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A trial on calculating the equivalent reflection coefficient by acoustic distance measurement method based on phase interference in the actual sound actual field

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ABSTRACT

Since the distance to target is very important information, we have proposed an acoustic distance measurement (ADM) method using a standing wave, which is generated by interference between transmitted and reflected waves. The proposed method is very simple in that the distance between the microphone and the target is estimated as the peak position of the range spectrum (i.e., the absolute value of the Fourier transform with respect to the power spectrum of the observed wave). The ADM method can be used to measure distance under the assumption that the transmitted and reflected waves are plane waves, even if the target is placed in a very close range and the reflection coefficient of the target is unknown. The ratio of the magnitude of the reflected wave to that of the transmitted wave (which is referred to as the equivalent reflection coefficient) can be estimated for the special case of a single target. The equivalent reflection coefficient contains the reflection coefficient and the distance decay. The present paper describes a new method for calculating the equivalent reflection coefficient using the ADM method based on phase interference in the actual sound field. We also examine the validity and effectiveness of the proposed method through a computer simulation and by applying the proposed method to an actual sound field.

Keywords: Phase interference, Range spectrum, Reflection coefficient, Distance decay
I-INCE Classification of Subjects Number(s): 74.9

1. INTRODUCTION

In many engineering fields, the distance to the target is fundamental and contains very important information. Several methods that use sound to measure distance have been proposed (1, 2). Most of these methods use the time delay of the reflected wave, which is measured in reference to the transmitted wave. However, this method cannot be used to measure short distances because the transmitted wave will not be sufficiently attenuated when the reflected wave is received and will suppress the reflected wave. Therefore, we have previously proposed an acoustic distance measurement (ADM) method that uses a standing wave generated by the interference between the transmitted and reflected waves, which can be used to measure short distances (3, 4). The proposed method is very simple in that the distance between the microphone and the target is estimated as the peak position of the range spectrum, which is the absolute value of the Fourier transform with respect to the power spectrum of the observed wave. The ADM method can be used to measure the distance under the assumption that the transmitted and reflected waves are plane waves, even if the target is placed at a very short distance and the reflection coefficient of the target is unknown.

On the other hand, it is very important to know the acoustic characteristics, such as the reflection coefficient, the acoustics impedance, and the absorption coefficient of, for example, humans, absorbing materials,

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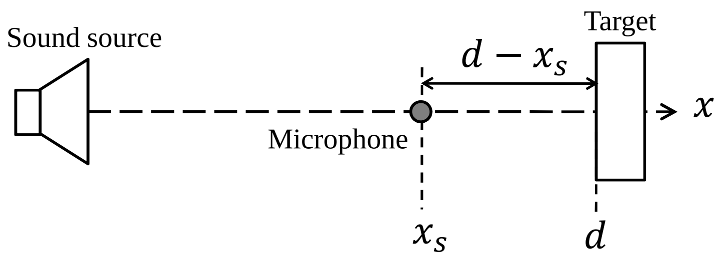

Figure 1 – Geometric positions of the sound source, the target, and the single microphone.

and all other objects in a sound environment. However, evaluation of such acoustic characteristics requires special rooms (e.g., a reverberant room) or special apparatuses (e.g., an impedance tube) for measurement (5). Moreover, the actual sound field is so complicated that the acoustic characteristics measured in an ideal situation do not always match those of the real sound environment. Confining our discussion to the reflection coefficient, since the proposed ADM method is based on the interference between the transmitted and reflected waves, we can estimate the reflection coefficient using the ADM method under the assumption that the transmitted and reflected waves are plane waves. Therefore, the reflection coefficient estimated by the ADM method is referred to as the equivalent reflection coefficient rather than the strictly defined reflection coefficient. This equivalent reflection coefficient involves the distance decay as well as the ratio of the reflected wave to the transmitted wave.

