AN IMPLEMENTATION ON PROTOTYPE COMPACT SYSTEM OF TWO-CHANNEL ACOUSTIC DISTANCE MEASUREMENT METHOD MEASURABLE FROM 0M BASED ON THE STANDING WAVE CONSIDERING DIRECT CURRENT COMPONENT AND PHASE SPECTRUM

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The distance to a target is basic information in many engineering fields. Recently, the acoustic distance measurement (ADM) method based on the phase interference between transmitted and reflected waves has been proposed. The power spectrum of an observed signal is a periodic function whose period is inversely proportional to the distance between microphone and target. So this ADM is a practical method that just applies Fourier transform to the power spectrum. Furthermore, the theoretically expanded ADM method has been proposed, which can measure the distance from 0 m by introducing analytic signal instead of power spectrum, where the analytic signal is derived from the power spectra of observed signals of two-channel (2ch) microphones. However, when the distance from a target is very close, the expanded ADM method has error due to Direct Current (DC) components of the power spectra. Besides, authors attempted to implement the ADM method measurable from 0 m with the power spectra into compact system. However, the compact system did not have enough computational power. This paper describes a fundamental study on the ADM method by using the phase spectra of observed signals of 2ch microphones instead of the power spectra and an implementation of the ADM method into prototype compact system introducing high speed microcomputer system, considering DC component of the power spectra. More concretely although the phase spectrum is also a periodic function whose period is inversely proportional to the distance between microphone and target, it has no DC components. We confirmed the validity of the new ADM method measurable from 0 m with phase spectrum by performing a computer simulation and by applying it to an actual sound field and also confirmed the effectiveness of prototype compact system by implementing this ADM theory.

Keywords: Distance measurement measurable from 0 m, prototype compact system, phase interference, range spectrum, phase spectrum

1. Introduction

The distance to target is basic information in various engineering fields. Until now, distance measurement technique has been proposed from various viewpoints. For example, there is microwave or milliwave radar, using radio waves. Although these techniques are used widely (e.g. for vehicle), these are regulated by the Radio Law. Besides, there is also distance measurement technique with acoustic signal. This technique is referred to as Sonar and is widely used. Naturally, this is not regulated the Radio Law.

As one of well-known distance measurement methods, there is distance measurement using TOF (Time of Flight) between transmitted signal of pulse wave and its reflected signal [1, 2]. However, when targets are placed in a close range such as the transmitted wave overlapping with its reflected signal, this method cannot estimate the distance [3].

For close range target, in the field of microwave radar, the distance measurement method using standing wave by phase interference between transmitted and reflected waves has been proposed and can measure the distance from 0 m [4]. We apply this method to audible signal and have proposed the acoustic distance measurement (ADM) method based on phase interference [5, 6].

The ADM method measures the distance using a power spectrum of observed wave. The power spectrum is a periodic function, whose period is inversely proportional to the distance between microphone and target. By applying a Fourier transform to the power spectrum and taking its absolute value, range spectrum $|P(x)|$ can be obtained. The peak position of range spectrum corresponds to the distance between microphone and target. However, since the power spectrum is real, the components in the positive and negative regions of the range spectrum are symmetric with respect to the $|P(x)|$-axis. When there exists a target at close position such as overlapping the components in the positive and negative regions to each other, the distance between microphone and target cannot be estimated correctly by interference of the components. Therefore, we have expanded the ADM method measurable from 0 m [7, 8] and implement this expanded method into prototype system [9, 10].

The expanded ADM method eliminates the negative component of the range spectrum by introducing an analytic signal instead of power spectrum, where the analytic signal is derived from the power spectra of two-channel (2ch) microphones. However, when there exists a target at close range such that only the power spectra within one period are obtained, Direct Current (DC) components of the power spectra cannot be eliminated perfectly, since DC components are estimated with each average of power spectra.

In this paper, we propose ADM method measurable from 0 m considering DC component. The proposed ADM method starts with the analytic signal using phase spectra of 2ch microphones, since the phase spectra have no DC components and the analytic signal can be obtained correctly. When the ADM methods are implemented with personal computer, we may need some space and cost. Therefore, to overcome this problem, we actually built a prototype compact system. We confirmed the validity of the proposed ADM method by performing a computer simulation and by applying it to an actual sound field and also confirmed effectiveness of prototype compact system by implementing the proposed ADM method.

