ACOUSTIC DISTANCE MEASUREMENT BASED ON PHASE INTERFERENCE USING THE CROSS-SPECTRAL METHOD WITH ADJACENT MICROPHONES

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ABSTRACT

In a number of engineering fields, information on the distance to the target is very important. We previously proposed an acoustic distance measurement method based on interference between the transmitted and reflected waves, which can be used for distance measurement over a short range. In the previously proposed method, a sound source of the transmitted wave must be known in advance. In the present paper, we propose a new acoustic distance measurement method based on phase interference obtained using the cross-spectral method with adjacent microphones, which does not require the condition that a sound source of the transmitted wave is known. Finally, we confirmed the validity and effectiveness of the newly proposed method through both computer simulation and evaluation experiment in a real environment.

Index Terms— Acoustic distance measurement, Phase interference, Short range, Cross-spectral method, Adjacent microphones

1. INTRODUCTION

Estimating short distances to targets is important in a number of engineering fields. In particular, the distances must be known for practical use of hands-free speech interfaces and nursing-care robots. A number of distance measurement methods, which use the time delay of a reflected wave measured with reference to the transmitted wave, have been proposed [1, 2]. However, these methods cannot measure short distances because the transmitted wave, which has not attenuated sufficiently at the time of a reflected wave reception, suppresses reflected waves for short distances [3, 4, 5]. Therefore, we previously proposed an acoustic distance measurement method based on interference between transmitted and reflected waves that can measure short distances [6, 7, 8]. The previously proposed method requires equipment such as a loudspeaker and a microphone for a cancellation processing of background components due to the spectrum of the transmitted wave and the transfer function of the measurement system in real environments.

Meanwhile, the cross-spectral method has been proposed as a measurement method for the acoustic transfer function [9]. This method can measure the transfer function between two microphones using reference and measurement microphones. Thus, the cross-spectral method does not require the condition that a sound source of the transmitted wave is known because the frequency responses of the sound source and measurement system are whitened. This suggests that we can estimate the distance to targets without known information of a sound source by introducing the concept of the cross-spectral method to the acoustic distance measurement.

Therefore, in the present paper, we propose a new acoustic distance measurement method based on phase interference using the cross-spectral method with adjacent microphones, which does not require the condition that a sound source of the transmitted wave is known. In the newly proposed method, unlike in the conventional cross-spectral method, the measurement microphone is placed near the reference microphone. Thus, the power of the whitened cross spectrum captures the fluctuation of the periodic function, which is inversely proportional to the distance between each microphone and a target, due to interference between transmitted and reflected waves. The distance to a target can be measured by extracting and analyzing this power fluctuation, which is the phase interference. Finally, we confirm the validity and effectiveness of the newly proposed method through both computer simulation and evaluation experiment in a real environment.

2. PRINCIPLE OF THE PROPOSED METHOD

In this section, we describe the theory behind the new acoustic distance measurement method based on phase interference obtained using the cross-spectral method with adjacent micro-

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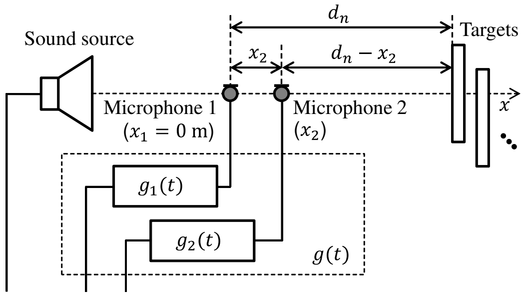


Fig. 1. Measurement environment of the proposed method.

phones.

Let the transmitted wave v_{T}, which expresses the sound pressure, be a function of position x [m] and time t [s], as follows:

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

where f [Hz] is the frequency, f_1 [Hz] and f_N [Hz] correspond to the lowest and highest frequencies, respectively, $A(f)$ is the spectrum of the transmitted wave, and c [m/s] is the speed of sound.

