{\mathrm{S}}(n). \tag{3}$$

To minimize the error signal $e(n)$, the noise control filter is updated by the adaptive filtering algorithm. The filtered-x least mean square (FxLMS) and filtered-x normalized least mean square (FxNLMS) algorithms [2, 20] are widely used in the ANC system. In this paper, the FxNLMS algorithm is used. The update equation for the FxNLMS algorithm is represented by

$$\mathbf{w}(n+1) = \mathbf{w}(n) + \frac{\alpha}{\|\mathbf{x}_{\mathrm{S}}(n)\|^2 + \beta} e(n)\mathbf{x}_{\mathrm{S}}(n), \tag{4}$$

$$x_{\mathrm{S}}(n) = \hat{\mathbf{s}}^{\mathrm{T}}(n)\mathbf{x}(n), \tag{5}$$

where $x_{\mathrm{S}}(n)$ and $\mathbf{x}_{\mathrm{S}}(n)$ are the filtered reference signal and its vector, respectively, $\|\cdot\|$ denotes the L_2 norm, α is the step size parameter ($0 < \alpha < 2$), β is the regularization parameter with a small positive value, and $\hat{\mathbf{s}}(n)$ is the impulse response of the secondary path model.

2.2 Causality Constraint in Feedforward Active Noise Control System

In the feedforward ANC system, the unwanted noise firstly reaches the reference microphone. Then, the unwanted noise reaches the error microphone while the ANC system generates and emits the anti-noise and updates the noise control filter. Here, the ANC system should satisfy the causality constraint [12, 14] to reduce unwanted noise. In other words, anti-noise should be generated and reach the error microphone before the unwanted noise reaches the error microphone. To satisfy the causality constraint, the time delays should satisfy the following inequality:

$$n_{\mathrm{P}} - n_{\mathrm{R}} > n_{\mathrm{C}} + n_{\mathrm{S}}, \tag{6}$$

where n_{P}, n_{R}, and n_{S} are the delays for the primary, reference, and secondary paths, respectively, and n_{C} is the computational time delay for the feedforward ANC system. The operational delay $n_{\mathrm{C}} + n_{\mathrm{S}}$ should be smaller than the propagation delay $n_{\mathrm{P}} - n_{\mathrm{R}}$. If the feedforward ANC system does not satisfy inequality (6), the noise reduction performance degrades.

From inequality (6), if the reference and error microphones are placed close to each other, the computational time delay n_{C} and the propagation delay of the secondary path, n_{S}, are strictly restricted. Hence, it is difficult to satisfy the causality constraint when the reference and error microphones are close to each other. In the next section, the proposed feedforward ANC system with the optical laser microphone is demonstrated to relax the causality constraint.

3 Proposed Feedforward Active Noise Control System with Optical Laser Microphone

In this section, we describe the proposed feedforward ANC system with an optical laser microphone [11].

3.1 Optical Laser Microphone

The optical laser microphone [5, 25] emits an optical laser beam to the surface of a vibrating object and measures sound as the vibration of the object. An example of the optical laser microphone is shown in Figure 3. The measurement principle of the optical laser microphone is shown in Figure 4. Firstly, the

Figure 3: Example of optical laser microphone (OFV-5000 Extra, Polytec GmbH).

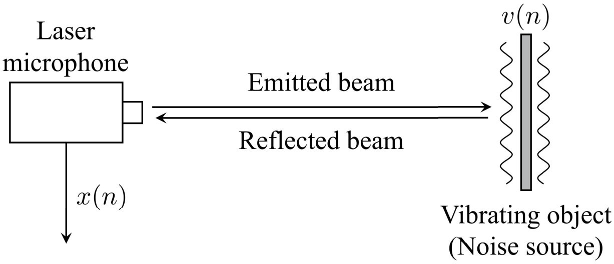

Figure 4: Principle of optical laser microphone.

optical laser microphone emits an optical laser beam to the surface of the vibrating object. Then, the emitted laser beam is reflected and input to the optical sensor of the microphone. The frequency of the reflected laser beam changes owing to the Doppler shift while the frequency of the emitted laser beam does not change. By calculating the difference between the frequencies of the emitted and reflected laser beams, we can measure the velocity of the vibration. That is, the optical laser microphone measures sound as the velocity of the vibrating object that generates the unwanted noise.

Although the optical laser microphone cannot pick up high-frequency sounds owing to the vibration being small, it can pick up low-frequency sounds with high accuracy. Moreover, the propagation delay from the noise source to the reference microphone is smaller than that to an ordinary microphone because of its measurement principle. For example, when the distance between the noise source and the reference microphone is 3.4 m, the ordinary microphone requires a time delay of 1.0×10^{-2} s with a sound velocity of 340 m/s to pick up the unwanted noise. On the other hand, the optical laser microphone requires a time delay of about 2.3×10^{-8} s with a light velocity of 3.0×10^{8} m/s. Here, the computational time for the calculation of the vibration velocity (e.g., 1.0×10^{-4} s for OFV-5000 Extra, Polytec GmbH) is much longer than the time delay of 2.3×10^{-8} s. Assuming that the error microphone is placed 1.0 m away from the reference microphone and that the secondary loudspeaker is placed 0.1 m away from the error microphone, the propagation delays of the primary and secondary paths are about 1.3×10^{-2} s and 2.9×10^{-4} s, respectively. Under this condition, the computational delays for the basic and proposed ANC systems should be 2.6×10^{-3} s and 1.3×10^{-2} s, respectively. Thus, the optical laser microphone can pick up the unwanted noise very rapidly and the proposed feedforward ANC system can use a longer operation time than the conventional ANC system.

