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LETTER

Active Noise Control Systems with Sound Source Localization Robust to Noise Source Movement

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SUMMARY This letter proposes a method that can track the movement of noise sources in fixed filter ANC and virtual sensing ANC systems by using source localization with multiple microphones. Since the optimal noise control filter depends on the location of the noise source, the proposed system prepares optimal noise control filters in advance for multiple locations where the noise is expected to move. The noise source location is then identified using the noise source localization method during the operation of the ANC system, and the appropriate noise control filter is selected according to the location. Simulation results using actual impulse responses show that a noise reduction of approximately 20 dB is possible even if the noise source moves.

key words: *ANC system, Fixed filter ANC system, Virtual sensing, AFVS, Sound source localization*

1. Introduction

In recent years, the development of industrial equipment has made noise problems more serious. Machinery noise is often biased toward low frequencies. Active noise control (ANC) systems are effective for such low-frequency noise; ANC systems generate an anti-noise with the same amplitude and opposite phase as the noise and superimpose it on the noise to reduce the noise [1]–[4]. The algorithm often used in ANC systems is the filtered-x algorithm [5], [6], which uses adaptive processing to update the filter coefficients. However, multi-channel ANC systems [7], [8] and wideband noise as a target for noise reduction require high sampling rates and long filter lengths, which are computationally expensive. In addition, traditional adaptive ANC systems require the installation of error microphones, which poses geometric problems.

The fixed-filter ANC system [9], [10] is the simplest solution to these problems. The fixed-filter ANC system works by pre-creating an optimal noise control filter for the control point, without any adaptive processing of the filter coefficients. Thus, there is no need to place error microphones at the control points. Similarly, the virtual sensing method [11]–[16] is a system that does not place microphones at the control points. Compared to fixed-filter ANC systems, it is known to be more robust against path fluctuations and noise changes.

However, fixed-filter and virtual-sensing ANC systems significantly degrade noise reduction performance when environmental changes occur, such as when noise source moves. Although there are previous studies [17]–[20] that consider the movement of noise sources, they do not consider the convergence speed of noise control filters or the change of transfer function due to the speed and direction of moving noise sources. In virtual sensing, some previous studies [21], [22] have focused on the characteristics of noise sources, but these also do not mention the change in transfer function due to noise source movement. In order to solve these problems, the reference [23] has proposed a machine learning approach, while a signal processing approach (e.g. TDOA based approach) has not been proposed.

In this letter, we propose an ANC system with sound source localization in a fixed-filter and virtual sensing ANC systems to select the optimal noise control filter or optimal auxiliary filter even when the location of the noise source changes.

2. Conventional ANC system

2.1 Fixed filter ANC system

Figure 1 shows the block diagram of a single-channel feedforward ANC system with fixed filter. Two microphones are used, namely, an $\mathrm{M_R}$ is the reference microphone, an $\mathrm{M_E}$ is the error microphone. Also, the primary path $P_m(z)$ and the secondary path $S_m(z)$ are the transfer functions from the noise source and secondary source to the error microphone, respectively. In addition, $R(z)$ is the reference path from the noise source to the reference microphone, and $W^o(z)$ is the optimal noise control filter, respectively. These functions are denoted by the respective z-transforms.

First, a noise control filter is designed to minimize the squared error of $e_m(n)$ with adaptive processing. The optimal noise control filter $W^o(z)$ converges to the following equation,

$$W^o(z) = -\frac{P_m(z)}{S_m(z)R(z)}. \tag{1}$$

The fixed filter ANC system is then operated without updating the coefficients of the noise control filter according to Fig.1. This allows operation without the use of adaptive filters, which is computationally efficient, and also makes it easier to implement multi-channel ANC systems. It also enables noise reduction at the desired point without placing an error microphone, so that the user does not have to wear any equipment.

One problem with fixed filter ANC system is that it is not robust to changes in the implementation environment.

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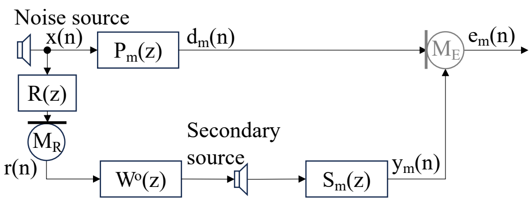


Fig. 1 Block diagram of the feedforward fixed filter ANC system.

As can be seen from (1), the noise control filter depends on the coefficients of the primary path, the secondary path and the reference path. Therefore, when the microphone or noise source moves, the impulse responses of the related paths change and the noise reduction performance degrades.