The present paper describes a new method for calculating the equivalent reflection coefficient using the ADM method based on phase interference in the actual sound field for the special case of a single target. We also examine the validity and effectiveness of the proposed method through a computer simulation and by applying the proposed method to an actual sound field.

2. THEORETICAL CONSIDERATION

2.1 Principle of distance estimation using phase interference (3, 4)

Figure 1 shows the geometric positions of the observation position (microphone), the sound source (loudspeaker), and the target assumed in the present study. Denoting the horizontal axis as x-axis and letting the origin be an arbitrary position, the microphone and target are set at positions $x = x_s$ [m] and d [m], respectively.

Let transmitted wave $v_{\mathrm{T}}(t,x)$ be a function of position x [m] and time t [s], where the sound pressure is expressed as:

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

where f [Hz] denotes the frequency (f_1 and f_N correspond to the lowest and highest frequencies, respectively), $A(f) = |A(f)|e^{j\theta(f)}$ is the frequency characteristics of the transmitted wave, and c [m/s] is the speed of sound. For simplicity, let us consider the transmitted wave to be reflected by a single target. The wave $v_{\mathrm{R}}(t,x)$ reflected by the target can be expressed as follows:

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

where d is the distance to the target, and $\gamma(f) = |\gamma(f)|e^{j\phi(f)}$ is the reflection coefficient of the target.

Letting the observation position be $x_s = 0$ [m], the observed wave $v_{\mathrm{C}}(t,0)$, which is the composition of all transmitted and reflected waves, is formulated as:

$$v_{\mathrm{C}}(t,0) = v_{\mathrm{T}}(t,0) + v_{\mathrm{R}}(t,0). \tag{3}$$

By applying the Fourier transform:

$$V_{\mathrm{C}}(f,0) = \int_{-\infty}^{\infty} v_{\mathrm{C}}(t,0) e^{-j2\pi f t} dt \tag{4}$$

to $v_{\mathrm{C}}(t,0)$, the power spectrum of $v_{\mathrm{C}}(t,0)$ can be easily obtained:

$$p(f,0,) = |V_{\mathrm{C}}(f,0)|^2. \tag{5}$$

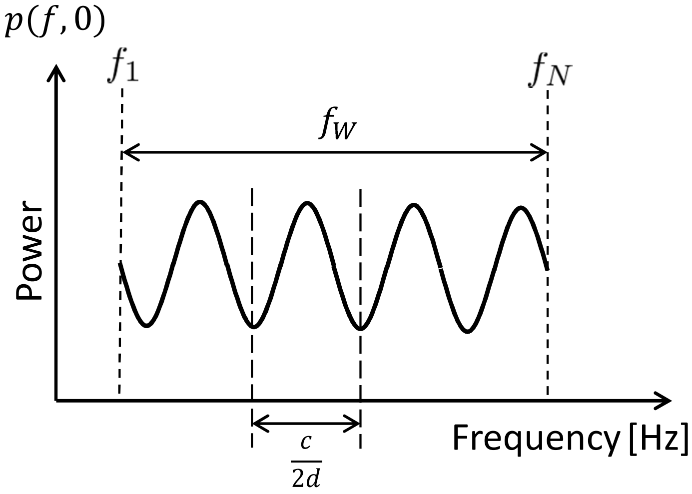

Figure 2 – Power spectrum of composite signal $v_C(t,0)$ for single target.

Assuming that the spectrum of the transmitted wave and the reflection coefficient are constant ($A(f) = A$, $\gamma(f)e^{j\phi(f)} = \gamma e^{j\phi}$), the power $p(f,0)$ of the composite wave can be approximated as

$$p(f,0) = |A|^2 \left\{ 1 + \gamma^2 + 2\gamma \cos\left(\frac{4\pi f}{c}d - \phi\right) \right\} \tag{6}$$