2. Theoretical consideration

2.1 Principle of ADM method based on phase interference [5, 6]

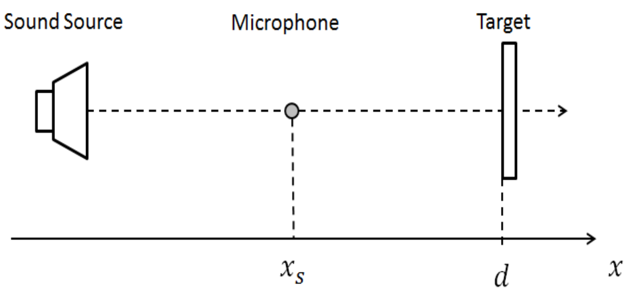


Figure 1: Geometrical position of sound source, microphone and target.

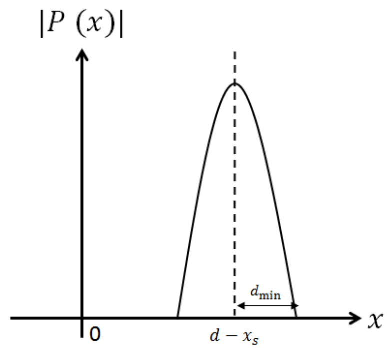


Figure 2: Example of range spectrum $|P(x)|$

Figure 1 indicates the geometrical position of sound source, microphone and target. Let transmitted wave $v_{\mathrm{T}}(t, x)$ be a function of position x[m] and time t[s] which expresses sound pressure as follows:

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

where x_s[m] is arbitrary position of microphone, f[Hz] is frequency (f_1 and f_N correspond to the lowest and highest frequencies, respectively), c[m/s] is the velocity of sound, $A(f)$ is the magnitude and $\theta(f)$[rad] is the initial phase.

The wave $v_{\mathrm{R}}(t, x_s)$ reflected by the target can be expressed as follows:

$$v_{\mathrm{R}}(t, x_s) = \int_{f_1}^{f_N} A(f)\gamma(f) e^{j(2\pi f t - \frac{2\pi f}{c}(2d - x_s) + \theta(f) + \phi(f))} df, \tag{2}$$

where $\gamma(f) e^{j\phi(f)}$ is the reflection coefficient of the target.

The composite wave of transmitted and reflected waves, $v_{\mathrm{C}}(t, x_s) = v_{\mathrm{T}}(t, x_s) + v_{\mathrm{R}}(t, x_s)$, causes a standing wave. By applying the Fourier transform to the composite wave $v_{\mathrm{C}}(t, x_s)$, the power spectrum $p(f, x_s) = |V_{\mathrm{C}}(f, x_s)|^2$ can be approximated as follows, assuming that the magnitude of the reflection coefficient is sufficiently small ($\gamma \ll 1$),

$$p(f, x_s) \approx A^2(f) \left\{ 1 + 2\gamma(f) \cos\left(\frac{4\pi f d}{c} - \phi(f)\right) \right\}. \tag{3}$$

The first and second terms in Eq. (3) pertain to the transmitted and standing waves, respectively. Since $p(f, x_s)$ is a periodic function with period inversely proportional to the distance between microphone and target, the distance can be obtained by applying the Fourier transform again.

Concretely letting a Δ-power $\Delta p(f, x_s)$ be the power spectrum after subtracting DC component $\overline{p(f, x_s)}$ from $p(f, x_s)$, we have

$$\Delta p(f, x_s) = p(f, x_s) - \overline{p(f, x_s)}, \tag{4}$$

where $\overline{p(f, x_s)}$ is an average of $p(f, x_s)$. We call $\Delta p(f, x_s)$ Δ-power spectrum. By applying the Fourier transform to $\Delta p(f, x_s)$, we get

$$P(x) = \int_{f_1}^{f_N} \Delta p(f, x_s) e^{j2\pi \frac{2x}{c} f} df. \tag{5}$$

The absolute value $|P(x)|$ is referred to as range spectrum, whose peak positon corresponds to the estimated value $d - x_s$ of the distance between microphone and target.

