Acoustic distance measurement method based on phase interference using the cross-spectral method

Masato Nakayama\(^1\,^2\,*\), Noboru Nakasako\(^2\), Tetsuji Uebo\(^2\,^3\) and Manabu Fukushima\(^4\)

\(^1\)College of Information Science and Engineering, Ritsumeikan University, 1–1–1 Noji Higashi, Kusatsu, 525–8577 Japan
\(^2\)Faculty of Biology-Oriented Science and Technology, Kinki University, 930 Nishi-mitani, Kinokawa, Wakayama, 649–6493 Japan
\(^3\)WIRE AUTOMATIC DEVICE Co., Ltd., 1–9–27 Jokoji, Amagasaki, 660–0811 Japan
\(^4\)Faculty of Engineering, Nippon Bunri University, 1727 Ichigi, Oita, 870–0397 Japan

(Received 19 March 2012, Accepted for publication 5 November 2012)

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. The previously proposed method requires equipment such as a loudspeaker and a microphone for cancellation processing of background components due to the spectrum of the transmitted wave and the transfer function of the measurement system in real environments. Therefore, 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 stereo microphones, which does not require the condition that a sound source of the transmitted wave is known. The conventional cross-spectral method requires a measuring remote microphone and a reference microphone to be placed near a loudspeaker, meanwhile the proposed method requires stereo microphones to be placed near a sound source. Finally, we confirmed the validity and effectiveness of the newly proposed method through computer simulations and evaluation experiments in real environments.

Keywords: Acoustic distance measurement, Phase interference, Short range, Cross-spectral method, Stereo microphones

PACS number: 43.60.Ac, 43.20.Ks [doi:10.1250/ast.34.197]

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 [3–5]. This is caused by the transient response characteristics of the equipment in real environments. Accordingly, even if an impulse response can be measured, distance measurement cannot be achieved for short distances. Therefore, we previously proposed an acoustic distance measurement method based on interference between transmitted and reflected waves that can measure short distances [6–8]. 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. More specifically, this method requires recording of either the transmitted wave under the condition without targets [6, 7], or an impulse response of the measurement system as preprocessing [8]. Thus, a sound source of the transmitted wave must be known in advance.

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. More specifically, an input signal is observed by a reference microphone located near a sound source, and the output signal is observed by a measurement microphone located at a remote position. Here, the transfer function is measured by whitening the cross spectrum between the input and output signals using the power spectrum of the input signal. 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 stereo 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 computer simulations and evaluation experiments in real environments.

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 stereo microphones.

Let the transmitted wave \( v_T \), which expresses the sound pressure, be a function of position \( x \) [m] and time \( t \) [s], as follows:

\[
v_T(t, x) = \int_{f_1}^{f_2} A(f)e^{i\left(2\pi ft - \frac{2\pi}{c}x\right)} df,
\]

where \( f \) [Hz] is the frequency, \( f_1 \) [Hz] and \( f_2 \) [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. Then, \( A(f) \) is represented in terms of the amplitude and phase spectrum as follows:

\[
A(f) = |A(f)|e^{i\phi(f)},
\]

where \(|A(f)|\) and \( \phi(f) \) [rad] are the amplitude and phase of the transmitted wave, respectively.

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

\[
v_{R_n}(t, x) = \int_{f_1}^{f_2} A(f)\gamma_n e^{-j\left(\frac{2\pi}{c}2d_n - 2x\right) + \phi_n} df,
\]

where \( d_n \) [m] is the distance to the \( n \)-th target, and \( \gamma_n \) and \( \phi_n \) [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, \( g_i(t) \) is assumed to be approximated by \( g_2(t) \), as follows:

\[
g(t) = g_1(t) \approx g_2(t),
\]

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

\[
v_C(t, 0) \approx g(t) \ast \left\{ v_T(t, 0) + \sum_{n=1}^{m} v_{R_n}(t, 0) \right\},
\]

\[
v_C(t, x_2) \approx g(t) \ast \left\{ v_T(t, x_2) + \sum_{n=1}^{m} v_{R_n}(t, x_2) \right\},
\]

where \( \ast \) is a convolution operator.

