Non Contact High Precision Distance Measurement Using Single Probe Ultrasonic Transducer

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Abstract. The distance measurement has been used in a wide variety of applications such as robotic control, vehicle navigation, precision liquid level measurement, precise machinery control and so on. Of the different technologies, ultrasonic based technology has the advantage of being very simple to implement, less costly and highly precise for distance measurement. The high accuracy of ultrasonic based range measurement is mainly due to the low velocity of propagation of ultrasonic waves in the medium allowing estimating precise distance based on time of flight (TOF) measurement. Several methods for TOF measurement have been developed over the years and each of these methods has got its on limitation for precise distance measurement. The main factors which affect precise distance measurement include poor signal to noise ratio and phase sensitivity of the received signal causing errors in the TOF measurement, blanking zone created by the ringing of the transmitting transducer and the random medium displacements and changes in the speed of sound with humidity and temperature changes in the medium.

The paper discusses the product realization of a novel concept for highly precise distance measurement using single probe ultrasonic transducer. The measurement of phase variation of ultrasonic signal allows for a very high precision displacement/TOF measurement. However measurement resolution depends on phase sensitivity and the signal-to-noise ratio of ultrasonic wave signals. In these situations, for obtaining high resolution measurement a highly accurate phase detection technique needs to be employed. The measured time of flight values are subjected to real time velocity calibration algorithm to compensate for errors due to change in environmental parameters and hence to improve precision in distance measurements. The paper discuss in details the innovative methods used for sub sample accurate TOF measurement, the innovative method used for reverberation cancellation and real time velocity calibration algorithm. These innovative methods are used to realize a high precision ultrasonic diameter measuring system which is capable of measuring diameter with < 10μm precision and accuracy in water. The system accuracy is verified using calibrated master setting discs.

Keywords: ultrasonic transducer, time of flight, blanking zone, velocity calibration, transceiver, accuracy, precision, signal to noise ratio

1. Introduction

The non-contact distance measurement is used for wide variety of applications such as robotic control, vehicle navigation, precision liquid level measurement, precise machinery control and so on. Different types of distance measurement techniques have been

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introduced making use of various technologies such as laser, infra-red, radio frequency and ultrasonic signals. Of these different technologies, ultrasonic based technology has the advantage of being very simple to implement, less costly and highly precise for range measurement. The high accuracy of ultrasonic based range measurement is mainly due to the low velocity of propagation of ultrasonic waves in the medium allowing estimating precise distance based on time of flight (TOF) measurement [1]. In ultrasonic technology, an ultrasonic pulse wave leaves the transducer, strikes the target and returns an echo. The time delay of transmitted pulse and received echo, which is called time of flight (TOF), is estimated to calculate the distance by the product of TOF and sound speed in the medium. Several methods for TOF measurement have been developed over the years and each of these methods has got its on limitation for precise distance measurement. The main factors which affect precise distance measurement include poor signal to noise ratio and phase sensitivity of the received signal causing errors in the TOF measurement, dead zone created by the ringing of the transducer and the random medium displacements and changes in the speed of sound with humidity and temperature changes in the medium.

The precision in distance measurement means precision in TOF measurement and precision in measuring the velocity of the medium. There are a multitude of different methods available for measuring the TOF. Some of the popular methods include threshold based detection, cross correlation and Fourier domain phase based methods [1][2][3]. Theoretically, the maximum precision in TOF measurement that can be obtained using the above methods is one sampling period. In order to measure distance with micro-meter precision, there should be sub-sample accuracy in TOF measurement. This paper discusses an innovative signal processing technique which is used to obtain sub-sample accuracy in TOF measurement. Another factor which affects the precision in distance measurement is the reverberation of the transducer. A novel method is devised to completely eliminate the transducer reverberation and to extract the echo signal embedded inside the reverberation signal. Even if high precision time of flight measurement is achieved, the distance computation cannot match the precision achieved in time of flight measurement, the reason being the instantaneous variations in velocity of the medium due to varying environmental conditions. To eliminate the impact of instantaneous environmental conditions affecting measurement, a real time velocity calibration technique is employed. The real time calibration technique is also discussed. These methods have been verified experimentally.

Based on the experiments conducted for the feasibility of high precision (<10μm) distance measurement using the innovative signal processing methods, a new application, viz, ultrasonic diameter measuring system (UDMS) is conceptualized and implemented. The system is used to measure precisely the internal diameter of the pipe structures such as composite alloy pipes used in nuclear power plants. The system architecture, block level design, implementation and system operation are explained in Section 3. Section 4 discusses the important test results such as measurement precision, measurement accuracy, effect of temperature on precision etc obtained using UDMS.

2. Ultrasonic Distance Measurement

2.1 Principle of Operation

Block diagram of a typical ultrasonic based distance measurement system is shown in Fig.1.