Due to the Fourier transform of the finite frequency bandwidth, the range spectrum is not a line spectrum but rather has some width, which corresponds to twice the minimum measurable distance d_{min} as shown in Fig. 2. The minimum measurable distance d_{min} is defined in terms of the frequency bandwidth $f_W (= f_N - f_1)$ and the velocity of sound c as:

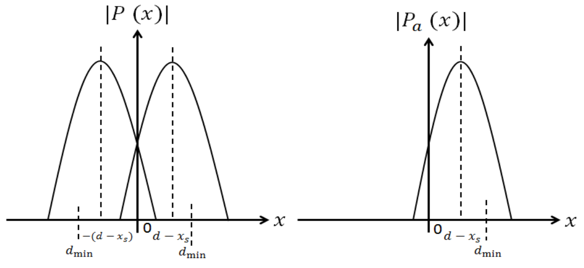
$$d_{\mathrm{min}} = \frac{c}{2 f_W}. \tag{6}$$

2.2 ADM method measurable from 0 m [7, 8, 9, 10]

Since the Δ-power spectrum $\Delta p(f, x_s)$ is real, the components in the positive and negative regions of the range spectrum are symmetric with respect to the $|P(x)|$-axis. When there exists a target at a position closer than the minimum measurable distance, the components in the positive and negative regions of the range spectrum overlap to each other, as shown in Fig. 3 (a).

To eliminate the component in negative region, an analytic signal $p_a(f, x_s)$ is introduced for $\Delta p(f, x_s)$ as

$$p_a(f, x_s) = \Phi(f) e^{j\Theta(f)}, \tag{7}$$



(a) (b)

Figure 3: Example of range spectra: (a)$|P(x)|$ and (b)$|P_a(x)|$.

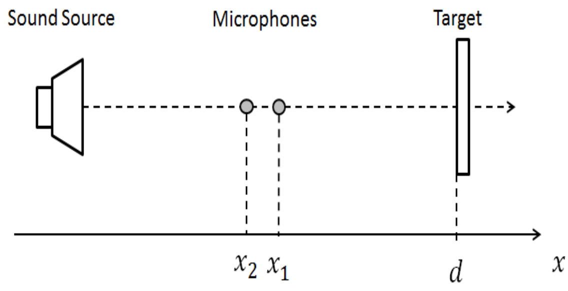


Figure 4: Geometrical position of sound source, 2ch microphones, and target.

where $\Phi(f)$ and $\Theta(f)$ is amplitude information and phase information respectively, and thus the range spectrum in the negative region is eliminated.

When two microphones are placed at x_1 and x_2 as shown in Fig. 4, phase information is obtained as follows:

$$\Theta(f) = \tan^{-1}\left(\frac{\Delta p(f,x_1)\cos(\frac{4\pi f}{c}x_2) - \Delta p(f,x_2)\cos(\frac{4\pi f}{c}x_1)}{\Delta p(f,x_2)\sin(\frac{4\pi f}{c}x_1) - \Delta p(f,x_1)\sin(\frac{4\pi f}{c}x_2)}\right), \tag{8}$$

and amplitude information is obtained as follows:

$$\Phi(f) = \frac{\Delta p(f,x_1)}{\cos(\frac{4\pi f}{c}x_1 - \Theta(f))} \text{ or } \frac{\Delta p(f,x_2)}{\cos(\frac{4\pi f}{c}x_2 - \Theta(f))}. \tag{9}$$

Equations (8) and (9) mean that the amplitude and phase informations can be calculated by using Δ-power spectra at two microphone positions.

Since this $p_a(f,x_1)$ is also a periodic function, the period of which is inversely proportional to the distance between microphone and target, the Fourier transform $P_a(x)$ can be obtained using Eq.(5). The absolute value $|P_a(x)|$ is also referred to as a range spectrum, whose peak positon corresponds to the estimated value $d - \frac{x_1+x_2}{2}$ of the distance between microphone and target. Figure 3 (b) shows an example of range spectrum $|P_a(x)|$. It is clear that a peak of the range spectrum in negative region is eliminated.

2.3 ADM method measurable from 0 m considering DC component

When the distance to target is very close, the power spectrum $p(f,x_s)$ has information shorter than one period though $p(f,x_s)$ is a periodic function. So, since average (or DC component) of power spectrum $\overline{p(f,x_s)}$ cannot be obtained correctly, Δ-power spectrum $\Delta p(f,x_s)$ have error in Eq. (4). Therefore, $p_a(f,x_1)$ does not yield the distance estimation correctly.