By applying the Fourier transform to \( v_C(t, 0) \) and \( v_C(t, x_2) \), Fourier spectra \( V_C(f, 0) \) and \( V_C(f, x_2) \) can be easily obtained as follows:

\[
V_C(f, 0) = A(f)G(f) + \sum_{n=1}^{m} A(f)G(f)\gamma_n e^{-j\left(\frac{2\pi}{c}2d_n - \phi_n\right)},
\]

\[
V_C(f, x_2) = A(f)G(f)e^{-j\left(\frac{2\pi}{c}2d_n - \phi_n\right)} + \sum_{n=1}^{m} A(f)G(f)\gamma_n e^{-j\left(\frac{2\pi}{c}2d_n - \phi_n\right)},
\]

where \( G(f) \) is the transfer function of the measurement system. Then, \( G(f) \) is represented in terms of the amplitude and phase spectrum as follows:
where \( G(f) \) and \( \xi(f) \) [rad] are the amplitude and phase of the measurement system, respectively.

By applying \( v_c(t, 0) \) and \( v_c(t, x_2) \) as the input and output signals, respectively, in the cross-spectral method, the cross spectrum is obtained as follows:

\[
C(f, 0, x_2) = \frac{V_c^*(f, 0)V_c(f, x_2)}{V_c^*(f, 0)V_c(f, 0)},
\]

where \( V_c^*(f, 0) \) is the complex conjugate of \( V_c(f, 0) \).

For the case in which the observation point is located near a sound source, we can assume that \( \gamma_n \approx 1 \). Thus, from \( \gamma_n \ll 1 \), Euler’s formula, and Eqs. (7) through (10), \( C(f, 0, x_2) \) is approximated as follows:

\[
C(f, 0, x_2) \approx \frac{e^{iD(f)} + \sum_{n=1}^{m} \gamma_n e^{i\alpha_n(f)} + \sum_{n=1}^{m} \gamma_n e^{-i\beta_n(f)}}{1 + \sum_{n=1}^{m} \gamma_n e^{i\alpha_n(f)} + \sum_{n=1}^{m} \gamma_n e^{-i\beta_n(f)}}
\]

\[
e^{iD(f)} + 2 \sum_{n=1}^{m} \gamma_n \cos(\alpha_n(f))
\]

\[
\frac{1 + 2 \sum_{n=1}^{m} \gamma_n \cos(\beta_n(f))}{1 + 2 \sum_{n=1}^{m} \gamma_n \cos(\beta_n(f))},
\]

(11)

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

(12)

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

(13)

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

(14)

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:

\[
p(f, 0, x_2) = |C(f, 0, x_2)|^2
\]

\[
\approx 1 + 4 \cos(D(f)) \sum_{n=1}^{m} \gamma_n \cos(\alpha_n(f))
\]

\[
= 1 + 2 \sum_{n=1}^{m} \gamma_n \left( \cos \left( \frac{4\pi f}{c} d_n - \phi_n \right) \right.
\]

\[
+ \cos \left( \frac{4\pi f}{c} (d_n - x_2) - \phi_n \right)
\]

(15)

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. (15) 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, in order to extract phase interference corresponding to the distance, the average of \( p(f, 0, x_2) \) is calculated as follows:

\[
\overline{p(f, 0, x_2)} = \frac{1}{f_N - f_1} \int_{f_1}^{f_N} p(f, 0, x_2) df.
\]

(16)

By subtracting \( \overline{p(f, 0, x_2)} \) from \( p(f, 0, x_2) \), we can extract phase interference corresponding to distance as follows:

\[
\Delta p(f, 0, x_2) = p(f, 0, x_2) - \overline{p(f, 0, x_2)}.
\]

(17)

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:

\[
F(f) = \int_{-\infty}^{\infty} f(t) e^{-j2\pi ft} dt,
\]

(18)

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

\[
P(x) = \int_{f_1}^{f_N} \Delta p(f, 0, x_2) e^{-j2\pi \frac{2x}{c}} df,
\]

(19)

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,

\[
d_{\min} = \frac{c}{2f_w}.
\]

(20)

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

3. COMPUTER SIMULATIONS

In order to confirm the validity of the proposed method, we performed computer simulations 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
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 $x_2 = 0.05$ m and a single target, respectively. As a result of Fig. 4, the first peak of the range spectrum is detected at 0.50 m, and the second peak of the range spectrum is detected at 0.44 m. This indicates that peaks tend to be detected at $d_m$ m and $d_m - x_2$ m under the condition in which the microphone interval is sufficiently broad. In addition, $\Delta p(f, 0, x_2)$ shows the amplitude modulation due to the different tones. As a result, a small peak is detected at 0.05 m.

