High Resolution Time-of-Flight Measurement with Narrow-band COTS Ultrasonic Transducers

Mondo SAITO and Jin MITSUGI
Keio University, Fujisawa, Japan
mondo@sfc.keio.ac.jp

Abstract— **Ultrasonic transducers (a pair of speaker and microphone) are extensively used in distance and wind speed measurements. The measurement of Time-of-Flight (TOF) between an ultrasonic speaker and a microphone dominates the accuracy. This paper presents a method to improve the TOF measurement accuracy using narrow-band commercial off-the-shelf (COTS) ultrasonic transducers. The method features the use of an experimentally captured waveform to correlate the transmitted and received signals and the use of a phase modulated ultrasonic signal. The method is experimentally evaluated to show that the proposal can significantly reduce the TOF measurement error, from 25.5% to 0.3%.**

Keywords—Cross correlation, time of flight estimation, ultrasonic measurement

I. INTRODUCTION

Sailing competition is regarded as an information warfare and often called "Chess on the sea". Utilization of sensor data, especially the direction and speed of winds, is a world trend in the trainings of competitive sailing teams. Objective wind data can be conveniently used in a sailing training to analyze and evaluate the sailor's decision particularly when the wind is weak.

Among various types of anemometers [1], ultrasonic anemometers are commonly used in the sailing because of the absence of mechanical moving parts. A high accuracy ultrasonic anemometer, however, usually demands an expensive broadband ultrasonic transducer pair (transmitter and receiver). Our goal is to measure the wind speed by using inexpensive narrow-band ultrasonic transducers. Since a sailing race is usually canceled when the wind is very weak, say, below 2m/sec, we define the required resolution of wind speed measurement as 1 m/sec in this study. This resolution needs TOF measurement error to be less than 0.3% (=1/340m/sec). The wind direction can be known by assembling several pairs of wind speed measurement system.

In this paper, we propose two techniques that enable the accurate TOF measurement with narrow bandwidth transducers. The first technique is to correlate the transmitted and received waveform with an experimentally captured waveform replica. The second technique is the use of phase modulated signal to provide a distinct waveform signature which enhances the peak of cross correlation of transmitted and received signals without increasing the bandwidth.

The rest of this paper is organized as follows. In Section Ⅱ, the related researches on the distance and the wind speed measurement with ultrasonic transducers are introduced. In Section Ⅲ, we introduce our proposal. In Section Ⅳ, we experimentally evaluate the proposal. Section Ⅴ concludes the paper.

II. RELATED RESARCH

Barshan [2] classified existing methods to calculate TOF of acoustic (including ultrasonic) signal into the following four methods, namely i) thresholding, ii) curve-fitting, iii) sliding window and iv) optimum correlation detection, to reveal the optimum correlation always provides the best result. But it was also pointed out the inherent problems of the optimum correlation are the preparation of appropriate signal replica and the processing delay. The difficulty to choose an appropriate signal replica stemming from the facts that the waveform at the receiver is influenced by the distance, the wind velocity and the temperature in addition to the mechanical characteristics of transducers. In their experimental result, the received signal seems to be used as the replica to eliminate the problem of selecting appropriate replica. That should be why the optimum correlation data exhibits surprisingly good result, zero bias in simulation and 0.0003 cm bias in the experiment. Jackson [3] provides an updated review of TOF measurements by classifying the existing methods into i) time-domain methods and ii) frequency-domain methods and iii) hybrid methods and concluded that the cross correlation either in frequency domain with frequency modulated signal (from 20 kHz to 120 kHz) provides the best result. Jackson [3] also recommends the time-domain cross correlation with a narrowband signal referring the result in Barshan [2]. But as we pointed out earlier, this result may be an overestimation because we usually don't know the accurate wave shape at the receiver. Queiros [4] and Gueuning [5] examine a combination of envelop cross-correlation and the carrier phase measurement. The dual calibration increases the measurement accuracy but entails small measurement deviation caused by disturbances.

According to this survey of existing studies, the authors are in the view that we still need a TOF measurement with commercial of the shelf (COTS) narrowband ultrasonic transducers. The two key problems are the appropriate waveform replica creation and the enhancement of signal correlation without increasing the bandwidth.

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III. PROPOSAL

A. Creating an waveform replica through measurement

Before a TOF measurement, we measure the actual waveform of received signal using the same model of transmitter and receiver hardware pair at a known distance in a stationary environment and use the measured waveform as the replica in cross correlation analysis. By doing this, we can eliminate the measurement errors caused by the frequency and mechanical characteristics of ultrasonic transducers. This technique is motivated after observing the significant difference between the electrical excitation waveform plugged into a transmitter and the received waveform.

