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ACOUSTIC DISTANCE MEASUREMENT USING INCOMPLETE SEPARATION FOR A PAIR OF ADJACENT 2CH NOISY OBSERVATIONS

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Abstract. *In various fields, the distance to a target is important information. An acoustic distance measurement (ADM) method based on interference between transmitted and reflected waves using audible sound has been proposed. Environmental noise inevitably contaminates observations, and countermeasures against noise are indispensable. Synchronous addition is a method of reducing noise, but this method requires multiple measurements, and correct results cannot be obtained if the sound environment changes. There is also an attempt to reduce noise based on independent component analysis (ICA) using two-channel (2ch) observation signals. In the present study, the goal is to perform distance estimation in a single measurement under high noise. Signal separation by complex ICA using 2ch microphones (mic's) is less accurate when the mic's are closer than the sampling interval. In other words, it is difficult to obtain an accurate separation result only using two mic's. Therefore, ICA is applied to two sets of two signals among 3ch observation signals with one additional mic, and after restoring two ranging signals to the mic positions, the ADM method using the cross-spectral method is applied. Finally, in order to confirm the effectiveness of the proposed method, this method is applied to an actual sound environment.*
Keywords: Acoustic distance measurement, Pair of adjacent 2ch microphones, Cross-spectral method, ICA

1. **Introduction.** The total population of Japan was 126.71 million as of October 1, 2017. The population of individuals of 65 years or over was 35.15 million, and the proportion of the total population (aging rate) was 27.7%. The number of individuals of 75 years or over was 17.48 million, accounting for 13.8% of the total population [1]. This aging trend in Japan is ahead of the world and is expected to accelerate further in the future. Support for medical and welfare workers as well as families is indispensable for caring for the elderly, but due to the recent shortage of human resources, the introduction of nursing and welfare robots is eagerly desired [2]. Such robots must be in contact with patients and the elderly.

The distance to the target is basic and important information in various fields, as well as in the nursing and welfare fields. Optical range sensors such as light detection and ranging (LIDAR) sensors and depth sensors using infrared light are often equipped in the nursing robot for the distance measurement [3, 4, 5]. Although optical range sensor can measure the distance accurately, it is not easy to detect transparent objects like a glass and specular objects like a mirror [6]. On the other hand, acoustic range sensors such as sonar are also installed in the nursing robot [3]. Since the acoustic range sensors consist of only transmitter like a loudspeaker and receiver like a microphone, they can be implemented very compactly in size at very low cost. Furthermore, since the acoustic range sensors are

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not affected by the characteristics of the object surface which are difficult to detect by the optical range sensors, they can be used as complementary measures for the optical sensors. In order to estimate the distance to target using an acoustic signal, a method is generally used in which a pulse sound is transmitted toward a measurement target, and the distance is estimated from the time until the pulse sound returns as a reflected wave (i.e., time of flight [TOF]) [7, 8, 9, 10]. However, this method is difficult to apply for short distances in which the transmitted and reflected waves overlap in time. Taking the example of a level meter or range finder using acoustic signals that are currently in the market, the measurable distance is from 1 m to 50 m using an audible sound of 20 kHz and from 0.3 m to 10 m using an ultrasonic sound of 40 kHz. To range-find using acoustic signals, some methods have been proposed to remove measurement errors caused by changes in the environment, or to improve measurement accuracy and range [11, 12, 13].

In the field of microwave radar, a distance estimation method, i.e., standing wave radar, has been proposed for short-range estimation of multiple targets (even if the distance to the targets is approximately 0 m) [14]. Standing wave radar uses a standing wave generated by the interference between the transmitted and reflected waves to estimate distance and is different from other radars in the sense that standing wave radar does not separate the transmitted and reflected waves.

