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ACOUSTIC DISTANCE MEASUREMENT WITH PRACTICAL AMBIENT NOISE REDUCTION USING DIFFERENCE SIGNALS BETWEEN ADJACENT TWO-CHANNEL OBSERVATIONS

Noboru Nakasako, Itsuki Yamakado, Toshihiro Shinohara and Tetsuji Uebo

Faculty of Biology-Oriented Science and Technology
Kindai University
930 Nishi-Mitani, Kinokawa City, Wakayama 649-6493, Japan
{ nakasko; 2033730006h; sinohara; uebo }@waka.kindai.ac.jp

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Abstract. *Acoustic distance measurement (ADM) has been proposed as an accurate method by which to measure distances. The ADM method is based on the phase interference between the transmitted and reflected signals. However, the presence of ambient noise degrades the ranging performance. In previous studies, the noise component has been reduced by using three microphones in a noisy environment and applying independent component analysis or generating two difference signals from three observed data. The present paper describes a new, more compact, and practical method by which to reduce the ambient noise and perform ranging using only two adjacent microphones. Specifically, the noise component is reduced by generating a difference signal between the two observations in a noisy environment. Then, the distance is estimated by applying the cross-spectrum method with the difference signal as the input and one of the observed signals as the output. Furthermore, the influence of noise is reduced by applying mask processing to the obtained result. The effectiveness of the proposed method was confirmed in a real room for a signal-to-noise ratio (SNR) of −10 dB. The results showed that the SNR for the difference signal was improved and the estimated distance agreed well with the true value, indicating the effectiveness of the proposed method.*
Keywords: Acoustic distance measurement with cross-spectrum, Two adjacent microphones, Range spectrum, Signal difference as preprocessing, Masking as postprocessing

1. **Introduction.** The distance to a target is important information, and ranging devices are applied to various applications. Numerous methods have been proposed and used for distance measurements, such as stereo cameras, light detection and ranging (lidar), radio detecting and ranging (radar), and sound navigation and ranging (sonar). Stereo cameras and lidar cannot detect objects with transparent or specular reflective surfaces, such as glass and mirrors [1, 2, 3], or in harsh environments such as fog and smoke [4]. In addition, stereo cameras have poor performance in limited lighting conditions. Radar is a method of ranging using radio waves (microwaves and millimeter waves) [5]. Radar is inconvenient to use because it is regulated by the Radio Law and cannot be used freely. Furthermore, radar ranging is affected by sensor noise and multipath reflections [6, 7]. Sonar is a method that uses acoustic signals. The general method of distance measurement to the target using acoustic signals is used, in which a pulse sound is transmitted toward the target, and the distance is estimated from the time until the pulse sound returns as a reflected wave (i.e., time of flight (TOF)) [8, 9, 10, 11]. However, if the target is located at a short distance, it is difficult to estimate the distance because the transmitted wave and the reflected wave overlap in time. Moreover, ambient noise degrades the measurement performance in practical situations [12, 13]. Each method has advantages and disadvantages, so it is

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necessary to appropriately select a ranging method according to the situation or combine several methods to compensate for weaknesses [14].

We are interested in distance measurement using acoustic signals because such signals are easy to handle, and the system can be constructed at low cost [15]. In addition, many studies have been conducted on distance measurement using acoustic signals [16, 17, 18, 19]. We have proposed an acoustic distance measurement (ADM) method that can accurately estimate the position of a target at a distance close to 0 m [20] by applying the short-range measurement method in microwave radar [21]. In actual acoustic measurement, the measurement performance is degraded due to the influence of non-flatness of frequency response of the system elements. In order to remove the non-flatness, we have also proposed ADM applying the cross-spectrum method (2ch ADM) using two observations [22]. Regarding the ambient noise, the sonar images have been denoised by image processing methods such as filtering and deep learning in underwater sonar imaging [12, 13]. In order to reduce the ambient noise, we have proposed a method using independent component analysis (ICA), which is not a practical method due to its large computational cost and complicated parameter settings [23, 24, 25]. For practical noise reduction, we have also proposed a method by which to measure distance by generating two difference signals from observations at three microphones and applying the cross-spectrum method to the difference signals. However, both methods require three microphones.

