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RELATIONSHIP BETWEEN TIME OF FLIGHT (TOF) MEASUREMENT ERROR AND PHASE CHARACTERISTICS OF SOUND PROBE

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Abstract

Sound probe used for measurement of a time of flight (TOF) consists of a pair of a loudspeaker and a microphone. A TOF is obtained by a cross correlation between a transmitted and a received signals. The TOF measurement error exists in any frequency of a transmitted signal, and the value is not constant. Improvement of the measurement accuracy is difficult, because the reason of the error factor is not sufficiently clarified. We measured the difference in an experimental value of a phase of the received signal against a true value. Measurement error according to the phase characteristics of the sound probe is added to the TOF. The TOF calculated from the experimental value of the phase has the measurement error and this error has the similar characteristic to the measurement error of the TOF that is calculated from the cross correlation of the transmitted and the received signal. Either characteristic suggests that measurement error is larger in the low frequencies and becomes smaller as a frequency increases. This result suggests that the phase difference of the received signal from the true phase according to phase characteristic of the sound probe is one of the error factors of the TOF. Therefore, there is some relationship between measurement error of the TOF and phase characteristic of the sound probe. This relationship may apply to analysis of the measurement error factor of the TOF and more accurate measurement of the TOF.

INTRODUCTION

An acoustical temperature measurement using a sound probe is suitable method for a temperature measurement of a wide area [1, 2]. This measurement method uses a sound probe that consists of a loudspeaker (SP) and a microphone (MIC). Advantage of using the sound probe is that it has no impact on environment, is able to obtain a mean temperature of a wide area with quick response and does not occupy working space [3]. In the acoustical temperature measurement, a time of flight (TOF) between an SP and an MIC is an important factor. The TOF is obtained by a cross correlation between a transmitted and a received signals. The transmitted signal is received by the MIC with an impulse response of a transducer and a waveform is distorted. The measurement error in the TOF has been finally produced in the cross correlation result [4]. Therefore, the TOF measurement error exists in any frequency, and the value is not constant. An improvement of the measurement accuracy is difficult, because the reason of the error factor is not sufficiently clarified [5]. The TOF is one of the phase information; therefore there will be some relationship between the phase difference of the sound probe and the TOF. We measured the difference in an experimental value of a phase against true value of the phase in the received signal. This phase difference is calculated by the impulse response of the sound probe. In this paper, we compared the phase difference that calculated by the impulse response with measurement error of the TOF.

MEASUREMENT OF TIME OF FLIGHT (TOF) OF SOUND PROBE

Composition of Sound Probe

Figure 1 shows schematic diagram of a sound probe. The sound probe consists of a SP, a MIC and the propagation path. The sound probe is used for measuring propagation characteristics as the parameters of complex amplitude along the sound path. In this paper, the sound probe is used to measure the TOF between the SP and MIC. In following experiments, the distance L between the SP and MIC is set to 3.0 m.

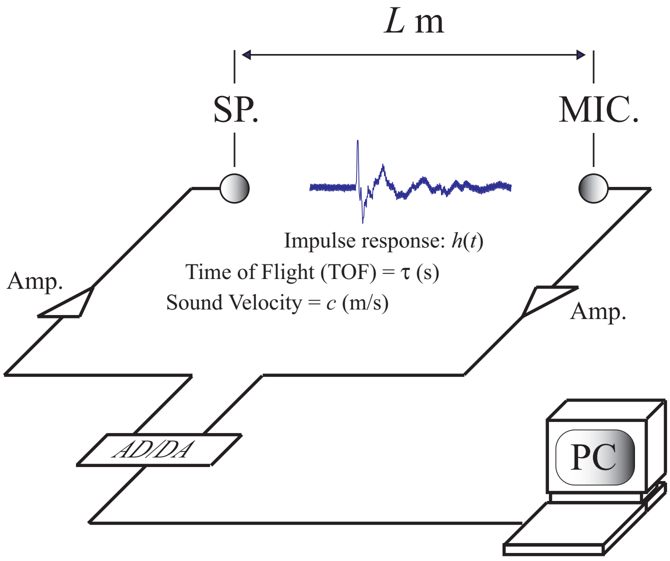

Figure 1: Schematic diagram of a sound probe

Measurement of TOF

The TOF of the sound probe τ is determined as the parameter that maximizes the cross correlation of a transmitted and a received signals, which is calculated by

$$\phi = \frac{1}{2T}\int_{-\infty}^{\infty} s(t)x(t+\tau)dt\ . \tag{1}$$

$s(t)$ is the transmitted signal and $x(t)$ is the received signal. The cross correlation is one of the most suitable technique for the TOF measurement by high accuracy [6]. Relationship between a space mean temperature T and the TOF τ is expressed as [7]

$$T = \frac{\mathrm{T}_0}{331.32^2}\left(\frac{L}{\tau}\right)^2 - \mathrm{T}_0\ . \tag{2}$$

T_0 is 273.15 K. The space mean temperature T can be measured by using Eq. (2) [8-11]. In this paper, a sampling frequency f_s is 250 kHz and a sampling period t_s is 0.004 ms (= 4μs). The temperature resolution ΔT is expressed as

$$\Delta T = \frac{\mathrm{T}_0}{331.32^2} L^2 \left\{\frac{1}{t_f^{\ 2}} - \frac{1}{(t_f + t_s)^2}\right\} \tag{3}$$

t_f is the TOF at the given temperature. From this equation, ΔT is 0.26 deg. C.