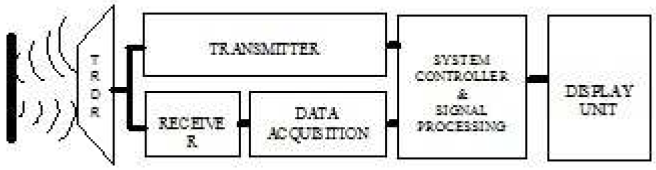

Fig.1. Block diagram of distance measurement system

The system consists of an ultrasonic transducer, transmitter, receiver, system controller, digital signal processor and display unit. The system sends a tone burst signal of the required frequency, transmission level and width to the transducer. The transmitted signal get reflected from the target object is picked up by the same ultrasonic transducer. The received echo signal is amplified, conditioned, digitized and processed to extract the required distance information. The distance information is send to the display unit for display. The major step involved in precise distance measurement is to find out the actual signal start from the echo signal using signal processing techniques. Using the identified echo start, the time of flight of the signal is computed. The distance is calculated from the time-of-flight (TOF) and the real time calibrated velocity using the Eqn. (2.1).

$$d = t \times v \qquad \textit{Eqn. (2.1)}$$

Where d is the distance, t is the time-of-flight and v is the velocity of the medium.

2.2 Challenging Factors Affecting Precision Distance Measurement

The most important challenges in precise distance measurement using single ultrasonic transducer are

i. Blanking zone due to ringing of the transmitting transducer.
ii. Error in detecting the signal start due to poor signal to noise ratio and phase sensitivity of the received signal
iii. Error in distance computation due to the random medium displacements and changes in the speed of sound with humidity and temperature changes in the medium.

These factors and the novel methods devised for eliminating these factors on precision distance measurement are explained in detail in next section.

2.3 Novel Methods used for Precision Distance Measurement

2.3.1 Elimination of Blanking Zone

Blanking zone refers to distance between the surfaces of the transducer to the target specimen where measurements cannot be made due to the ringing of the transducers, since echoes, if present in the blanking zone cannot be properly detected. Ringing is the continued vibration of the piezoelectric transducer element beyond the electrical excitation pulse. All piezo-electric transducers show this phenomenon irrespective of their design [6]. The received signal always contains a high amplitude ringing signal in single probe measurement, resulting in the formation of blanking zone. The blanking zone starts immediately after the transmission burst and lasts a few microseconds, duration of which is depended on the medium, transducer design etc. If echo signal gets embedded in this ringing region, it cannot be properly detected. Blanking zone causes a reduction of measurement range of the system. The method employed here ensures that the echo signal can be found out even if the signal falls inside the blanking zone. The ringing frequency is same as the excitation and echo frequency, thereby eliminating the possibility of using filtering for reduction of the blanking zone. The ringing signal follows an exponential decay pattern and it has been observed that the phase of the ringing signal is not consistent between successive transmissions. These factors are taken into consideration while creating an effective mechanism for removal of the ringing signal without affecting the echo.

In this method, a signature ringing pattern of the transducer is created prior to actual measurement. The signature ringing pattern is then processed to create a library of ringing signature signals at different phases, each with a high phase resolution. A high accuracy phase matching is performed with the ringing portion of the received signal and each of the signature signals created in different phases. Once precise phase matching is achieved, the ringing portion of the received signal can be effectively removed by subtracting the phase matched signature signal from the received echo signal.

2.3.2 Precise TOF Measurement

Conventional methods for signal extraction use thresholding, which is simple and works well for non high precision measurements [2][3][4]. Here the threshold based signal start computation is used as an initial estimate. The accuracy of the estimate is then further enhanced by accounting for a correction using a dynamic threshold calculated using the signal to noise ratio of the acquired signal itself.

The next better estimate of signal start is obtained by applying zero cross detection technique [2]. The signal start estimate so found can always contain an error corresponding to one sample. This zero cross computation error affects both transmitted and received signal start which is used in the flight time computation, thus resulting in an accumulated error corresponding to two samples.

An accuracy greater than one sample is achieved by accounting for this error using a phase difference computation methodology. A reference signal of zero phase is cross correlated with the received signal to find out the phase difference between the identified zero cross point of the received signal and the actual zero cross point. The same process is repeated for transmitted signal also and the resultant phase shift is computed. The phase differences so obtained corresponding to the transmitted and received signals are used for error compensation during time of flight computation.

2.3.3 Real Time Velocity Calibration

Even if high precision time of flight measurement is achieved, the distance computation cannot match the precision achieved in time of flight measurement, the reason being the instantaneous variations in velocity of the medium due to varying environmental conditions. To eliminate the impact of instantaneous environmental conditions affecting measurement, a real time calibration technique is employed. The output of real time calibration is constantly fed to the distance computation algorithm to achieve high precision in distance measurements.