In Eq. (6), the first and second terms represent the power of the transmitted wave and that of the reflected wave, respectively, and the third term corresponds to the power fluctuation induced by the interference between the transmitted and reflected waves. Figure 2 shows an illustration of the ideal $p(f,0)$ observed in the presence of a single target located at a distance of d for the case in which the amplitude is constant over all frequencies (i.e., $|A(f)| = A$) and the phase $\phi(f)$ of the reflection coefficient is also assumed to be constant. From this figure and Eq. (6), it is obvious that $p(f,0)$ is periodic with respect to the frequency f, and its period is inversely proportional to the distance d between the microphone and the target, so the distance d can be estimated by the Fourier transform of $p(f,0)$. More concretely, since the DC component $\overline{p(f,0)}$ (i.e., the average power) of the composite wave is cumbersome in investigating the relationship between the transmitted wave and the reflected wave, we can subtract the average power $\overline{p(f,0)}$ from the power $p(f,0)$ to remove the DC component from the composite wave:

$$\begin{aligned} \Delta p(f,0) &= p(f,0) - \overline{p(f,0)} \\ &= 2|A|^2 \gamma \cos\left(\frac{4\pi f}{c}d - \phi\right). \end{aligned} \tag{7}$$

We refer to this $\Delta p(f,0)$ as the Δ power spectrum.

Thus, in the formula of the Fourier transform $H(f) = \int_{-\infty}^{\infty} h(t)e^{-j2\pi ft}dt$, replacing f by $\frac{2x}{c}$, t by f, and $h(t)$ by $\Delta p(f,0)$, and considering the frequency bandwidth, the spectrum $P(x)$ can be obtained as follows:

$$P(x) = \int_{f_1}^{f_N} \Delta p(f,0) e^{-j2\pi \frac{2x}{c} f} df. \tag{8}$$

The absolute value $|P(x)|$ is referred to as the range spectrum, and its peak position is the estimated distance d from the microphone to the target. Figure 3(a) shows an example of the range spectrum $|P(x)|$ for a single target.

The minimum measurable distance $d_{\min}$ is defined by the frequency bandwidth f_W and the velocity of sound c as (4):

$$d_{\min} = \frac{c}{2 f_W}. \tag{9}$$

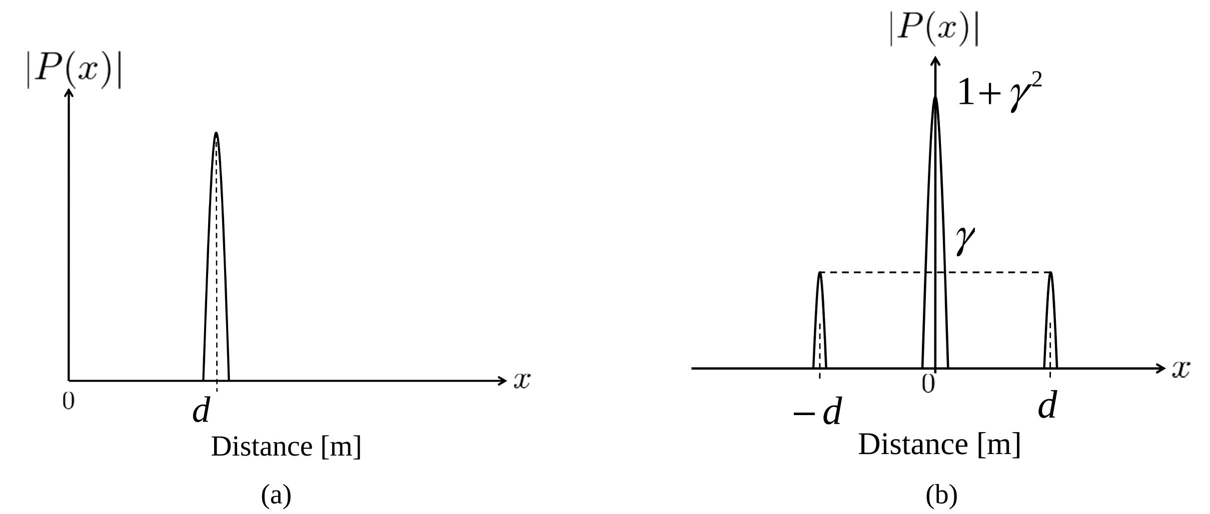

Figure 3 – Examples of range spectra for single target: (a) for the conventional method and (b) for the purpose of evaluating the reflection coefficient.