3.2 Proposed Feedforward Active Noise Control System

The structure of the proposed feedforward ANC system is shown in Figure 5. As mentioned in Section 3.1, the propagation delay for the optical laser microphone is satisfactorily small because the microphone uses the optical laser light whose velocity is greater than the sound velocity. Hence, the proposed ANC system considers only the computational delay D_{C} and the delay for the secondary path D_{S}. However, the proposed ANC system uses an ordinary microphone (e.g., electret condenser microphone) as the error microphone and the frequency spectra of the obtained signals of the reference and error microphones differ from each other. That is, the obtained signal at the reference microphone is for the velocity of the noise source. On the other hand, the obtained signal at the error microphone is for the sound pressure. Therefore, the coherence between these signals becomes small and the noise reduction performance degrades [16].

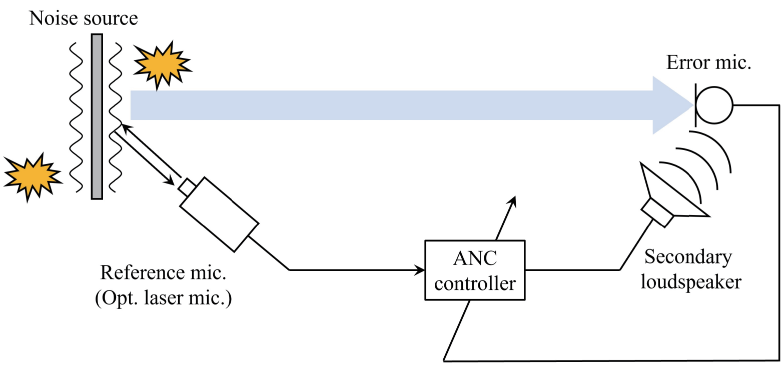

Figure 5: Structure of proposed ANC system.

To solve this problem, the first-order differentiator is adopted in the proposed ANC system.[1] This process is based on the relationship between the

[1]In [11], the bilinear filter was used. However, it is difficult to apply the bilinear filter to the practical ANC system because the amplitude of the bilinear filter goes to infinite at the Nyquist frequency.

volume velocity of the point source and the sound pressure, which can be represented as

$$D(s) = \frac{\rho}{4\pi r} s Q(s) e^{-s\frac{r}{c}}, \tag{7}$$

where $D(s)$ is the Laplace transform of the sound pressure, $Q(s)$ is the Laplace transform of the volume velocity, s is the complex variable ($s = j\omega$), j is the imaginary unit, ω is the angular frequency, r is the distance between the sound source and the microphone, and c is the speed of sound.[2] From (7), the sound pressure $P(s)$ is obtained by the first-order differentiation of the volume velocity $sQ(s)$. Hence, the sound pressure at the reference microphone can be estimated by the differentiation of the velocity obtained by the optical laser microphone.[3]

In the proposed ANC system, the first-order differentiator $H_{\mathrm{L}}(s) = s$ is realized as

$$H_{\mathrm{D}}(z) = \frac{1}{2T_{\mathrm{S}}}\left(1 - z^{-1}\right), \tag{8}$$

where T_{s} is the sampling period and z is the complex variable of the z transform ($z = e^{sT_{\mathrm{S}}}$). Here, $1/2T_{\mathrm{S}}$ is treated as the gain for the differentiator. A block diagram of the proposed ANC system is shown in Figure 6, where $x_{\mathrm{D}}(n)$ represents the differentiated reference signal. The proposed ANC system uses the FxNLMS algorithm the same as the basic ANC system shown in Figure 2.

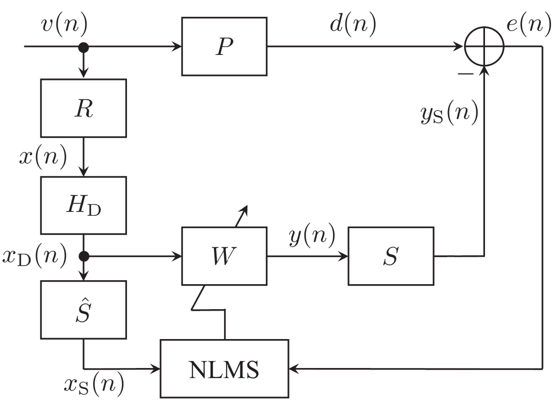

Figure 6: Block diagram of proposed ANC system.

[2]This relationship is for the point source condition. However, the volume velocity is proportional to the vibration of the sound source. Hence, we can adopt this relationship for not only the point source but also other sound sources.

[3]We obtain the acceleration of vibration through the differentiation; however, the acceleration and sound pressure have similar frequency spectra, which show attenuations at low frequencies. Hence, the coherence can be improved by using the differentiator.

3.3 Optimal Noise Control Filter of Proposed ANC System

The optimal noise control filter in the proposed ANC system is derived.[4] In this derivation, the point sources are assumed to be the noise and secondary sources. Moreover, omnidirectional microphones are assumed for the reference and error microphones. To simplify the discussion, the free sound field is assumed. It is also assumed that the optical laser microphone picks up the vibration velocity without any disturbances.

