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Air-coupled ultrasonic time-of-flight measurement system using amplitude-modulated and phase inverted driving signal for accurate distance measurements

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Abstract: This paper proposes an amplitude-modulated and phase-inverted (AMPI) ultrasonic driving signal for accurate distance measurements. Undesirable part of the ultrasonic wave was canceled using the phase-inverted wave and its active canceling effect was enhanced by the amplitude-modulation, so that a unique ultrasonic waveform having a sharp envelope could be generated even with a narrow-band transducer of frequency 40 kHz (wavelength $\lambda \cong 9$ mm). The sharp envelope generated by the AMPI signal determined a zero-crossing time without any uncertainty. As a result, an accuracy better than 0.02 mm was achieved in the range of $0.1 - 0.5$ m.

Keywords: amplitude-modulated and phase-inverted signal, sharp envelope, time-of-flight, zero-crossing time, narrow-band transducer, distance measurement

Classification: Ultrasonic electronics

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1 Introduction

Air-coupled ultrasonic distance measurements have been widely used in many fields such as robotic applications. In the distance measurements, a signal-to-noise ratio (SNR) of ultrasonic wave signals is decreased by a large attenuation of ultrasound in air and a huge acoustic-impedance mismatch between the transmitter and air. To obtain sufficient amplitude of the ultrasonic wave signals, a narrow-band transducer [1, 2, 3] has been essential and widely used. However, narrow-band transducers generate an ultrasonic wave with a broad envelope. This characteristic causes large errors in time-of-flight (TOF) measurements to determine the propagation distance [3].

In the simplest TOF, the time when amplitude of the ultrasonic wave exceeds the threshold level is detected. But the detected time is affected by amplitude changes of the ultrasonic waveform depending on the ultrasonic propagation distance. One effective method to solve the problem of the amplitude changes is the detection of the time when the envelope of the ultrasonic wave has a maximum value [4]. However, a peak of the broad envelope generated by the narrow-band transducer is not clear. The broad envelope can be improved by using wide-band transducers [4], but they have disadvantages such as a low sensitivity compared with the narrow-band transducers. If a sharp envelope can be realized using the narrow-band transducers, then an accuracy of the TOF measurement will be improved with the high sensitivity. When the TOF measurement has accuracy better than a half of the wave period of the ultrasonic wave, the TOF measurement can be combined with the phase-detection (PD) measurement [1, 2, 3]. This combination [4, 5, 6, 7] enables us to extend the measurable range with high measurement accuracy.

To produce a sharp envelope with the narrow-band transducer, this paper proposes a new amplitude-modulated and phase-inverted (AMPI) driving signal. In a distance measurement system using the AMPI signal, a high measurement accuracy much better than λ is achieved over a wide range larger than λ by the combination of the TOF and PD.

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2 Method

Fig. 1 (a) shows the air-coupled ultrasonic system composed by narrow-band transducers. The ultrasonic propagation distance d_u is expressed as

$$d_u = cT_u, \tag{1}$$

where c is the ultrasonic velocity, and T_u is the ultrasonic propagation time determined from an instance when a maximum occurs on the envelope. Generally, a burst wave signal with a large number of wave cycles shown in Fig. 1 (c) drives the narrow-band transducer at its resonance frequency to get a sufficient rising of amplitude in the ultrasonic wave. In this case, the envelope of the ultrasonic wave is broad because high frequency components of the driving signal are diminished by the narrow-band characteristic of the transducer, as shown in Fig. 1 (d). Therefore, its envelope peak is not clear. To improve the broad envelope, we propose the new driving signal of the AMPI signal consisting of two components as shown in Fig. 1 (e). The