2.2 Equivalent reflection coefficient obtained by the ADM method

As mentioned above, it is clear that the distance between the microphone and the target can be obtained using the ADM method based on interference. Conversely, since the range spectrum contains information on the reflection coefficient of the target as well as the distance between the microphone and the target, the reflection coefficient can be obtained based on the range spectrum. In this case, the reflection coefficient is not the formally defined reflection coefficient, but rather the equivalent reflection coefficient, which contains the distance decay, for example. First, the power spectrum of $p(f,0)$ in Eq. (6) can be rewritten as follows:

$$\begin{aligned} p(f,0) =& |A|^2 \left\{ 1+\gamma^2+2\gamma\cos\left(\frac{4\pi f}{c}d-\phi\right)\right\} \\ =& |A|^2 \left\{ 1+\gamma^2+2\gamma\frac{e^{j\left(\frac{4\pi f}{c}d-\phi\right)}+e^{-j\left(\frac{4\pi f}{c}d-\phi\right)}}{2}\right\} \end{aligned} \tag{10}$$

Thus, the spectrum $P(x)$ with respect to the distance x can be obtained through Fourier transform of $p(f,0)$, as follows:

$$P(x) = |A|^2 \left\{(1+\gamma^2)\delta(x)+\gamma(\delta(x-d)e^{-j\phi}+\delta(x+d)e^{j\phi})\right\}, \tag{11}$$

where $\delta(x)$ denotes the Dirac delta function (i.e., strictly speaking, Sinc function). Thus, the range spectrum $|P(x)|$ can be approximated as follows:

$$|P(x)| \approx |A|^2 \left\{(1+\gamma^2)\delta(x)+\gamma\delta(x-d)+\gamma\delta(x+d)\right\} \tag{12}$$

In Eq. (12), the first term represents the peak at 0 m caused by the transmitted and reflected waves. The second term corresponds to the peak at distance d m between the microphone and the target, and the third term represents the spurious peak at negative distance $-d$ m between the microphone and the target. Figure 3(b) shows an illustration of the ideal range spectrum $|P(x)|$ used to evaluate the reflection coefficient.

Thus, the equivalent reflection coefficient γ_{ADM}, which is estimated using the ADM method, can be obtained by letting the ratio of the first term to the second term in Eq. (12) be $\rho(=\gamma/(1+\gamma^2))$, as follows:

$$\gamma_{\mathrm{ADM}} = \frac{1-\sqrt{1-4\rho^2}}{2\rho} \tag{13}$$

3. VERIFICATION OF ESTIMATING THE EQUIVALENT REFLECTION COEFFICIENT USING THE ADM METHOD

3.1 Computer simulation

We verify the estimation of the equivalent reflection coefficient by simulating the assumed audible spectrum as a fundamental problem. We adopted a band-limited impulse wave of uniform amplitude $A(f) = 1$

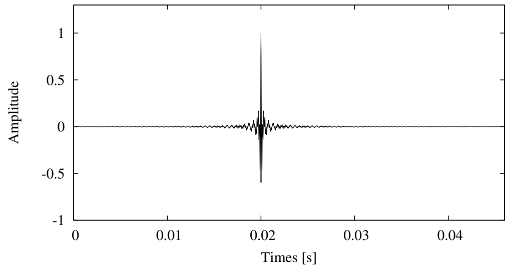

Figure 4 – Transmitted signal $v_{\mathrm{T}}(t,0)$ at $x_s = 0$.