Firstly, the optimal noise control filter is derived for the basic ANC system. The error signal at the analog domain is represented by

$$E(s) = D(s) - Y_{\mathrm{S}}(s), \tag{9}$$

where $D(s)$ and $Y_{\mathrm{S}}(s)$ are the Laplace transforms of the unwanted noise and anti-noise. Moreover, the anti-noise $Y_{\mathrm{S}}(s)$ is obtained as

$$Y_{\mathrm{S}}(s) = S(s)Y(s), \tag{10}$$

$$Y(s) = W(s)X(s), \tag{11}$$

where $X(s)$ and $Y(s)$ is the Laplace transform of the reference signal and the control signal, and $W(s)$ is the transfer function of the noise control filter. According to (7), the relationship between the volume velocity of the noise source and each signal is represented by

$$X(s) = \frac{\rho}{4\pi r_{\mathrm{R}}} sQ(s)e^{-st_{\mathrm{R}}}, \tag{12}$$

$$D(s) = \frac{\rho}{4\pi r_{\mathrm{P}}} sQ(s)e^{-st_{\mathrm{P}}}, \tag{13}$$

$$Y_{\mathrm{S}}(s) = \frac{\rho}{4\pi r_{\mathrm{S}}} sQ_{\mathrm{LS}}(s)e^{-st_{\mathrm{S}}}, \tag{14}$$

where r_{R} and r_{P} are the distances from the noise source to the reference and error microphones, respectively, and r_{S} is the distance from the secondary source to the error microphone. Moreover,

$$t_{\mathrm{R}} = \frac{r_{\mathrm{R}}}{c}, \tag{15}$$

$$t_{\mathrm{P}} = \frac{r_{\mathrm{P}}}{c}, \tag{16}$$

$$t_{\mathrm{S}} = \frac{r_{\mathrm{S}}}{c}. \tag{17}$$

Here, the volume velocity of the secondary source is generated by the secondary loudspeaker, that is,

$$Q_{\mathrm{LS}}(s) = H_{\mathrm{V}}(s)Y(s), \tag{18}$$

[4] In this derivation, the optimal filter is represented as the analog domain because the relationship in (7) is used in the derivation.

where $H_\mathrm{V}(s)$ is the transfer function of the secondary loudspeaker.[5] By solving (14) and (18), we can represent the anti-noise picked up by the error microphone as

$$Y_\mathrm{S}(s) = \frac{\rho}{4\pi r_\mathrm{S}} s H_\mathrm{V}(s) W(s) X(s) e^{-s\Delta t_\mathrm{S}}. \tag{19}$$

When $E(s) = 0$, the optimal noise control filter is obtained.

$$W_\mathrm{O,Bas}(s) = \frac{r_\mathrm{R} r_\mathrm{S}}{\rho r_\mathrm{P}} \frac{1}{s H_\mathrm{V}(s)} e^{-s(\Delta t_\mathrm{P} - \Delta t_\mathrm{R} - \Delta t_\mathrm{S})}. \tag{20}$$

Next, the optimal noise control filter for the proposed ANC system is derived. In the proposed ANC system, the reference signal is obtained as the vibration velocity and represented by[6]

$$X_\mathrm{OLM}(s) = Q(s). \tag{21}$$

By replacing $X_\mathrm{OLM}(s)$ with $X(s)$ in (11), we can represent the optimal noise control filter for the proposed ANC system as

$$W_\mathrm{O,OLM}(s) = \frac{r_\mathrm{S}}{r_\mathrm{P}} \frac{1}{H_\mathrm{V}(s)} e^{-s(\Delta t_\mathrm{P} - \Delta t_\mathrm{S})}. \tag{22}$$

From (22), $W_\mathrm{O,OLM}(s)$ is the inverse of $H_\mathrm{V}(s)$ whose amplitude and phase are adjusted. The transfer function $H_\mathrm{V}(s)$ also shows the frequency response similar to that of a second-order band-pass filter with the Butterworth characteristic [8–10, 28, 29] and $W_\mathrm{O,LDV}(s)$ is similar to a notch filter.

As mentioned in Section 3.2, the differentiated reference signal is used in the proposed ANC system. The output of the first-order differentiator is represented by

$$X_\mathrm{OLM,D}(s) = s X_\mathrm{OLM}(s). \tag{23}$$

By replacing $X_\mathrm{OLM,D}(s)$ with $X(s)$ in (11), we can represent the optimal noise control filter including the first-order differentiator as

$$W_\mathrm{O,OLM,D}(s) = \frac{r_\mathrm{S}}{r_\mathrm{P}} \frac{1}{s H_\mathrm{V}(s)} e^{-s(\Delta t_\mathrm{P} - \Delta t_\mathrm{S})}. \tag{24}$$

In (24), the denominator $sH_\mathrm{V}(s)$ represents the acceleration characteristic of the secondary loudspeaker, which is similar to the second-order high-pass filter with the Butterworth characteristic. The optimal noise control filters (20) and (24) are similar to each other, although the optimal noise control filter (22) is different from them. Thus, the proposed ANC system with the differentiator achieves better noise reduction similar to the basic ANC system without a large delay.

[5] $H_\mathrm{V}(s)$ is the transfer function between the input of the loudspeaker and the velocity of the diaphragm of the loudspeaker.

[6] Here, it is assumed that the vibration velocity is equal to the volume velocity. Actually, the volume velocity is proportional to the vibration velocity.

4 Simulation Results

Some simulations were conducted to confirm the effectiveness of the proposed feedforward ANC system. In this section, the effectiveness of the proposed ANC system was compared with that of the basic feedforward ANC system shown in Figure 2 that utilizes the ordinary microphone as the reference microphone. Hereafter, the proposed and basic feedforward ANC systems are called the proposed and conventional ANC systems, respectively. The effectiveness of the proposed ANC systems with and without the differentiator was also evaluated.

