A novel method for digital ultrasonic time-of-flight measurement

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(Received 5 March 2010; accepted 3 September 2010; published online 25 October 2010)

Most ultrasonic ranging measurements are based on the determination of the ultrasonic time-of-flight (TOF). This paper develops a novel method for the TOF measurement which combines both the improved self-interference driving technique and the optional optimization signal processing algorithms. By stimulating the transmitter with the amplitude modulation and the phase modulation envelope square waveforms (APESWs), the proposed system can effectively reduce the errors caused by inertia delay and amplitude attenuation. In addition, based on different signal-to-noise ratio test conditions, the resultant received zero-crossing samples, which are deteriorated by noise, can be precisely inspected and calculated with two optimized algorithms named zero-crossing tracking (ZCT) and time-shifted superposition (TSS) method. The architecture of the designed system is divided into two parts. The novel APESW driving module, the received envelope zero-crossings phase detection module, and the ZCT method processing module are designed in a complex programable logic device. The TSS signal processing module and the optimization algorithm discrimination program module are integrated in a digital signal processor. The TOF measurements calibrated in ultrasonic ranging experiments indicate that the relative errors of the method are limited in ±0.8%. Therefore, a feasible method is provided with the advantages of high noise immunity, accuracy, low cost, and ease of implementation. © 2010 American Institute of Physics. [doi:10.1063/1.3493046]

I. INTRODUCTION

Accurate determination of ultrasonic time-of-flight (TOF) as the key technique used in flow and ranging measurements has been rapidly developed in recent years.1–3 To improve the TOF measurement resolution, different methods have been introduced into the industrial applications. According to the articles mentioned before, the simplest way is the threshold-crossing technique, in which the time of arrival is determined by certain received threshold signal levels.4,5 However, due to the inertia phenomenon of amplitude delay, low signal-to-noise ratios (SNRs) and uncertainty in the environment caused by temperature and humidity variations have an important impact on the accuracy and stability of the measurements, all these factors will give rise to substantial measurement errors. Basically, among all these factors, the influences of environment variations can be satisfactorily compensated by adding a temperature and humidity sensor circuit to the ultrasonic system.6 Nevertheless, the errors caused by other factors are difficult to be eliminated.

The root cause of the inertia phenomenon of amplitude delay when starting vibration is derived from the piezoelectric characteristics of the ultrasonic transducer, which induces relatively long rise time of the echo waves.7 Accordingly, when the piezoelectric transducer detects these received signals coming from the transmitter, the inertia delay time will definitely add to the TOF results and cause errors. Moreover, the order of this issue on the threshold-crossing measurement will lead to deviations up to several cycles. On the other side, noise is another important factor that will affect the precision of measurements. In the low SNR regimes, as the received ultrasonic waves are interfered by noise, the threshold-crossing detectors cannot respond to the original received signals accurately. Therefore, these two factors constitute the main reasons for nonaccurate TOF measurements.

