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CONSIDERATION OF ACOUSTIC DISTANCE MEASUREMENT USING THE HILBERT TRANSFORM OF 2CH OBSERVATIONS WITH A LINEAR CHIRP SIGNAL FOR MULTIPLE TARGETS

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Abstract. *The distance to targets is fundamental information in many engineering applications. Recently, an acoustic distance measurement (ADM) method has been proposed based on the interference between transmitted and reflected waves, but this method requires the Fourier transform to be applied twice. The ADM method, in which a linear chirp for which the frequency changes linearly with time is adopted as a transmitted sound, has been proposed to reduce the number of applications of the Fourier transform to one. However, due to the influence of the transfer characteristic of a measurement system that includes a loudspeaker and a microphone, the ADM method often estimates a spurious short distance that is different from the true distance. In order to reduce the number of applications of the Fourier transform and eliminate the adverse effect of the measurement system, an ADM method that uses a Hilbert filter has been proposed. In this method, a Hilbert transform filter is used to obtain the analytic signal of a linear chirp for the cross-spectrum. Although this method can theoretically measure distances even when there are multiple targets, its feasibility has not been confirmed. The present paper describes the feasibility of the chirp-based ADM method for multiple targets. We confirmed the validity of the chirp-based ADM method for multiple targets through computer simulation and by applying the method to an actual sound field.*
Keywords: Distance measurement, Phase interference, Chirp, Cross-spectrum, Hilbert transform, Multiple targets

1. **Introduction.** The distance to objects (targets) is fundamental information in many engineering applications, and various methods for measuring such distances have been proposed. In recent years, to estimate distances, many distance measurement methods were proposed such as a method for various shapes using a radar [1], a method of applying Kalman filter to data obtained from monocular camera and data from radar [2], a method applying extended Kalman filter to data obtained from monocular camera [3], a method using stereo camera [4] and a method using time of flight estimate by phase correlation between observed waves of ultrasound [5]. However, since radar is regulated by radio act, we cannot use it freely. Often the camera cannot estimate the exact distance due to fog or smoke. Ultrasound has a sharp directivity, so it can only estimate the distance in a narrow angle. From these facts, we focused on the audible sound which can be freely used, propagate even in fog or smoke and propagate in a wide angle. As a distance estimation method using audible sound, the time difference between transmitted waves and waves reflected from the target is generally used to measure this distance [6, 7, 8, 9, 10]. However, in a close range where the reflected wave returns before the transmitted wave is not sufficiently attenuated, the reflected wave is buried in the transmitted wave, and so the distance to

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the target is difficult to measure. A method for removing the influence of the transmitted wave has been proposed [11], but this method requires multiple elements. On the other hand, in the field of microwave radar, there is a technique for short-range measurement that uses standing waves (i.e., phase interference) [12, 13]. Distance measurement using standing waves is a very practical approach because distance can be measured by simply applying a Fourier transform to the power spectrum of the observed wave. The absolute value of the Fourier transform is called a range spectrum, and the position of its peak is the estimated value d of the distance from the microphone to the target. We extended the method for measuring short distances using the standing wave in the audible sound signal [14, 15]. By using acoustic distance measurement (ADM), it is possible to measure the distance over a wide range. Furthermore, unlike microwaves, since sound is not regulated by act, ADM is advantageous in that the method can be used by anyone. However, the conventional ADM method requires the Fourier transform to be applied twice.

In order to reduce the number of applications of the Fourier transform to one, the ADM method in which a linear chirp whose frequency changes linearly with lapse of time is adopted as a transmitted sound has been proposed. Then, the power spectrum of the observed wave contains the distance information as the period in the time domain (corresponding to the frequency domain at the same time in the chirp signal). However, the ADM method is influenced by the transfer characteristic of the measurement system, including the loudspeaker and the microphones; it often estimates a spurious short distance as well as the true distance. In order to reduce the number of applications of the Fourier transform and eliminate the effect of the measurement system, an ADM method that applies the cross-spectral method to observed signals of adjacent two-channel (2ch) microphones using the linear chirp as a transmitted sound has also been proposed. In this method, a Hilbert transform filter is used to obtain an analytic signal of the linear chirp for the cross-spectrum [16]. Although this method can theoretically measure distance even when there are multiple targets, its feasibility has not been confirmed.

