Correction Method of Estimated Distance Using Geometrical Information on Sound Source and Microphone

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***Abstract*—In many engineering fields, distance to target is very important and fundamental information. Acoustical signal often plays an essential role in measurement of distance. Though there are distance measurement methods using a time delay between transmitted and reflected waves, it is difficult to measure short distance because the transmitted wave suppresses the reflected waves for short distance. Recently, in a research field of microwave, a method for measuring the short distance has been proposed using interference (i.e., standing wave) of transmitted and reflected waves. We applied the fundamental principle of this method to the estimation of short distance using audible sound as a transmitted wave. Until now, this method supposed that microphone was set at the straight line between a sound source and a target. However, we can not estimate exactly the distance between the microphone and target when the microphone is not set on the straight line due to the restriction of measuring environment. This paper describes a principle and its correction method for the distance estimation when a microphone is not set on the straight line between the sound source and microphone. Then, we perform a computer simulation under the condition that audible sound is used as a transmitted wave. Finally, we experimentally confirm the validity and effectiveness of the method proposed by applying it to the distance estimation problem in an actual sound field.**

I. Introduction

In many engineering fields, distance to target is very important and fundamental information. Acoustical signal often plays an essential role in measurement of distance [1]. Though there are distance measurement methods using a time delay between transmitted and reflected waves, it is difficult to measure short distance because the transmitted wave suppresses the reflected waves for short distance [2], [3], [4]. Recently, in a research field of microwave, a method for measuring the short distance has been proposed using interference (i.e., standing wave) of transmitted and reflected waves [5], [6], [7]. The interference enables us to estimate the distance to target, because the interference includes the information on the distance to targets.

We applied the fundamental principle of this method to the estimation of short and multi-target distances using the audible sound as a transmitted wave [8], [9], [10], [11], [12]. By extending this method to audible sound instead of microwave, we can measure the distance easily without restriction due to the radio law. However, since this method supposed that microphone was set at the straight line between a sound source and a target, we can not estimate exactly the distance between the microphone and target when the microphone is not set on the straight line due to the restriction of measuring environment.

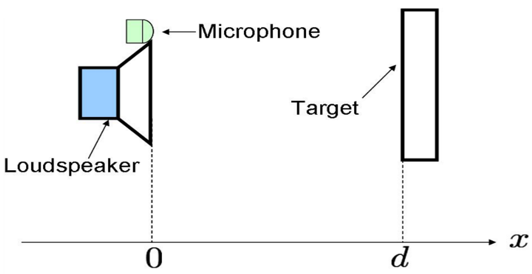

Fig. 1. Positions of loudspeaker, microphone and target.

This paper describes a principle and its correction method for the distance estimation when a microphone is not set on the straight line between the sound source and microphone. Then, we perform a computer simulation under the condition that audible sound is used as a transmitted wave. Finally, we experimentally confirm the validity and effectiveness of the proposed method by applying it to the distance estimation problem in an actual sound field.

II. Theoretical consideration

A. Distance estimation based on interference

For example, as shown in Fig.1, we supposed that a microphone was set on a sound source (loudspeaker) and a target was set at the position of $x = d$ m by denoting the horizontal axis as x-axis and letting the position of sound source be the origin. If the microphone is set at an arbitrary point, we can estimate the distance between the microphone and target using the same technique, as long as positions of microphone and sound source are known. If we measure the distance in such a situation, the estimated value d' obtained as a result becomes shorter than distance d between the microphone and target. This is why it is possible that the distance from the center

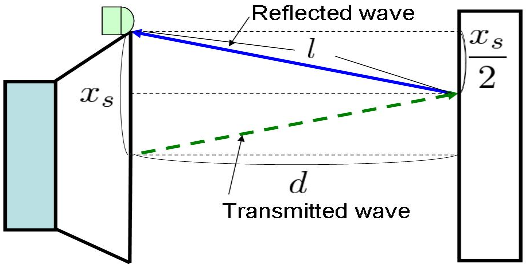

Fig. 2. Geometrical positions of sound source, microphone and target.

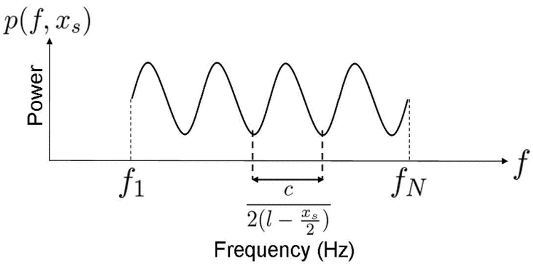

Fig. 3. Power spectrum of composite signal $v_C(t, x_s)$ for single target.

of a sound source surface to a microphone is not considered [12]. Consequently, in order to exactly estimate the distance between the microphone and target, we need to correct the estimated value d'.