2.2 ANC system with virtual sensing

Another ANC system that does not require a microphone at the desired location is virtual sensing. There are several methods for virtual sensing, but this letter uses the Auxiliary Filter-based Virtual Sensing (AFVS[11]–[16]). Figure 2 shows the block diagram of a single-channel feedforward AFVS-ANC system. In AFVS, three microphones are used, M_R, M_E and M_V. M_V is called a virtual microphone installed at the desired location to reduce noise. Also, the primary path $P_v(z)$ and the secondary path $S_v(z)$ are the transfer functions from the noise source and secondary source to the virtual microphone, respectively. In addition, $H(z)$ is the auxiliary filter.

The operating principle of AFVS is described in [11]–[16]. In the AFVS method, there are no restrictions on the geometric arrangement of the error microphones and virtual microphones, so the microphones can be placed freely in the ANC implementation. AFVS-ANC systems are more robust than fixed-filter ANC systems. However, they cannot deal with large path fluctuations, such as noise source movement.

3. Proposed methods

3.1 Sound Source Localization

This section describe the sound source localization method used for the proposed ANC systems. The technique of estimating the sound source location by means of a microphone array of multiple microphones is called sound source localization. When sound enters microphones placed at regular intervals, sound waves arrive at each microphone at different times. They are called time difference of arrival (TDOA). The sound source location can be estimated by using TDOA. In this letter, the TDOA is estimated by the cross-correlation method [24]. The cross-correlation method calculates the cross-correlation between the signals using the following equation,

$$\phi(\tau) = \frac{1}{N} \sum_{n=0}^{N-1} x_1[n] \cdot x_2[n+\tau], \tag{2}$$

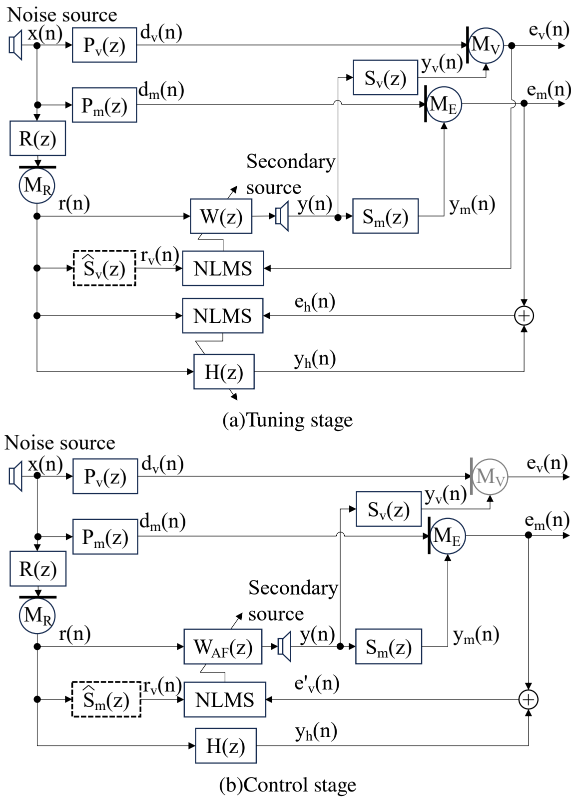


Fig. 2 Block diagram of the feedforward ANC system with AFVS.

where ϕ is the cross-correlation coefficient, τ is the time index and N is the number of samples. TDOA is estimated by calculating the cross-correlation of the received signals between the microphones using (2) and finding the time τ_{max} at which the cross-correlation is maximum. TDOA is calculated as follows,

$$\text{TDOA} = \underset{\tau}{\operatorname{argmax}} \phi(\tau). \tag{3}$$

The difference in distance from the sound source to the two microphones can be determined by TDOA, and the position of the sound source, which is the distance difference, can be limited to one hyperbolic curve. By using three microphones, it is possible to draw three hyperbolas, and the intersection of the hyperbolas is the source location.

3.2 Fixed filter ANC system with sound source localization

Figure 3 shows the block diagram of the proposed fixed filter ANC system with sound source localization. In Fig. 3, $P_{v,n}(z)$, $R_{1,n}(z)$, $R_{2,n}(z)$, $\cdots R_{L,n}(z)$ denote the primary and reference paths at time n and L the number of reference microphones used for source localization. In the proposed fixed filter ANC system, optimal noise control filters are generated in advance for multiple locations where noise source is expected to move, according to Fig.1. Next, the generated noise control filter is selected according the noise source localization shown in Fig. 3. The operating procedure of the proposed method is as follows.

1. Several microphones located close to the noise source

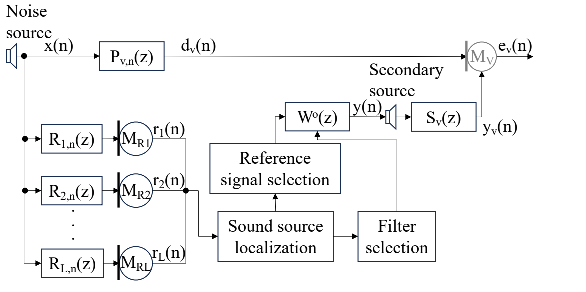


Fig. 3 Block diagram of the feedforward fixed filter ANC system with sound source localization.

are used to acquire reference signals from the noise source.