For the purpose of solving these problems, some methods have been developed, such as dynamic detection threshold method,8 various digital signal-processing algorithms, and envelope self-interference analysis.9,10 Applying the dynamic detection threshold method, the errors can be diminished by making the threshold level variable or by using the automatic gain controlled technique. But this method cannot eliminate the errors fundamentally. Hence, we cannot use this method to achieve high-precision measurements.11 Digital signal processing algorithms, for instance, may improve the measurement accuracy by correlation of the transmitted and the received signals.12 However, such approach needs to increase the sampling frequency and resolution as high as possible. Obviously, the accuracy of the digital signal processing algorithms is limited by the resolution of the analog to digital converter (ADC). In addition, this technique is more expensive due to the complex hardware and software. Envelope self-interference analysis technique is a new approach for the determination of the TOF by detecting the time differences between the envelope self-interference zero-crossings of the transmitted and received ultrasound which was first proposed in 1992. Nevertheless, this technique can only be used in the high SNR regimes.13 Furthermore, since the zero-crossings are susceptible to noise, the promotion of this technique has been severely suppressed after publication.
As the TOF determination is difficult to be calibrated because of the two factors mentioned above, a new DSP-based system is presented in this paper. A novel amplitude modulation and phase modulation envelope square waveform (APESW) driving approach combining both the amplitude modulation and the phase modulation is proposed for overcoming the inertia delay phenomenon of the received pulses. In addition, to suppress the influences of noise, zero-crossing tracking (ZCT) and time-shifted superposition (TSS) method discriminated by different SNR regimes are designed for post signal processing. This proposed system has several advantages. First, since controlling the time intervals between the sequential transmitted pulse trains will produce phase inversions during the envelope zero-crossings by simple digital means, it is possible to retrieve the original received pulse trains accurately rather than to deduce from the amplitudes. Second, self-diagnosing the actual SNR situations in experiments can facilitate the choice of appropriate algorithms for post signal processing. Finally, as the signal processing algorithms are selected based on SNR, the system is less sensitive to noise, resulting in a better overall measurement performance.

II. THE MEASUREMENT METHOD

A. Standard self-interference driving technology

Ultrasonic waves produced by piezoelectric transducers can be modeled as a damped sinusoid wave as

\[ g(t) = Ate^{-\alpha t} \sin(\omega t + \phi). \]  

In this mathematical model, \( n, \alpha, \omega, \phi \) are transducer dependent parameters: \( A \) is the wave amplitude, \( \omega \) is the undamped angular resonance frequency of the piezoelectric transducer, \( t \) represents time, \( n \) and \( \alpha \) are empirical constants that are determined by experiments. For the transducers used in our experiments, values for \( n \) ranges between 1 and 3 provide good approximations, \( \alpha \approx 10^4 \text{s}^{-1} \). Suppose two sequential such waves are generated from a single piezoelectric transducer,

\[ g_1(t) = Ate^{-\alpha t} \sin(\omega t + \phi)u(t), \]

\[ g_2(t) = A(t-t_d)e^{-\alpha(t-t_d)} \sin(\omega t - \omega t_d + \phi) \cdot u(t-t_d), \]  

where \( t_d \) is the time interval between the starting points of the two pulse trains, and \( u(t) \) represents the unit step function. The output of the transmitter is a self-interference signal \( g_{\text{inf}}(t) \) that can be expressed as

\[ g_{\text{inf}}(t) = g_1(t) + g_2(t) = Ate^{-\alpha t} \left[ 1 - \left(1 - \frac{t_d}{t} \right)^n \right] \sin(\omega t + \phi). \]  

Here, assuming \( t_d = (2k+1)\pi/\omega \) is smaller than the effective signal length, the sequential two waves will coexist during some periods of time, and an interfered ultrasonic wave is produced. The envelope is zero for \( t=t_d \), satisfying

\[ t_z = \frac{t_d}{1 - e^{-(\omega/\alpha)t_d}}. \]  

Hence, the TOF can be directly acquired by detecting the time intervals between the transmitted and received self-interference zero-crossings. In addition, when \( t_d \) is chosen, there will be a phase inversion \( \pi \) that occurs before and after the envelope zero-crossing between the two ultrasonic waves \( g_1(t) \) and \( g_2(t) \). Therefore, the time intervals mentioned above can be procured by inspecting the phase inversion time of the transmitted and the received pulse trains.