Assuming that the transmitted wave is reflected by m targets, the wave reflected by the n-th target can be expressed as follows:

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

where d_n [m] is the distance to the n-th target, and γ_n and ϕ_n [rad] are the amplitude and phase of the reflection coefficient for the n-th target, respectively.

Figure 1 shows the measurement environment of the proposed method. As shown in Fig. 1, $g_1(t)$ is assumed to be approximated by $g_2(t)$, as follows:

$$g(t) = g_1(t) \approx g_2(t), \tag{3}$$

where $g(t)$ is the impulse response of the measurement system. For m targets, the composite wave, which is a composition of all transmitted and reflected waves at x_1 (= 0 m) and x_2 m, is formulated as

$$v_{\mathrm{C}}(t,0) \approx g(t) * \left\{ v_{\mathrm{T}}(t,0) + \sum_{n=1}^{m} v_{\mathrm{R}_n}(t,0) \right\}, \tag{4}$$

$$v_{\mathrm{C}}(t,x_2) \approx g(t) * \left\{ v_{\mathrm{T}}(t,x_2) + \sum_{n=1}^{m} v_{\mathrm{R}_n}(t,x_2) \right\}, \tag{5}$$

where $*$ is a convolution operator.

By applying the Fourier transform to $v_{\mathrm{C}}(t,0)$ and $v_{\mathrm{C}}(t,x_2)$, Fourier spectra $V_{\mathrm{C}}(f,0)$ and $V_{\mathrm{C}}(f,x_2)$ can be easily obtained as follows:

$$V_{\mathrm{C}}(f,0) = A(f)G(f) + \sum_{n=1}^{m} A(f)G(f)\gamma_n e^{-j\left(\frac{2\pi f}{c} 2d_n - \phi_n\right)}, \tag{6}$$

$$V_{\mathrm{C}}(f,x_2) = A(f)G(f) e^{-j\{\frac{2\pi f}{c} x_2\}} + \sum_{n=1}^{m} A(f)G(f)\gamma_n e^{-j\left(\frac{2\pi f}{c}(2d_n - x_2) - \phi_n\right)}, \tag{7}$$

where $G(f)$ is the transfer function of the measurement system.

By applying $v_{\mathrm{C}}(t,0)$ and $v_{\mathrm{C}}(t,x_2)$ as the input and output signals, respectively, in the cross-spectral method, the cross spectrum is obtained as follows:

$$C(f,0,x_2) = \frac{V_{\mathrm{C}}^*(f,0) V_{\mathrm{C}}(f,x_2)}{V_{\mathrm{C}}^*(f,0) V_{\mathrm{C}}(f,0)}, \tag{8}$$

where $V_{\mathrm{C}}^*(f,0)$ is the complex conjugate of $V_{\mathrm{C}}(f,0)$.

For the case in which the observation point is located near a sound source, we can assume that $\gamma_n \ll 1$. Thus, from $\gamma_n \ll 1$, Euler's formula, and Eqs. (6) through (8), $C(f,0,x_2)$ is approximated as follows:

$$C(f,0,x_2) \approx \frac{e^{jD(f)} + \sum_{n=1}^{m} \gamma_n e^{j\alpha_n(f)} + \sum_{n=1}^{m} \gamma_n e^{-j\alpha_n(f)}}{1 + \sum_{n=1}^{m} \gamma_n e^{j\beta_n(f)} + \sum_{n=1}^{m} \gamma_n e^{-j\beta_n(f)}} = \frac{e^{jD(f)} + 2\sum_{n=1}^{m} \gamma_n \cos(\alpha_n(f))}{1 + 2\sum_{n=1}^{m} \gamma_n \cos(\beta_n(f))}, \tag{9}$$