We proposed an accurate distance estimation method for targets at close range near 0 m by applying the principle of standing wave radar to distance estimation using acoustic signals [15]. In particular, by using an audible sound of approximately 10 kHz, which is less attenuated by airborne propagation than ultrasonic waves and is considered to be suitable for long-distance measurements, acoustic distance measurement (ADM) can be performed for multiple targets from long to close distances. In addition, an acoustic signal has the advantage that anyone can use this signal freely without being restricted by the Radio Law, in the same manner as microwaves. In actual measurement, since the measurement system from the loudspeaker to the microphone (mic) affects the distance measurement result, we also proposed a method of removing these effects using the cross-spectral method for the adjacent two-channel (2ch) observation signals [16]. In actual situations, since the observation signal is inevitably contaminated by environmental noise, countermeasures against environmental noise are indispensable. Synchronous addition is known as a technique for reducing noise but requires multiple measurements, and when the sound environment is changed, correct results may not be obtained. In addition, noise reduction based on independent component analysis (ICA) has been attempted using 2ch observation signals [17].

The purpose of the present study is to estimate the distance with a single measurement under high noise. Even when the mic's are closer than the distance corresponding to the sampling interval, signal separation by complex ICA using 2ch adjacent mic's shows the passable separation performance. However, applying the ADM method (using the cross-spectral method) to the reconstructed signals at each observation point, the range spectrum has a spurious peak near 0 m. This means that ADM with ICA pre-processing using 2ch noisy observations provides a single-channel noise-free ranging signal from which environmental noise has been considerably removed but still contains the effect of the measurement system (i.e., incomplete separated signal). Therefore, ICA is applied to two sets of two signals among the three channels of observation signals added with one mic, and the two ranging signals are restored to the mic positions. We herein propose a method for practical distance estimation based on incomplete separation using a pair of adjacent 2ch mic's. Finally, in order to confirm the effectiveness of the proposed method, this method is applied to an actual sound environment.

2. Independent Component Analysis Preprocessing in ADM Using a Pair of Adjacent 2ch Mic's.

2.1. **Two-channel ADM using cross-spectral method.** Consider the measurement environment shown in Figure 1(a), in which the sound source, two mic's, and the target are in a straight line. Here $g_s(t)$ $(= g_{\mathrm{L}}(t) * g_{\mathrm{M}s}(t)$ with $*$ being a convolution operator) $(s = 1, 2)$ is the impulse response including the impulse responses $g_{\mathrm{L}}(t)$ for the transmission system and $g_{\mathrm{M}s}(t)$ for the s-th sound receiving system. Transmitted wave $v_{\mathrm{T}}(t, x)$ radiated from the sound source toward the target is formulated as:

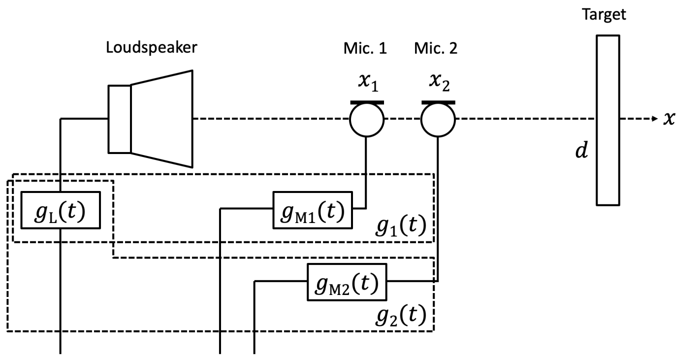
$$v_{\mathrm{T}}(t, x) = \int_{f_1}^{f_N} A(f) e^{j\left(2\pi f t - \frac{2\pi f x}{c} + \theta(f)\right)} df, \tag{1}$$

where t is the time [s], x is an arbitrary position [m], c is the propagation velocity [m/s], and $A(f)e^{j\theta(f)}$ is the frequency spectrum of the transmitted sound. In addition, f_1 and f_N are the lowest and highest frequencies [Hz], respectively. If there are m targets, then the reflected wave $v_{\mathrm{R}_n}(t, x)$ from the n-th target can be expressed as follows:

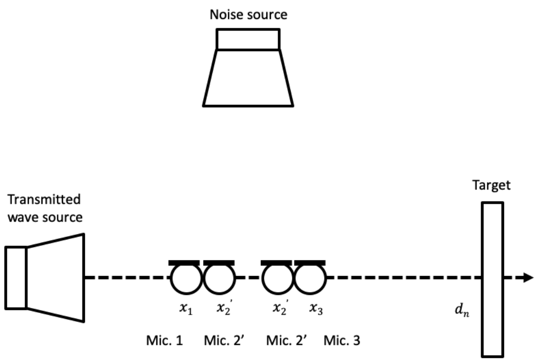
$$v_{\mathrm{R}_n}(t, x) = \int_{f_1}^{f_N} A(f)\gamma_n(f) e^{j\left(2\pi f t - \frac{2\pi f}{c}(2d_n - x) + \theta(f) + \phi_n(f)\right)} df, \tag{2}$$

where $\gamma_n(f)e^{j\phi_n(f)}$ is the reflection coefficient of the n-th target, d_n is the position of the n-th target [m]. For convenience, by letting the mic position be $x = x_s$ $(s = 1, 2)$, the composite wave (specifically referred to herein as the ranging signal) at the mic position is

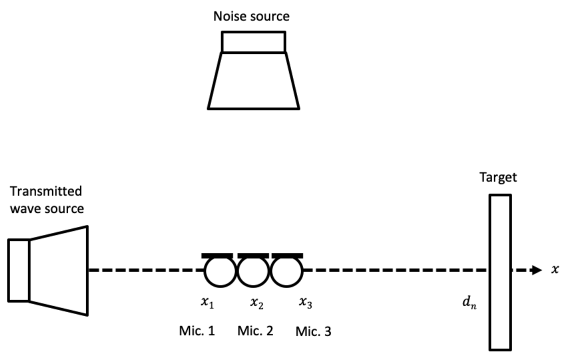
$$v_{\mathrm{C}}(t, x_s) = g_s(t) * \left\{ v_{\mathrm{T}}(t, x_s) + \sum_{n=1}^{m} v_{\mathrm{R}_n}(t, x_s) \right\}. \tag{3}$$



(a) Original measurement environment



(b) Pair of adjacent 2ch mic's



(c) Pair of adjacent 2ch mic's with one shared mic

Figure 1. Overview of original ADM with adjacent 2ch mic's and the proposed ADM with adjacent 3ch mic's

For simplicity, assuming the case of a single target ($m = 1$), the subsucript n in the reflection coefficient $\gamma_n(f)e^{j\phi_n(f)}$ can be neglected. Further supposing that the reflection coefficient is constant as $\gamma e^{j\phi}$ and letting $V_{\mathrm{C}}(f, x_s)$ ($s = 1, 2$) be the Fourier transform of the s-th observation, the cross-spectrum $C(f, x_1, x_2) = V_{\mathrm{C}}^*(f, x_1)V_{\mathrm{C}}(f, x_2)\big/\big\{V_{\mathrm{C}}^*(f, x_1)V_{\mathrm{C}}(f, x_1)\big\}$ can be obtained with $V_{\mathrm{C}}(f, x_1)$ as the input signal and $V_{\mathrm{C}}(f, x_2)$ as the output signal:

$$C(f, x_1, x_2) = \frac{A^2(f)G_1^*(f)G_2(f)V_{\mathrm{C}}^*(f, x_1)V_{\mathrm{C}}(f, x_2)}{A^2(f)|G_1(f)|^2 V_{\mathrm{C}}^*(f, x_1)V_{\mathrm{C}}(f, x_1)}, \tag{4}$$

where $V_{\mathrm{C}}^*(f, x_1)$ is the complex conjugate of $V_{\mathrm{C}}(f, x_1)$.