Figures 5(a) and 5(b) show $\Delta p(f, 0, x_2)$ and the range spectrum under the simulation condition of $x_2 = 0.006$ m and a single target, respectively. As a result of Fig. 5, a peak of the range spectrum is detected at 0.50 m. This indicates that the peak tends to be detected at $d_m$ m under the condition in which the microphone interval is sufficiently narrow. In addition, $\Delta p(f, 0, x_2)$ shows the amplitude modulation due to the different tones, although its period is longer than $f_W$.

### Table 1 Simulation conditions.

| Parameter                      | Value                  |
|--------------------------------|------------------------|
| 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–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 environments.

$\Delta p(f, 0, x_2)$ 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:

$$\Delta d = \frac{cL}{2f_W L'},$$

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. (10), a number of synchronous addition is 1 times.

Figures 2(a) and 2(b) show the computer simulation environments. As shown in Fig. 2, in this simulation, we evaluate two conditions in which the interval between microphones 1 and 2 is set as $x_2 = 0.05$ m and 0.006 m. Figure 3 shows the transmitted wave for this simulation. This band-limited impulse is created using Eq. (1).
Figures 6(a) and 6(b) show $\Delta p(f, 0, x_2)$ and the range spectrum under the simulation condition of $x_2 = 0.05$ m and two targets, respectively. As a result of Fig. 6, the peaks of the range spectrum are detected at $d_1$ m, $d_2$ m, $d_1 - x_2$ m, and $d_2 - x_2$ m.

Figures 7(a) and 7(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. 7, the peaks of the range spectrum are detected at $d_1$ m and $d_2$ m. The results for two targets indicate that the proposed method is valid for multiple targets.

4. EVALUATION EXPERIMENTS

In order to confirm the effectiveness of the proposed method, we performed experiments to evaluate the proposed method in real environments.

4.1. Experimental Conditions for a Single Target

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. Figures 8 through 11 show the experimental environment. As shown in Figs. 8 through 11, we conduct experiments at four microphone locations. In addition, the experimental environments have microphone intervals of $x_2 = 0.05$ m and 0.006 m for each microphone.

| 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–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 | Sound absorption panel (H30 cm × W22.5 cm × D0.5 cm) |

| 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 |
Thus, we evaluate a total of eight experimental environments.

4.2. Experimental Results for a Single Target

Figures 12 through 19 shows the experimental results. In Figs. 12 through 19, (a) and (b) show $\Delta p(f, 0, x_2)$ and the range spectrum obtained in the evaluation experiments, respectively.

Figures 12 and 13 show the experimental results for microphone location 1, as shown in Fig. 8. Figures 12 and 13 also show experimental results under the conditions of $x_2 = 0.05$ m and $0.006$ m, respectively.

Based on Figs. 12 and 13, under the condition in which the microphones are placed on the straight line connecting the loudspeaker and the target, the peak in the range spectrum is detected exactly, although a false peak due to multiple reflection arises at approximately 0 m. In addition, under the condition in which the microphone interval is wider, as shown in Fig. 12, the peaks are detected at $d_1$ m and $d_1 - x_2$ m. On the other hand, under the condition in which the microphone interval is narrow, as shown in Fig. 13, the peak is detected at approximately $d_1$ m.

Figures 14 and 15 show the experimental results for microphone location 2, as shown in Fig. 9. In addition, Figs. 14 and 15 show the experimental results under the conditions of $x_2 = 0.05$ m and $0.006$ m, respectively. Based on Figs. 14 and 15, under the condition in which microphone 1 is placed on the straight line connecting the loudspeaker and the target, and microphone 2 is placed on the line perpendicular to this straight line, a false peak due to multiple reflection arises at approximately 0 m, which is similar to the results shown in Figs. 12 and 13. In particular, under the condition in which the microphone interval is wider, as shown in Fig. 14, the false peak is very high because the amplitude difference of the direct wave at each microphone is large. On the other hand, under the condition in which the microphone interval is narrow, as
shown in Fig. 15, the experimental results are similar to those shown in Fig. 14.