The present paper describes the feasibility of the ADM method using the Hilbert transform of 2ch observations with a linear chirp signal for multiple targets. We confirm the validity of the ADM method using the Hilbert transform of 2ch observations with a linear chirp signal for multiple targets by performing a computer simulation and applying the method to an actual sound field.

This paper consists of five sections. First, in the introduction of Section 1, the background and outline of this study will be described. Section 2 describes acoustic distance measurement method using cross spectral method between 2ch observations of linear chirp. We will examine the validity of the proposed method through the simulation in Section 3 and the experiment in the actual sound field in Section 4. Finally, we will conclude this study in Section 5. As a result, we could estimate distance accurately for both simulation and experiment.

2. **Acoustic Distance Measurement Using a Cross-Spectral Method between Adjacent 2ch Observations of Linear Chirp.** Although the ADM method is given in a very simple form based on the phase interference between transmitted and reflected waves, it requires the Fourier transform to be applied twice. In order to reduce the number of Fourier transforms to one, we expanded the ADM method by adopting a linear chirp, the frequency of which increases linearly with time, as a transmitted sound. The observed wave obtained by the linear chirp signal contains the distance information as the periodicity in the time domain. Figure 1 shows the positions of the microphones, the sound source (loudspeaker), and the targets. The impulse response $g(t)$ (consisting of the impulse response $g_L(t)$ of the audio playback system and the impulse responses $g_{M1}(t)$ and $g_{M2}(t)$ of the audio recording systems) of a measurement system affects sound observations.

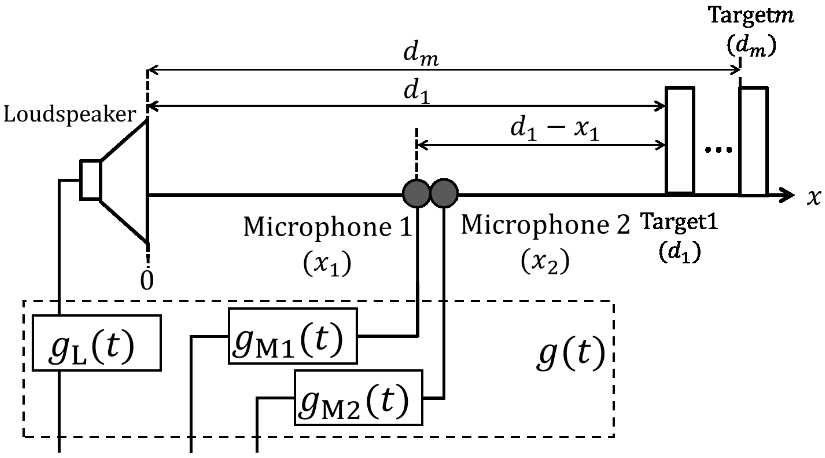


FIGURE 1. Positions of the loudspeaker, microphones, and targets

Here, $g_{M1}(t)$ can be assumed to be approximated by $g_{M2}(t)$, because microphones 1 and 2 (abbr. mic. 1 and mic. 2) are located in very close proximity to each other.