From a practical point of view, the present paper describes a new ADM method that is robust against ambient noise and uses two microphones only. As a pre-processing, a noise-reduced difference signal is created by the difference of observations at adjacent microphones. We apply the conventional ADM using 1ch observation (1ch ADM) to the difference signal and also apply the 2ch ADM using the cross-spectrum method with the difference signal and one of the noisy observations. The 1ch ADM is affected by non-flatness of the frequency response of the system elements, and the 2ch ADM is slightly affected by the ambient noise. Thus, by combining these results, we can estimate the distance to the target more accurately. Finally, the effectiveness of the proposed method is confirmed by experiments.

The remainder of the present paper is organized as follows. Section 2 presents an outline of the ADM with two adjacent microphones. The ADM with 1ch and 2ch observations is explained briefly in Section 2.1. Section 2.2 presents the proposed practical method in detail. A comparison of the experimental results with the conventional method is described in Section 3. Section 4 summarizes the proposed approach and provides suggestions for potential future research.

2. Outline of ADM with Two Adjacent Microphones.

2.1. ADM with 1ch and 2ch observations.

Consider the measurement environment shown in Figure 1(a), in which there is a loudspeaker and a single microphone, and the targets are on the x-axis. Here, the sound source is an audible sound with a frequency f_1 to f_N, and $x = x_s$ is the microphone position. Transmitted wave $v_{\mathrm{T}}(t, x_s)$ radiated from the loudspeaker toward the target is formulated as

$$v_{\mathrm{T}}(t, x_s) = \int_{f_1}^{f_N} A(f) e^{j\left(2\pi f t - \frac{2\pi f x_s}{c} + \theta(f)\right)} df, \tag{1}$$

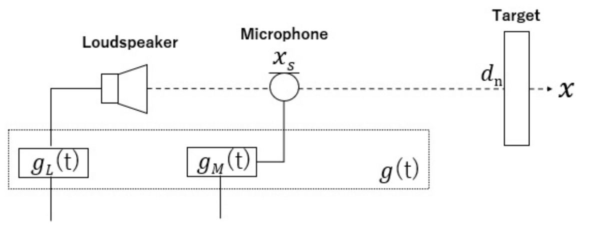
where t is the time in seconds, c is the acoustic velocity in meters per second, and $A(f)e^{j\theta(f)}$ is the frequency spectrum of the sound source. Assuming that the transmitted wave is reflected by m targets, the reflected wave $v_{\mathrm{R}_n}(t, x_s)$ by the n-th target can be expressed as follows:

$$v_{\mathrm{R}_n}(t, x_s) = \int_{f_1}^{f_N} A(f) \gamma_n(f) e^{j\left(2\pi f t - \frac{2\pi f}{c}(2d_n - x_s) + \theta(f) + \phi_n(f)\right)} df, \tag{2}$$

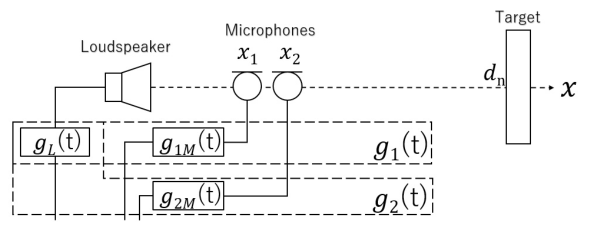
where $\gamma_n(f)e^{j\phi_n(f)}$ is the reflection coefficient for the n-th target, and d_n is the position of the n-th target in meters. The composite wave (specifically referred to herein as the ranging signal) at the microphone position x_s is

$$v_{\mathrm{C}}(t, x_s) = g_s(t) * \left\{ v_{\mathrm{T}}(t, x_s) + \sum_{n=1}^{m} v_{\mathrm{R}_n}(t, x_s) \right\}, \tag{3}$$

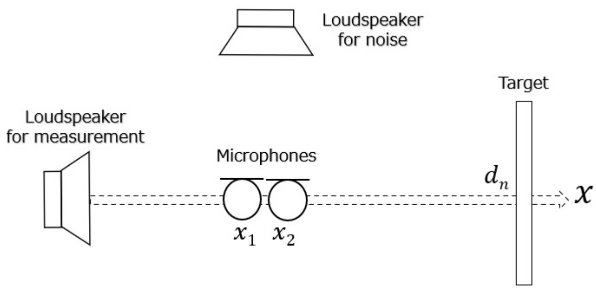
where $g_s(t)$ $(= g_{\mathrm{L}}(t) * g_{s\mathrm{M}}(t))$ is the impulse response of the measurement system, and $*$ is the convolution operator.