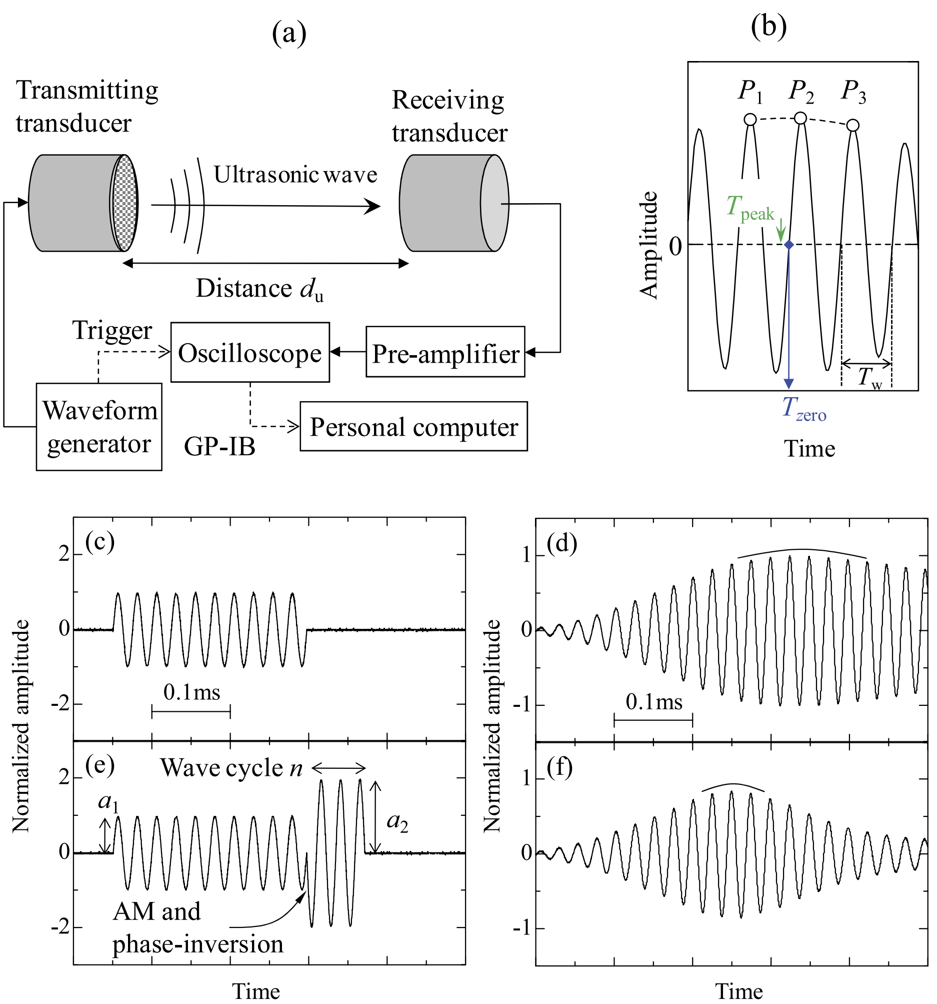

Fig. 1. System and ultrasonic waveform. (a) Measurement system. (b) Determination of T_{peak} and T_{zero} (c) Conventional driving signal and (d) its received waveform. (e) AMPI driving signal and (f) its received waveform.

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first component has amplitude of a_1 and ten wave cycles, and it is the same form as the conventional signal shown in Fig. 1 (c). The second component having the number of wave cycles n and the inverse-phase with respect to the first component is added to cancel the undesirable part appearing after the unclear envelope peak of the conventional ultrasonic wave. Moreover, a high amplitude of a_2 with the ratio $k = a_2/a_1$ is introduced to accelerate the cancellation. As shown in Fig. 1 (f), a sharp envelope with a clear peak is produced, where the undesirable part of the conventional ultrasonic wave is actively diminished by an ultrasonic wave generated from the second component of the AMPI signal. Its sharp envelope improves the measurement accuracy of T_{peak} through the following procedure. As shown in Fig. 1 (b), first, three peak values of P_1, P_2, and P_3 in the ultrasonic waveform are detected at time of t_1, t_2, and t_3, respectively. Next, two derivative values given by $S_1 = (P_2 - P_1)/(t_2 - t_1)$ and $S_2 = (P_3 - P_2)/(t_3 - t_2)$ is calculated. The T_{peak} when the derivative value becomes zero is finally calculated from the values of S_1 and S_2 with a linear interpolation. If the measurement error of T_{peak} is smaller than a half of the wave period T_{W}, a zero-crossing time T_{zero} nearest to T_{peak} can be used as a more exact measured value of T_{u}; in Fig. 1 (b), T_{zero} is defined as the time when the ultrasonic wave signal changes from negative value to positive one. By this combination of T_{peak} and T_{zero}, the measurement accuracy becomes higher than that in T_{peak} and the measureable range is longer than λ equal to that in T_{zero}.

