Study on Feedforward Active Noise Control System with Optical Laser Microphone to Detect Reference Signal with Short Delay

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***Abstract*—In this paper, a feedforward active noise control (ANC) system with an optical laser microphone is proposed. The feedforward ANC system consists of a reference microphone, error microphone, and secondary loudspeaker. The main problem of the feedforward ANC system is the degradation of its noise reduction performance owing to the causality constraint, that is, there is a need for the ANC system to update the noise control filter and emit the anti-noise until the unwanted noise reaches the error microphone. The feedforward ANC system with the optical laser microphone is proposed to solve this problem. The proposed ANC system utilizes the optical laser microphone as the reference microphone that detects the vibration of the noise source. Since the optical laser microphone uses an optical laser, the unwanted noise is picked up more quickly than by an ordinary microphone. However, the coherence of the signals obtained by the reference and error microphones decreases and noise reduction performance may degrade since the proposed ANC system uses the ordinary microphone as the error microphone. To solve this problem, the proposed ANC system utilizes a differentiator for the reference signal because of the relationship between the sound pressure and the velocity. That is, the sound pressure is obtained by the differentiation of the velocity. Simulation results show that the proposed ANC system with the differentiator can reduce unwanted noise by almost the same amount as the conventional feedforward ANC system.**

I. Introduction

The use of a feedforward active noise control (ANC) system is one of the noise reduction methods [1]–[6]. The structure of the basic feedforward ANC system is shown in Fig. 1. The feedforward ANC system consists of a reference microphone, error microphone, and secondary loudspeaker. In the feedforward ANC system, the placements of the reference microphone and error microphone are important for satisfying the causality constraint [7], [8]. That is, the noise reduction performance degrades when the propagation delay of the unwanted noise from the reference microphone to the error microphone is smaller than the delay of the computation time and the propagation delay of anti-noise from the secondary loudspeaker to the error microphone.

To solve this problem, in this paper, the feedforward ANC system with the optical laser microphone [9], [10] is proposed. This system utilizes the optical laser microphone as the reference microphone. The optical laser microphone uses an optical laser to detect the sound as the vibration of an object. Although the optical laser microphone cannot detect 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 the ordinary microphone because of its measurement principle. Thus, the proposed feedforward ANC system is effective and can relax the causality constraint.

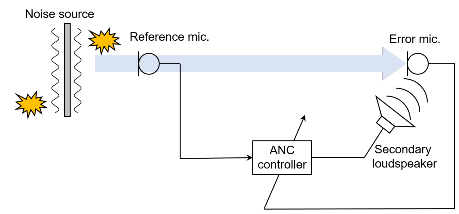


Fig. 1. Block diagram of basic feedforward ANC system.

However, the obtained signal of the optical laser microphone is the velocity of the object's vibration 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 [4]. To solve this problem, in the proposed feedforward ANC system, we adopted a differentiator for the reference signal obtained as the velocity of the surface 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, some computer simulation was conducted.

II. Feedforward active noise control system and its problem

A. Feedforward active noise control system

The feedforward ANC system has a noise control filter that minimizes the error signal obtained at the error microphone. The block diagram of the feedforward ANC system is shown in Fig. 2. In Fig. 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

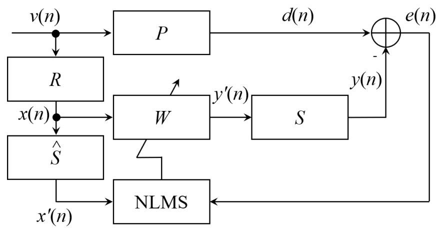


Fig. 2. Block diagram of basic feedforward ANC system.

the error microphone, W is the noise control filter, and $\hat{S}$ is the secondary path model.