$$D(f) = -\frac{2\pi f}{c} x_2, \tag{10}$$

$$\alpha_n(f) = \frac{2\pi f}{c}(2d_n - x_2) - \phi_n, \tag{11}$$

$$\beta_n(f) = \frac{4\pi f}{c} d_n - \phi_n. \tag{12}$$

Furthermore, for the case in which $\gamma_n \ll 1$, we have the following approximation: $1 + 2\sum_{n=1}^{m} \gamma_n \cos(\beta_n(f)) \approx 1$. Thus, the power of $C(f,0,x_2)$ is approximated as follows:

$$p(f,0,x_2) \approx 1 + 2\sum_{n=1}^{m} \gamma_n \left\{ \cos\left(\frac{4\pi f}{c} d_n - \phi_n\right) + \cos\left(\frac{4\pi f}{c}(d_n - x_2) - \phi_n\right) \right\}, \tag{13}$$

where $p(f,0,x_2)$ is the power of $C(f,0,x_2)$, and the terms of cos indicate phase interference. Therefore, Eq. (13) indicates that $p(f,0,x_2)$ is periodic with respect to frequency f and that the period of $p(f,0,x_2)$ is inversely proportional to the distances between the observation points and the target. Here, we can extract phase interference corresponding to distance as follows:

$$\Delta p(f,0,x_2) = p(f,0,x_2) - \overline{p(f,0,x_2)}, \tag{14}$$

where $\overline{p(f,0,x_2)}$ is the average of $p(f,0,x_2)$. Consequently, the distances between the observation points and the target can be determined by applying the Fourier transform again to $\Delta p(f,0,x_2)$. Namely, in the Fourier transform formula:

$$F(f) = \int_{-\infty}^{\infty} f(t)e^{-j2\pi ft}\mathrm{d}t, \tag{15}$$

replacing f with $2x/c$, t with f, and $f(t)$ with $\Delta p(f,0,x_2)$, $P(x)$ can be obtained by the following formula:

$$P(x) = \int_{f_1}^{f_N} \Delta p(f,0,x_2)e^{-j2\pi\frac{2x}{c}f}\mathrm{d}f, \tag{16}$$

where this transform differs from the cepstrum [10] in that this transform is not the inverse Fourier transform, but rather the Fourier transform. The peaks of the range spectrum $|P(x)|$ correspond to the distances d_n m and $d_n - x_2$ m to be estimated.

In addition, minimum measurable distance (MMD) d_{min} is defined by the frequency bandwidth f_{W} $(= f_N - f_1)$ [6, 7]. Namely, the period of $C(f)$ must be shorter than f_{W} in order to find peaks of $|P(x)|$ exactly. Thus,

$$d_{\mathrm{min}} = \frac{c}{2f_{\mathrm{W}}}. \tag{17}$$

In addition, the length of targets should be sufficiently longer than the minimum wavelength of the transmitted wave.

3. COMPUTER SIMULATION

In order to confirm the validity of the proposed method, we performed the computer simulation of the proposed method.

3.1. Simulation conditions

Table 1 shows the simulation conditions. In this simulation, we employ a small reflection coefficient because we assume that $\gamma_n \ll 1$. When the reflection coefficient is large, the peak of range spectrum tends to arise at x_2 m. Fourier transform is performed with the fast Fourier transform (FFT). The analyzed data length of $\Delta p(f,0,x_2)$ is 256 samples (5.5 kHz). Applying zero padding to $\Delta p(f,0,x_2)$, FFT data length of $\Delta p(f,0,x_2)$ is 2048 samples (44.1 kHz). The step size of distance axis can be obtained as follows:

$$\Delta d = \frac{cL}{2f_{\mathrm{W}}L'}, \tag{18}$$

Table 1. Simulation conditions.