In the present study, we examine the feasibility of the ADM method using the cross-spectral method between adjacent 2ch observations of linear chirp for multiple targets. When adopting linear chirp as a sound source, let the transmitted wave $v_{\mathrm{TI}}(t,x)$ be a function of position x [m] and time t [s] as follows:

$$v_{\mathrm{TI}}(t,x) = A\cos\left(2\pi\int_0^{t-x/c} f(\tau)d\tau + \theta\right) \quad \text{with } f(t) = \frac{f_W}{T}t + f_1, \tag{1}$$

where A is the amplitude, θ [rad] is the initial phase, c [m/s] is the speed of sound, $f(t)$ [Hz] is the instantaneous frequency, T [s] is the duration of the transmitted sound, and f_W [Hz] ($= f_N - f_1$) is the width between the lowest frequency f_1 [Hz] and the highest frequency f_N [Hz]. When the transmitted wave $v_{\mathrm{TI}}(t,x)$ is reflected by m targets, the wave reflected by the n-th target $v_{\mathrm{RI}n}(t,x)$ can be represented as follows:

$$v_{\mathrm{RI}n}(t,x) = A\gamma_n\cos\left(2\pi\int_0^{t-(2d_n-x)/c} f(\tau)d\tau + \theta + \phi_n\right), \tag{2}$$

where γ_n is the magnitude of the reflection coefficient of the n-th target, ϕ_n is the phase of the reflection coefficient, and d_n [m] is the position of the n-th target.

In the present paper, as shown in Figure 1, both microphones, the sound source, and the target are all assumed to be located on the x axis. The sound source and the two microphones were placed at $x = 0$ [m], x_1 [m], and x_2 [m], respectively. Therefore, at the i-th microphone position $x = x_i$ $(i = 1, 2)$ [m], the composite wave $v_{\mathrm{CI}}(t,x_i)$ is formulated as follows:

$$v_{\mathrm{CI}}(t,x_i) = v_{\mathrm{TI}}(t,x_i) + \sum_{n=1}^{m} v_{\mathrm{RI}n}(t,x_i). \tag{3}$$

In the actual measurement, the impulse response $g(t)$ affects $v_{\mathrm{CI}}(t,x_i)$, and thus the actual observation is the convolution of $g(t)$ and $v_{\mathrm{CI}}(t,x_i)$. The cross-spectral method is very effective for measuring the distance between the microphone and the target, while eliminating the influence of the measurement system. The cross-spectrum can be constructed using the observation and its analytic signal in the frequency domain. In order to obtain the analytic signal, $v_{\mathrm{CQ}}(t,x_i)$ orthogonal to $v_{\mathrm{CI}}(t,x_i)$ can be computed using the Hilbert transform filter as

$$h(n) = \begin{cases} \dfrac{2}{n\pi} & n : \text{odd}, \\ 0 & n : \text{even}. \end{cases} \tag{4}$$

Thus, the analytic signal $v_{\mathrm{C}}(t, x_i)$ can be obtained by making $v_{\mathrm{CI}}(t, x_i)$ and $v_{\mathrm{CQ}}(t, x_i)$ corresponding to the real and imaginary parts, respectively, where

$$v_{\mathrm{C}}(t, x_i) = v_{\mathrm{CI}}(t, x_i) + jv_{\mathrm{CQ}}(t, x_i) \quad \text{with } j = \sqrt{-1}. \tag{5}$$

The complex composite wave $v_{\mathrm{C}}(t, x_i)$ in the time domain is expressed by the frequency response $V_{\mathrm{C}}(f, x_i)$ by substituting $t = \frac{T}{f_W}(f - f_1)$ into t. In the frequency domain, when γ is sufficiently small ($\gamma \ll 1$), the cross-spectrum is approximated by the following equation:

$$C(f, x_1, x_2) = \frac{V_{\mathrm{C}}^*(f, x_1)V_{\mathrm{C}}(f, x_2)}{|V_{\mathrm{C}}(f, x_1)|^2} \approx e^{j(\alpha_1 - \alpha_2)} \left\{ 1 + \sum_{n=1}^{m} \gamma_n \left(e^{j(\beta_{n2} - \alpha_2)} - e^{-j(\beta_{n1} - \alpha_1)} \right) \right\} \tag{6}$$

with

$$\alpha_i = 2\pi \int_0^{\frac{T}{f_W}(f - f_1) - \frac{x_i}{c}} f(\tau)d\tau + \theta, \quad \beta_{ni} = 2\pi \int_0^{\frac{T}{f_W}(f - f_1) - \frac{2d_n - x_i}{c}} f(\tau)d\tau + \theta + \phi_n. \tag{7}$$