The unwanted noise $v(n)$ reaches the reference microphone through the reference path. Then, the noise control filter $\mathbf{w}(n)$ is updated using the reference signal $x(n)$ picked up by the reference microphone. After updating the noise control filter $\mathbf{w}(n)$, anti-noise $y'(n)$ is emitted from the secondary loudspeaker to reduce the unwanted noise $d(n)$ passing along the primary path. Here, the error signal $e(n)$ obtained at the error microphone is represented by

$$e(n) = d(n) - y(n), \tag{1}$$

where n is the time index. $y(n)$ is the anti-noise emitted from the secondary loudspeaker and is represented as

$$y(n) = \mathbf{s}^{\mathrm{T}}(n)\mathbf{y}'(n), \tag{2}$$
$$y'(n) = \mathbf{w}^{\mathrm{T}}(n)\mathbf{x}(n), \tag{3}$$

where $\mathbf{s}(n)$ is the impulse response of the secondary path, T is the transpose operator, $\mathbf{y}'(n)$ is the anti-noise vector, and $\mathbf{x}(n)$ is the reference signal vector. To update the noise control filter $\mathbf{w}(n)$, the filtered-x least mean square (FxLMS) and filtered-x normalized least mean square (FxNLMS) algorithms [11], [12] are widely used. The update equation for the FxNLMS algorithm is represented by

$$\mathbf{w}(n+1) = \mathbf{w}(n) + \frac{\alpha}{\|\mathbf{x}'(n)\|^2 + \beta} e(n)\mathbf{x}'(n), \tag{4}$$
$$x'(n) = \hat{\mathbf{s}}^{\mathrm{T}}(n)\mathbf{x}(n), \tag{5}$$

where $x'(n)$ and $\mathbf{x}'(n)$ are the filtered reference signal and its vector, $\|\cdot\|$ denotes the l_2 norm, α is the step size parameter ($0 < \alpha < 2$), β is the regularization parameter with small positive value, and $\hat{\mathbf{s}}(n)$ is the impulse response of the secondary path model.

B. *Problem of feedforward active noise control system*

In the feedforward ANC system, the unwanted noise is picked up by the reference and error microphones. Then, the unwanted noise obtained by the reference microphone is used as the reference signal $x(n)$ to update the noise control filter $\mathbf{w}(n)$ and generate anti-noise $y'(n)$. To reduce the unwanted noise, the causality constraint [7], [8] should be satisfied. That is, anti-noise should be generated and reach the error microphone before the unwanted noise reaches the error microphone. This relationship can be represented as

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

where D_{P}, D_{R}, and D_{S} are the delay for the primary, reference, and secondary paths, respectively, and D_{C} is the computational time delay for the feedforward ANC system. If the feedforward ANC system does not satisfy inequality (6), the noise reduction performance degrades. Here, the left-hand side of inequality (6) represents the propagation delay between the reference microphone and the error microphone. From inequality (6), if the reference and error microphones are placed close to each other, the computational time delay D_{C} and the propagation delay of the secondary path D_{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.

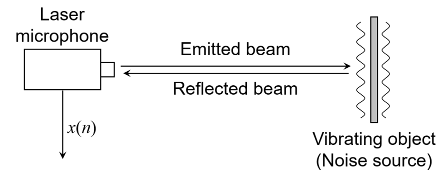


Fig. 3. Principle of optical laser microphone.

III. 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 [9], [10], which is utilized as the reference microphone.

A. *Optical laser microphone*

The optical laser microphone emits an optical laser beam to the surface of a vibrating object and measures sound as the vibration of the object. The measurement principle of the optical laser microphone is shown in Fig. 3. Firstly, the 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. Because of the Doppler shift, the frequency of the reflected laser beam differs from that of the emitted laser beam. By calculating the difference between the frequencies of the emitted and reflected laser beams, we can obtain the velocity of the vibration. That is, the optical laser microphone measures sound as the velocity of the vibrating object, that generates unwanted noise.