B. Optimized self-interference driving technology

Although the above method can acquire the TOF measurement, the results are always affected by noise in practical experiments. In this paper, a novel self-interference driving technique is proposed to overcome this problem. Supplying four sequential similar pulse trains to a piezoelectric transducer will generate four waves \( g_1(t), g_2(t), g_3(t), \) and \( g_4(t) \), respectively, as

\[ g_1(t) = Ate^{-\alpha t} \sin(\omega t + \phi)u(t), \]

\[ g_2(t) = A(t-t_d)e^{-\alpha(t-t_d)} \sin(\omega t - \omega t_d + \phi)u(t-t_d), \]

\[ g_3(t) = A(t-t_d-t_h)e^{-\alpha(t-t_d-t_h)} \]

\[ \times \sin(\omega t - \omega t_d - \omega t_h + \phi)u(t-t_d-t_h), \]

\[ g_4(t) = A(t-t_d-t_h-t_j)e^{-\alpha(t-t_d-t_h-t_j)} \]

\[ \times \sin(\omega t - \omega t_d - \omega t_h - \omega t_j + \phi)u(t-t_d-t_h-t_j), \]

where \( t_d, t_h, \) and \( t_j \) are the time intervals between the starting points of the four pulse trains. Every sequential two pulse trains combine a new self-interference ultrasonic wave \( g_{\text{inf}}^i(t) \), which \( i \) represents the interference number as

\[ g_{\text{inf}}^1 = g_1(t) + g_2(t) = Ate^{-\alpha t} \left[ 1 - \left(1 - \frac{t_d}{t} \right)^n \right] e^{\omega t_d} \]

\[ \times \sin(\omega t + \phi), \]

\[ g_{\text{inf}}^2 = g_2(t) + g_3(t) = A(t-t_i)e^{-\alpha(t-t_i)} \left[ e^{\omega t \left( \frac{t - 2t_i}{t-t_i} \right)^n} - 1 \right] \]

\[ \times \sin(\omega t + \phi), \]

\[ g_{\text{inf}}^3 = g_3(t) + g_4(t) = A(t-2t_i)e^{-\alpha(t-2t_i)} \left[ 1 - e^{\omega t \left( \frac{t - 3t_i}{t-2t_i} \right)^n} \right] \]

\[ \times \sin(\omega t + \phi). \]  

Assuming \( t_i = t_d = t_h = t_j = (2k+1)\pi/\omega \) is smaller than the effective signal length, the envelope zero-crossings for \( t=t_z \), satisfying

\[ t_z = \frac{t_d}{1 - e^{-(\omega/\alpha)t_d}}. \]
warm up waves, which are equal to 180° waves will have different phases compared with the first six measurement waves and the following six low-amplitude waves are transmitted. As a result, the double-width pulse for phase modulation. After that, another produced, which have higher amplitudes and start with a tertia delay caused by the piezoelectric effect of the ultrasonic transducer. The optimized driving waveforms consist of three reduplicate APESWs with three components. First, it transmits six low-amplitude pulses to warm up both the transmitter and the receiver, which can eliminate the inertia delay caused by the piezoelectric effect of the ultrasonic transducer. Second, for the purpose of distinguishing from the original waves and enhancing the accuracies, two ampli-
tude and phase modulated measurement waves are intro-
duced, which are equal to the predesigned fixed time, the received zero-crossings will be considered free from noise. From the table, the symbols “yes” and “no” are marked to reveal whether the comparison results meet the preset test requirements. Moreover, as the system detects the authenticity of the received envelope zero-crossings relying on the relationships between the zero-crossings themselves, the combination of one no and two times yes as well as only one correct envelope zero-crossings is not possible. Therefore, by summing up from what is in Table I, there are a total of five different test conditions that are listed in column 1 which are marked from 1 to 5. These conditions lead to the following conclusions: if test results meet the requirements from case 1 to 4, there exist at least two zero-crossings that are not interrupted by noise. ZCT algorithm can be used to calculate the TOF results. On the contrary, if none of the comparison results satisfies the above mentioned requirements in the experiments, all the zero-crossings are submerged in noise, which results in ZCT algorithm failure. Accordingly, TSS algorithm will replace ZCT algorithm to complete the TOF calculation.