Waveform Distortion

We should change parameters of the transmitted signal such as frequency according to the characteristics of a measured object. If a phase difference is zero in any frequencies, the TOF is accurately obtained at any frequency. However in a real situation, an impulse response of an acoustical system (a SP- a MIC) is added to the received signal and a waveform distortion including the phase difference has been occurred [12].

Figure 2 shows the transmitted and the received signal at 5, 10, 15 kHz. These figures suggest that the waveform distortion of the received signal occurs in any frequency and this distortion is not uniform. The relation between the transmitted and the received signals of the acoustical system is expressed as

$$x(t) = \int_{-\infty}^{\infty} s(t)h(t-k)dk = s(t) * h(t)\,. \tag{4}$$

$s(t)$ is the transmitted signal, $h(t)$ is the impulse response of the sound probe and $x(t)$ is the received signal. Eq. (4) says that $x(t)$ is a convolution of $s(t)$ and h(t).

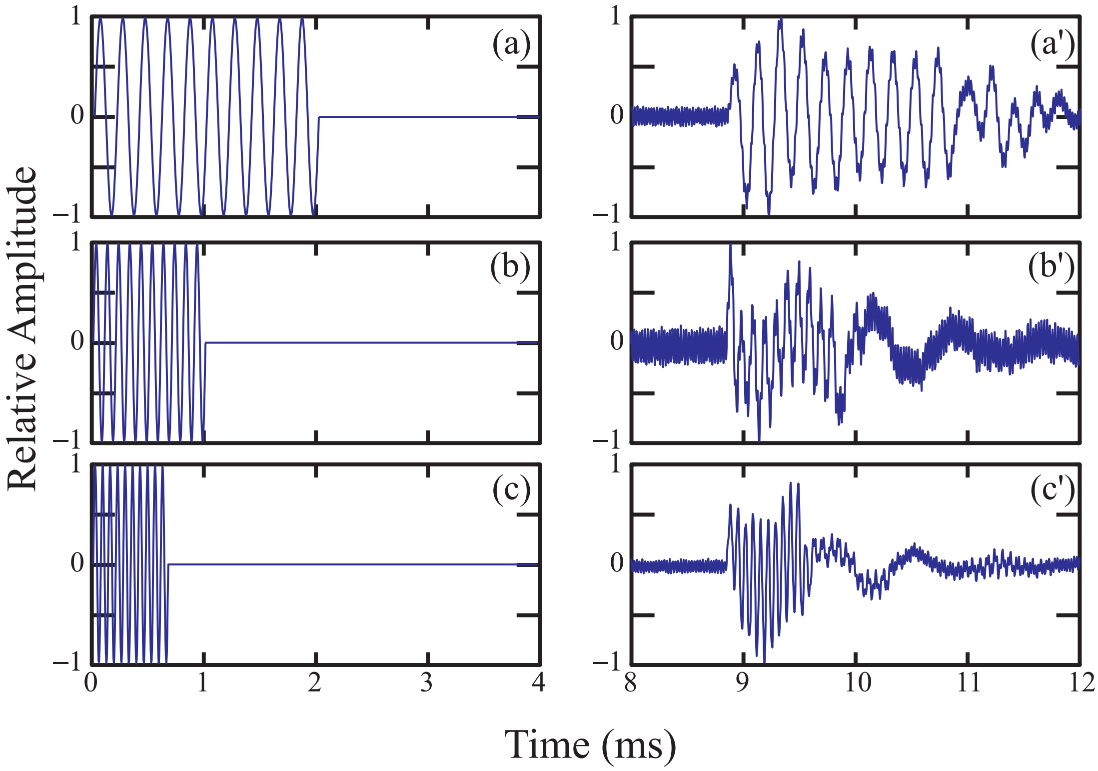

Figure 2: Transmitted and received signals. (a): Transmitted signal at 5 kHz. (b): Transmitted signal at 10 kHz. (c): Transmitted signal at 15 kHz. (a'): Received signal at 5 kHz. (b'): Received signal at 10 kHz. (c'): Received signal at 15 kHz.