2. After a given number of samples of reference signals are obtained, the correlations of the reference signals between microphones are calculated using (2) to obtain the TDOA.
3. The noise source location is estimated by solving a set of simultaneous equations based on the TDOA.
4. The noise control filter corresponding to the preset noise source location that is closest to the estimated noise source location is selected.
5. Calculate the distance between the estimated noise source location and each reference microphone, and use the reference signal from the reference microphone with the smallest distance.

By operating the system according to the above procedure, the noise control filter corresponding to the estimated location of the noise source can be selected even when the noise source moves. Thus, even a fixed-filter ANC system that does not use error microphones and performs noise control without adaptive processing can track to the movement of the noise source.

3.3 AFVS-ANC system with sound source localization

Figure 4 shows the block diagram of the proposed AFVS-ANC system with sound source localization. In the proposed AFVS-ANC system, several auxiliary filters are generated for the locations where the noise source is assumed to move in advance, according to Fig.2(a). The proposed AFVS-ANC system operates in a similar fashion to the proposed fixed filter ANC system, but differs in that it switches auxiliary filters rather than noise control filters. Unlike the proposed fixed-filter ANC system, the proposed AFVS-ANC system updates noise control filters, which takes time to converge, but it is expected to improve robustness against path variations.

4. Evaluation of the noise reduction performance

To demonstrate the effectiveness of the proposed ANC systems, the noise reduction performance is compared with the typical adaptive ANC system through simulations for a single channel feedforward ANC.

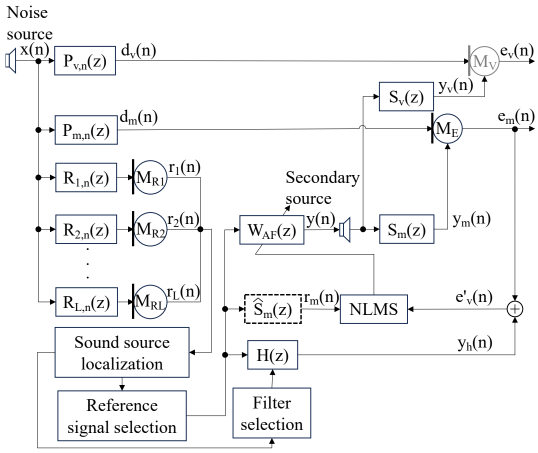


Fig. 4 Block diagram of the feedforward ANC system using AFVS with sound source localization.

4.1 Simulation condition

The simulation conditions are shown in Table 1 and the measurement arrangement of each acoustic path used in the simulation is shown in Figure 5. Each path was measured in a soundproof room. Also, a movement pattern of the noise source is shown in Figure 5. The noise source location at the start of ANC system operation is Position 1, and the noise source is assumed to move from Position 1 to Position 8 every 2 seconds.

According to the reference [25], the near-field range is given as $\rho < \frac{2D}{\lambda}$, where ρ is the distance from the center of the microphone array to the source, D is the distance between adjacent microphones, and λ is the wavelength. In the experimental environment in this letter, since $D = 1$ and $\lambda = 0.34$, ρ is approximately 5.88 m. In ANC, reference microphones are usually placed near the noise source, which results in a nearfield, but the theory of the proposed method is derived based on the assumption of a farfield. Nevertheless, we show in this letter that the proposed method works successfully in a near-field experimental environment.

4.2 Comparison of noise reduction performance

Figure 6 shows the evaluation of the noise reduction and the frequency spectrum of the error signal at the desired location for the two proposed and conventional ANC systems, respectively. The noise reduction is defined as follows.

$$\text{Reduction} = 10\log_{10}\left[\frac{\sum_{n=(k-1)L+1}^{kL} d_v^2(n)}{\sum_{n=(k-1)L+1}^{kL} e_v^2(n)}\right], \tag{4}$$

where k is the block number, L is the average number of samples and $L = 1000$. From Fig. 6, it can be seen that both proposed ANC systems have high noise reduction of approximately 20 dB, except immediately after the noise source moves, which is almost the same as the conventional ANC system that operates by setting a physical microphone at the desired location. By using sound source localization,

Table 1 Simulation condition.