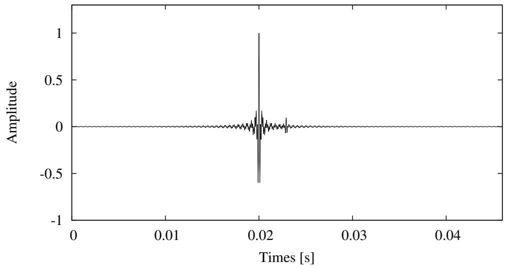

Figure 5 – Observed signal $v_{\mathrm{C}}(t,0)$ at $x_s = 0$.

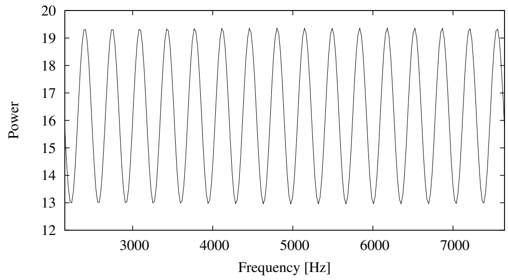

Figure 6 – Power spectrum $p(f,0)$ for simulation.

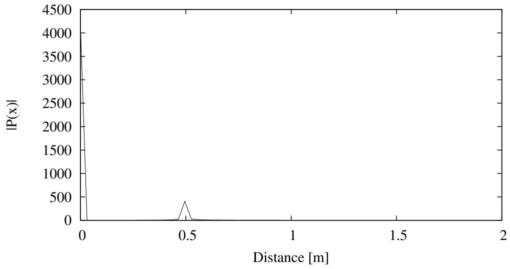

Figure 7 – Range spectrum $|P(x)|$ for simulation.

(constant) and zero initial phase $\theta(f) = 0$ given by Eq. (1) as the transmitted wave. Figure 4 shows the waveform of the transmitted wave.

In the simulation, since the observation position x_s is taken as the origin, we consider the reflected wave for the case in which the distance d to be measured is 0.49 m, where the magnitude $\gamma(f)$ is set to range from 0.01 to 0.99 at 0.01 intervals and the phase $\phi(f)$ of the reflection coefficient is set to be π rad. The speed of sound c is 340 m/s. Figure 5 shows a composite wave for $\gamma = 0.1$, as an example.

The sampling frequency is set to be 44,100 Hz, and the number of sampling points is 2,048. The lowest frequency f_1 is 2,153 Hz, and the highest frequency f_N is 7,644 Hz. The frequency f_i of the i-th frequency component is $\frac{100+(i-1)}{2048} \times 44,100$ $(i = 1,2,\ldots,N)$, and the number N of sampling points in the frequency domain is 256. Here, from Eq. (9), the minimum measurable distance is 0.031 m. To realize Fourier transform in Eqs. (4) and (8), the FFT is introduced.

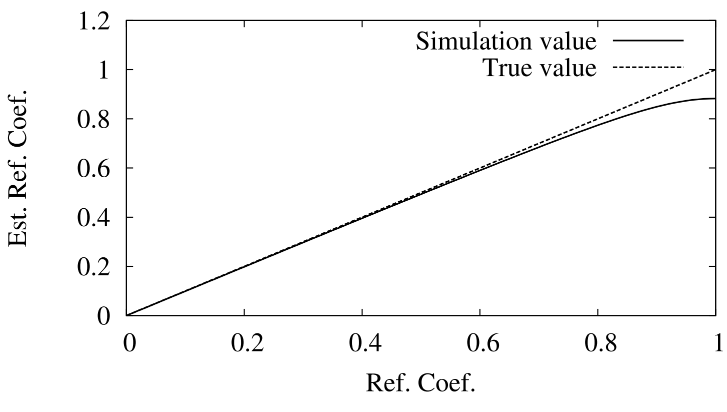

Figure 8 – Simulation results.