(a) Measurement environment for single microphone



(b) Measurement environment for two microphones



(c) Setup of ADM with two adjacent microphones

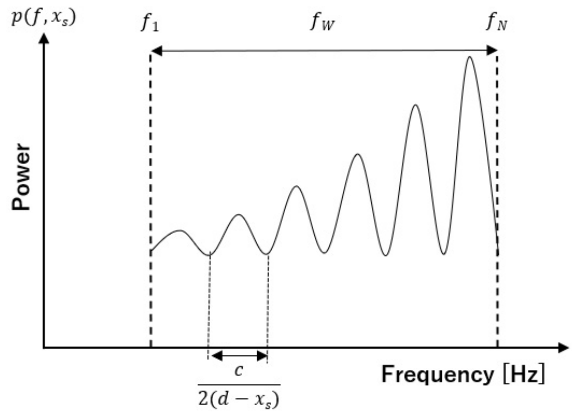
Figure 1. Overview of ADM with one or two microphones

For simplicity, assume that there is a single target ($m = 1$) and that the reflection coefficient is constant and is denoted simply as $\gamma e^{j\phi}$. Letting $V_{\mathrm{C}}(f, x_s)$ be the Fourier transform of the observation, the power spectrum $p(f, x_s) = |V_{\mathrm{C}}(f, x_s)|^2$ can be approximated when the reflection coefficient is sufficiently small ($\gamma \ll 1$) as follows:

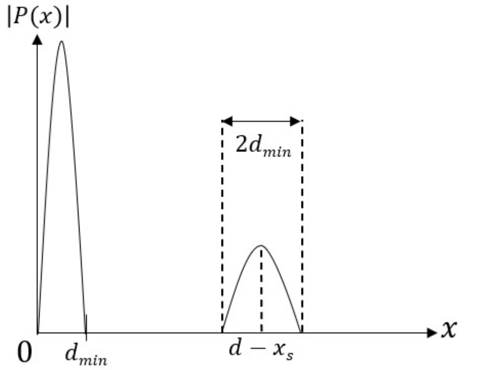
$$p(f, x_s) = A^2(f)|G_s(f)|^2 \left\{ 1 + 2\gamma \cos\left(\frac{4\pi f}{c}(d - x_s) - \phi \right) \right\}. \tag{4}$$

Here, $p(f, x_s)$ is a periodic function with a period inversely proportional to distance $d - x_s$ from the microphone to the target (see Figure 2(a)). By removing the DC component from and applying the Fourier transform to the power spectrum, the range spectrum $|P(x)|$ can be obtained. The peak position of $|P(x)|$ corresponds to the distance $d - x_s$ from the microphone to the target, as shown in Figure 2(b). This method is referred as 1ch ADM, because a single observation is used. The 1ch ADM is relatively resistant to ambient noise but may not estimate the distance accurately due to the influence of the measurement system $G_s(f)$.