Noise	White noise (50-4000 Hz)
Simulation time	25s
Waiting time for sound source localization	0.0625s
Tap length of $W(z)$,$H(z)$,$P(z)$,$R(z)$	500
Tap length of $S(z)$, $\hat{S}(z)$	200
Update algorithm $W(z)$,$H(z)$	NLMS
Step size parameter α	0.01
Regularization parameter β	1.0×10^{-6}
Sampling frequency	16000 Hz
Sound speed c	340 m/s

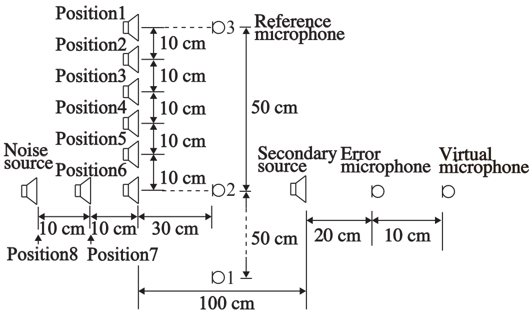


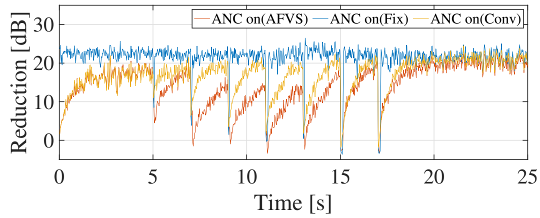
Fig. 5 Noise source movement pattern.

the proposed ANC systems can select the appropriate filter corresponding to the location of the noise source. Moreover, the proposed ANC systems can work without a physical microphone placed at the desired location. Since the proposed fixed-filter ANC system does not perform adaptive processing, it can maintain a high noise reduction performance immediately after switching noise control filter. On the other hand, the proposed AFVS-ANC system updates the noise control filter after switching the auxiliary filter, which degrades the noise reduction performance until its convergence. To prevent the degradation of noise reduction performance due to the convergence speed of the proposed AFVS-ANC system, the noise control filter should be switched in addition to the auxiliary filter. Since the computation time required for noise source localization under the present simulation conditions is about 4 ms on average, the proposed ANC system can track the noise source even when it moves at a relatively high speed.

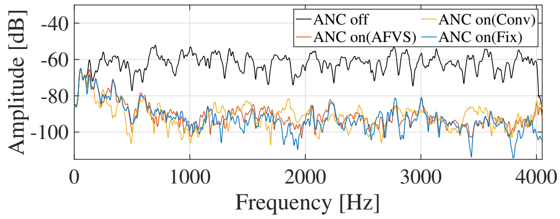
4.3 Robustness to noise source movement excluding pre-estimated locations.

In this section, the robustness of the proposed ANC systems when the noise source moves to elsewhere than the pre-estimated one is discussed. In Fig.5, only four noise control filters are created for the noise source locations of Position 1, 4, 6 and 8. Then, as in the previous section, the noise source moves from Position1 to Position8 every 2 second from 5 seconds after the start of ANC.

Figure 7 shows the noise reduction at the desired location for the proposed ANC systems. From Fig.7, the noise reduction effect of the proposed ANC systems degrades significantly when the noise source moves to elsewhere than the pre-estimated location because the proposed method cannot select the most appropriate noise control filter, and the fixed filter does not use adaptive processing. Although the AFVS-ANC provides better noise reduction performance than the fixed-filter ANC, there is still a significant performance degradation due to the inability to select the most appropriate filter. Therefore, interpolation methods need to be considered and introduced when noise sources move to locations other than those pre-estimated.



(a) Noise reduction at the desired location.



(b) Frequency spectra at the desired location.

Fig. 6 Comparison of noise reduction at the desired location for the two proposed and conventional ANC systems.

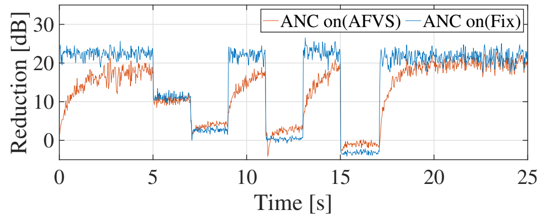


Fig. 7 Noise reduction at the desired location to source movement excluding pre-estimated locations for the proposed ANC systems.

5. Conclusions

In this letter, we proposed a fixed-filter and virtual-sensing ANC systems using noise source localization. In the proposed systems, noise source localization is performed using multiple reference microphones during the operation of the ANC system, and the appropriate noise control filter corresponding to the noise source location can be selected. The simulation results showed that high noise reduction can be achieved without placing error microphone at the desired location, and that appropriate noise control filters can be selected even if the noise source moves. However, the proposed ANC system can achieve high noise reduction performance only for the pre-assumed noise source location, and the noise reduction performance deteriorates when the noise source moves to other locations. In the future, we will study the interpolation method when the noise source moves to other than the assumed location and the algorithms that take Doppler effects into account.

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