Figures 6 and 7 show the power spectrum of the composite wave for $\gamma = 0.1$ and the range spectrum, respectively. The range spectrum has peaks at $x = 0$ m and 0.49 m (the distance in the negative region is omitted). Based on these results, the equivalent reflection coefficient can be calculated by the proposed method. Figure 8 shows the true and estimated magnitudes of the reflection coefficient γ. In this figure, the horizontal and vertical axes represent the true and estimated reflection coefficients, respectively. There is good agreement between the experimentally observed values and the values determined theoretically using the proposed method, except at high reflection coefficients. This might be because the range spectrum peaks of the sinc function overlap.

3.2 Measurement in an actual sound field

The validity and effectiveness of the proposed method were experimentally confirmed by applying the method to an actual sound field.

Figure 9 shows an overhead view of the experiment setup, and Table 1 shows the experimental equipment used in the experiment. The microphone was placed on the top of the loudspeaker, and the other conditions were the same as in the simulation. Here, we used a plywood square (H30 cm $\times$ W22.5 cm $\times$ D0.5 cm) as a target. In this experiment, we used the impulse response of the measurement system, which was measured using the Time Stretched Pulse (TSP) method (6). The distance d from the microphone to the target was set to range from 0.1 m to 1.5 m at 0.1 m intervals. Figure 10 shows an actually observed wave composed of the transmitted and reflected waves for $d = 0.5$ m as an example.

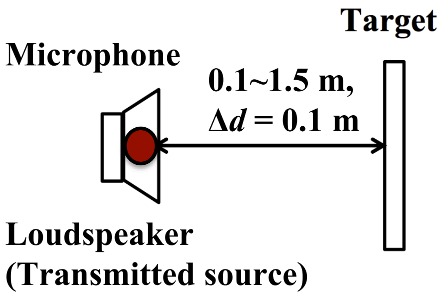

Figure 9 – Experimental environments.

Table 1 – Experimental equipment.

Microphone	SONY, ECM-88B
Microphone amplifier	PAVEC, MA-2016C
Loudspeaker	YAMAHA, MSP5 STUDIO
Audio interface	ROLAND, UA-55

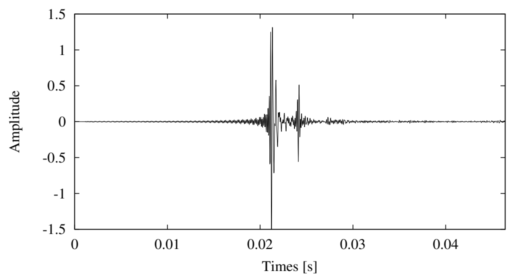

Figure 10 – Observed signal $v_{\mathrm{C}}(t,0)$ at $x_s = 0$.

Figures 11 and 12 show the power spectrum of the composite wave for $d = 0.5$ m and the range spectrum, respectively. The range spectrum has peaks at $x = 0$ m and 0.5 m (the distance in the negative region is omitted). Based on these results, the equivalent reflection coefficient can be calculated even in the actual sound environment using the proposed method.

Figure 13 shows the true and experimentally estimated values for each distance obtained using the range spectrum. The estimated distances match the true distances well. Based on the range spectrum, the equivalent reflection coefficient data, which was obtained using the proposed method, are shown by filled circles in

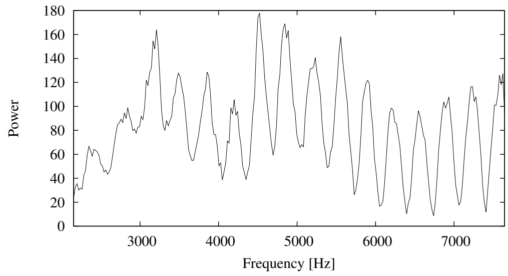

Figure 11 – Power spectrum $p(f,0)$ for an observed wave.

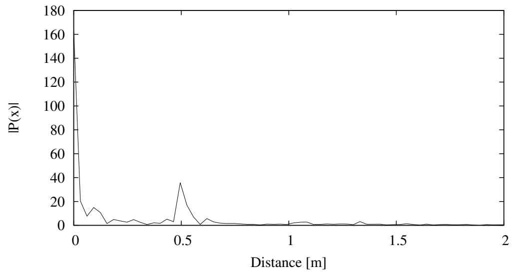

Figure 12 – Range spectrum $|P(x)|$ for the observed wave.