D. ZCT and TSS signal processing algorithms

For the purpose of reducing noise impacts on the measurements, two optional signal processing algorithms are proposed in this paper named the ZCT and the TSS algo-
rithm. Considering that the phase inversion phenomena occur before and after the envelope zero-crossings, the ZCT algorithm makes use of the phase inversion detection as the method to achieve the zero-crossings. If the time intervals between the phase inversion trigger samples meet the criteria mentioned above in Table I, from case 1 to 4, there are at least two envelope zero-crossings that can be used for the

\[
t_i = \frac{t_i}{1 - e^{-\alpha(n)t_i}},
\]

\[
t_z^2 = t_i + \frac{t_i}{1 - e^{-\alpha(n)t_i}} = t_i + t_z^1,
\]

\[
t_z^3 = t_i + t_i + \frac{t_i}{1 - e^{-\alpha(n)t_i}} = t_i + t_z^2.
\]

Obviously, two conclusions can be drawn from the above formulas. There is a phase inversion \( \pi \) during each envelope zero-crossing. In addition, the intervals between these envel-
lopes are equal to a constant value \( t_i \).

Figure 1 shows the proposed ultrasonic driving and resultant self-interference waveforms from the transmitting piezoelectric transducer. The optimized driving waveforms consist of three reduplicate APESWs with three components. First, it transmits six low-amplitude pulses to warm up both the transmitter and the receiver, which can eliminate the inertia delay caused by the piezoelectric effect of the ultrasonic transducer. Second, for the purpose of distinguishing from the original waves and enhancing the accuracies, two ampli-
titude and phase modulated measurement waves are intro-
duced, which have higher amplitudes and start with a double-width pulse for phase modulation. After that, another six low-amplitude waves are transmitted. As a result, the measurement waves and the following six low-amplitude waves will have different phases compared with the first six warm up waves, which are equal to 180°(\( \pi \)).

C. Self-diagnose criteria for different SNR situations

Since noise is the most important factor that influences the accuracy of the measurement results, the classification of the actual experiment conditions based on different SNR becomes a key issue in this paper. From the above formulas, the regularity of the time intervals between self-interference zero-crossings provides us with a convenient method of distinguishing different test conditions, as shown in Table I, where \( T_{inf}(1) \) and \( T_{inf}(2) \) are the time intervals between pulse envelope zero-crossings. \( T_i^1, T_i^2 \) and \( T_i^3 \), listed in the last column, are sequential received pulse envelope zero-crossings. Since there are fixed time intervals \( t_i \) between the adjacent self-interference zero-crossings like those proved in Eq. (7), the comparison results of these time differences can be used as the criteria for judging whether the received en-
velope zero-crossings are interfered by noise and identifying how many zero-crossings are appropriate for the following signal processing applications. In other words, the criteria also means that if the time intervals between zero-crossings are equal to the predesigned fixed time, the received zero-crossings will be considered free from noise. From the table, the symbols “yes” and “no” are marked to reveal whether the comparison results meet the preset test requirements. Moreover, as the system detects the authenticity of the received envelope zero-crossings relying on the relationships between the zero-crossings themselves, the combination of one no and two times yes as well as only one correct envelope zero-crossings is not possible. Therefore, by summing up from what is in Table I, there are a total of five different test conditions that are listed in column 1 which are marked from 1 to 5. These conditions lead to the following conclusions: if test results meet the requirements from case 1 to 4, there exist at least two zero-crossings that are not interrupted by noise. ZCT algorithm can be used to calculate the TOF results. On the contrary, if none of the comparison results satisfies the above mentioned requirements in the experiments, all the zero-crossings are submerged in noise, which results in ZCT algorithm failure. Accordingly, TSS algorithm will replace ZCT algorithm to complete the TOF calculation.

\[
T_{inf}(1) - t_i = 0, T_{inf}(2) - t_i = 0, T_{inf}(1) + T_{inf}(2) - 2t_i = 0, T_{inf}(1) + T_{inf}(2) - 2t_i = 0
\]

TABLE I. Self-diagnose criteria for algorithm selections. (CEZC means correct envelope zero-crossing.)