Although the optical laser microphone cannot detect high-frequency sounds owing to the vibration being small, it can detect low-frequency sounds with high accuracy. Moreover, the propagation delay from the noise source to the reference microphone is smaller than that of the 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 0.01 s with a sound velocity of 340 m/s to detect the unwanted noise. On the other hand, the optical laser microphone requires a time delay of 2.3×10^{-8} s with a velocity of light 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) is much longer than the time delay of 2.3×10^{-8} s. Thus, the optical laser microphone can detect the unwanted noise very quickly and the proposed feedforward ANC system can use a longer operation time than that of the conventional ANC system.

B. Proposed feedforward active noise control system

The structure of the proposed feedforward ANC system is shown in Fig. 4. As mentioned before, the propagation delay for the optical laser microphone is satisfactorily small because the microphone uses the optical laser, the light velocity of which 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) for the error microphone and the characteristics 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 [4].

To solve this problem, the first-order differentiator is adopted in the proposed ANC system. This process is based on the relationship between the volume velocity of the air and the sound pressure can be represented as

$$P(s) = \frac{\rho}{4\pi r} sQ(s)e^{s(t-kr/\omega)}, \tag{7}$$

where $P(s)$ is the Laplace transform of the sound pressure, $Q(s)$ is the Laplace transform of the volume velocity, s is the complex variable ($s = j\omega$), ω is the angular frequency, ρ is the air density, r is the distance between the sound source and the microphone, and k is the wave number. Here, s also represents the differentiation in the Laplace domain. 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.

In the proposed ANC system, the first-order differentiator $H_{\mathrm{L}}(s) = s$ is realized as a first-order infinite impulse response (IIR) filter obtained by the bilinear transform of s. The first-order differentiator $H_{\mathrm{D}}(z)$ is represented by

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

where T_{s} is the sampling period and z is the complex variable of the z transform ($z = e^{sT_{\mathrm{S}}}$). As seen from (8), the differentiator $H_{\mathrm{D}}(z)$ has low computational complexity and is suitable for the proposed ANC system. The block diagram of the proposed ANC system is shown in Fig. 5, where $x_{\mathrm{D}}(n)$ represents the differentiated reference signal.

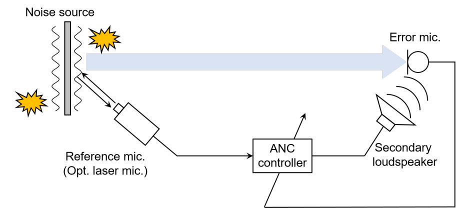


Fig. 4. Block diagram of the proposed ANC system.

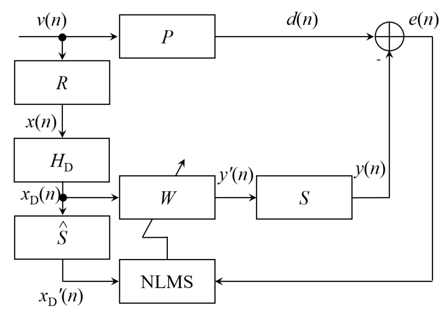


Fig. 5. Block diagram of the proposed ANC system.

IV. 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 that utilizes the ordinary microphone as the reference microphone, as shown in Fig. 2. Here after, the proposed feedforward ANC system and the basic feedforward ANC system are called the proposed ANC system and the conventional ANC system, respectively. Here, the effectiveness of the proposed ANC systems with and without the differentiator were also evaluated.

A. Identification of each path

In the simulations, the identified impulse responses of each path were used. The measurement of these impulse responses were conducted in a soundproof room (height : 1.1 m, width : 2.3 m, depth : 3.2 m) with a reverberation time of 100 ms. The measurement setup and identification conditions are shown in Fig. 6 and Table I, respectively. The identified impulse responses and their frequency responses are shown in Figs. 7 and 8, respectively. As mentioned before, 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 shows attenuation at high frequencies.