To obtain the distance between microphone and target considering the DC component error, Δ-phase spectrum $\Delta\angle V_{\mathrm{C}}(f,x_s)$ instead of Δ-power spectrum $\Delta p(f,x_s)$ is introduced. Letting $V_{\mathrm{T}}(f,x_s)$ be the Fourier transform of transmitted wave $v_{\mathrm{T}}(t,x_s)$, we obtain approximately Δ-phase spectrum $\Delta\angle V_{\mathrm{C}}(f,x_s)$ as follows, assuming that the magnitude of the reflection coefficient is sufficiently small ($\gamma \ll 1$),

$$\begin{aligned}\Delta\angle V_{\mathrm{C}}(f,x_s) &= \angle V_{\mathrm{C}}(f,x_s) - \angle V_{\mathrm{C}_0}(f,x_s) \\ &\approx \gamma(f)\sin(\frac{4\pi f}{c}d - \phi(f)),\end{aligned} \tag{10}$$

where $\angle V_{\mathrm{C}}(f,x_s)(=\tan^{-1}(\frac{\mathrm{Im}[V_{\mathrm{C}}(f,x_s)]}{\mathrm{Re}[V_{\mathrm{C}}(f,x_s)]}))$ and $\angle V_{\mathrm{C}_0}(f,x_s)(=\tan^{-1}(\frac{\mathrm{Im}[V_{\mathrm{T}}(f,x_s)]}{\mathrm{Re}[V_{\mathrm{T}}(f,x_s)]}))$ respectively.

Similar to the case of power spectrum, an analytic signal $p_a(f, x_s)$ is introduced for $\Delta p(f, x_s)$ as in Eq. (7). Phase information is obtained as follows:

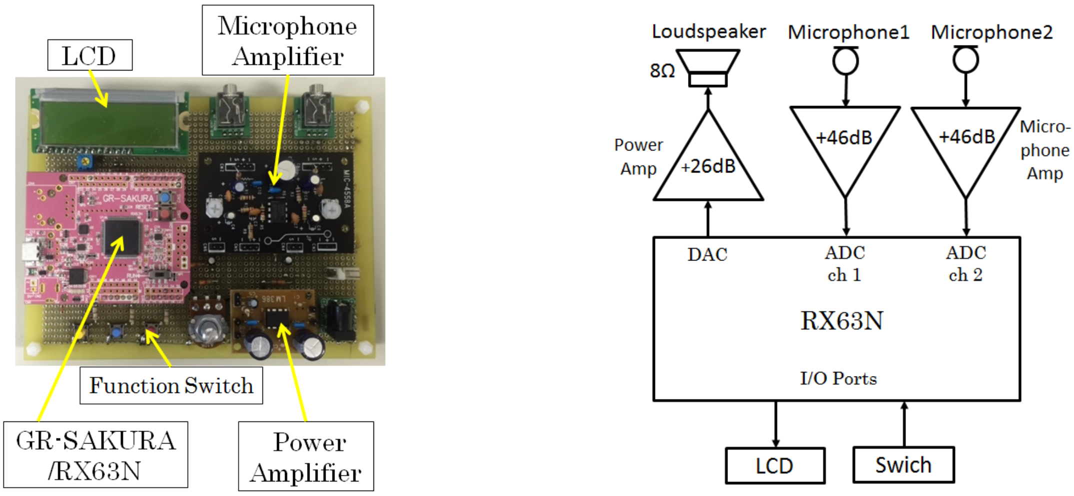
$$\Theta(f) = \tan^{-1}\left(\frac{\Delta\angle V_{\mathrm{C}}(f, x_2)\sin(\frac{4\pi f}{c}x_1) - \Delta\angle V_{\mathrm{C}}(f, x_1)\sin(\frac{4\pi f}{c}x_2)}{\Delta\angle V_{\mathrm{C}}(f, x_2)\cos(\frac{4\pi f}{c}x_1) - \Delta\angle V_{\mathrm{C}}(f, x_1)\cos(\frac{4\pi f}{c}x_2)}\right), \tag{11}$$

and amplitude information is obtained as follows:

$$\Phi(f) = \frac{\Delta\angle V_{\mathrm{C}}(f, x_1)}{\sin(\frac{4\pi f}{c}x_1 - \Theta(f))} \text{ or } \frac{\Delta\angle V_{\mathrm{C}}(f, x_2)}{\sin(\frac{4\pi f}{c}x_2 - \Theta(f))}. \tag{12}$$

Equations (11) and (12) mean that the amplitude and phase informantion can be calculated by using Δ-phase spectrum $\Delta\angle V_{\mathrm{C}}(f, x_s)$ at two microphone positions. The absolute value $|P_a(x)|$ is also referred to as a range spectrum, whose peak positon corresponds to the estimated value $d - \frac{x_1+x_2}{2}$ of the distance between microphone and target.