<table>
<thead>
<tr>
<th>No.</th>
<th>( T_{inf}(1) - t_i = 0 )</th>
<th>( T_{inf}(2) - t_i = 0 )</th>
<th>( T_{inf}(1) + T_{inf}(2) - 2t_i = 0 )</th>
<th>Method</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Yes</td>
<td>Yes</td>
<td>Yes</td>
<td>ZCT</td>
</tr>
<tr>
<td>2</td>
<td>Yes</td>
<td>No</td>
<td>No</td>
<td>ZCT</td>
</tr>
<tr>
<td>3</td>
<td>No</td>
<td>Yes</td>
<td>No</td>
<td>ZCT</td>
</tr>
<tr>
<td>4</td>
<td>No</td>
<td>No</td>
<td>Yes</td>
<td>ZCT</td>
</tr>
<tr>
<td>5</td>
<td>No</td>
<td>No</td>
<td>No</td>
<td>TSS</td>
</tr>
</tbody>
</table>
TOF measurements. Here, assuming $T_p^i$ is the correct envelope zero-crossing that is not interfered by noise, TOF can be calculated as the sum of two separated parts, as illustrated in Fig. 3. One part estimates the integer number $N$ of full-cycle clock, and the other calculates the phase shifts of the last one that is smaller than one complete cycle. In this paper, the system utilizes the counterclock 1 ($f_{clk} = 40$ kHz) that is derived from Xilinx XC2C128 CPLD system clock ($f_{clk} = 40$ MHz) divided by 1000 to calculate the integer numbers of the transmitted signals. In addition, the phase-shift quantity of the last cycle is counted by a high frequency phase compensation technique presented in Fig. 4, where $T_z$ represents the TOF measurement results derived from the ZCT method, $t_{int}$ is the time interval of the integer number ($N$) of the 40 kHz counterclock 1, and $t_{missing}$ is the time interval of the last incomplete cycle.

In Fig. 4, when phase detector senses the phase changes of the received signals, the high frequency counterclock 2 ($f_{clk} = 40$ MHz) is activated until the next rising edge of the counterclock 1. By calculating the clock numbers between these two trigger samples, the missing phase-shift quantity $t_{missing}$ and the TOF are derived from Eqs. (8) and (9). Here $T_1$ is equal to the counterclock 1’s period (25 $\mu$s), $T_2$ is the counterclock 2’s period (25 $\mu$s), and $n$ represents the numbers of the counterclock 2. The ZCT method can effectively reduce the limitations caused by the amplitude attenuation of the received signals and the finite bits of the A/D (analog to digital) converter. Since the high frequency 40 MHz counter is applied to the measurements for the last cycle, the maximum TOF resolution is 2.5 ns. Therefore, the ZCT method improves the detection accuracy 1000 times compared with the 40 kHz ultrasonic wave frequency.

\[
t_{missing} = T_1 - n \times T_2, \tag{8}
\]

\[
T_z = t_{int} + t_{missing} = N \times T_1 + (T_1 - n \times T_2) = (N + 1) \times T_1 - n \times T_2. \tag{9}
\]