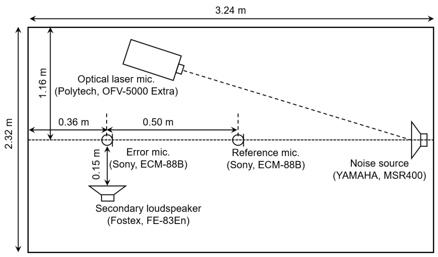


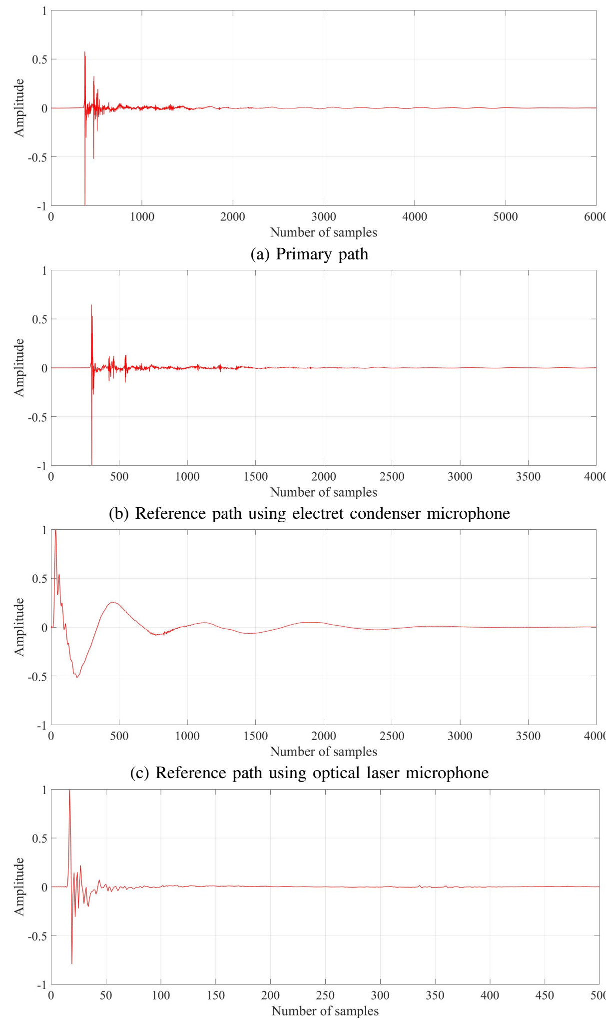
Fig. 6. Measurement setup for the identification of each path.

TABLE I
IDENTIFICATION CONDITIONS.

Algorithm	NLMS
Noise source	White noise
Sampling frequency	48000 Hz
Frequency range	70 – 12000 Hz
Tap length of primary path P	6000
Tap length of reference path R	4000
Tap length of secondary path S	500
Step size parameter	0.05
Regularization parameter β	1.0×10^{-6}

TABLE II
SIMULATION CONDITIONS.

Unwanted noise	White noise
Sampling frequency	48000 Hz
Frequency range	70 – 2000 Hz
Tap length of primary path P	6000
Tap length of reference path R	4000
Tap length of secondary path S	500
Tap length of secondary path model $\hat{S}$	500
Tap length of noise control filter W	1024
Step size parameter α	0.01
Regularization parameter β	1.0×10^{-6}



(a) Primary path

(b) Reference path using electret condenser microphone

(c) Reference path using optical laser microphone

(d) Secondary path

Fig. 7. Impulse responses of each path.

B. Simulation results

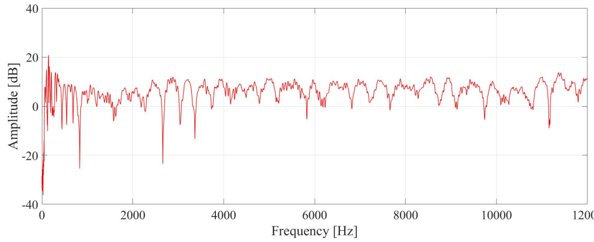
The impulse responses shown in Fig. 7 were used in the simulations. In the simulations, the time waveform of the error signal and the amount of noise reduction for each system were evaluated. The amount of noise reduction is defined as

$$\mathrm{Reduction}(n) = 10 \log_{10} \frac{\sum_{m=0}^{N-1} d^2(n-m)}{\sum_{m=0}^{N-1} e^2(n-m)}, \tag{9}$$