In the simulations, the identified impulse responses of each path were used. These impulse responses were measured in a soundproof room (height: 2.20 m; width: 2.32 m; depth: 3.24 m) with a reverberation time of 100 ms. The arrangement of the measurement equipment and the implementation of the identification system, and identification conditions are shown in Figures 7 and 8, and Table 1, respectively. The identified impulse responses and their frequency responses are shown in Figures 9 and 10, respectively. As mentioned in Section 3.1, the optical laser microphone picks up the vibration of the object, and the frequency response of the reference path obtained with the optical laser microphone is attenuated at high frequencies. On the other hand, the frequency response of the reference path obtained with the optical laser microphone and differentiator is not attenuated at high frequencies. The impulse responses shown in Figure 9 were used in the simulations. In the following simulations, the time waveform of the error signal and the amount of noise reduction for each system were evaluated. The amount of noise reduction is defined as

$$\text{Reduction}(n) = 10\log_{10}\frac{\sum_{m=0}^{N-1} d^2(n-m)}{\sum_{m=0}^{N-1} e^2(n-m)}, \tag{25}$$

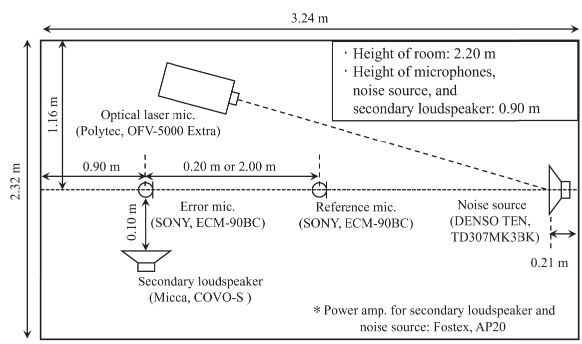

Figure 7: Arrangement of measurement equipment.

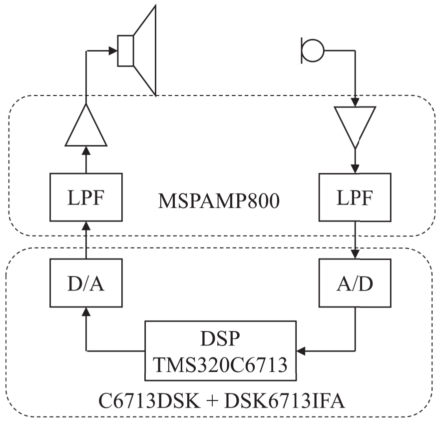

Figure 8: Implementation of identification system.

Table 1: Identification conditions.

Algorithm	NLMS
Noise source	White noise
Sampling frequency	8000 Hz
Frequency range	0–2000 Hz
Tap length of primary path P	200
Tap length of reference path R	200
Tap length of secondary path S	200
Step size parameter	0.01
Regularization parameter β	1.0×10^{-5}

where N is the tap length of the noise control filter. The amount of noise reduction was calculated for every N sample. Simulation conditions are shown in Table 2.

Time waveforms of error signals and the amount of noise reduction for each ANC system are shown in Figures 11 and 12, respectively, which show that each ANC system can reduce the unwanted noise by more than 5 dB. In particular, the proposed ANC systems with and without the differentiator reduce the unwanted noise by more than 18 dB. Comparing the proposed ANC systems with and without the differentiator, the proposed ANC system with the differentiator converges more rapidly than that without the differentiator. This is because the frequency characteristic of the reference path in the proposed ANC system with the differentiator (Figure 10 (e)) is similar to that of the conventional ANC system (Figure 10 (c)). On the other hand, the frequency characteristic of the reference path in the proposed ANC system without

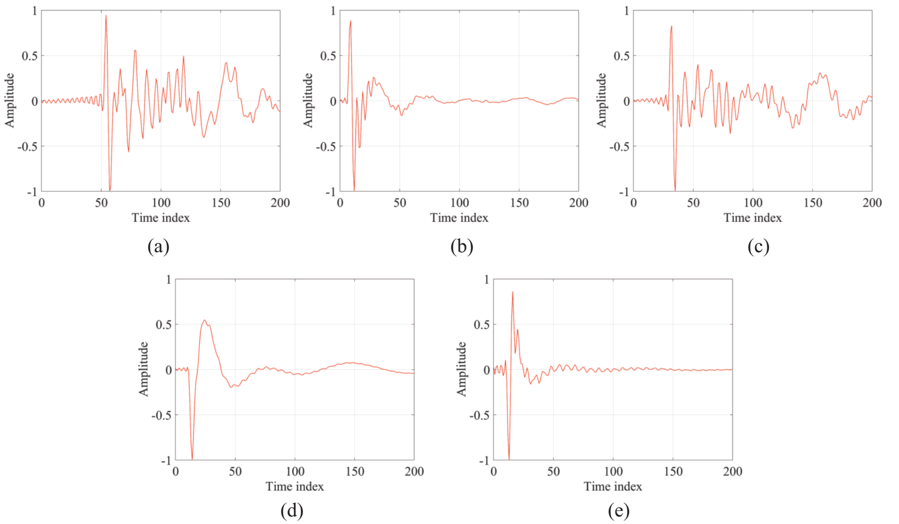

Figure 9: Impulse responses of each path. (a) Primary path. (b) Secondary path. (c) Reference path using ordinary microphone. (d) Reference path using optical laser microphone. (e) Reference path using optical laser microphone and differentiator.