If the spacing of two mic's is very small, then the influence of the measurement system can be removed in the numerator and denominator (i.e., $G_1(f) \approx G_2(f)$). The observation position x_1 is assumed to be the origin $x_1 = 0$. If the reflection coefficient is sufficiently small ($\gamma \ll 1$), then Equation (4) can be approximated as:

$$C(f, 0, x_2) \approx \frac{e^{-j\left(\frac{2\pi f}{c}x_2\right)} + \gamma e^{-j\left(\frac{2\pi f}{c}(2d - x_2) - \phi\right)}}{1 + \gamma e^{-j\left(\frac{4\pi f}{c}d - \phi\right)}}. \tag{5}$$

The squared absolute value of the cross-spectrum $p_{\mathrm{cr}}(f, 0, x_2) = |C(f, 0, x_2)|^2$ (referred to herein as the cross-power spectrum) is as follows:

$$p_{\mathrm{cr}}(f, 0, x_2) \approx 1 + 2\gamma\left\{-\cos\left(\frac{4\pi f}{c}d - \phi\right) + \cos\left(\frac{4\pi f}{c}(d - x_2) - \phi\right)\right\}. \tag{6}$$

The first term on the right-hand side of Equation (6) is the direct current (DC) component, and the second and third terms are the two types of periodic components, i.e., their periods are inversely proportional to distances $d - x_s$ ($s = 1, 2$) from the observation position x_s to the target position d (where $x_1 = 0$). By removing the DC component from Equation (6) and applying the Fourier transform, the range spectrum $|P_{\mathrm{cr}}(x)|$ can be obtained. The peak position of $|P_{\mathrm{cr}}(x)|$ corresponds to the distance from the observation position to the target. If the two mic's are in close proximity, then the two peaks overlap and the peak position is $d - \frac{x_2}{2}$ [16].

The ADM method using the cross-spectrum by placing two mic's at a distance closer than one sample interval has advantages as the following.

- Influences of the measurement system and transmitted wave can be removed by one measurement.
- Since the cross-spectrum is used, the ADM method can cope with environmental noise to some extent.

However, when the environmental noise becomes large, the ADM method using the cross-spectrum cannot be used.

2.2. **Acoustic distance measurement with complex ICA preprocessing using a pair of 2ch mic's.** In actual measurements, the observation signal is additively contaminated by environmental noise, and the measurement system from the loudspeaker to the mic also affects distance measurement. If the noise is small, then the ADM method using the cross-spectrum can remove the environmental noise passably. However, the measurement performance is degraded when the environmental noise increases. As a powerful tool for noise removal, ICA based on the statistical independency between source signals (here, the ranging signal and environmental noise) is a well-known technique. However, when the mic's are close to each other, only an incomplete separation signal can be obtained. "Incomplete" means that the ICA can separate the observed signals into the ranging signal and environmental noise passably, but cannot remove the influence of the measurement system due to the spacing being too short between the two mic's. Specifically, the two ranging signals restored to the mic position are approximately the same, and, even though a 2ch signal is used, the signal becomes a 1ch observation signal from which only environmental noise has been removed passably. As a result, a spurious peak appears near 0 m in the range spectrum.

Therefore, we consider two sets of 2ch mic's (Figure 1(b)) composed of one set of conventional 2ch mic's (Figure 1(a)) and another set of 2ch mic's. Since one mic can be shared, ICA can be applied in the state of a 3ch mic's (Figure 1(c)). In this research, 2ch-ICA is applied to two observations (i.e., observations at mic's 1 and 2 and mic's 2 and 3) among three observations. For the sake of convenience, we rewrite the transmitted wave in Equation (3) as $s(t) = v_{\mathrm{T}}(t, x_s)$.