Transmitted wave source	Band-limited impulse
Sampling frequency	44.1 kHz, 16 bit
Measurement time	46 ms
Frequency bandwidth	5.5 kHz (2.1 kHz $\sim$ 7.6 kHz)
MMD	0.03 m
Sound speed	340 m/s
Reflection coefficient	$\gamma_1 = 0.05$, $\phi_1 = \pi$

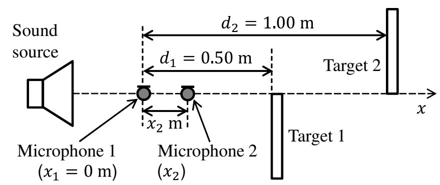


Fig. 2. Computer simulation environment.

where L is the analyzed data length of $\Delta p(f,0,x_2)$, and L' is FFT data length of $\Delta p(f,0,x_2)$. Therefore, the step size of distance axis can be set arbitrarily. However, the distance resolution depends on MMD, although the step size of the distance axis can be arbitrarily small. Here, if x_2 m is smaller than the distance resolution, the peak of the range spectrum is detected as a single peak rather than two peaks. In this simulation, the step size of the distance axis is $\Delta d = 0.003$ m. In calculating the cross spectrum shown in Eq. (8), a number of synchronous addition is 1 times.

Figure 2 shows the computer simulation environment. As shown in Fig. 2, in this simulation, we evaluate two conditions in which the interval between microphones 1 and 2 is set as $x_2 = 0.006$ m. Figure 3 shows the transmitted wave for this simulation. This band-limited impulse is created using Eq. (1).

3.2. Simulation results

Figures 4(a) and 4(b) show $\Delta p(f,0,x_2)$ and the range spectrum under the simulation condition of $x_2 = 0.006$ m and two targets, respectively. As a result of Fig. 4, the peaks of the range spectrum are detected at d_1 m and d_2 m.

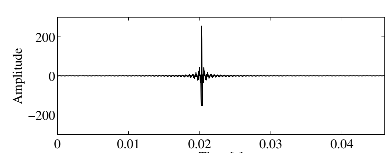
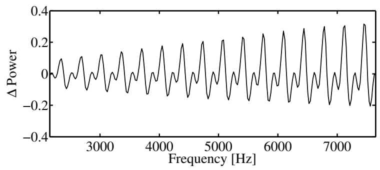
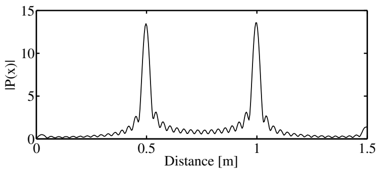


Fig. 3. Transmitted wave.



(a) $\Delta p(f, 0, x_2)$.



(b) Range spectrum.

Fig. 4. Simulation results ($x_2 = 0.006$ m).

Table 2. Experimental conditions.

Transmitted wave source	Band-limited impulse
Sampling frequency	44.1 kHz, 16 bit
Measurement time	46 ms
Frequency bandwidth	5.5 kHz (2.1 kHz $\sim$ 7.6 kHz)
MMD	0.03 m
Sound speed	340 m/s
Reverberation time	0.7 s
Ambient noise level	$L_A = 32$ dB
Target	Plywood square (H30cm $\times$ W22.5cm $\times$ D0.5cm)

4. EVALUATION EXPERIMENT

In order to confirm the effectiveness of the proposed method, we performed the evaluation experiment of the proposed method in a real environment.

4.1. Experimental conditions

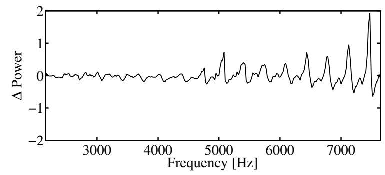
Tables 2 and 3 list the experimental conditions and the experimental equipment, respectively. In the experiment, the frequency bandwidth is expanded by zero padding of the frequency axis to 44.1 kHz. Therefore, the step size of the distance axis is $\Delta d = 0.003$ m. In order to reduce multiple reflection between the loudspeaker and the target, a sound absorption panel is placed in front of the loudspeaker. The transmitted wave is the same as the band-limited impulse for the simulation conditions, as shown in Fig. 3. The experimental environment is similar to the computer simulation as shown in Fig. 2.