Figures 16 and 17 show the experimental results for microphone location 3, as shown in Fig. 10. Figures 16 and 17 also show the experimental results under the conditions of $x_2 = 0.05$ m and 0.006 m, respectively.

Based on result of Figs. 16 and 17, under the condition in which the microphones are placed below the straight line connecting the loudspeaker and the target, the adverse effects of multiple reflection are reduced, as compared to the results shown in Figs. 12 through 15. In addition, under the condition in which the microphone interval is wider, as shown in Fig. 16, the peaks are detected exactly at $d_1$ m and $d_1 - x_2$ m, respectively. Meanwhile, under the condition in which microphone interval is narrow, as shown in Fig. 17, the peak is detected exactly at approximately $d_1$ m.

Figures 18 and 19 show the experimental results for microphone location 4, as shown in Fig. 11. Figures 18 and 19 also show experimental results under the conditions of $x_2 = 0.05$ m and 0.006 m, respectively. Based on the result of Figs. 18 and 19, under the condition in which microphone 1 is placed below the straight line connecting the loudspeaker and the target and microphone 2 is placed below the line perpendicular to this straight line, the amplitude of the false peak due to multiple reflection is reduced, as in the results shown in Figs. 16 and 17. However, under the condition in which the microphone interval is wider, as shown in Fig. 18, a false peak occurs...
at approximately 0 m because the amplitude difference of
the direct wave at each microphone is large. Meanwhile,
under the condition in which the microphone interval is
narrow, as shown in Fig. 19, the peak is detected exactly
at approximately $d_1$ m, as in the case of the results shown
in Fig. 17.

Table 4 shows the estimated distances to a target for
the results shown in Figs. 12 through 19. Table 4 confirms
that the performance of the proposed method tends to be
worse under the condition in which the microphone
interval is wider. In addition, under the condition in which
microphone interval is narrow, the proposed method
can estimate the distance to a target for all microphone
locations and can reduce the adverse effects of multiple
reflection for microphone locations 3 and 4.

4.3. Experimental Conditions for Two Targets

In order to confirm the effectiveness of the proposed
method for multiple targets, we performed experiments to
evaluate the proposed method for two targets. Experimental
conditions are similar to evaluation experiments using
a single target. However, we employ a plywood square
(H30 cm × W22.5 cm × D0.5 cm) as targets in evaluation
experiments for two targets. Figure 20 shows the experimental
environment for two targets. This is because microphone location 3 is suitable experimental conditions
to confirm the effectiveness of the proposed method for
multiple targets as shown in Sect. 4.2.

4.4. Experimental Results for Two Targets

Figures 21 and 22 show the experimental results for
microphone location 3 and two targets. Figures 21 and 22
also show the experimental results under the conditions of
$x_2 = 0.05$ m and 0.006 m, respectively.

Based on result of Figs. 21 and 22, the proposed
method is effective for multiple targets. Figure 21, the peaks are detected exactly at $d_1$ m, $d_2$ m, $d_3 - x_2$ m, and
$d_2 - x_2$ m, respectively. Meanwhile, under the condition in which microphone interval is narrow, as shown in Fig. 22, the peaks are detected exactly at approximately $d_1$ m and $d_2$ m.

5. CONCLUSIONS AND FUTURE RESEARCH

In the present paper, we proposed a new acoustic
distance measurement method based on phase interference
obtained using the cross-spectral method with stereo
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 computer simulations and evaluation experiments in real environments. In particular, the results of the evaluation experiments indicate that the proposed method is effective under the condition in which the microphone interval is narrow and the microphones are not placed on the straight line connecting the loudspeaker and the target. In the future, we intend to investigate theoretically the condition in which the reflection coefficient is large.

ACKNOWLEDGMENTS

We would like to thank Keiji Kawanishi and Kazuhiro Suzuki who supported experiments. The present study was supported in part by JSPS KAKENHI Grant Numbers 24560533, 24700126.