For example, we transmit a 40kHz sinusoidal unfiltered pulse for six cycles from a narrow-band ultrasonic transmitter. The exciting waveform to a narrowband ultrasonic transmitter (UT1612MPR, bandwidth ±1kHz) is shown in Figure 1.

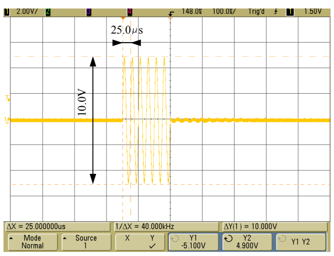

Figure 1. Exciting waveform plugged into an ultrasonic transmitter

The received waveforms at two fixed distance in a stationary environment are shown in Figure 2. Although we generated a constant envelop six cycles pulse, the generated ultrasonic waveform shows a smooth envelop with more than six cycles of fluctuation. Therefore, the cross-correlation between original excitation waveform and the received signal should yield a poor time accuracy simply because the two waveforms are so different. But if we use a measured waveform as the replica, the time accuracy is expectedly improved.

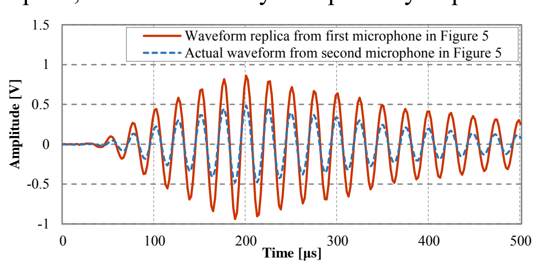

Figure 2. Received signal waveforms at maximum correlation value

The cross-correlation factor is calculated from the waveform replica $S_1(t)$ and the received waveform $S_2(t)$. It produces signal cross-correlation $c(\tau)$. This cross-correlation $c(\tau)$ is calculated for these signals as follows

$$c(\tau) = \int_{-\infty}^{\infty} s_1(t) s_2(t+\tau) dt.$$

B. Enhancement of signal correlation without increasing the bandwidth

To provide a distinct waveform signature without increasing the bandwidth, we apply a phase modulation in the middle of the exciting waveform as shown in Figure 3. By doing so, we can observe an amplitude drop point at the middle of received waveforms (Figure 4), which is generated by phase modulation of transmitted ultrasonic signal waveform.

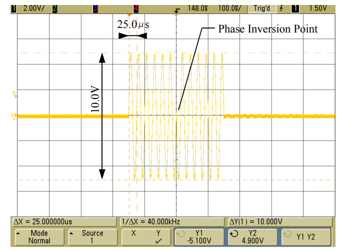

Figure 3. Improved exciting waveform plugged into an ultrasonic transmitter

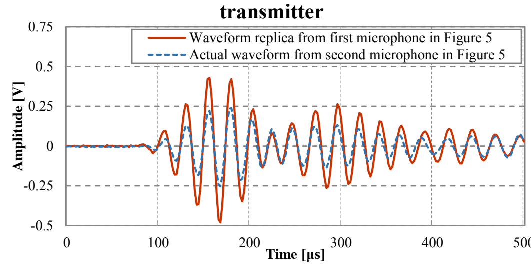

Figure 4. Received signal waveforms by modulated transmitted ultrasonic signal at maximum correlation value

IV. EXPERIMENTS EVALUATION

We examined the contribution of our proposal using an experiment using narrow-band ultrasonic transducers. The transmit signal generation and the received signal processing to calculate TOF is done with MATLAB and NI USB6361 A/D converter at 500ksps sampling rate. For the transmitter we use UT1612MPR whose operating frequency is 40kHz with bandwidth ±1kHz. The receivers, referred to as the first and the second microphones in Figure 5, are audio condenser microphone PRIMO EM258 which can be used in ultrasonic band. The first microphone captures the transmit signal to produce a waveform replica and the second receiver is to measure TOF.

The distance between the transmitter and the first receiver is 15 mm, and that of the second receiver is 250 ~ 270mm which can be changed. The transmitter and receivers are 140 mm above the ground to avoid floor reflections. The whole experiment system is shown in Figure 6.

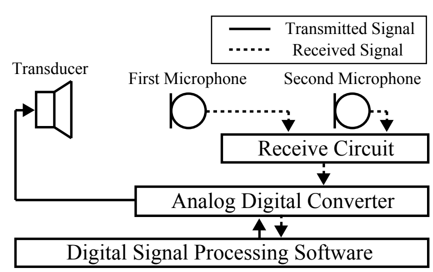

Figure 5. Schematic of the experimental setup

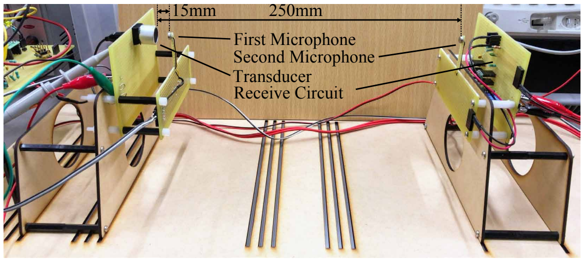

Figure 6. Experimental setup

The contribution of the two proposals are evaluated by measuring the TOF and the comparison with the theoretical TOF which is calculated from the geometry of the experimental setup.