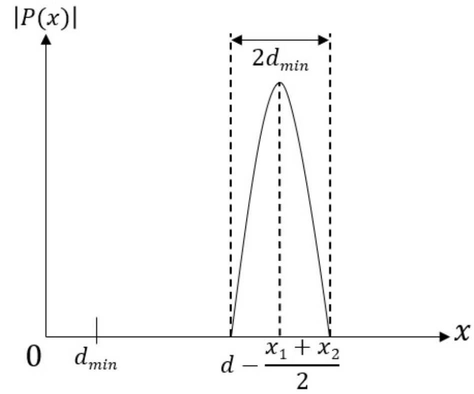
In order to overcome the disadvantage of 1ch ADM, two adjacent microphones at $x = x_1$ and x_2 are introduced (as shown in Figure 1(b)), and the cross-spectrum $C(f, x_1, x_2) = V_{\mathrm{C}}^*(f, x_1) \cdot V_{\mathrm{C}}(f, x_2) / \{V_{\mathrm{C}}^*(f, x_1) V_{\mathrm{C}}(f, x_1)\}$ is applied, where $V_{\mathrm{C}}^*(f, x_1)$ is the complex conjugate of $V_{\mathrm{C}}(f, x_1)$. Here, viewing $V_{\mathrm{C}}(f, x_1)$ as the input signal and $V_{\mathrm{C}}(f, x_2)$ as the output



(a) Power spectrum for single microphone



(b) Range spectrum for single microphone



(c) Range spectrum for two adjacent microphones

FIGURE 2. Examples of a power spectrum and range spectra

signal, the cross-spectrum $C(f, x_1, x_2)$ can be expressed as follows:

$$C(f, x_1, x_2) = \frac{A^2(f)G_1^*(f)G_2(f)V_C^*(f, x_1)V_C(f, x_2)}{A^2(f)|G_1(f)|^2V_C^*(f, x_1)V_C(f, x_1)}. \tag{5}$$

Since the spacing between the two microphones is very small in the case of two adjacent microphones, the transmitted wave component and the influence of the measurement system can be eliminated in the numerator and denominator (i.e., $G_1(f) \approx G_2(f)$). The cross-spectrum can then be expressed as

$$C(f, x_1, x_2) \approx \frac{e^{-j\frac{2\pi f}{c}x_2} + \gamma e^{-j\left(\frac{2\pi f}{c}(2d - x_2) - \phi\right)}}{e^{-j\frac{2\pi f}{c}x_1} + \gamma e^{-j\left(\frac{2\pi f}{c}(2d - x_1) - \phi\right)}}. \tag{6}$$

When the reflection coefficient is sufficiently small ($\gamma \ll 1$), the squared absolute value $p_{\mathrm{cr}}(f, x_1, x_2) = |C(f, x_1, x_2)|^2$ of the cross-spectrum can be approximated as

$$p_{\mathrm{cr}}(f, x_1, x_2) \approx 1 + 2\gamma \left\{ \cos\left(\frac{4\pi f}{c}(d - x_2) - \phi\right) - \cos\left(\frac{4\pi f}{c}(d - x_1) - \phi\right) \right\}. \tag{7}$$

Here, $p_{\mathrm{cr}}(f, x_1, x_2)$ is a periodic function with periods that are inversely proportional to distances $d - x_1$ and $d - x_2$ from the microphones to the target. By removing the DC component from and applying a Fourier transform to the power spectrum, the range spectrum $|P(x)|$ can also be obtained. The peak position of $|P(x)|$ corresponds to the distance from each microphone to the target. If the two microphones are in close proximity, then the two peaks overlap at $d - \frac{x_1+x_2}{2}$, as shown in Figure 2(c) [22].

The method using two microphones is called 2ch ADM. This method can remove the transmitted wave and the influence of the measurement system and can be used to estimate the distance to the target. However, when the ambient noise becomes large, the ADM method using the cross-spectral method is hardly applicable.

2.2. **ADM using difference signal between two observations.** We consider a set of two microphones (Figure 1(c)). In the actual environment, the observed signal at each microphone is represented as the sum of the composite wave v_C and the noise n. For the sake of convenience, we rewrite the composite wave in Equation (3) as

$$v'_C(t, x_i) = v_C(t, x_i) + n(t, x_i) \quad (i = 1, 2). \tag{8}$$

If the cross-spectrum method is applied under a noisy environment, then Equation (5) can be represented as

$$C(f, x_1, x_2) = \frac{V'^*_C(f, x_1)V'_C(f, x_2)}{V'^*_C(f, x_1)V'_C(f, x_1)} = \frac{(V^*_C(f, x_1) + N^*(f, x_1))(V_C(f, x_2) + N(f, x_2))}{(V^*_C(f, x_1) + N^*(f, x_1))(V_C(f, x_1) + N(f, x_1))}, \tag{9}$$

where $N(f, x_i)$ $(i = 1, 2)$ is the Fourier transform of the noise at the i-th microphone. In Equation (9), there is noise in each of the denominator and numerator terms, and the effect is significant, making it impossible to estimate the distance to the target.