In the actual environment, the observed signal at each mic is represented by the sum of convolutions with respect to the transmitted wave s and the noise n:

$$z_i(t) = g_{i1}(t) * s(t) + g_{i2}(t) * n(t) \quad (i = 1, 2, 3), \tag{7}$$

where $g_{i1}(t)$ and $g_{i2}(t)$ $(i = 1, 2, 3)$ represent the impulse response. The mixing and separating processes of each signal can be expressed as follows in the frequency domain [18]:

$$\boldsymbol{Z}(\omega, t_s) = \boldsymbol{G}(\omega)\boldsymbol{S}(\omega, t_s), \quad \boldsymbol{Y}(\omega, t_s) = \boldsymbol{W}(\omega)\boldsymbol{Z}(\omega, t_s), \tag{8}$$

where ω and t_s, respectively, denote the frequency bin and frame number generated by the short-time Fourier transform. Here, $\boldsymbol{S}(\omega, t_s)$, $\boldsymbol{Z}(\omega, t_s)$, $\boldsymbol{G}(\omega)$, $\boldsymbol{Y}(\omega, t_s)$, and $\boldsymbol{W}(\omega)$ are the frequency components of source signal, observed signal, impulse response, separated signal, and separation matrix, respectively, corresponding to the frequency ω.

Next, the separation update formula used this time is as follows [19]:

$$\boldsymbol{W}(\omega) = \boldsymbol{W}(\omega) + \eta\Delta\boldsymbol{W}(\omega), \quad \Delta\boldsymbol{W}(\omega) = \left\{\boldsymbol{I} + \left\langle \phi(\boldsymbol{Y}(\omega, t_s))\boldsymbol{Y}(\omega, t_s)^H \right\rangle_{t_s}\right\}\boldsymbol{W}(\omega), \tag{9}$$

where $\langle\cdot\rangle_{t_s}$ is the average over all frames, $\boldsymbol{I}$ is the identity matrix, η is the step size, and H represents a conjugate transpose. The score function $\phi(\boldsymbol{Y}(\omega, t_s))$ is adopted in order to avoid the permutation problem [20].

$$\phi(Y_k(\omega, t_s)) = -Y_k(\omega, t_s) / \left\langle |Y_k(\omega, t_s)|^2 \right\rangle_\omega \quad (k = 1, 2), \tag{10}$$

where $\langle\cdot\rangle_\omega$ denotes the average over all frequency bins. The separated signal can be restored to each mic position, and the distance can be measured by the method described in Section 2.1.

3. Verification in the Real Environment.

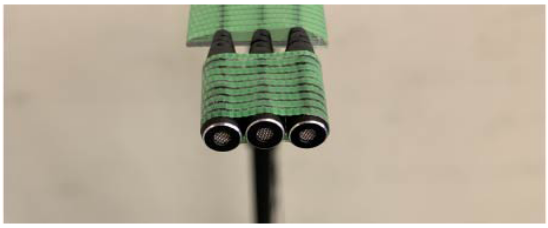
3.1. **Experimental conditions.** The experimental conditions are shown in Table 1. A band-limited impulse with amplitude $A(f) = 1$ (constant) and initial phase $\theta(f) = 0$ in Equation (1) was adopted as the transmitted wave. Noisy observations with Gaussian random numbers (S/N ratio $= -10$ dB) were separated using complex ICA, and the ranging signals at each observation position were restored. From observations 1 and 2, the amplitude was restored to the separated signal (ranging signal) at mic position 2, and from observations 2 and 3, the amplitude was restored to the separated signal (ranging signal) at mic position 3. Figures 2(a) and 2(b), respectively, show an overview of the measurement and microphones used in this experiment. Here, plywood was used as the target.

3.2. **Experimental results.** The transmitted wave is shown in Figure 3(a), and one of the three observed waves is shown in Figure 3(b). Separated signals 1 and 2 using the observed signals at mic's 1 and 2 are shown in Figures 4(a) and 4(b), and separated signals 3 and 4 using the observed signals at mic's 2 and 3 are shown in Figures 4(c) and 4(d). Separated signals 2 and 4 are ranging signals, and separated signals 1 and 3 are noise signals. Based on these results, the signal separation appears to be successful, but in fact, only incomplete separation is obtained. For example, even if separated signal 2