A. Contribution of waveform replica

In this experiment, we measured TOF by cross correlation between the received signal waveform and two types of waveform replicas, one is the excitation waveform shown in Figure 1and the other is the measured waveform shown in Figure 2. The left side of Figure 7 is the TOF measured with the excitation waveform. The right side is the TOF measured with the waveform replica. The theoretical TOF is calculated considering the room air temperature.

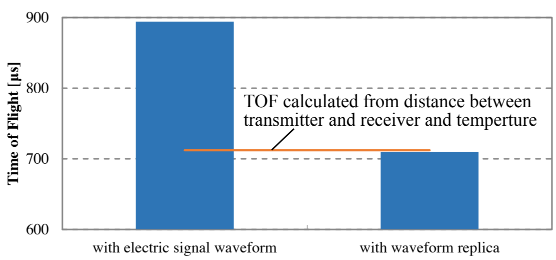

Figure 7. Comparison of TOF with electric signal waveform and waveform replica

It is shown that the TOF measurement with the waveform replica significantly reduces the error, from 25.5% to 0.3%. The TOF resolution is also evaluated at another distance between the transmitter and the second microphone. The bias from the theoretical TOF is constant in three different distances in Figure 8. Since the bias is constant irrespective to the choice of distance, we can improve the measurement accuracy by securing longer distance between the transmitter and the receiver, the required accuracy, less than 0.3%, can be achieved with about 26 cm.

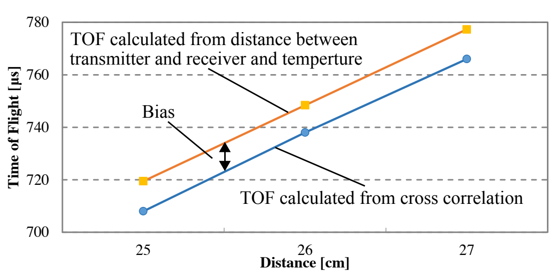

Figure 8. Comparison of TOF with changing the distance

B. Contribution of phase modulated signal to improve resistance to reflected wave

We measured the TOFs with three types of exciting waveforms, the constant envelope, a Chirp signal from 39kHz to 41kHz and the phase modulated waveform shown in Figure 3. Improved exciting waveform plugged into an ultrasonic transmitter. As is shown in Figure 9, the three TOF errors are the same.

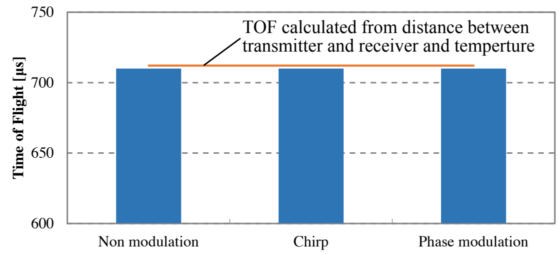

Figure 9. Comparison of TOF with three types of transmitted ultrasonic signal

To evaluate the sensitivity against disturbance, we also calculate the first and the second peaks of cross-correlation factor of the three exciting waveforms as shown in Figure 10. The immunity to disturbance can be measured as the difference between the first and second peaks of cross-correlation factor. When we have large difference between the first and second peaks, we can mitigate the TOF measurement error. It is shown that the phase modulated waveform shows the distinct first peak which infers the immunity to disturbances.

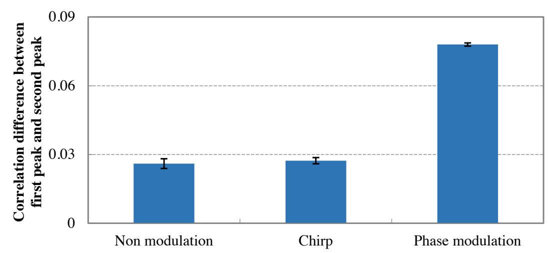

Figure 10. Comparison of correlation difference between first peak and second peak

V. Conclusion

High precision TOF measurement of narrow-band, COTS ultrasonic transducers can be achieved by using an experimentally obtained waveform replica and the use of a phase modulated excitation waveform. If we can secure more than 26 cm separation distance between the transmitter and the receiver, we can achieve less than 0.3% measurement accuracy.

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