When the spacing between two microphones is very small in the two adjacent microphones, the ambient noise is measured with almost the same waveform (i.e., $n(t, x_1) \approx n(t, x_2)$). Therefore, the difference between adjacent 2ch observed signals is expressed as

$$v_C(t, x_{12}) = v_C(t, x_1) - v_C(t, x_2), \tag{10}$$

where $v_C(t, x_{12})$ means the difference signal between $v_C(t, x_1)$ and $v_C(t, x_2)$. Although the amplitude of the difference signal is much smaller than the composite waves, the distance information from the center of the two microphones to the target is preserved.

If the noise component is sufficiently reduced in the difference signal, by viewing the difference signal as the input signal and the observed signal as the output signal, the cross-spectrum is given as

$$C(f, x_{12}, x_2) \approx \frac{V^*_C(f, x_{12})(V_C(f, x_2) + N(f, x_2))}{|V_C(f, x_{12})|^2}, \tag{11}$$

where $V_C(f, x_{12})$ indicates the Fourier transform of the difference signal $v_C(f, x_{12})$. When the cross-spectrum method is applied to the difference signal and the observed signal, it has a peak at position $d - \frac{x_1 + 3x_2}{4}$. In Equation (11), the noise affects the numerator, but the noise is greatly reduced in the denominator, so the effect of noise can be practically reduced for the distance measurement. Even with this technique, floor noise may still occur in the range spectrum due to the noise contained in the output signal, which degrades the ranging performance. In the proposed method, a mask for noise reduction is made by applying the constant false alarm rate (CFAR) [26] to 1ch ADM using the difference signal. The floor noise is reduced by masking the range spectrum of the 2ch ADM by this mask.

3. Verification in the Real Environment.

3.1. **Experimental conditions.** The experimental conditions are shown in Table 1. In this experiment, a simulation experiment was conducted to simulate a real sound field. The impulse responses of the space transfer characteristics to the ranging signal and the environmental noise from the transmitted source and the noise source to each observation point, respectively, were obtained using the time stretched pulse (TSP) signal [27]. The signals at each microphone position were reproduced on the computer by convolution of the impulse response with the transmitted and noise sources. A band-limited impulse with amplitude $A(f) = 1$ (constant) and initial phase $\theta(f) = 0$ in Equation (1) was adopted

TABLE 1. Experimental conditions

Sound source	Band-limited impulse
Sampling frequency	44.1 kHz
Frequency bandwidth	5.5 kHz (2.1 kHz $\sim$ 7.6 kHz)
Data points in time domain	2048
Data points in frequency domain	256
Data points (zero padding) in frequency domain	2048
Minimum measurable distance (= tolerance)	0.03 m
Distance between microphone x_2 and the target	1.0 m
Distance between two microphones	0.006 m
Temperature	26.0°C
Sound velocity	347 m/s
Noise	Gaussian (S/N = −10 dB)