If x_s m denote the distance from the center of a sound source (loudspeaker) surface to a microphone, let $v_T(t, x_s)$ be a transmitted wave, which is emitted from a sound source to a target, observed at microphone position x_s m as :

$$v_T(t, x_s) = \sum_{i=1}^{N} A_i e^{j(2\pi f_i t - \frac{2\pi f_i x_s}{c} + \theta_i)}, \tag{1}$$

where t s denote a time and c m/s a sound velocity. Also, A_i, f_i Hz and θ_i denote the amplitude, frequency and phase of ith frequency, respectively. And f_1 and f_N correspond to the lowest and highest frequencies, respectively.

The sound propagates from the sound source to the target as shown in Fig.2 and let l denote the 1/2 length of propagation path. The reflected wave $v_R(t, x_s)$ observed at the microphone position x_s can be expressed as follows :

$$v_R(t, x_s) = \sum_{i=1}^{N} A_i \gamma e^{j\phi} e^{j(2\pi f_i t - \frac{2\pi f_i}{c}(2l) + \theta_i)}, \tag{2}$$

where $\gamma e^{j\phi}$ denote reflection coefficient for a target. From Fig.2, it should be noted that $l = \sqrt{d^2 + (\frac{x_s}{2})^2}$ is not the true distance d between the microphone and target.

Thus, the composite wave $v_C(t, x_s)$ observed at microphone position x_s is formulated as :

$$v_C(t, x_s) = v_T(t, x_s) + v_R(t, x_s). \tag{3}$$

By applying Fourier transform to the above composite wave $v_C(t, x_s)$:

$$V_C(f, x_s) = \int_{-\infty}^{\infty} v_C(t, x_s) e^{-j2\pi f t} dt, \tag{4}$$

we can easily obtain the power spectrum at $x = x_s$.

$$p(f, x_s) = |V_C(f, x_s)|^2. \tag{5}$$

Assuming that magnitudes of the reflection coefficient γ is sufficiently small ($\gamma \ll 1$) and amplitudes A_i are constant for any i (i.e., $A_i = A$), from Eq.(1) to (5), the power of the composite wave $p(f, x_s)$ can be approximated as

$$p(f, x_s) \approx A^2 \Big\{ 1 + 2\gamma \cos\Big(\frac{4\pi f}{c}\big(l - \frac{x_s}{2}\big) - \phi \Big) \Big\}. \tag{6}$$

In Eq.(6), the first term represents the power of transmitted wave and the second term represents the power fluctuation induced by interference between the transmitted and reflected waves. Then, since the power of transmitted wave does not include the information of target, we subtract the average of power $p(f, x_s)$ from the power $p(f, x_s)$ to remove the transmitted wave component.

Figure 3 shows an ideal illustration of $p(f, x_s)$ observed in the case of single target which is located at a distance d. From Fig.3 and Eq.(6), it is obvious that $p(f, x_s)$ is periodical with respect to frequency f and its period is inversely proportional to $l - \frac{x_s}{2}$. This means that the distance between the microphone and target can be estimated by applying Fourier transform to $p(f, x_s)$ again as a function of f.

Thus, in the formula of Fourier transform

$$G(f) = \int_{-\infty}^{\infty} g(t) e^{-j2\pi f t} dt, \tag{7}$$

replacing f to $\frac{2x}{c}$, t to f, and $g(t)$ to $p(f, x_s)$, we transform $p(f, x_s)$ by the following formula :

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

As a result, we can obtain $l - \frac{x_s}{2}$ from this spectrum $P(x)$.

B. Correction method of estimated distance

The peak of the absolute value of $P(x)$, which is called a range spectrum $|P(x)|$ here, corresponds to the distance $l - \frac{x_s}{2}$, namely the estimated value d'.

$$d' = l - \frac{x_s}{2} \tag{9}$$

Figure 4 shows an ideal illustration of the range spectrum $|P(x)|$ in the presence of single target which is located at a distance d.