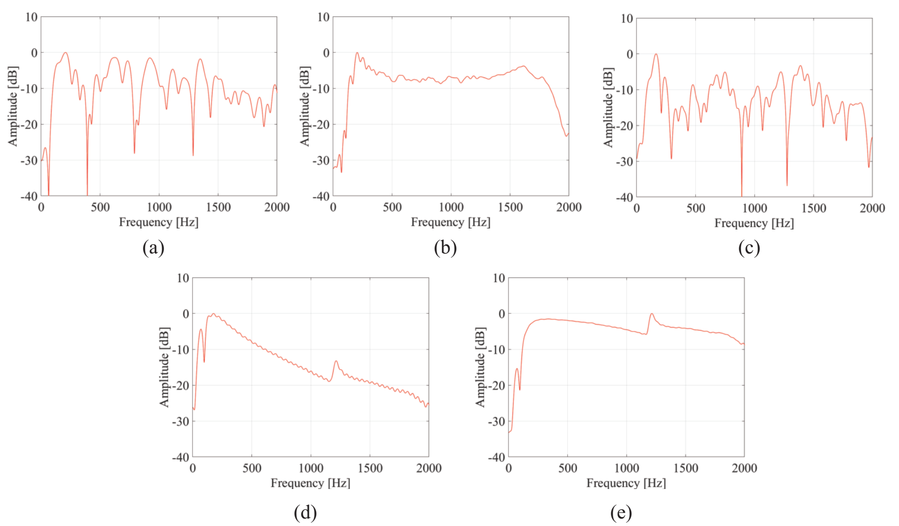

Figure 10: Frequency response of each path. (a) Primary path. (b) Secondary path. (c) Reference path using ordinary microphone. (d) Reference path using optical laser microphone. (e) Reference path using optical laser microphone and differentiator.

Table 2: Simulation conditions.

Unwanted noise	White noise
Sampling frequency	8000 Hz
Frequency range	60–2000 Hz
Tap length of primary path P	200
Tap length of reference path R	200
Tap length of secondary path S	200
Tap length of secondary path model $\hat{S}$	200
Tap length of noise control filter W	200
Step size parameter α	0.01
Regularization parameter β	1.0×10^{-5}

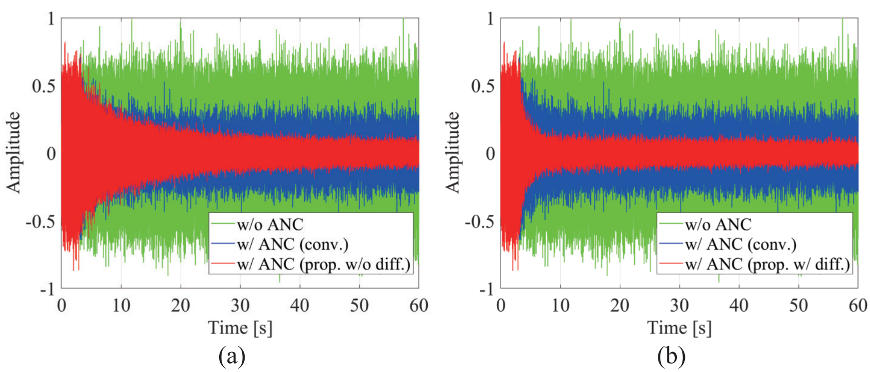

Figure 11: Time waveforms of unwanted noise and error signal in computer simulation. (a) Conventional ANC system and proposed ANC system without differentiator. (b) Conventional ANC system and proposed ANC system with differentiator.

the differentiator (Figure 10 (d)) is different from that of the conventional ANC system (Figure 10 (c)). Therefore, the proposed ANC system with the differentiator achieves better conditions to update the noise control filter than the basic ANC system and the proposed ANC system without the differentiator owing to the improvement of the coherence between the unwanted noises picked up by the reference and error microphones.

Next, we evaluate the effectiveness of the proposed ANC system using the spectra of the error signal and the magnitude-squared coherence (MSC) defined by

$$\mathrm{MSC}(f) = \frac{|P_{dx}(f)|^2}{P_{dd}(f)P_{xx}(f)}, \tag{26}$$

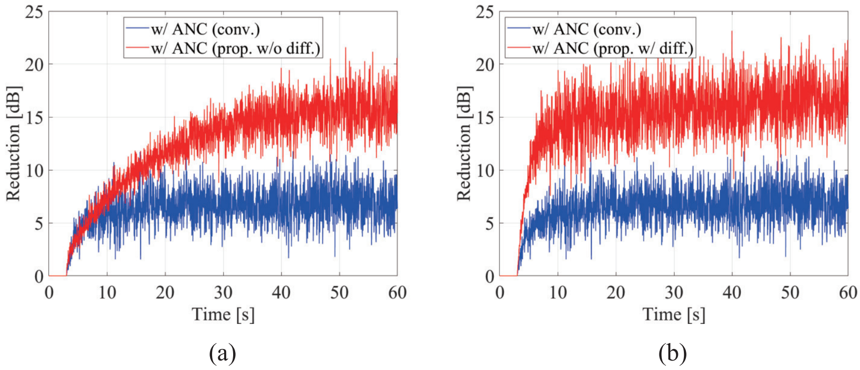

Figure 12: Amount of noise reduction in computer simulation. (a) Conventional ANC system and proposed ANC system without differentiator. (b) Conventional ANC system and proposed ANC system with differentiator.