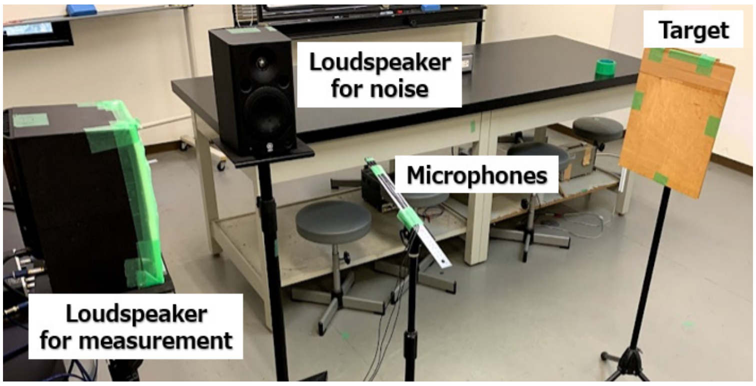
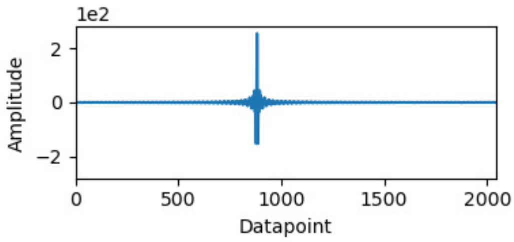
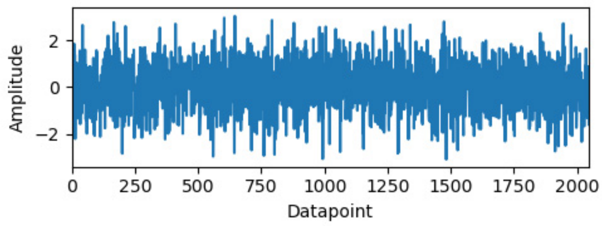


FIGURE 3. Overview of ADM with 2 adjacent microphones



(a) Transmitted source

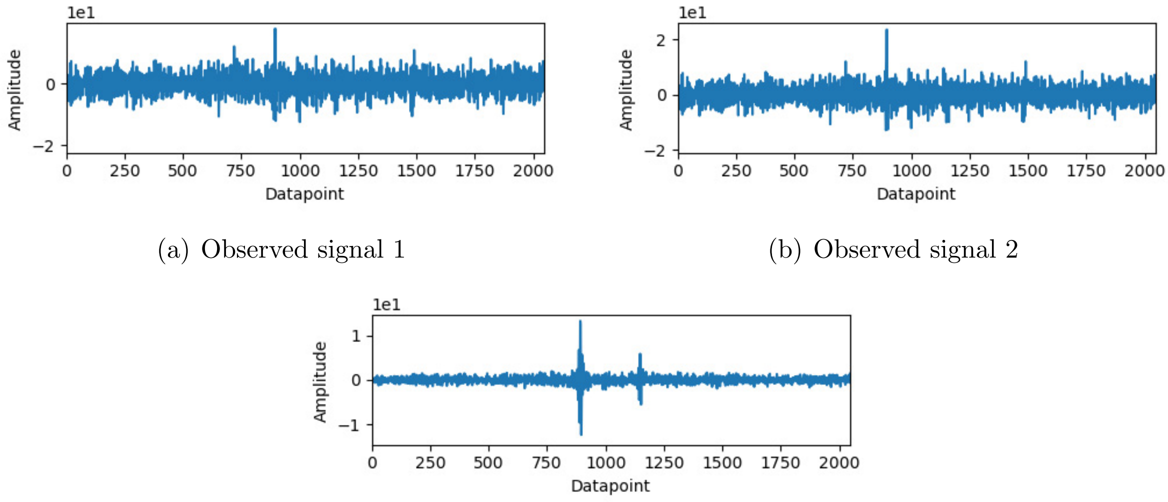


(b) Noise source

FIGURE 4. Transmitted and noise sources

as the transmitted source. A Gaussian random number was used as the noise source, and the SNR was set to −10 dB. The difference between two noisy observations generates one difference signal with reduced noise. The 1ch ADM using the difference signal and the 2ch ADM viewing the difference signal as the input signal and the observed signal as the output signal were conducted at the same time. The mask is made by binarized 1ch ADM using CFAR, and the spurious peak was removed by applying the mask to the range spectrum in 2ch ADM. Figure 3 shows an overview of the measurement in this experiment. Here, a plywood panel was used as the target.