The absolute squared value of $C(f, x_1, x_2)$, which is referred to as the cross-power, can be represented as follows:

$$|C(t, x_1, x_2)|^2 \approx 1 + 2\sum_{n=1}^{m} \gamma_n \left\{ \cos(\alpha_2 - \beta_{n2}) - \cos(\alpha_1 - \beta_{n1}) \right\}. \tag{8}$$

An example of the cross-power is shown in Figure 2. The cross-power is a periodic function, the period of which is inversely proportional to the distances $d_n - x_1$ and $d_n - x_2$.

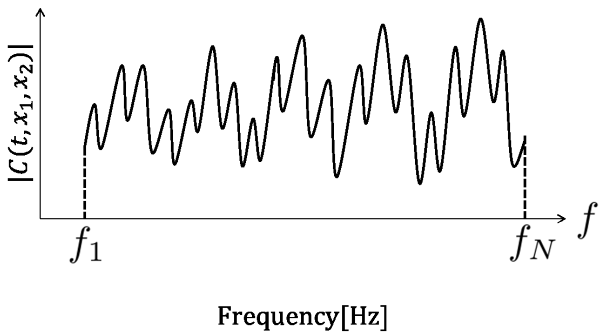


Figure 2. Cross-power

Therefore, by subtracting the average of $|C(f, x_1, x_2)|^2$ from Equation (8), the Δ cross-power $\Delta p(f, x_1, x_2)$ is obtained as follows:

$$\begin{aligned} \Delta p(f, x_1, x_2) = 2\sum_{n=1}^{m} \gamma_n \Bigg\{ &\cos\left(2\pi \frac{2d_n - 2x_2}{c} f + 2\pi \frac{2(d_n - x_2)f_1}{c} - \phi_n\right) \\ &- \cos\left(2\pi \frac{2d_n - 2x_1}{c} f + 2\pi \frac{2(d_n - x_1)f_1}{c} - \phi_n\right) \Bigg\}. \end{aligned} \tag{9}$$

Using the cross-spectrum, it is possible to eliminate the influences both of the transmitted signal and the measurement system. Applying the Fourier transform to $\Delta p(f, x_1, x_2)$ with respect to frequency f yields $P(x) = \int_{f_1}^{f_N} \Delta p(f, x_1, x_2) e^{-j2\pi \frac{2x}{c} f} df$. The absolute value $|P(x)|$ is referred to as the range spectrum. The peak positions of $|P(x)|$ are the estimated values $d_n - x_i$ $(i = 1, 2)$ of the distance from the i-th microphone to the targets. If the two microphones are placed in close proximity to one another ($|x_1 - x_2| \ll d_{\min}$), then the two peaks overlap at the single-peak position $x = d_n - (x_1 + x_2)/2$. Here, $d_{\min}$ is a minimum measurable distance defined as $d_{\min} = c/(2f_W)$. The ADM method can estimate the distances to two targets as well as the distance to a single target. An example of the range spectrum for the case of two targets is illustrated in Figure 3.

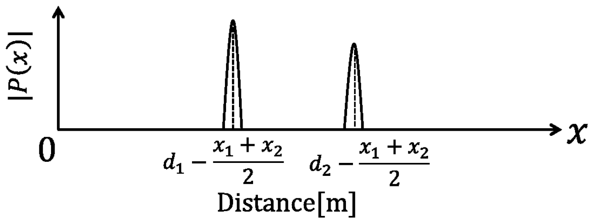


Figure 3. Range spectrum

3. Computer Simulations.

3.1. Simulation conditions. In order to confirm the validity of the ADM method, we performed computer simulations assuming two targets. The simulation conditions are listed in Table 1. The distances between mic. 1 and target 1 and between mic. 1 and target 2 are set to 0.2 m and 0.7 m, respectively. The spacing between mics. 1 and 2 is $x_2 - x_1 = 0.006$ m. Here, the cosine linear chirp is adopted as a transmitted wave, as shown in Figure 4.