REFERENCES

[1] T. Ihara and K. Fujimura, “Research and development trends of millimeter-wave short-range application systems,” IEICE Trans. Commun., E79-B, 1741–1753 (1996).

[2] T. Kodama, K. Nakahira, Y. Kanaya and T. Yoshikawa, “Application of digital polarity correlations in a sonar ranging system,” IEEJ Trans. EIS, 127, 317–323 (2007).

[3] M. Parrilla, J. J. Anaya and C. Fritsch, “Digital signal processing techniques for high accuracy ultrasonic range measurements,” IEEE Trans. Instrum. Meas., 40, 759–763 (1991).

[4] M. Yang, S. L. Hill, B. Bury and J. O. Gray, “A Multi-frequency AM-based ultrasonic system for accuracy distance measurement,” IEEE Trans. Instrum. Meas., 43, 861–866 (1994).

[5] M. Okugumo, A. Kimura, M. Ohki and M. Ohkita, “Development research on high performance ultrasound sensor system,” IEEJ Trans. C, 128, 55–61 (2008) (in Japanese).

[6] N. Nakasako, T. Uebo, A. Mori and N. Ohmata, “Fundamental consideration on distance estimation using acoustical standing wave,” IEICE Trans. Fundam., E91-A, 1218–1221 (2008).

[7] M. Nakayama, S. Hanabusa, N. Nakasako and T. Uebo, “Robust acoustic distance measurement method based on interference in noisy environments,” Proc. ISCTI2010, pp. 176–181 (2010).

[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. A, E94-A, 1638–1646 (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 —,” Proc. ICA2004, P2.E.3, V3463–V3466 (2004).

[10] D. G. Childers, D. P. Skinner and R. C. Kemerait, “The Cepstrum: A Guide to Processing,” Proc. IEEE, 65, 1428–1443 (1977).

Masato Nakayama received his B.E. degree from Kinki University in 2001, his M.E. degree from Waseda University in 2003 and his Dr. Eng. degree from Ritsumeikan Univ. in 2010. He is currently a research associate at College of Information Science & Engineering, Ritsumeikan Univ., and a researcher at the Faculty of Biology-Oriented Sci. & Tech., Kinki Univ. His current research interests include array signal processing, acoustic distance measurement, ultrasonic signal processing, and sound field reproduction. He is a member of IEICE.

Noboru Nakasako received his B.E., M.E., and Dr. Eng. degrees from Hiroshima Univ. in 1982, 1984, and 1990, respectively. He served as a research assistant and an assistant professor in the Dept. of Electrical Eng., the Hiroshima Inst. of Tech. He joined the Faculty of Biology-Oriented Sci. & Tech., Kinki Univ. as an associate professor. He has been a professor at Kinki Univ. since 2002. His research interest includes acoustic signal processing, sound and vibration control, independent component analysis and their application to acoustics. He is a member of IEICE, SICE, ISCIE, and INCE Japan.

Tetsu Uebo received his B.E. and Dr. Eng. degrees from Tokushima Univ. in 1987 and 2001, respectively. He was a lecturer at the Faculty of Engineering, Tokushima Univ. He is a researcher at the Faculty of Biology-Oriented Sci. & Tech., Kinki Univ. He has been a general manager and senior research fellow at the Laboratory of Microwave Application, WADECO Co., Ltd. since 2010. His research interest includes range finding utilizing microwave, millimeter-wave, and acoustic wave. He is a member of IEICE, IEEJ, and IEEE.

Manabu Fukushima received his B.E., and Dr. Eng. degrees from Chiba Inst. of Tech. in 1989 and 1999, respectively. He served as a member in the Syste Tech. Dev. Center, Fuji Xerox Co., Ltd., a research assistant in the Dept. of Comp. Sci. Eng., the Chiba Inst. of Tech., an assistant professor in the Dept. of Comp. Sci. the Fukuoka Inst. of Tech., and professor in the Dept. of Media Tech. the Nippon Bunri Univ. His research interest includes digital signal processing, transfer system analysis and control, and their application. He is a meber of IEEE, IEICE, INCE Japan, IPSJ, and ISME.