TABLE 1. Experimental conditions

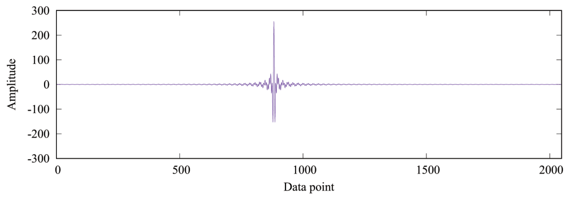
Sound source	Band-limited impulse
Sampling frequency	44.1 kHz
Frequency bandwidth	5.5 kHz (2.1 kHz $\sim$ 7.6 kHz)
Data points in time domain	2048
Data points in frequency domain	256
Data points (zero padding) in frequency domain	2048
Minimum measurable distance	0.0040 m
Distance between mic x_2 and the target	1.0 m
Distance between adjacent microphones	0.006 m
Sound velocity	347.09 m/s
Noise	Gaussian noise (S/N = -10 dB)
Window function	Hanning window (half overlap)
Frame number, size, shift	63, 64, 32

(a) Overview of ADM with adjacent 3ch mic's

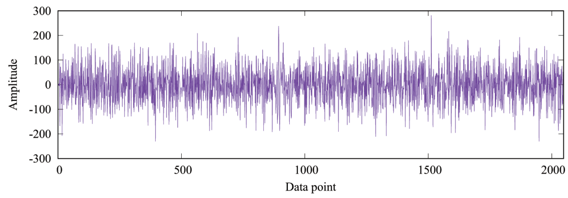


(b) Closeup of adjacent 3ch mic's (= a pair of adjacent 2ch mic's)

FIGURE 2. Experimental environment

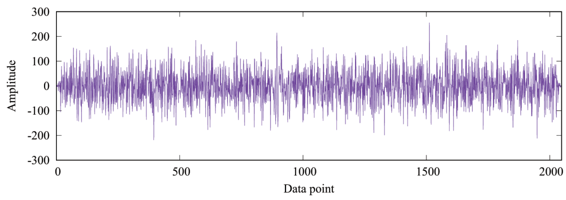


(a) Transmitted wave

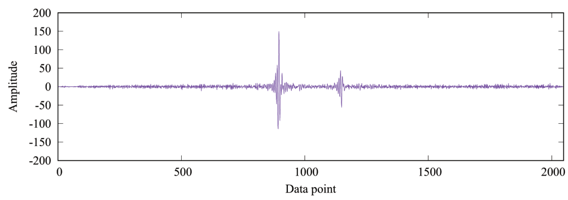


(b) Observed wave 1

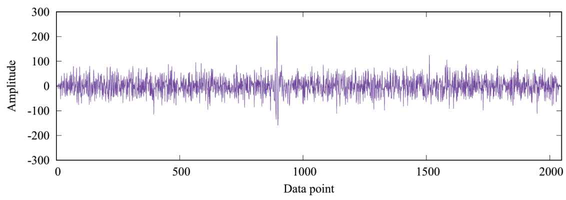
FIGURE 3. Transmitted and observed waves



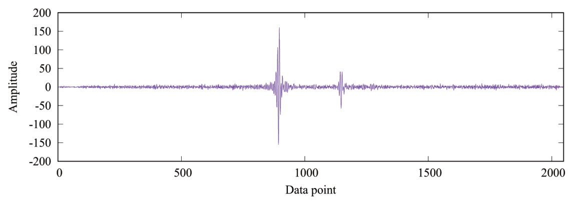
(a) Signal 1 separated from observations 1 and 2