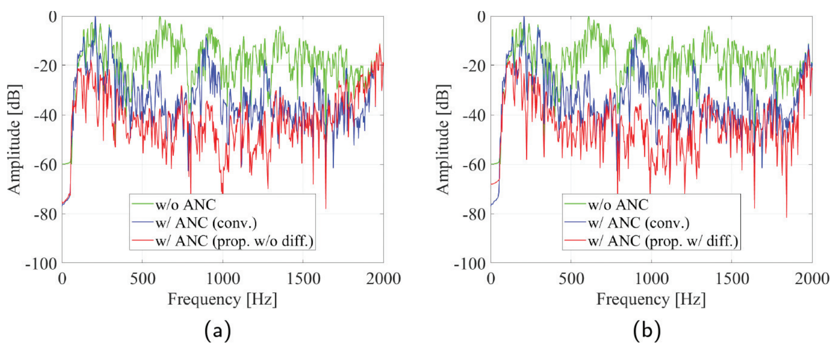

Figure 13: Frequency spectra of error signals in computer simulation. (a) Conventional ANC system and proposed ANC system without differentiator. (b) Conventional ANC system and proposed ANC system with differentiator.

where f is the frequency index, $P_{dx}(f)$ is the cross power spectral density of the reference signal $x(n)$ and unwanted noise $d(n)$, and $P_{dd}(f)$ and $P_{xx}(f)$ are the power spectral densities of the reference signal $x(n)$ and unwanted noise $d(n)$, respectively. Here, $x(n)$ is replaced by $x_D(n)$ for the proposed ANC system with the differentiator. Figures 13 and 14 show the error spectra of the conventional and proposed ANC systems. It can be seen from Figure 13 that the proposed ANC system with the differentiator shows the best performance of noise reduction in three systems. It can also be seen from Figures 13 and 14 that the proposed ANC system with the differentiator improves the noise reduction performance at the frequency band in which the MSC of the

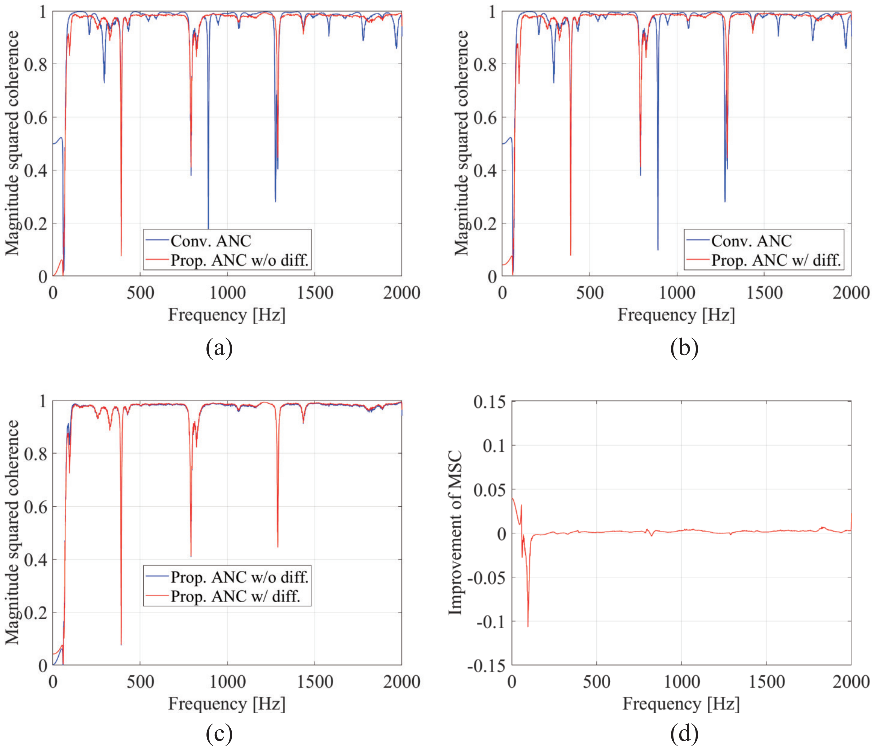

Figure 14: Coherence of each ANC system. (a) Conventional ANC system and proposed ANC system without differentiator. (b) Conventional ANC system and proposed ANC system with differentiator.(c) Proposed ANC systems with and without differentiator. (d) Improvement of coherence between proposed ANC systems with and without differentiator.

proposed ANC system with the differentiator to a greater extent than the proposed ANC system without the differentiator.[7]

Finally, the causality constraint of the proposed ANC system was evaluated by examining the propagation delays in the impulse responses shown in Figure 9. In Figure 9, the propagation delays for each path in samples are $n_{\mathrm{P}} = 57$, $n_{\mathrm{S}} = 12$, and $n_{\mathrm{R}} = 35$ for the ordinary microphone, $n_{\mathrm{R}} = 14$ for the optical laser microphone, and $n_{\mathrm{R}} = 13$ for the optical laser microphone with the differentiator. They are equivalent to the time delays of $t_{\mathrm{P}} = 7.125$ ms, $t_{\mathrm{S}} = 1.500$ ms, and $t_{\mathrm{R}} = 4.375$ ms for the ordinary microphone, $t_{\mathrm{R}} = 1.750$

[7]The coherence is improved below 100 Hz; however, the ANC system cannot the reduce unwanted noise owing to the time delay of the secondary loudspeaker. Furthermore, since the amplitude of the secondary loudspeaker is small, it is difficult to amplify the gain of the noise control filter that includes the inverse of the transfer function of the secondary path.