Consequently, from Eq.(9) and the relation $l = \sqrt{d^2 + (\frac{x_s}{2})^2}$ in Fig.2, we can calculate d which is the distance between the microphone and target.

$$d = \sqrt{(d')^2 + x_s d'} \tag{10}$$

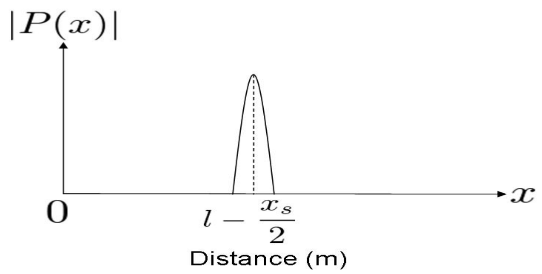

Fig. 4. Range spectrum for single target.

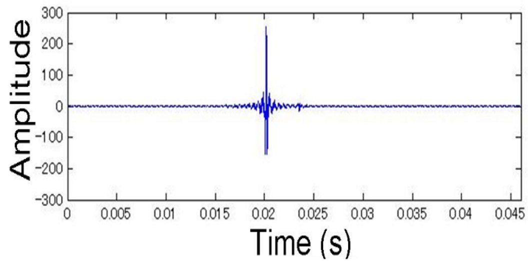

Fig. 6. Simulated composite wave with single target at $d_1 = 0.6$ m.

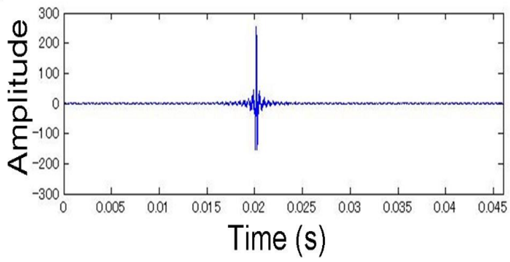

Fig. 5. Transmitted impulse wave.

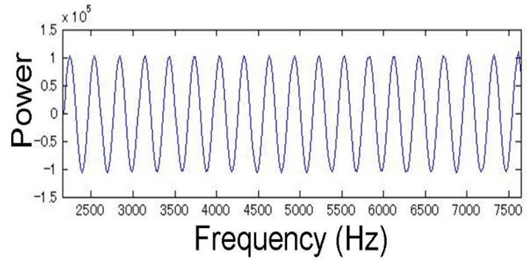

Fig. 7. Power spectrum of composite wave with single target.

III. EXPERIMENTAL CONSIDERATIONS

To confirm the validity and effectiveness of this method, especially for audible sound, computer simulation and actual measurement have been performed. The sampling frequency is set to 44,100 Hz, the data length 2,048 points, and the sound velocity 342.48 m/s. The band-limited sound from the lowest frequency $f_1 = 2,153$ Hz to highest frequency $f_N = 7,644$ Hz is adopted as a transmitted wave and the distance x_s from the center of the sound source (loudspeaker) surface to the microphone is 0.06 m. Also, the magnitude A_i in Eq.(1) is fixed as 1.0 and the phase θ_i as 0 rad. Here, distance resolution, which depends on the bandwidth of transmitted sound, has been about 0.03 m.

A. Computer simulation

A computer simulation is performed in order to confirm the theoretical principle. From Eq.(1), Figure 5 shows the transmitted wave observed at the microphone position x_s.

Let a single target be located at $d = 0.60$ m. Here, the reflection coefficient γ is set to 0.05 and the phase ϕ to π. From Eq.(2), the reflected wave is simulated at the microphone position x_s, and we obtain the composite wave shown in Fig.6, which is a sum of the transmitted wave and the reflected wave.

Power $p(f, x_s)$ was obtain by Fourier transform of this composite wave, and for the purpose of removing the effect of the transmitted wave on $p(f, x_s)$, we subtract the average of power $p(f, x_s)$ from the power $p(f, x_s)$. Figure 7 shows the power fluctuation after subtraction in frequency domain.

From Eq.(8), we obtained the range spectra $|P(x)|$ shown in Fig.8. The dashed line corresponds to the range spectrum for the power $p(f, x_s)$ and the peak of range spectrum before correction is located 0.56 m. The solid line denotes the range spectrum corrected by Eq.(10) which has the peak at 0.59 m. Consequently, it is found that the proposed correction method improves the estimated distance between the microphone and target, especially taking the geometrical information on the sound source and microphone.

B. Actual measurement

We carried out experiment of the distance estimation in an actual sound field. Figure 9 shows the experimental setup with a single target and Table I shows equipment used in this experiment. The microphone was set on the sound source (loudspeaker) and the target was a plywood square.