(b) Signal 2 separated from observations 1 and 2

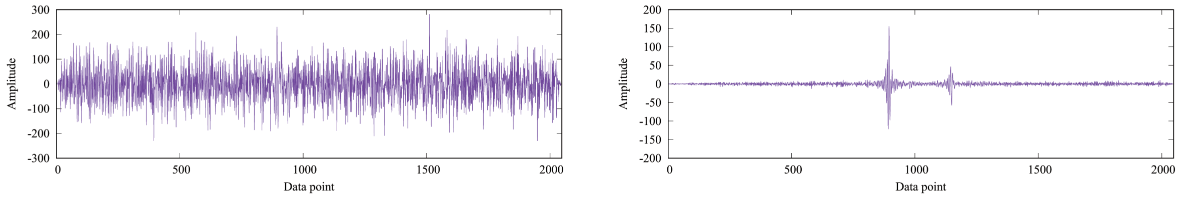


(c) Signal 3 separated from observations 2 and 3



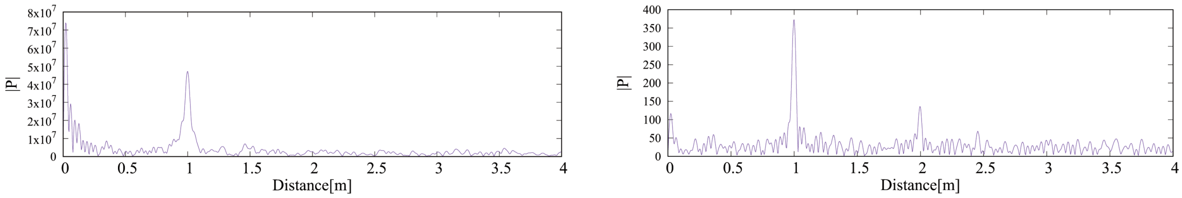
(d) Signal 4 separated from observations 2 and 3

FIGURE 4. Separated waves



(a) Reconstructed wave 1 (b) Reconstructed wave 2

Figure 5. Reconstructed waves at mic's 1 and 2



(a) Without cross-spectrum (b) With cross-spectrum

Figure 6. Range spectra

is used to reconstruct the ranging signals at the mic's 1 and 2, the distance cannot be obtained (e.g., reconstructed waves for noise and the ranging signal are shown in Figures 5(a) and 5(b)). This is because the two reconstructed signals have approximately the same waveform. That is, even if measurement is performed with two adjacent mic's, noise can be considerably removed, but the influence of the measurement system cannot be removed. An example of this is shown in Figure 6(a). Due to the influence of the measurement system, a spurious peak appears near 0 m. In this case, the true peak is at $d-(x_1+x_2)/2$, i.e., the distance from the center of mic's 1 and 2 to the target. Therefore, applying ICA to the adjacent 2ch observation signals under high noise can considerably remove the environmental noise, but the influence of the measurement system remains.

Therefore, when the same processing is applied to observation signals 2 and 3 at mic's 2 and 3, a reconstructed signal having a range spectrum peak at a distance $d-(x_2+x_3)/2$ is obtained from the separated signal. When mic's 1, 2, and 3 are close to each other at equal intervals, letting the ranging signal obtained from mic's 1 and 2 be an input, and letting the ranging signal obtained from the mic's 2 and 3 be an output, the cross-spectral method can be applied. The range spectrum obtained in this way is shown in Figure 6(b). The peak position of Figure 6(b) is 1.0025 m, and the tolerance is within 0.0040 m with respect to the true value (1.0 m). Moreover, the spurious peak near 0 m is eliminated.

4. **Conclusions.** Acoustic distance measurement by means of a single measurement under high noise has been proposed, especially using a pair of adjacent 2ch mic's (i.e., as a result, adjacent 3ch mic's). More concretely, incomplete separated signals have been obtained from two sets of 2ch observations from adjacent 3ch mic's, based on complex ICA. After restoring the two ranging signals to the mic positions, the ADM method using a cross-spectral method was applied. As a result, the spurious peak near 0 m was removed from the range spectrum, and the estimated peak was confirmed to have appeared near the true value.

In the experiment with S/N = −10 dB, the distance from the mic to the target was estimated as 1.0025 m for an actual distance of 1 m, which is within the error tolerance of 0.0040 m.

These results suggest that the proposed ADM method is sufficiently accurate and robust for practical use. However, although the proposed method requires 3ch observations, an ADM method using only 2ch observations will need to be considered in future research.

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