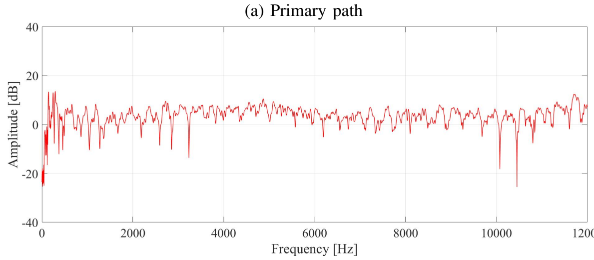
where N is the tap length of the noise control filter. The amount of noise reduction was calculated every N sample. Simulation conditions are shown in Table II. Here, white noise with bandwidth from 70 Hz to 2000 Hz was used as the unwanted noise. This is because the frequency response of the reference path with the optical laser microphone is attenuated at high frequencies and does not maintain sufficient amplitude above 2000 Hz.

Time waveforms of the error signals and amounts of noise reduction for each ANC system are shown in Figs. 9 and 10, respectively. The results in Figs. 9 and 10 show that each ANC system can reduce the unwanted noise by about 7 dB. However, in Fig. 9(a), the error signal of the proposed ANC system without the differentiator is seen to be larger than that of the conventional ANC system. Moreover, as seen in Figs. 10(a) and (b), the proposed ANC system without the differentiator indicates a larger fluctuation of the amount of noise reduction than the conventional ANC system. On the other hand, as seen in Fig. 9(b), the error signal of the proposed ANC system with the differentiator is almost at the same level as that of the conventional ANC system. Moreover, from Figs. 10(a) and (c), the fluctuation of the amount of noise reduction for the proposed ANC system is reduced by the differentiator. The results indicate that the proposed ANC system is effective when used with the differentiator is effective for noise reduction.

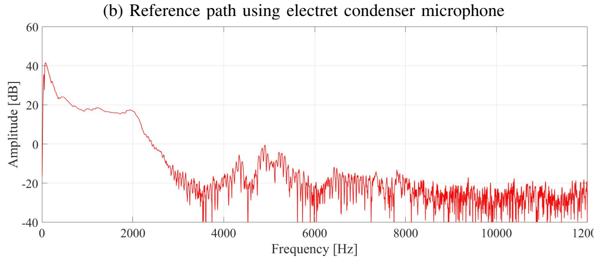
Next, the causality constraint of the proposed ANC system was evaluated by examining the group delays of each path, shown in Fig. 11. In Figs. 11(a) and (b), the group delay of the reference path with the optical laser microphone is smaller than that with the ordinary microphone. As described in Sec.