However, due to the fact that the SNR in the vicinity of the envelope zero-crossing is quite poor, there exist conditions in which all the envelope zero-crossings are submerged in noise. The TSS algorithm is introduced into the system as another option to replace ZCT algorithm for the TOF measurements in these low SNR situations. Figure 5 shows the diagram of the TSS algorithm. The key issue of the TSS algorithm lies in effectively improving the SNR of the measurements. Since the optimized driving APESW waveforms are composed of predefined time sequence ultrasonic signals, all the time intervals are equal to $t_i$ between adjacent envelope zero-crossings that have been proved in Eq. (7). The TSS algorithm is to process the received signals by summing up the original received samples and their time-shifted copies. Therefore, the resultant samples, having an improved signal-to-noise ratio, are reconstructed from this summation. Furthermore, the peak value of the synthesis samples enlarges the SNR compared to the remaining parts, which provides reference for deriving the first received envelope zero-crossing to achieve the TOF. To implement the superposition in the system, “averaging” and “stacking” methods are used for reconstructing. Moreover, the received 40 KHz signals are sampled by a 40 MSPS (million samples per second) ADC to obtain the high-precision TOF calculations. According to the method of design, when the received signals exceed the preset threshold value, the ADC is triggered at the rising edge of this sample and transmits 50 000 sampled signals into the SRAM (Static random access memory). Besides, the proposed ultrasonic driving and resultant self-interference waveforms are made up of three reduplicate APESW parts that have phase inversions between the adjacent waveforms. The superposition of the adjacent waveforms will definitely reduce the level of the samples. Therefore, for the purpose of acquiring the enhanced SNR resultant waveforms, the original received samples must superpose with the samples that have the same phase. In this paper, as the time interval between the adjacent APESW of the opposite phase is equal to $t_0$, the original received samples and their $2 \times t_0$ time-shifted copies will have the same phase. From the diagram, $T_{amp}$ represents the time interval between the transmitted envelope zero-crossing and the peak value of the resultant samples derived by TSS algorithm. To obtain an accurate value of TOF $T_z$, as shown in Eq. (10), a zero-crossing in the received samples has chosen a fixed number of cycles $T_p$ before the fifth envelope zero-
crossing, after which the resultant envelope experiences a
quarter of cycle to arrive at its peak value,

\[ T_z = T_{\text{amp}} - T_s = T_{\text{amp}} - \frac{5}{20} T_1 - 0.25 \times T_1. \]  

III. SYSTEM IMPLEMENTATION

A. Hardware system description

An overview of the total hardware measurement system that is made up of the analog and digital circuits is shown in Fig. 6. The optimized APESW transmitted signals are generated in a digital format by a joint processing with a DSP (TMS320 F2812, Texas Instruments, USA), a CPLD (XC2C128, Xilinx, USA), and a power regulation circuit. The stimulating pulses are then supplied to a piezoelectric ceramic transducer with a resonance frequency of 40 kHz. Additionally, in the receiver circuits, the received analog signals are amplified, modulated, and sent to a comparator for zero-crossing and threshold detections. When the received signals meet the preset threshold voltage requirements, the comparator triggers the ADC circuit and converts the analog signals into a series of square pulses whose widths are measured by the CPLD. Meanwhile, the sampled signals from the ADC are directly transmitted to a SRAM chip for the following signal processing. Subsequently, after CPLD completes the calculations of the time differences between the received envelope zero-crossings, all the digital results are gathered and analyzed by the DSP system. Lastly, according to Table I, the system will select the final algorithm between the ZCT and TSS to achieve the TOF calculations.

Figure 7 shows the block diagram of the CPLD chip. The programmable logic circuits inside the CPLD system include five functional modules: the clock module, the APESW generator module, the time interval measurement module, the phase detector module, and the TOF determination of the ZCT method module. According to the system, the CPLD is designed to use a 40 MHz crystal as the active system clock source. After initialization from the clock frequency divider module, the system clock frequency is divided into two parts: the low frequency 40 kHz signal is used as a reference clock for the APESW generation process, the integer clock counter for TOF measurement, and the phase inversion quantity counter. The high-frequency 40 MHz signal is applied to the phase compensation module as a reference clock counter to calculate the precise phase inversion time. Additionally, the APESW generator module uses the 40 kHz clock as the standard pulse clock to generate the reference waves. After finishing phase modulation by the CPLD and amplitude modulation by the power regulation circuit, the optimized APESW waves are synthesized and supplied to a piezoelectric transducer. In the CPLD, the phase detector module is comprised of two phase detectors 1 and 2, which is in charge of monitoring the transmitted and received phase inversion signals. By measuring the time differences between the triggering samples of the phase detector 2, the time interval measurement module sends the obtained phase inversion time delay to the DSP. If the test results satisfy the qualification of the ZCT method requirements, the TOF calculating block will combine the integer and the phase compensation counter values to achieve the TOF result.