3. Ultrasonic Diameter Measuring System

Based on the experiments conducted for the feasibility of high precision (<10µm) distance measurement using the novel methods described in section 2.3, a new application, viz, Ultrasonic Diameter Measuring System (UDMS) is conceptualized and implemented. UDMS is used to measure the diameter of pipe structures with high precision better than 10µm (in water). The precise distance measurement is achieved using innovative digital signal processing techniques and real time calibration algorithm to compensate for errors due to change in environmental parameters described in 2.3.

3.1 System Architecture

System model of the Ultrasonic Diameter Measurement System is shown in Fig. 2.

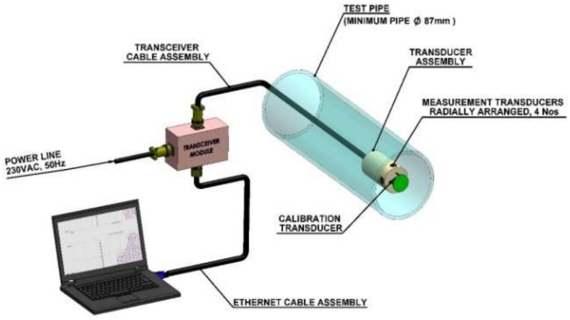

Fig. 2. System model of UDMS

The UDMS system consists of 2MHz transducer assembly, transceiver module, laptop preloaded with application software and associated cables for interconnecting the system parts. The system operates from 230V, 50Hz supply. The transducer assembly consists of 4 Nos of transducers arranged radially for taking orthogonal diameter measurements. The transceiver module resides all the electronics required for the operation of the system. It has an ethernet interface for communicating with the laptop. The application software runs on a laptop. The measured parameters are displayed on laptop and the user can configure the system parameters from the GUI of application software.

3.2 System Implementation

The block diagram of the Ultrasonic Diameter Measurement System is shown in Fig 3.

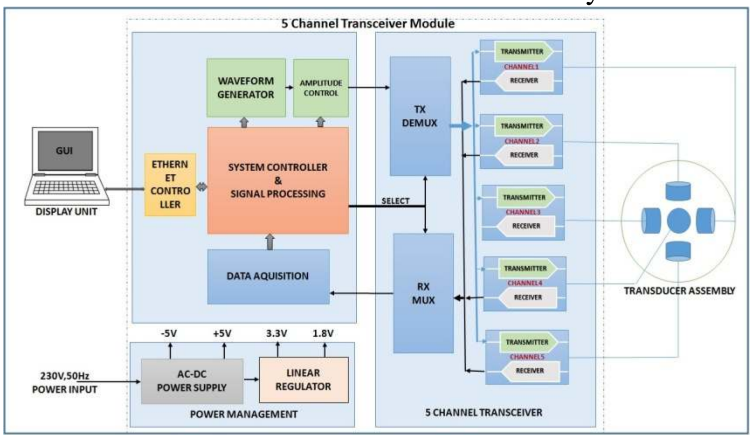

Fig. 3. Block Diagram of UDMS

The UDMS system consists of 2MHz transducer assembly, transceiver module and a display unit. The transceiver module consist of transmitter and receiver for five channels, Rx multiplexer, Tx channel de-multiplexer, system controller & signal processing block, data acquisition, waveform generation, amplitude control, Ethernet controller and power management blocks. The Table 2 given below shows the physical realization of each of these functional blocks.

Table 2. Physical Realization of logical blocks

Functional Blocks	Physical Realization (Hardware)	Physical Realization (Software)
Transmitter, Receiver, Tx Demux, Rx Mux,	2MHz Transceiver Board	--
Amplitude Control, Waveform Generation, System Controller & Signal Processing, Data Acquisition, Ethernet Controller	System Controller Data Aquisition Waveform Generator (SCDAWG)	Firmware on DSP

	Board	
Power Management	Power Supply Module	--
Transducer Mounting	Transducer Assembly	--
Display Unit (Measured parameters)	Laptop	Application software on Laptop

The implementation of each of this physical hardware is described below.

Fig.4. 2 MHz Transducer Assembly

2MHz transducer assembly consists of 5 Nos of 2MHz ultrasonic transducers, a fixed reference plate for velocity calibration and the transducer mounting arrangements. The transducer assembly is made of stainless steel (SS 304 grade) and fabricated using CNC machines. The transducer assembly is IP67 rated and is pressure tested for 7 bar pressure. The transducers are mounted as shown in Fig 4.