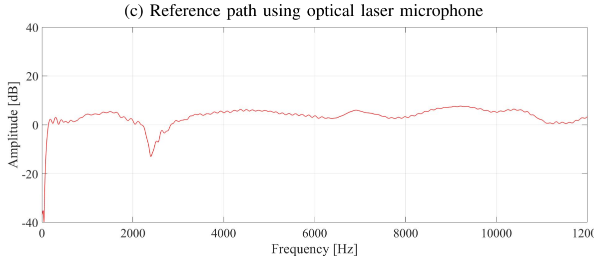
(a) Primary path



(b) Reference path using electret condenser microphone

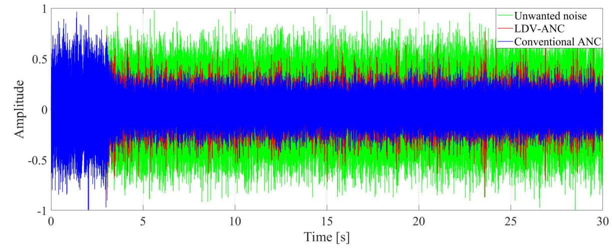


(c) Reference path using optical laser microphone

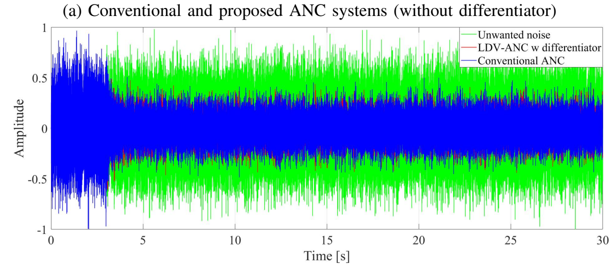


(d) Secondary path

Fig. 8. Frequency response of each path.

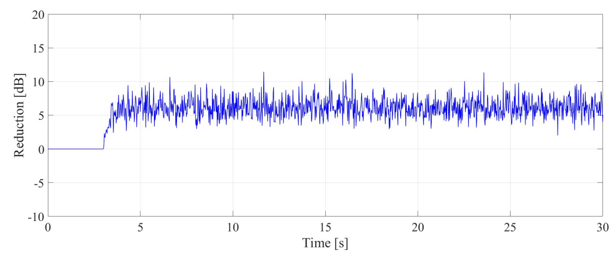


(a) Conventional and proposed ANC systems (without differentiator)

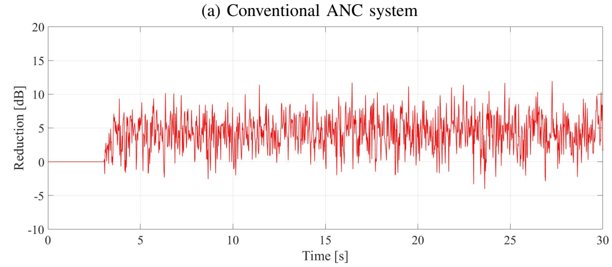


(b) Conventional and proposed ANC systems (with differentiator)

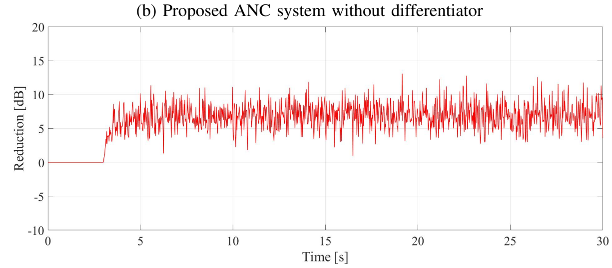
Fig. 9. Time waveforms of the unwanted noise and error signal.



(a) Conventional ANC system



(b) Proposed ANC system without differentiator



(c) Proposed ANC system with differentiator

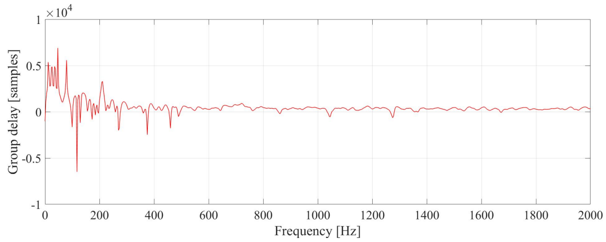
Fig. 10. Amount of noise reduction.

III, the optical laser microphone can detect the unwanted noise. On the other hand, the ordinary microphone should detect the unwanted noise after the unwanted noise propagates a long distance. From Fig. 11, the delay of each path are $D_{\mathrm{P}} = 7.75$ ms, $D_{\mathrm{S}} = 0.33$ ms, and $D_{\mathrm{R}} = 6.21$ ms for the ordinary microphone, and $D_{\mathrm{R}} = 0.71$ ms for the optical laser microphone, respectively. Substituting these values, the computational time delays for the proposed and conventional systems should be $D_{\mathrm{C}} < 6.71$ ms and $D_{\mathrm{C}} < 1.21$ ms, respectively. Hence, in the proposed ANC system, 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.