B. Software system description

A software block diagram of the DSP ultrasonic TOF measurement system is illustrated in Fig. 8. After system initialization, the amplitude modulated ultrasonic waves are sent to the CPLD chip to generate the optimized APESW waves. And then, the DSP real-time interrupt handling mechanism is pending for the TOF algorithm selection and the TOF calculation. During the interrupt processing, the
time intervals gathered from the CPLD will be used to judge whether the criteria are qualified to apply the ZCT or TSS algorithm. Later on, the final selected algorithm from the ZCT and TSS will be carried out to calculate the TOF. In this paper, the ZCT algorithm for the TOF measurement is integrated in the CPLD programmed circuit chip other than the TSS method that is stored in the DSP system. The final TOF measurement results are processed and saved in the DSP system for the peripheral devices.

**IV. EXPERIMENT RESULTS AND DISCUSSIONS**

Figure 9 presents an overview of the experiment platform for the TOF measurement. To validate the accuracy of the TOF data, the calculation results are applied to an ultrasonic ranging measurement system for the calibrations, as shown in Eq. (11). Here, $S_{\text{TOF}}$ represents the distance calculated by TOF measurement, $C$ means ultrasonic velocity in air, $T_{\text{TOF}}$ is the propagation time. In the experiment platform, two 40 kHz acoustic transducers are fixed face to face on a standard measurement scale ranged from 0 to 200 mm that has been guaranteed by a calibrated optical liner scale system. All the measurement system is realized in a PCB (printed circuit board) formed with DSP and CPLD, as well as other functional modules. The measurement results are sent to a computer via an RS-232 interface to achieve the visual displaying. A calibration procedure has been implemented before conducting the actual measurements, considering the influence of temperature changes in the environment. As a result, the ultrasonic ranging measurement equation can be revised in Eq. (12). Here, the correction factor $k$ varies with different temperatures. In this paper, due to the facts that all the experiments are conducted in the laboratory, three temperature conditions (5 °C, 15 °C, 25 °C) have been calibrated with the help of temperature sensor,

$$S_{\text{TOF}} = C \times T_{\text{TOF}},$$

(11)

$$S_{\text{TOF}} = k \times C \times T_{\text{TOF}}.$$  

(12)

A graph of the ultrasonic ranging measurement relative errors versus incremental distances at three different temperatures is shown in Fig. 10. To reduce the impacts of temperature variations on the measurement accuracies, a compensation factor $k$ has been introduced into each distance calculation, as shown in Eq. (12). Considering that the actual transducer position variations and the circuit delay time uncertainties may influence the resolution of the tests as well, a relative calculation based on a specified location is implemented in the system to eliminate these errors. Furthermore, constraints by the existing conditions where only a limited distance has been guaranteed by a calibrated optical liner scale system, the ranges of the distance measurement are set between 40 and 180 mm. All the distance measurements are then calculated relative to an artificially defined starting point of 40 mm and an increase of 10 mm/step.

Table II summarizes three separate experiments with results of distance measurements that are derived from TOF at 5 °C, 15 °C, 25 °C. In order to facilitate the comparisons and to enhance the understanding among the groups of results, a total of 4500 experiment data is gathered at different temperatures. To achieve the real-time monitoring, each measurement is limited to 1 s to complete the entire processes.

![FIG. 9. The experiment platform of the ultrasonic ranging measurement.](image)

**FIG. 9.** The experiment platform of the ultrasonic ranging measurement.

**FIG. 10.** The graph of the ultrasonic ranging measurement relative errors vs incremental distances at 5 °C, 15 °C, 25 °C.