Table 1. Simulation conditions

Sound source	Linear chirp signal
Measurement time	0.464 s
Sampling frequency	44.1 kHz
Data points in time domain	2048
Data points in frequency domain	2048
Frequency bandwidth	5490.9 Hz (2153.3-7644.2 Hz)
Minimum measurable distance	0.03 m
Sound speed	340 m/s
Reflection coefficient	0.05
Distance between mic. 1 and target	0.2 m, 0.7 m

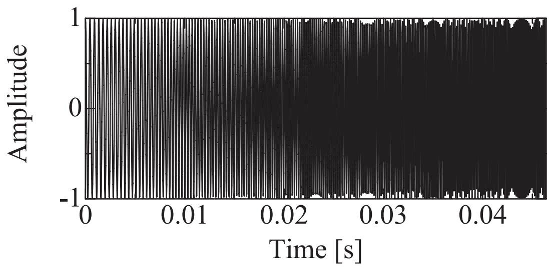
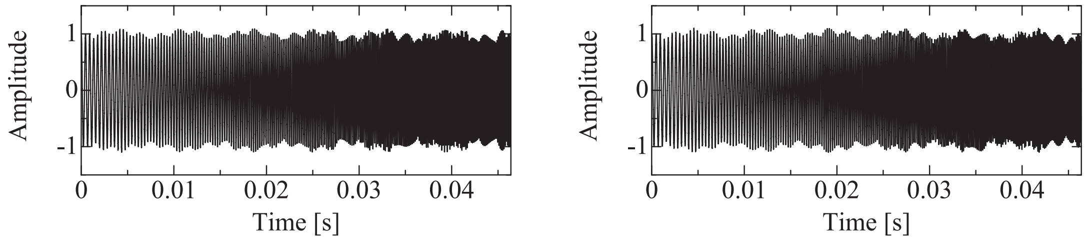


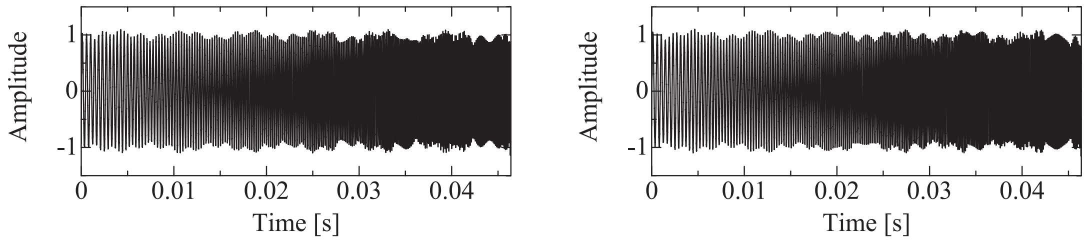
Figure 4. Transmitted wave

3.2. **Simulation results.** The composite waves at mic. 1 and mic. 2 are shown in Figures 5(a) and 5(b), respectively, and are regarded as the real parts of analytic functions. Transformed waves using the Hilbert transform filter, which are regarded as the imaginary parts of analytic functions, are shown in Figures 6(a) and 6(b). Based on these results, the Δ cross-power and the range spectrum are shown in Figures 7(a) and 7(b). In Figure 7(b), the peak positions are 0.19 m and 0.68 m. Thus, the estimated distances approximate the true values of 0.2 m and 0.7 m within an error of 0.03 m, which is the minimum measurable distance. This might demonstrate the validity of the ADM method.