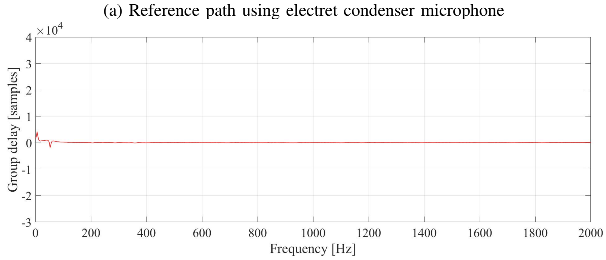
Finally, the coherence between the reference signal and the unwanted noise obtained at the error microphone was calculated to evaluate the effectiveness of the differentiator. To calculate the coherence, the magnitude-squared coherence (MSC) was used,

$$\mathrm{MSC}(f) = \frac{|P_{dx}(f)|^2}{P_{dd}(f)P_{xx}(f)}, \tag{10}$$

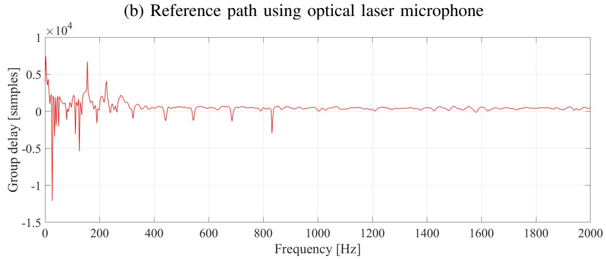
where f is the frequency index, $P_{dx}(f)$ is the cross power



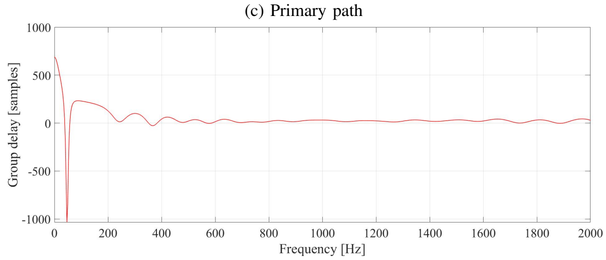
(a) Reference path using electret condenser microphone



(b) Reference path using optical laser microphone



(c) Primary path



(d) Secondary path

Fig. 11. Group delay of each path.

spectral density of the reference signal $x(n)$ and the unwanted noise $d(n)$, and $P_{dd}(f)$ and $P_{xx}(f)$ are the power spectral densities of the reference signal $x(n)$ and the unwanted noise $d(n)$, respectively. Here, $x(n)$ is replaced by $x_D(n)$ for the proposed ANC system with the differentiator. The MSCs for each system are shown in Fig. 12. As seen in Fig. 12, the MSC of the proposed ANC system with the differentiator is greater than that of the proposed ANC system without the differentiator. However, the MSC of the proposed ANC system with the differentiator is still smaller than that of the conventional ANC system. Hence, it can be said that the additional processing adopted in the proposed ANC system should be studied to improve the noise reduction performance.

V. Conclusion

In this paper, a feedforward ANC system with the optical laser microphone as the reference microphone is proposed. The proposed ANC system utilizes the optical laser 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 method and the reference signal is differentiated. Simulation 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 the future, the noise reduction performance of the proposed ANC system will be improved, and the noise reduction experiment will be conducted in a real environment.

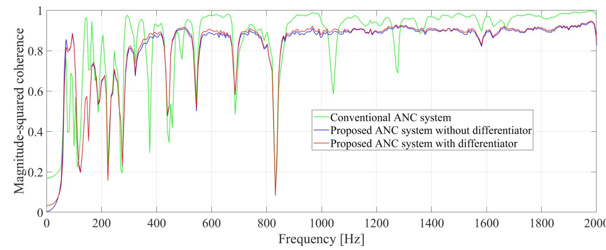


Fig. 12. Coherence of each ANC system.

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