3. Prototype compact system



(a) (b)

Figure 5: Prototype compact system; (a)Appearance and (b)Block diagram.

To realize compact ADM system based on the proposed method, we built a prototype compact system. Figures 5 (a) and (b) indicate appearance and block diagram of prototype compact system. The prototype compact system has RX63N which is 32bit CPU with 96MHz clock frequency and has floating point unit. Therefore, signal processing is performed by 32bit floating point operation.

Transmitted signal is generated through 10bit DA converter built-in RX63N. Signals observed with two-microphones are also imported by 12bit AD converter built-in RX63N. Sampling frequency is 44.1kHz.

4. Computer simulation

4.1 Simulation condition

Table 1 shows simulation conditions. A transmitted signal is a band-limited impulse signal as shown in Fig. 6. Since bandwidth is 5.5kHz(=f_W) from 2.1kHz(=f_1) to 7.6kHz(=f_N), $d_{\mathrm{min}} = 0.03$ m by Eq. (6). Since the number of data points in frequency domain are 256, in processing FFT, data points in frequency domain increase to 2048 by 0-padding. Thus, the step width on the distance axis is 3.8×10^{-3} m. In addition, if Δ-phase spectrum has a value out of range $\pm\pi$, we performed phase-wrapping so as to make it within $\pm\pi$.

Table 1: Simulation conditions.

Sound source	Band-limited impulse signal
Sampling frequency	44.1kHz
Data points in time domain	2048
Data points in frequency domain	256
Data points in frequency domain (after 0-padding)	2048
Frequency bandwidth	5.5kHz(2.1kHz∼7.6kHz)
Magnitude of reflection coefficient γ	0.05
Phase of reflection coefficient ϕ	$\pi/2$ rad
Minimum measurable distance	3.8×10^{-3} m
Position of microphone 1 x_1	0.0 m
Position of microphone 2 x_2	-0.006 m
Distance from microphone to target	0.01 m

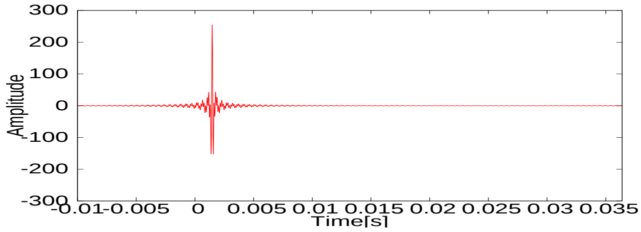


Figure 6: An example of transmitted wave.

4.2 Simulation results

Figures 7 (a) and (b) show the observed wave and its Δ-phase spectrum at microphone 1 position (x_1). Figures 7 (c) and (d) show the amplitude information and the phase information derived from Δ-phase spectra at x_1 and x_2. Figures 7 (e) and (f) show range spectrum and its enlargement around peak position. In Fig. 7 (f), the estimated distance is 0.0115 m. The error between the estimated distance and the true distance is smaller than the step width on distance axis 3.8×10^{-3} m. Therefore, this result could show the validity of considering the DC component by using the phase spectra.