**TABLE II.** Experimental data summary.

<table>
<thead>
<tr>
<th>Temp.</th>
<th>5 °C</th>
<th>15 °C</th>
<th>25 °C</th>
</tr>
</thead>
<tbody>
<tr>
<td>Measuring time (s)</td>
<td>4500</td>
<td>4500</td>
<td>4500</td>
</tr>
<tr>
<td>Effective detection number</td>
<td>4461 99.1%</td>
<td>4428 98.4%</td>
<td>4419 98.2%</td>
</tr>
<tr>
<td>Algorithm selection</td>
<td>ZCT 3240 76%</td>
<td>ZCT 4182 70.7%</td>
<td>ZCT 3339 74.2%</td>
</tr>
<tr>
<td></td>
<td>TSS 1041 23.1%</td>
<td>TSS 1246 27.7%</td>
<td>TSS 1080 24.0%</td>
</tr>
<tr>
<td></td>
<td>39 0.9%</td>
<td>72 1.6%</td>
<td>81 1.8%</td>
</tr>
<tr>
<td>Average relative error (%)</td>
<td>0.14</td>
<td>0.20</td>
<td>0.34</td>
</tr>
<tr>
<td>Standard deviation of relative error (%)</td>
<td>0.19</td>
<td>0.24</td>
<td>0.16</td>
</tr>
</tbody>
</table>
such as pulse emission, data acquisition, algorithm selection, and signal processing. According to the results listed in Table II, the effective detection numbers in different situations are 4461, 4428, and 4419 times, which account for 99.1%, 98.4%, and 98.2% of the total measurements, respectively. Furthermore, as the tests are subject to variations of the temperatures and the on-site conditions, the proportion of the algorithms selected by the system to calculate TOF between ZCT and TSS is different. In addition, considering the effect of noise in experiments that is inevitable, there exist 39, 72, and 81 test results that exhibit significant deviations from the actual results. As a consequence, these abnormal points of measurements will be replaced by the average value of the nearby points in actual experiments. In Table II, the bottom two rows show the results of the statistical analysis of the experimental data which resulted from different temperatures. Through calibrations, the average relative errors are equal to 0.14%, 0.20%, and 0.34%, and the experimental standard deviations of the linearity with respect to the relative errors are found to be 0.19%, 0.24%, and 0.16%.

V. CONCLUSIONS

Noise as the most common cause of error has a great impact on the ultrasonic TOF measurement accuracy. In this paper, a novel system that combines an improved APESW waveform driving technique with two optimized signal processing algorithms is proposed to solve this problem. By making use of the new driving technique, the primary errors in the received ultrasonic waves caused by inertia delay and amplitude attenuation can be effectively reduced. In addition, by combining the regularity derived from Eq. (7) that all the time intervals are constant between received envelope zero-crossings, a simple method is provided in this paper to discriminate the different SNRs in practical experiments. Accordingly, two optional signal processing algorithms named ZCT and TSS are designed for the high and low SNR measurements. In the high SNR situations, since at least two envelope zero-crossings are captured by the phase detector in the CPLD, the TOF determination can be achieved by detecting the time intervals between the phase inversion time of the transmitted and received signals, which is named ZCT algorithm. On the contrary, when the TOF measurement stands in the low SNR situations, the TSS algorithm replaces the ZCT algorithm to effectively increase the intensity of the received signals compared with noise. After detecting the peak value of the received ultrasonic waves from synthesis samples by averaging and stacking, TOF measurement can then be carried out by calculating the time intervals between the transmitted and received signals with an empirical equation. In this article, all the signal processing methods are integrated in a single PCB board that is constituted with DSP, CPLD, as well as other functional modules. To validate the accuracy of the TOF algorithms, all the results are applied to an ultrasonic ranging experiment platform for the calibrations. The results obtained at different temperatures indicate that the proposed measurement system can achieve a real-time, high accurate, and stable TOF detection.