Figures 10 and 11 show the composite wave and power spectrum in this experiment, respectively. In terms of the range spectrum, at first, the peak of range spectrum appeared at 0.03 m other than around 0.60 m, since in the actual sound field the frequency response of the system between the loudspeaker and microphone is not uniform. Wherein, for lightening the influence of equipment, the power spectra shown in Fig.10 were the result that the power of observed wave without

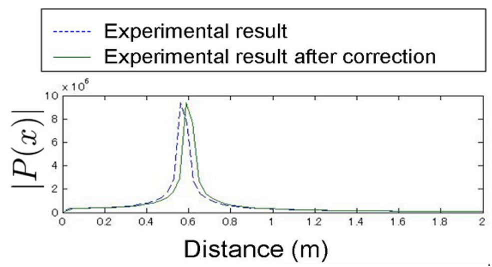

Fig. 8. Range spectra in simulation with single target.

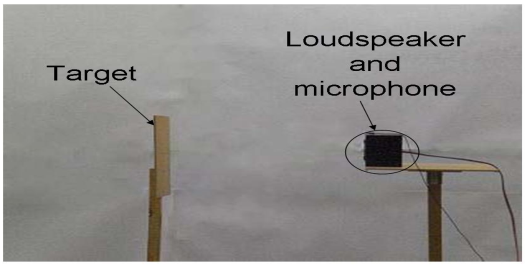

Fig. 9. Experimental setup with single target.

TABLE I
EQUIPMENT USED IN EXPERIMENTAL SYSTEM.

Microphone	Audio Technica,AT-805F
Loudspeaker	Fostex,FE87E
Speaker Box	Daito-Voice,SV-70
Power Amplifier	YAMAHA,A100a
Preamp	M-Audio,MOBILE PRE USB
Personal Computer	IBM,ThinkPad T60(Core 2 Duo)
Target	Plywood square (H30cm $\times$ W22.5cm $\times$ D0.5cm)

setting target was subtracted from the power of observed wave with target. In this way, the distance spectrum was obtained, denoted by the dashed line in Fig.11. The peak of range spectrum was located at 0.56 m. The correction method by Eq.(10) gives us the solid line in Fig.11 for the range spectrum. The peak of range spectrum after correction was located at 0.59 m. Consequently, even in the actual sound field, the geometrical information on the sound source and microphone improves the estimated distance between the microphone and target.

IV. CONCLUDING REMARKS

In this paper, we have firstly proposed a principle and its correction method for the distance estimation when a microphone is not set on the straight line between the sound source and microphone. Then, we have performed a computer simulation under the condition that audible sound is used as a transmitted wave. Finally, we have experimentally confirmed the validity and effectiveness of the proposed method by applying it to the distance estimation problem in an actual sound field.

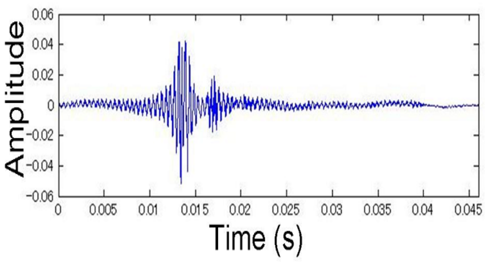

Fig. 10. Actual composite wave with target at d=0.60 m.

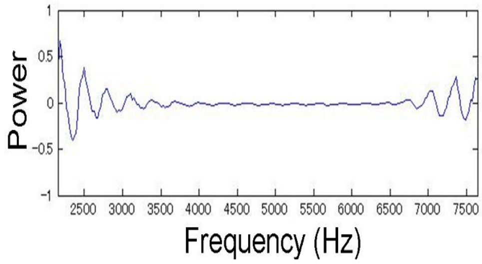

Fig. 11. Power spectrum of actual composite wave (d=0.60 m).

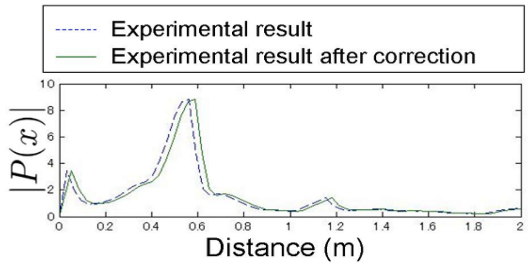

Fig. 12. Range spectra in experiment (d=0.60m).

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