3.2. **Experimental results and discussion.** Figures 4(a) and 4(b) present waveforms of the transmitted source and noise source, respectively. As described in Section 3.1, the source for distance measurement in Figure 4(a) is a band-limited impulse signal with a delay of 20.0 ms. In addition, the noise source in Figure 4(b) corresponds to Gaussian



(a) Observed signal 1

(b) Observed signal 2

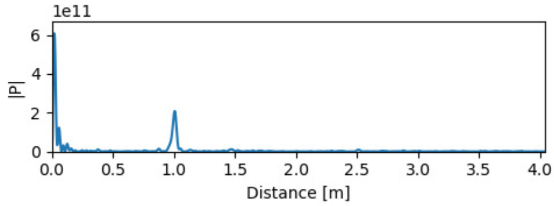
(c) Difference signal

FIGURE 5. Observed and difference signals

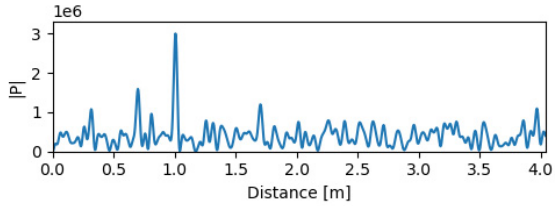
white noise. The ranging signal is obtained by convolving this band-limited impulse signal with the impulse response from the transmitted source point to the observation point. Similarly, convolving the Gaussian noise source with the impulse response from the noise source point to the observation point yields the environmental noise. The observed signals at each microphone position were reproduced on the computer by addition of the ranging signal and the environmental noise. To reduce the effect of environmental noise, noisy observed signal 2 was subtracted from noisy observed signal 1. Figures 5(a), 5(b), and 5(c) indicate the two observed signals and the difference signal between the observed signals, respectively. From Figures 5(a) and 5(b), it can be seen that the observed signal, especially the reflected wave, is buried in the environmental noise, and in Figure 5(c), where practical noise reduction is applied, the reflected wave can be considerably distinct. However, this difference signal is affected by the measurement system. The SNR of the observed signal was -10 dB, but the SNR of the difference signal was 2.54 dB, which confirms that the noise was reduced considerably.

Range spectra are shown in Figures 6(a), 6(b), and 6(c). Figure 6(a) shows the range spectrum with 1ch ADM for a difference signal reducing the ambient noise, even though there is a large spurious peak around 0 m due to the influence of the measurement system. Figure 6(b) exhibits the range spectrum with 2ch ADM for difference and noisy observed signals reducing the influence of the measurement system, although a floor noise appears by the noise at the output side. Figure 6(c) illustrates a combination of 1ch and 2ch ADMs, in which the spurious peaks that appeared in the 1ch and 2ch ADMs are reduced and the peak is at 1.007 m, which is within tolerance. Therefore, the distance to the target can be estimated by 2ch ADM. Moreover, the spurious peaks can be mostly removed by combining 2ch ADM with 1ch ADM.

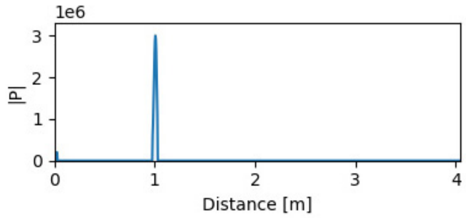
4. **Conclusions.** A practical method of acoustic distance measurement under ambient noise has been proposed using two adjacent microphones. More concretely, the noise component is reduced by generating a difference signal among two observations in the noisy environment. The proposed method performed 1ch ADM using the difference signal and performed 2ch ADM using the difference signal as the input signal and one of the observed signals as the output signal. The range spectrum of 1ch ADM is binarized by CFAR as a mask, and the masking process is applied to the range spectrum of 2ch ADM. As a result, the influences of the measurement system and environment noise were greatly



(a) 1ch ADM for difference signal



(b) 2ch ADM for difference and noisy observed signals



(c) Combination of 1ch and 2ch ADMs with mask processing

FIGURE 6. Range spectra

removed, and the estimated peak was confirmed to have appeared near the true value. Moreover, since there is no complicated process and the computational cost is small, the proposed method is practical. In the experiment, the SNR of the difference signal improved from −10 dB to 2.54 dB. The distance from the microphone to the target was estimated as 1.007 m for the actual distance of 1 m, which is within tolerance. These results suggest that the proposed ADM method is sufficiently practical and robust against the ambient noise. However, since the performance of noise reduction with pre-processing depends on the location of the noise source, we would like to conduct further verification.

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