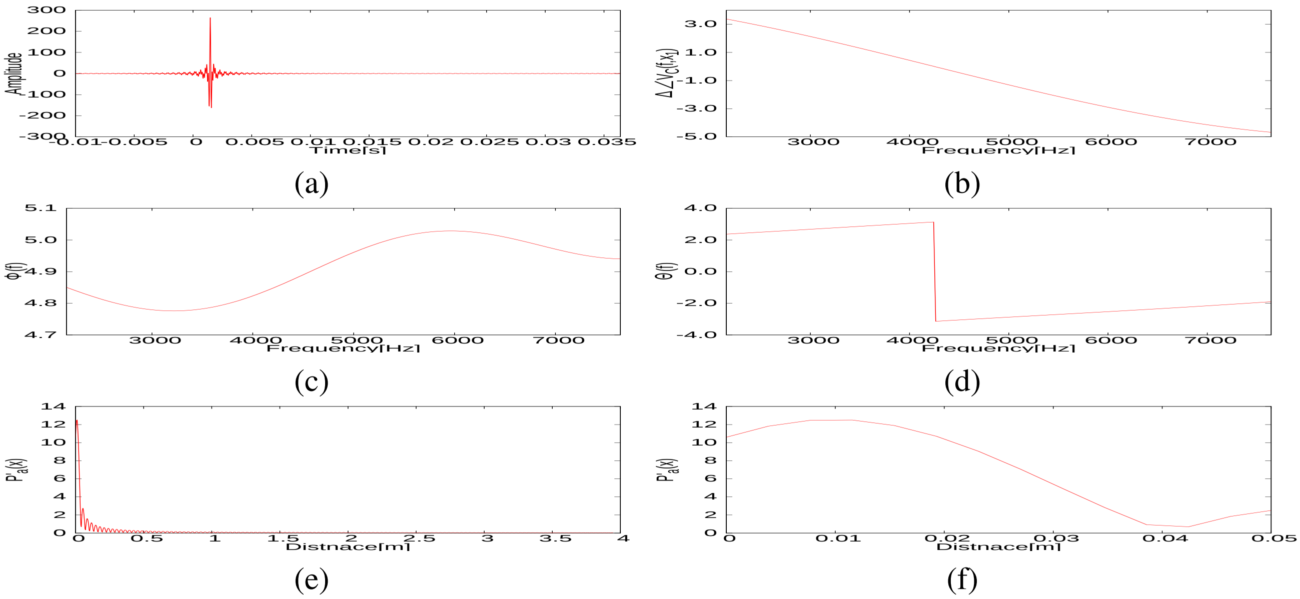


Figure 7: Simulation results; (a)Observed wave at x_1, (b)Δ-phase spectrum at x_1, (c)Amplitude informantion, (d)Phase information, (e)Range spectrum and (f)Enlargement of range spectrum around peak position.

5. Evaluation of the prototype comapact system and the proposed method in an actual sound field

5.1 Experimental condition

The experimental conditions are basically same as the simulation conditions. To obtain Δ-phase spectrum in Eq.(10), we need the phase spectrum $\angle V_{C_0}(f, x_s)$. In actual sound field, we obtain the phase spectrum $\angle V_{C_0}(f, x_s)$ by measuring the observed wave without target. This time, a plywood square is adopted as a target. Letting the position of microphone 1 be the origin ($x_1 = 0$ m), microphone 2 is placed on -0.006 m. The velocity of sound is 342.9 m/s (i.e. Room temperature is

19°C). Table 2 indicates the experimental apparatus and system specification and Figure 8 shows the experimental environment. Experiment is performed in a part of room (Depth:5.97 m, Width:6.18 m, Height:2.56 m).

Table 2: Experimental apparatus and system specification.

Target	Plywood square (H:30cm × W:30cm × D:0.5cm)
Noise meter	Brüel&Kjær, Type2236
Microphone	AUDIO-TECHNICA, AT9904
Loudspeaker	8Ω8W
Speaker Drive amplitude	3V(max)
Microphone amplifier Gain	46dB
Sampling frequency	44.1kHz
Quantization	12bit(AD), 10bit(DA)

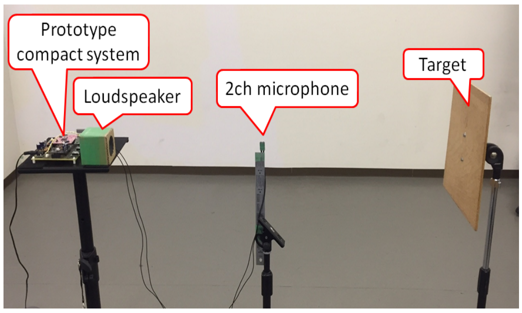


Figure 8: Experimental environment.