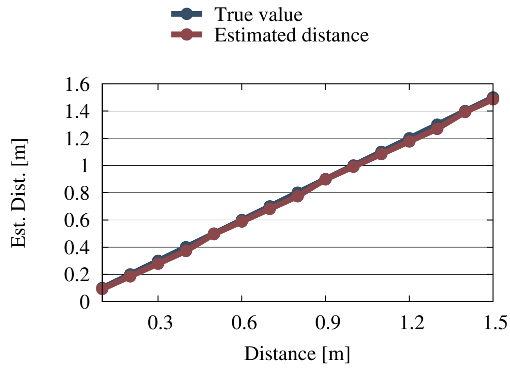

Figure 13 – Experimental results (target: plywood square).

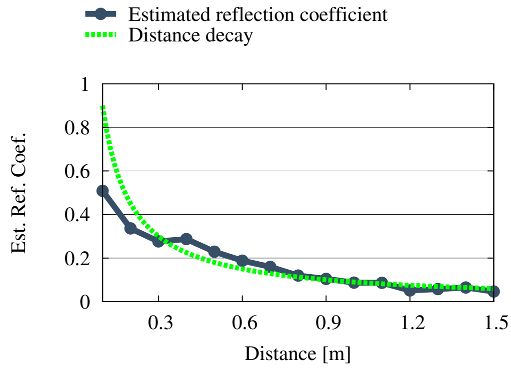

Figure 14 – Estimated reflection coefficient.

Figure 14. For reference, the theoretical curve of the distance decay is shown in the same figure. The estimated equivalent reflection coefficient has a similar tendency to the theoretical distance decay curve. The estimation of the phase of the reflection coefficient is left as a problem for future study.

4. CONCLUDING REMARKS

In the present paper, we have proposed a new method for calculating the equivalent reflection coefficient using the ADM method based on phase interference in an actual sound field for the special case of a single target. In order to confirm the validity and effectiveness of the proposed method, we performed a computer simulation and applied the proposed method to an actual sound field. The experimental results indicate that the proposed method is valid and effective for use in an actual sound field. In the future, we intend to perform experiments using several other types of target with various reflection coefficients. Also, we intend to test the proposed method in a noisy environment. Note that it might be difficult to measure the equivalent reflection coefficient at very short distances using the proposed method, because the distance decay property changes abruptly at close range. Thus, we intend to perform experiments in which the distance to the target is very short.

ACKNOWLEDGMENTS

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REFERENCES

1. Ihara, T. and Fujimura, K. Research and Development Trends of Millimeter-wave Short-range Application Systems, *IEICE Trans. Commun.*, **E79B**, 1741-1753, (1996)

2. Kodama, T., Nakahira, K., Kanaya, Y. and Yoshikawa, T. Application of Digital Polarity Correlations in a Sonar Ranging System, *IEEJ Trans. EIS*, **127**, 317-323, (2007)

3. Nakasako, N., Uebo, T., Mori, A. and Ohmata, N. Fundamental Consideration on Distance Estimation Using Acoustical Standing Wave, *IEICE Trans. Fundamentals*, **E91-A**(4), 1218-1221, (2008)

4. Uebo, T., Nakasako, N., Ohmata, N. and Mori, A. Distance Measurement Based on Standing Wave for Band-limited Audible Sound with Random Phase, *Acoustical Science and Technology*, **30**(1), 18-24, (2009)

5. Kuttruff, H., Room Acoustics (3rd ed.), Elsevier, London (1991).

6. Suzuki, Y., Asano, F., Kim, H.-Y. and Sone, T. An Optimum Computer-generated Pulse Signal Suitable for the Measurement of Very Long Impulse Responses, *J. Acoust. Soc. Am.*, **97**(2), 1119-1123, (1995)