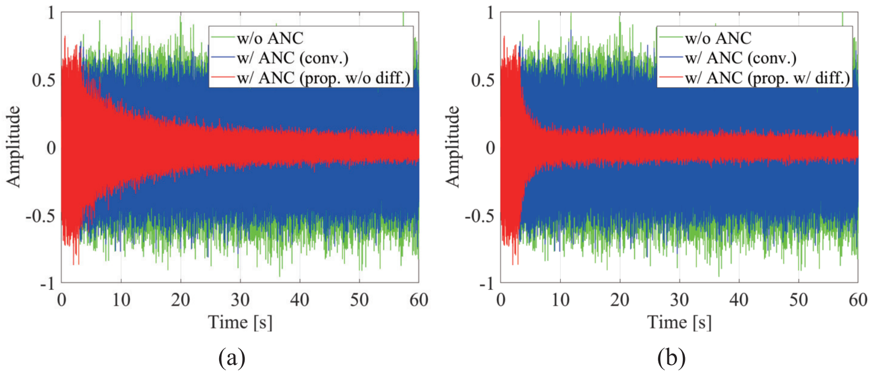

Figure 15: Time waveforms of unwanted noise and error signal under non-causal condition in computer simulation. (a) Conventional ANC system and proposed ANC system without differentiator. (b) Conventional ANC system and proposed ANC system with differentiator.

ms for the optical laser microphone, and $t_{\mathrm{R}} = 1.625$ ms for the optical laser microphone with the differentiator. By substituting these values into the inequality (6), we find that the computational time delays for the conventional system should be $t_{\mathrm{C}} < 1.250$ ms. Moreover, the computational time delays for the proposed ANC systems with and without the differentiator should be $t_{\mathrm{C}} < 4.000$ ms and $t_{\mathrm{C}} < 3.875$ ms, respectively. In the case that the reference microphone of the conventional system is placed 0.20 m from the error microphone, $t_{\mathrm{R}} = 6.625$ ms and the inequality of the causality constraint becomes $t_{\mathrm{C}} < -1.00$. Hence, the causality constraint is not satisfied and the capability to reduce the unwanted noise significantly degrades. The time waveform of the error signal is shown in Figure 15, indicating that the conventional ANC system cannot reduce the unwanted noise. On the other hand, the proposed ANC systems with and without the differentiator reduces the unwanted noise.

Hence, in the proposed ANC systems, the causality constraint can be relaxed and the degradation of the noise reduction performance resulting from the violation of the causality constraint can be avoided.

5 Experimental Results

Real-world experiments were conducted to confirm the effectiveness of the proposed feedforward ANC system. As shown in Section 4, the effectiveness of the proposed ANC system was compared with that of the conventional feedforward ANC system shown in Figure 2. The arrangement of measurement equipment and the implementation of the identification system, and identification condi-

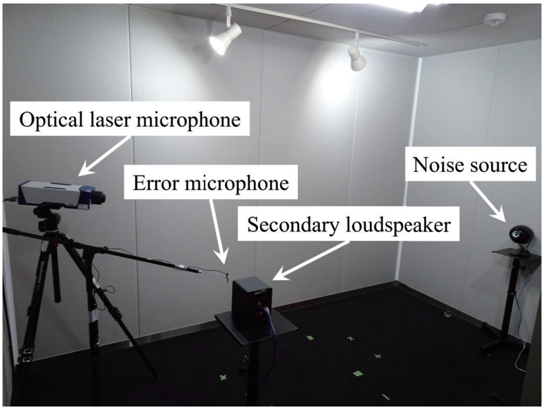

Figure 16: Experimental environment.

Table 3: Experimental conditions.

Unwanted noise	White noise
Sampling frequency	8000 Hz
Frequency range	60–2000 Hz
Tap length of secondary path model $\hat{S}$	200
Tap length of noise control filter W	200
Step size parameter α	0.01
Regularization parameter β	1.0×10^{-5}

tions are the same as those shown in Figures 7 and 8, and Table 1, respectively. Moreover, we conducted an experiment on noise reduction in the case that the reference microphone was placed 0.20 and 2.00 m from the error microphone. The causality constraint was not satisfied when the reference microphone was placed 0.20 m from the error microphone. The secondary path model was identified in advance and used in each ANC system. The experimental environment and conditions are shown in Figure 16 and Table 3.

The time waveforms and frequency spectra of the error signals are shown in Figures 17 and 18, respectively, indicating that the proposed ANC system with the differentiator reduces the unwanted noise similarly to the conventional ANC system with the reference microphone placed 2.00 m from the error microphone. Here, the conventional ANC system cannot reduce the unwanted noise with the reference microphone placed 0.20 m from the error microphone. On the other hand, the proposed ANC system without the differentiator reduces the unwanted noise to a lesser degree than the conventional ANC system and converges more slowly than the proposed ANC system with the differentiator.