5.2 Experimental results

Figures 9 (a) and (b) show the observed wave with target by recording with microphone 1 (x_1) and the its Δ-phase spectrum. Figures 9 (c) and (d) show the amplitude information and the phase information derived from Δ-phase spectra at x_1 and x_2. Figures 9 (e) and (f) show range spectrum and its enlargement around peak position. In Fig. 9, the estimated distance is 0.0117 m. The error between the estimated distance and the true distance is smaller than the step width on distance axis 3.8×10^{-3} m. Also, the processing time in this experiment is about 0.1 sec. Therefore, even in an actual sound field, we were able to confirm the validity of the proposed ADM method and the effectiveness of prototype compact system.

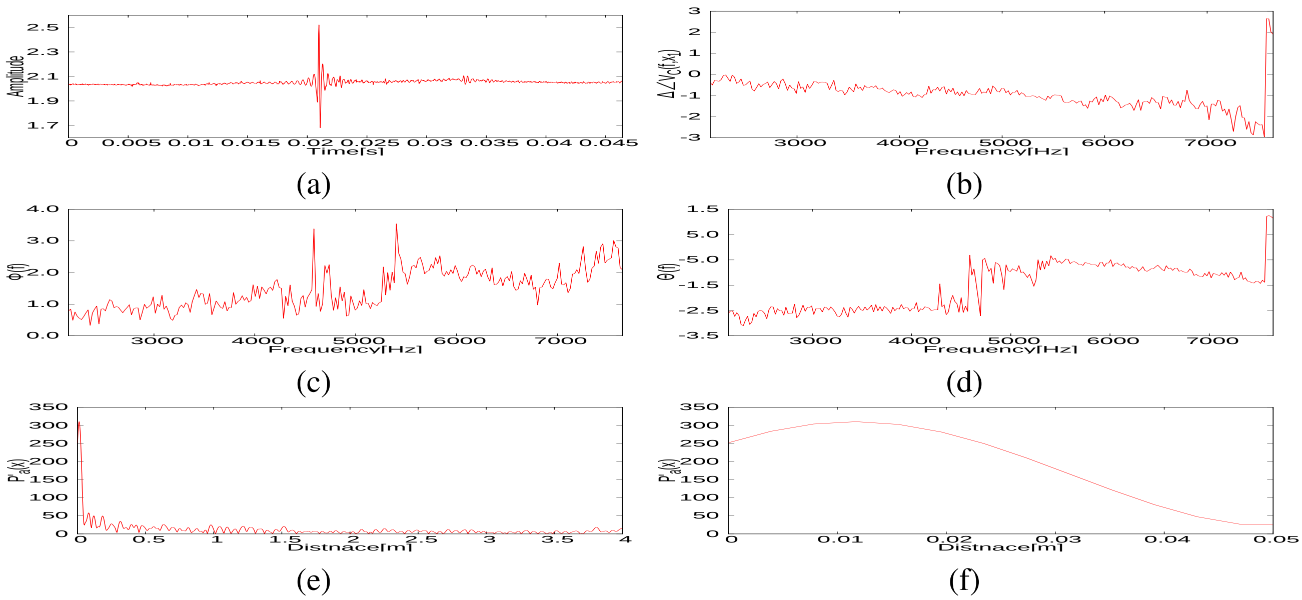


Figure 9: Experimantal results; (a)Observed wave at x_1, (b)Δ-phase spectrum at x_1, (c)Amplitude information, (d)Phase information, (e)Range spectrum and (f)Enlargement of range spectrum around peak position.

6. Conclusion

We have proposed the ADM method measurable form 0 m considering DC component and implement this method to prototype compact system. In simulation, we could confirm the validity of the proposed theory. In experiment in an actual sound field, we could obtain the distance between microphone and target. The error between the estimated value and the true value is smaller than the step width on distance axis 3.8×10^{-3} m. Therefore, we could confirm the effectiveness of the proposed theory in the actual sound field. Also, a processing time of the experiment was about 0.1 sec. It can be considered that the prototype compact system can be sufficiently withstood in real environment. In the future, we confirm the validity of the proposed ADM method by applying to the various environment and also comfirm the effectiveness of the prototype compact system by implementing various ADM methods.

Acknowledgments

The present study was supported in part by a grant from the Strategic Research Foundation Grant-aided Project for Private Universities from the Ministry of Education, Culture, Sport, Science, and Technology, Japan(MEXT), 2013–2017(S1311045).

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