RELATIONSHIP BETWEEN TOF AND PHASE CHARACTERISTICS

Phase Frequency Characteristics of Sound Probe

The impulse response of the sound probe: $h(t)$ contains a information of phase frequency characteristics of the sound probe; therefore the phase frequency characteristics of the sound probe would be obtained from the impulse response of the sound probe. To acquire the impulse response of the sound probe, there are many methods; for example, crossing spectrum method, maximum length sequence (MLS) method [13], and time stretched pulse (TSP) method are typical ones [14, 15] of such methods.

In this paper, the impulse response is acquired by using a square wave with limited amplitude and short duration because this method is simpler than above-mentioned methods and a generation of the square wave is easy. This square wave has a flat frequency response at least in a demanded range. **Figure 3** shows the impulse response of the sound probe acquired by using this method. **Figure 4** shows the frequency characteristics of the transmitted signal (the square wave) and the

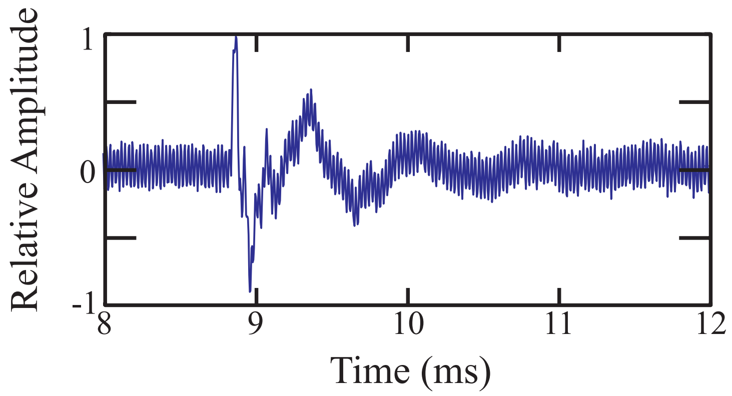

Figure 3: The impulse response of the sound probe: h(t)

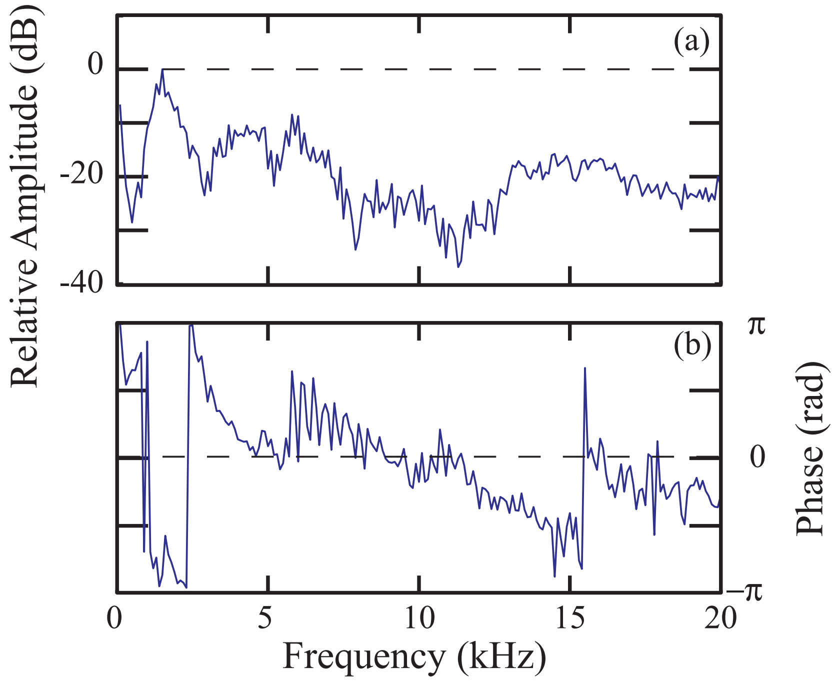

Figure 4: Frequency characteristics of the transmitted signal (square wave) and the impulse response: (a): Dashed-line: power spectrum of the transmitted signal, Solid line: power spectrum of the impulse response, (b): Dashed-line: phase frequency characteristics of the transmitted signal, Solid-line: phase frequency characteristics of the impulse response

impulse response of the sound probe. Fig. 4 (a) shows a power spectrum, Fig. 4 (b) shows a phase characteristics. These frequency responses of the sound probe are not flat; therefore the received signal would contain the waveform distortion including the phase difference. Fig. 4 shows that the power spectrum of the sound probe calculated by the impulse response and the phase frequency characteristic of the sound probe calculated by the impulse response $\theta(\omega)$ is not flat. It is difficult to improve