Fig.5. 2 MHz Transceiver Board **Fig.6.** SCDAWG Board

2MHz transceiver board shown in Fig 5 consists of transmitter and receiver circuits for each of the five channels, the transmit de-multiplexer and receive multiplexer circuits. The board operates from ±5V DC supply. SCDAWG Board consists of the circuits for amplitude control, waveform generation, system controller and signal processing, data acquisition and Ethernet controller. The board operates from ±5V DC supply. The system controller and signal processing is implemented using TMS320F2810 DSP. The code composer studio is the IDE used for developing DSP firmware. The DSP code is written using assembly and C language. The SCDAWG Board is show in Fig 6.

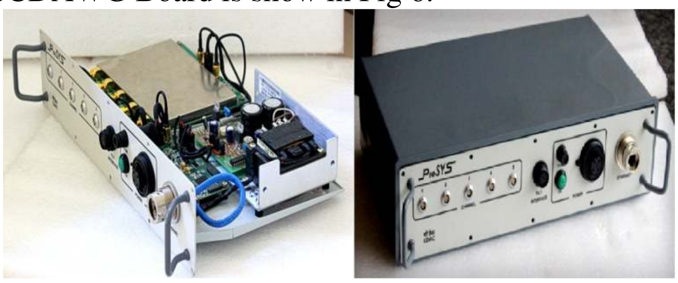

Fig.7. Power Supply Module **Fig.8.** Transceiver Module

Power supply module shown in Fig 7 is a linear power supply which generates +5V, 1.5A and -5V, 1.5A from 230V, 50Hz AC input. The power supply module provides power for 2MHz Transceiver Board and SCDAWG Board. The laptop used is a bought out laptop having i7 core and 4GB RAM. The application software runs on laptop. The measured parameters and the individual channel transmit and receive signals are displayed on GUI. The GUI also provides facility for system calibration, user settings, advanced parameters display etc. The application software is developed in Visual Studio Environment using

VC++. The Transceiver Module as shown in Fig 8 consists of 2MHz Transceiver Board, SCDAWG Board and Power Supply Module inter connected using cables and housed in a mechanical enclosure. The enclosure is made up of stainless steel (SS-304 Grade) and is fabricated using CNC machines. The whole module is IP67 rated.

3.3 System Setup

Fig.9. Ultrasonic Diameter Measuring System

UDMS setup consists of 2MHz transducer assembly inserted in a test pipe specimen inside a water tank, transceiver module and laptop interconnected using cables as shown in Fig 9. The system operates from 230V, 50Hz supply.

4. Test Results

Some of the important test results such as accuracy, precision, temperature dependence on measurement accuracy etc. are discussed in the following sections.

4.1 Measurement Accuracy

Table 3. Measurement accuracy

Actual MSC Diameter(mm)	Measured Diameter(mm)	Measurement Error (µm)	Remarks
82.000	82.002, 81.007	3	10 readings
85.000	85.001,84.998	2	10 readings
95.000	95.002,94.997	3	10 readings
110.000	110.002,109.996	4	10 readings

Calibrated master settings disc (MSC) were used to verify the measurement accuracy. The results show that the measurement accuracy of the system is better than 5µm.

4.2 Measurement Precision

Table 4. Measurement precision

Measurement Time (Hrs)	Measured Diameter (85.000 mm pipe)	Measured Diameter (110.000 mm pipe)
0	85.001	109.999
1	85.002	110.002
2	84.998	110.001
5	85.000	109.998
8	85.002	110.002

The readings are taken repeatedly at different intervals of time and verified the deviation of the measurement results. The maximum deviation is 2µm and hence the measurement precision is better than 2µm.

4.3 Effect of Temperature

Table 5. Effect of temperature

Temperature (^{o}C)	**Measured Diameter (85.000 mm pipe)**	**Velocity of medium (m/s)**
20	85.001	1482.4
25	85.001	1497.1
30	85.002	1509.5
35	85.001	1520.1
40	85.002	1528.7

The change in temperature does not affect the measurement accuracy.

5. Conclusion

High precision ultrasonic range measurement systems have potential use in wide variety of applications. The high precision performance of a distance measurement system is affected by factors such as presence of reverberation signal due to the ringing of the transducer in the echo signal, poor signal to noise ratio and phase sensitivity of the received signal causing error in the precise time of flight measurement and error in computed distance due to the variations in the environmental parameters such as humidity and temperature. In this paper, innovative methods used for achieving high precision distance measurement are discussed. These methods have been experimentally validated. Based on the experiments conducted for the feasibility of high precision (<10µm) distance measurement using ultrasonic transducers, a new application, viz, Ultrasonic Diameter Measuring System (UDMS) is conceptualized. UDMS has the potential use in measuring precisely the diameter of the heat resistant composite alloy pipes used in nuclear power plants. The UDMS is successfully designed, implemented and tested. The test results show that measurement accuracy and precision better than 5µm are achieved and the measurement accuracy is independent on the temperature of the medium.

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