3 System and its characteristics

The air-coupled ultrasonic system using the AMPI driving signal was constructed as shown in Fig. 1 (a). A waveform generator (Tektronix, AWG2005) drove the transmitting transducer placed face-to-face with the receiving transducer. These transducers were low-cost and commercially available narrow-band transducers (MURATA, MA40B8T/R) with a resonance frequency of 40 kHz (the wave period $T_{\mathrm{W}} = 25\,\mu$s, the wavelength $\lambda \cong 9$ mm). The received signal after being fed to a pre-amplifier (the input impedance: 10 kΩ) was observed on a digital oscilloscope (Tektronix, TDS744A) with an 8-bit voltage resolution, and the waveform data sampled at intervals of 1 μs was fed to a personal computer via the GPIB interface.

To examine the effect of the AMPI signal shown in Fig. 1 (e), first, the 3 dB envelope width of the received waveform was evaluated as shown in Fig. 2 (a) when the wave cycles n and the amplitude ratio k were changed. In Fig. 2 (a), the measured 3 dB envelope width W was normalized by the width of approximately 0.4 ms for $n = 0$. At $k = 1$, W became narrower with increasing n, but this improvement had saturation around $n = 5$. Further improvements of W were successfully obtained with increasing k. Next, T_{peak} of the received waveform was measured with the method described in Sec.2 at a fixed distance d_{u} of 0.3 m. The standard deviation σ for one hundred measurements of T_{peak} was calculated. The σ was approximately $T_{\mathrm{W}}/4$ at $n = 0$, and it was improved to approximately $T_{\mathrm{W}}/11$ with $n = 4$ and $k = 1$.

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The remarkable improvement of $\sigma = T_W/18$ was achieved with $n = 3$ and $k = 2$. When k was increased from 2 to 4, an effective improvement in σ was not obtained, although W became narrow as shown in Fig. 2 (a). Finally, the zero-crossing time T_{zero} for the AMPI signal at $n = 3$ and $k = 2$ were measured. The measurement was repeated ten times at the interval of about 0.5 s, and the variations of T_{peak} and T_{zero} from the first measurement are shown in Fig. 2 (c). The same measurement for the conventional driving signal at $n = 0$ was also performed for the comparison, and the results are shown in Fig. 2 (b). In Fig. 2 (b), T_{peak} measured at $n = 0$ involved the deviation larger than $T_W/2$, and then T_{zero} jumped by one wave period T_W. In contrast, as shown in Fig. 2 (c), the deviation of T_{peak} measured at $n = 3$ and $k = 2$ was much smaller than $T_W/2$, so that the jump of T_{zero} did not occur. For one hundred measurements at $n = 3$ and $k = 2$, T_{peak} could always determine T_{zero} without any uncertainty. Therefore, the AMPI signal at $n = 3$ and $k = 2$ is used for distance measurements in the next section.