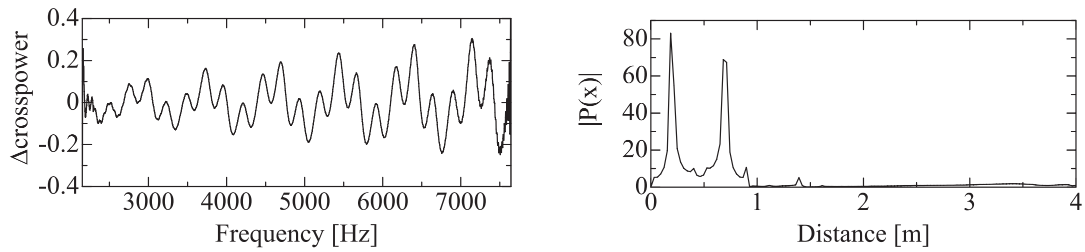
(a) At mic. 1 (b) At mic. 2

Figure 5. Composite waves at mic. 1 and mic. 2 (Real part)



(a) At mic. 1 (b) At mic. 2

Figure 6. Hilbert-transformed composite waves (Imaginary part)



(a) Δ cross-power spectrum (b) Range spectrum

Figure 7. Simulation results for two targets

4. **Experiment in an Actual Sound Field.**

4.1. **Experimental conditions.** The parameters and conditions of the experiment were the same as those in the simulation. The equipment used in the experiment is listed in Table 2, and the experimental environment is shown in Figure 8. Two plywood boards were adopted as targets. In this experiment, from the viewpoint of knowing the influences of the measurement system and the transmitted sound, the impulse response including the loudspeaker, the microphones, and the targets is obtained by the time-stretched pulse (TSP) method [17] (note that the number of synchronous additions is 1) and is convoluted with the transmitted sound.

Table 2. Experimental apparatus

Targets	Plywood square (H:30cm×W:30cm×D:0.5cm) (H:30cm×W:23cm×D:0.5cm)
Audio interface	ROLAND, UA-55
Loudspeaker	YAMAHA, MSP5 STUDIO
Microphone	AUDIO-TECHNICA, AT9904
Microphone amplifier	PAVEC, MA-2016C

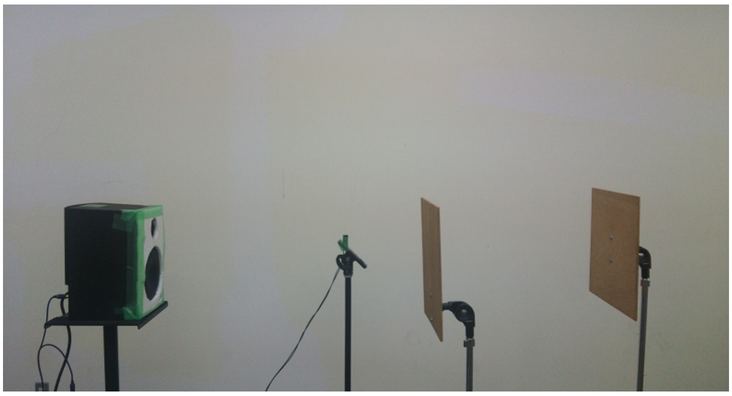
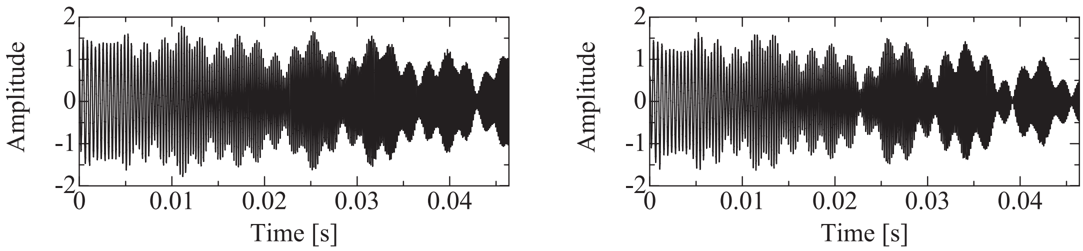