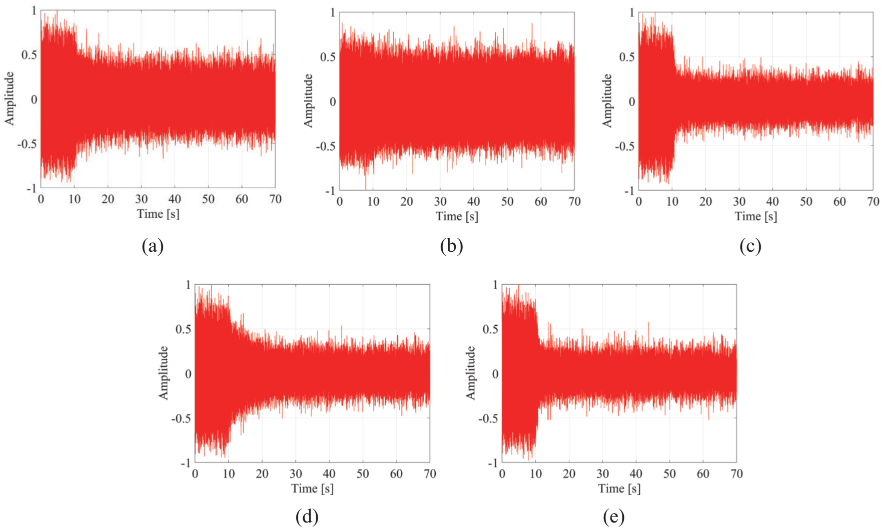

Figure 17: Time waveforms of the unwanted noise and error signal in actual measurements. (a) Conventional ANC system with the reference microphone at 1.00 m from error microphone. (b) Conventional ANC system with the reference microphone at 0.20 m from error microphone. (c) Conventional ANC system with the reference microphone at 2.00 m from error microphone. (d) Proposed ANC system without differentiator. (e) Proposed ANC system with differentiator.

This is because this system directly utilizes the vibration velocity of the noise source as the reference signal. Then, the coherence between the reference and unwanted noise decreases, the noise reduction performance deteriorates, and the convergence speed decreases. This result depicts the reasonability of adopting the differentiator to the proposed ANC system.

Also, from Figure 18, the proposed ANC system with the differentiator reduces the unwanted noise compared with the proposed ANC system without the differentiator. This is because the frequency spectrum of the velocity decreases at high frequencies in the single vibration system. On the other hand, the frequency spectrum of the acceleration has sufficient power at high frequencies.

From the simulation and experimental results, it can be considered that the proposed ANC system with the differentiator is effective for reducing the unwanted noise with a less computational complexity that the basic ANC system.[8]

[8]In a real system, the conventional ANC system has a problem that the anti-noise reaches the reference microphone, which is placed close to the error microphone. This problem causes the degradation of the capability to reduce the unwanted noise. On the other hand, the proposed ANC system does not have this problem.

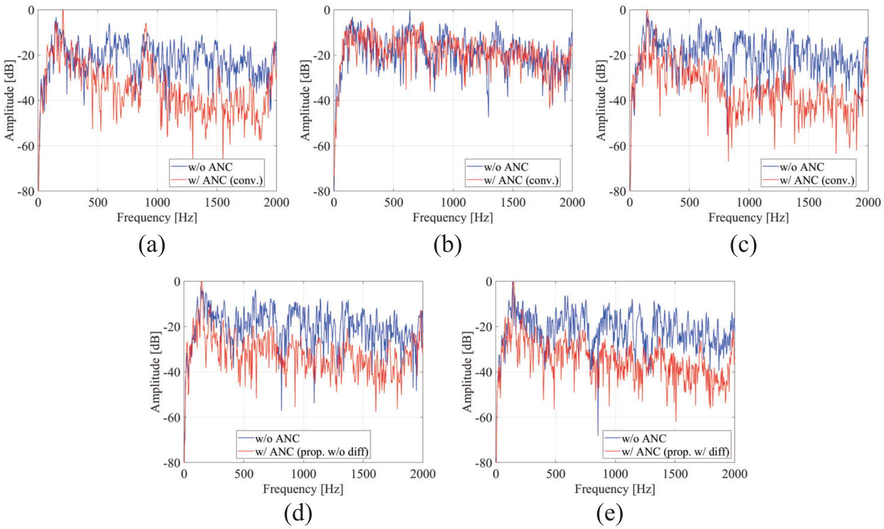

Figure 18: Frequency spectra of error signals in actual measurements. (a) Conventional ANC system with the reference microphone at 1.00 m from error microphone. (b) Conventional ANC system with the reference microphone at 0.20 m from error microphone. (c) Conventional ANC system with the reference microphone at 2.00 m from error microphone. (d) Proposed ANC system without differentiator. (e) Proposed ANC system with differentiator.

6 Conclusion

In this paper, a feedforward ANC system with an optical laser microphone as a reference microphone is proposed. The main problem with the feedforward ANC system is the degradation of its noise reduction performance owing to the causality constraint. To solve this problem, the proposed ANC system utilizes the optical laser microphone as the reference microphone to relax the causality constraint; however, the coherence between the signals obtained by the reference and error microphones becomes small. Hence, the first-order differentiator is utilized in the proposed ANC system and the reference signal is differentiated according to the relationship between the vibration velocity and the sound pressure.

Simulation and experimental results show that the proposed ANC system with the first-order differentiator can reduce the unwanted noise to almost the same level as that of the basic feedforward ANC system and simultaneously relax the causality constraint.

In this paper, the proposed ANC system utilizes the first-order differentiator, however, the frequency response of the differentiator is very simple and will be adjusted more suitably for the proposed ANC system. Hence, in the future, we will improve the noise reduction performance by optimizing the differentiator. Moreover, only one optical laser microphone is used in the proposed ANC system; however, the vibration area is wide on the noise source in real environments. Hence, we will develop the proposed ANC system considering the vibration area by using multiple optical laser microphones, simultaneously using the optical laser and ordinary microphones.

Acknowledgments

This work was supported by KDDI Foundation Research Grant Program 2019, and JSPS KAKENHI (JP19H04142, JP21K17773).

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