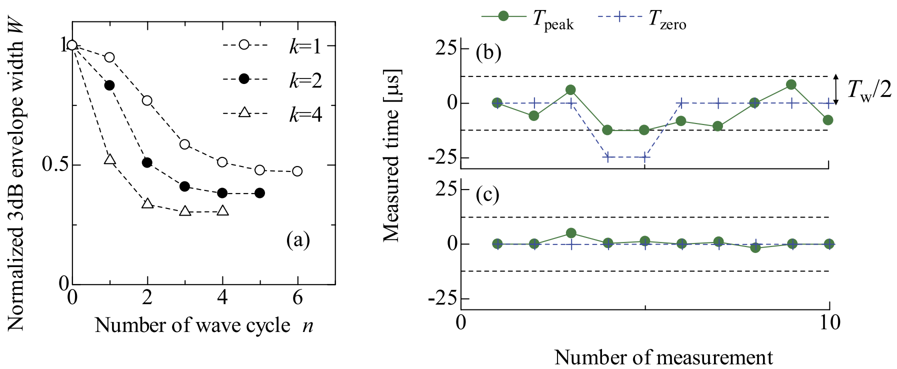

Fig. 2. Experimental results to show effect of AMPI driving signal. (a) The n and k dependence of 3 dB envelope width of received waveform. Measured T_{peak} and T_{zero} at (b) $n = 0$ and (c) $n = 3$, $k = 2$.

4 Distance measurement

A distance d_s between the transmitting and receiving transducers was changed using a mechanical stage (Edmund Optics Japan) on which the receiving transducer was mounted. Since the physical limit in the displacement of the stage was about 0.5 m, d_s was changed from 0.1 m to 0.5 m at the intervals of 0.1 m. It is difficult to determine an absolute value of T_{zero} between the transmitting and receiving ultrasonic wave because the transmitted ultrasonic waveform is not the same as the waveform of the driving signal. For this difficulty, d_s of 0.1 m was regarded as a reference point and the changes of T_{zero} were measured at the different values of d_s. The changes of T_{zero} were substituted into Eq. (1), and 0.1 m was added to the calculated distance to obtain the measured distances of d_{zero}. The ultrasonic velocity c was calculated by substituting the measured temperature and humidity into the equation described in Ref. [7]. The mean values d_m and standard devia-

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tions σ_m were calculated from one hundred measured values of d_{zero} at each of five distances of d_s, as shown in Fig. 3. Distances d_s of up to 0.5 m were successfully measured with σ_m smaller than 0.02 mm. The difference between d_m and d_s was smaller than 0.2 mm at each d_s. These differences were due to the straightness accuracy of 0.1 − 0.25 mm in the mechanical stage.

Therefore, an accuracy better than 0.02 mm could be achieved in the range of 0.1 − 0.5 m that is larger than λ. Longer distance measurements involving a bad SNR will be possible because the measurement accuracy of T_{peak} was still much higher than $T_W/2$ at d_s of 0.5 m. Further improvements of the measurement accuracy of T_{peak} in the current system can be achieved by further studies on the peak determination method.

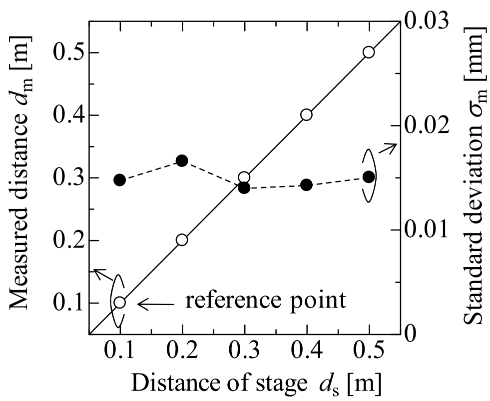

Fig. 3. Experimental result of relative distance measurements with the system at $n = 3$ and $k = 2$.

5 Conclusion

A sharp envelope was generated by the AMPI driving signal with a narrow-band transducer. The T_{peak} whose measurement accuracy was improved by the AMPI signal determined T_{zero} without any uncertainty. As a result, an accuracy better than 0.02 mm was achieved in the range of 0.1 − 0.5 m. Longer distance measurements utilizing a maximum capacity of the system are future work.

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