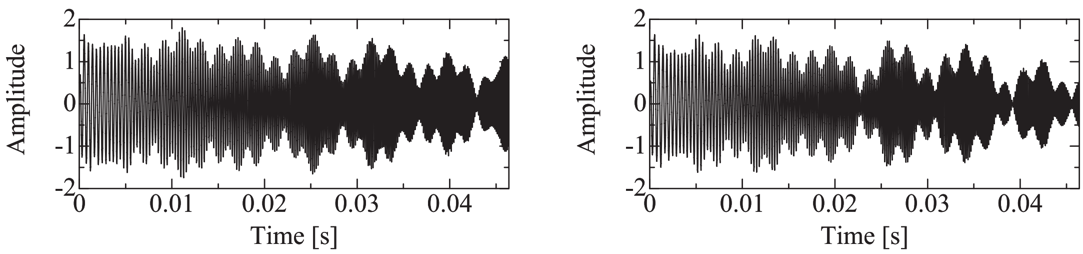
Figure 8. Experimental environment



(a) At mic. 1

(b) At mic. 2

Figure 9. Actually observed waves at mic. 1 and mic. 2 (Real part)

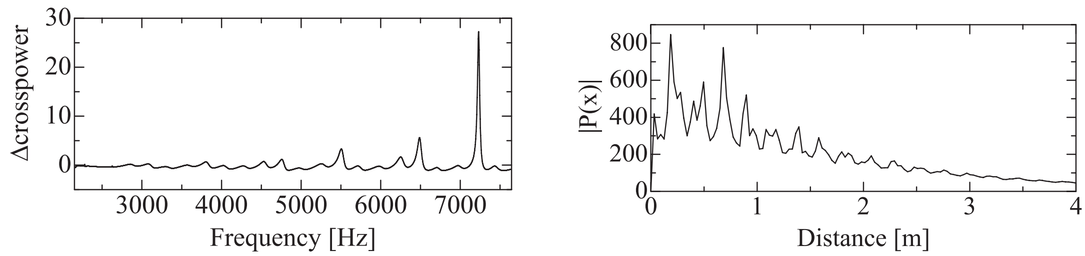


(a) At mic. 1

(b) At mic. 2

Figure 10. Hilbert transform of actually observed waves (Imaginary part)

4.2. **Experimental result.** The observed waves at mic. 1 and mic. 2, which are regarded as the real parts of the analytic signals, are shown in Figures 9(a) and 9(b), respectively. These observed waves are transformed into the imaginary parts of the analytic signals by a Hilbert transform filter, as shown in Figures 10(a) and 10(b). Using these results, Δ cross-power and the range spectrum $|P(x)|$ are obtained in Figures 11(a) and 11(b).



(a) Δ power spectrum (b) Range spectrum

Figure 11. Experimental results obtained by the proposed method for two targets

In Figure 11(b), since the estimated distances are 0.197 m and 0.697 m, the estimated distances approximate the true values of 0.2 m and 0.7 m within an error of 0.03 m, which is the minimum measurable distance. These results might demonstrate the effectiveness of the ADM method for multiple targets, even in an actual sound field. In the range spectrum of Figure 11(b) unlike Figure 7(b) in the simulation, there are several small peaks other than the true peak. This might be because noise, multiple reflections and other effects influence the observations, but we want to discuss it as a future problem.

5. **Conclusion.** We have examined the feasibility of an ADM method that uses the cross-spectrum between analytic signals of 2ch observations and their Hilbert transforms for multiple targets. We confirmed the effectiveness of the ADM method by performing a simulation and an experiment in an actual sound field. Although confined to the experimental environment set here, the proposed method could estimate the distance with an error within the minimum measurable distance of 0.03 m for $d_1 = 0.2$ m and $d_2 = 0.7$ m. Needless to say, the measurement accuracy and noise immunity performance of the ADM method also depends on the characteristics of the target. Therefore, in the future, it will be necessary to study the details of the measurement accuracy and noise resistance.

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