4.2. Experimental results

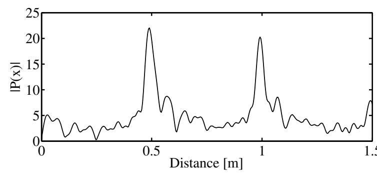
Figure 5 shows the experimental results. Based on result of 5, the proposed method is effective for multiple targets. As shown in Fig. 5, the peaks are detected exactly at d_1 m and d_2 m because these are detected within the distance resolution of MMD.

Table 3. Experimental equipment.

Audio interface	ROLAND, UA-25EX
Loudspeaker	BOSE, 101MM
Power amplifier	BOSE, 1705II
Microphone	AUDIO-TECHNICA, AT9904
Microphone amplifier	PAVEC, MA-2016B



(a) $\Delta p(f, 0, x_2)$.



(b) Range spectrum.

Fig. 5. Experimental results ($x_2 = 0.006$ m).

5. CONCLUSIONS

In the present paper, we proposed a new acoustic distance measurement method based on phase interference obtained using the cross-spectral method with adjacent microphones, which does not require the condition that a sound source of the transmitted wave is known. We confirmed the validity and effectiveness of the proposed method through both computer simulation and evaluation experiment in a real environment. In future, for practical use of the proposed method, we intend to perform evaluation experiments with different types of targets in noisy environments.

6. REFERENCES

[1] T. Ihara and K. Fujimura, "Research and development trends of millimeter-wave short-range application systems," *IEICE Trans. Commun.*, vol. E79-B, pp. 1741–1753, Dec. 1996.

[2] T. Kodama, K. Nakahira, Y. Kanaya, and T. Yoshikawa, "Application of digital polarity correlators in a sonar ranging system," *IEEJ Trans. EIS*, vol. 127, pp. 317–323, Oct. 2007.

[3] M. Parrilla, J.J. Anaya, and C. Fritsch, "Digital signal processing techniques for high accuracy ultrasonic range measurements," *IEEE Trans. Instrum. Means.*, vol. 40, no. 4, pp. 759–763, Aug. 1991.

[4] M. Yang, S.L. Hill, B. Bury, and J.O. Gray, "A multifrequency am-based ultrasonic system for accuracy distance measurement," *IEEE Trans. Instrum. Means.*, vol. 43, no. 6, pp. 291–294, Dec. 1994.

[5] M. Okugumo, A. Kimura, M. Ohki, and M. Ohkita, "Development research on high performance ultrasound sensor system," *IEEJ Trans. EIS*, vol. 128, no. 1, pp. 55–61, Jan. 2008.

[6] N. Nakasako, T. Uebo, A. Mori, and N. Ohmata, "Fundamental consideration on distance estimation using acoustical standing wave," *IEICE Trans. Fundamentals*, vol. E91-A, no. 4, pp. 1218–1221, Apr. 2008.

[7] M. Nakayama, S. Hanabusa, N. Nakasako, and T. Uebo, "Robust acoustic distance measurement method based on interference in noisy environments," in *Proc. ISCIT2010*. IEEE, 2010, pp. 176–181.

[8] M. Nakayama, S. Hanabusa, T. Uebo, and N. Nakasako, "Acoustic distance measurement method based on phase interference using calibration and whitening processing in real environments," *IEICE Trans. Fundamentals*, vol. E94-A, no. 8, pp. 1638–1646, Aug. 2011.

[9] M. Fukushima, H. Inoue, K. Kamura, H. Yanagawa, and K. Kido, "A method for the determination of noise factor in estimated transfer function - cross spectral technique by use of 1-0 and 1-000 windows -," in *Proc. of ICA2004*. ASJ, 2004, vol. 25, pp. 166–169.

[10] D.G. Childers, D.P. Skinner, and R.C. Kemerait, "The cepstrum: A guide to processing," *Proc. the IEEE*, vol. 65, no. 10, pp. 1428–1443, Oct. 1977.