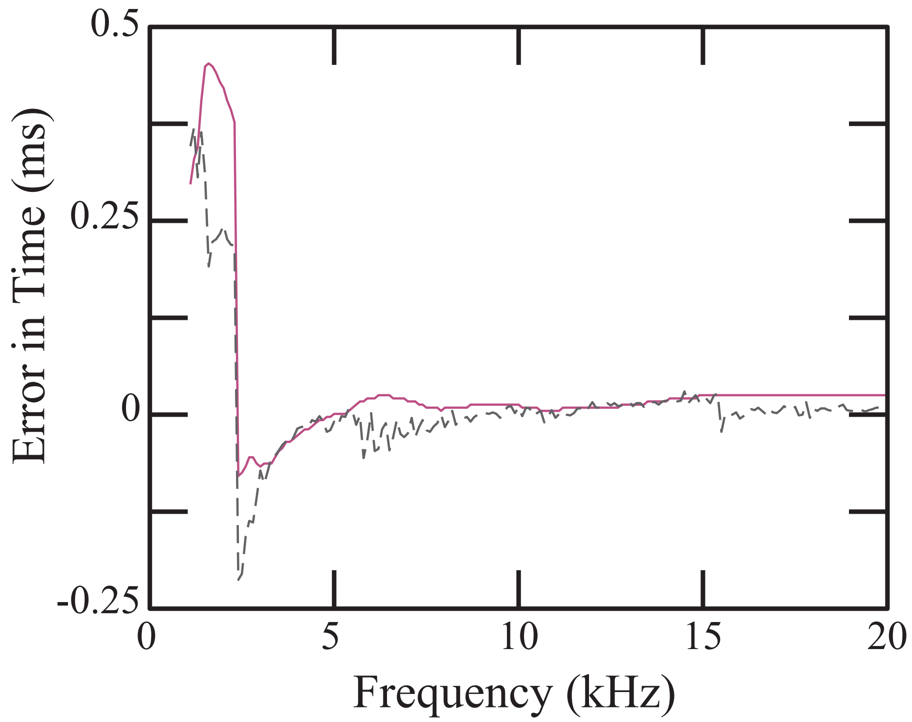

Figure 5: time deviation of TOF: Dashed line: expected time deviation of TOF τ_{p1}, Solid line: calculated time deviation of TOF τ_{p2} by cross correlation of the transmitted and the received signal.

a measurement accuracy, because a definition of the error factor is not sufficient.

Relationship between TOF measurement error and phase characteristics

The TOF is one of the phase information; therefore the phase characteristics of the sound probe $\theta(\omega)$ contains information of an time deviation of the TOF calculated from the phase characteristics: τ_p. The time deviation of the TOF calculated from the phase characteristics: τ_p would have some relationship to the error of the TOF measurement calculated by the cross correlation of the transmitted and the received signal. Relationship between the phase characteristics of the sound probe $\theta(\omega)$ and the expected time deviation of TOF τ_p is expressed as

$$\tau_p = -2\pi \frac{\theta(\omega)}{\omega}. \tag{5}$$

Figure 5 shows the time deviation of the TOF measurement. Dashed line shows the time deviation of the TOF calculated from the phase characteristics: τ_{p1} obtained by using Eq. (5) and Solid line shows a time deviation of the TOF calculated from the cross correlation of the transmitted and the received signal: τ_{p2}. τ_{p1} and τ_{p2} do not completely correspond, but they express similar characteristics. For example, either characteristic suggests that the measured time deviation of TOF of the sound probe is larger in the low frequencies and the measurement error that is equal to the time deviation becomes smaller as frequency increases. Fig. 5 shows that the characteristics of the error in TOF measurement depends on the phase characteristics of the sound probe. These results suggest that there is some relationship between the TOF measurement error and the phase frequency characteristics of the sound probe. And the waveform distortion due to the phase difference between the experimental value of the phase in the received signal from and the true value of the phase in the received signal according to the phase frequency characteristic of the sound probe is main error factors of the TOF measurement.

CONCLUSIONS

We measured the phase difference in the experimental value of the phase of the received signal against the true value. The measurement error according to the phase characteristics of the sound probe is added to the TOF measurement. The expected time deviation of the TOF calculated from the phase difference: τ_{p1} has the similar characteristic to the time deviation of the TOF calculated from the cross correlation of the transmitted and the received signal: τ_{p2}. Either characteristic suggests that the measurement error is larger in the low frequencies and the measurement error becomes smaller as the frequency increases. The characteristic of the TOF measurement error depends on the phase characteristics of the sound probe. These results suggest that the phase difference between the experimental value of the phase in the received signal and the true value of the phase in the received signal according to the phase characteristic of the sound probe is one of the error factors of the TOF. Therefore, there is some relationship between measurement error of the TOF and the phase characteristic of the sound probe. In other words, the phase characteristic of the sound probe is main error factor of the TOF measurement. This relationship may apply to analysis of the error factor of the TOF measurement and more accurate measurement of the TOF.

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