Measurement of ultrasonic velocity with improved accuracy in pulse echo setup

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In the present work a personal computer based circuit adopted in pulseecho setup has been developed for the measurement of time-of-flight between the two successive echoes using a differential time measurement with a 16 bit counter and an external clock frequency of 32 MHz. A control program is developed in C to display the time of flight and wave propagation velocity on a user screen. The technique, so developed, minimizes the errors in time delay measurements due to the variation in threshold trigger points of echoes and improves the ultrasonic velocity measurement. © *2007 American Institute of Physics.* [DOI: 10.1063/1.2766820]

I. INTRODUCTION

In the pulse echo technique, a short duration ultrasonic pulse is introduced into the sample using a piezoelectric transducer. The ultrasonic pulse travels through the sample and an echo is registered each time it returns to the transducer. The amplitudes of the successive echoes decrease exponentially due to attenuation in the sample[1–3] and elaborate methods have been developed to measure attenuation and velocity with improved resolution.[4,5]

Measurement of ultrasonic velocity can be achieved with better resolution using a high-frequency counter by measuring the delay between two successive echoes accurately.[6–10] The difference between the two corresponding trigger points (delays) for which the counter starts and stops is the source of error in the time delay measurement. Successive pulses are not necessarily generated at the instant of arrival of trigger pulse at the trigger point, but are initiated somewhat later depending on the shape of leading edge of the trigger pulse and the voltage level at which the trigger is initiated,[11] as shown in Fig. 1. For precise ultrasonic velocity measurement, one must measure the time delay at the peaks of the two successive echoes (Td_{12}). But the circuits employing threshold comparators measure time delay (Td'_{12}) between the threshold points, say, P_1 and P_2. This error in time delay measurement is compensated in calibration by subtracting the extra time (t_1-t_2) from the measured time delay value. Hence, it is necessary to implement a circuit that will reduce the error due to the delay in the trigger point and thus improve accuracy.

Due to the development in digital computers, its use for measurement and control applications has been vastly increased.[12,13] The basic objective of computer based instrumentation is to improve the response time, computing power, flexibility, and fault tolerance.

In the present work, we have attempted the design of a precise time measurement circuit based on a differential time measurement technique. A 10 MHz ultrasonic pulser-receiver module and an ISA based DIO card to interface to the personal computer (PC) has been designed in our laboratory.[14]

II. EXPERIMENT

A. Pulser-receiver module

Figure 2 shows the block diagram of the designed pulser-receiver module. A 10 MHz rf oscillator has been designed using 10 MHz crystal (Raltron Electronics, USA) and NOT gates.[14,15] The pulse repetition rate generator has been designed using an NE566 voltage controlled oscillator for the frequency range of 100–400 Hz. The output of the repetition rate generator drives a gate width controller unit, which defines the time duration for which the 10 MHz rf will be transmitted through the sample. It uses a monostable multivibrator having a time constant of about 1 μs (variable). The output of the monostable is fed to the AND gate, whose second input is driven by the rf oscillator. Hence, the output of the AND gate provides a 10 MHz rf pulse for 1 μs duration with a pulse repetition frequency of 100 Hz. The pulsed rf obtained at the output of the AND gate is further amplified by transistor amplifier stages. The stages are coupled by a parallel RC element to improve the high-frequency response of the stage.[16] The final stage is the power amplifier to increase the current level in order to drive the circulator. A circulator is a transformer having toroid core with three windings. The first winding is excited by the transmitter output, the second winding is used to connect the transducer, and the third winding provides balanced output for the receiver. The advantages of using a circulator are as follows.

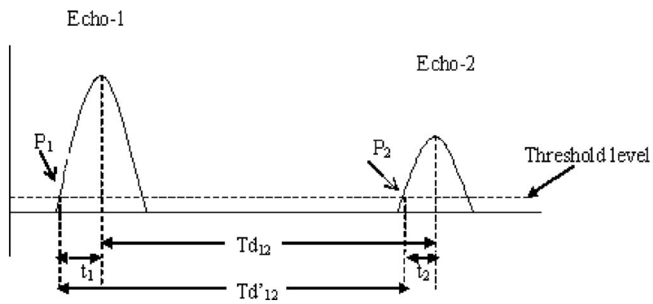

FIG. 1. Dependence of the measured time delay between two successive echoes on the threshold trigger point.

- It physically isolates the transmitter and receiver so that large voltage transmitted pulses will not damage the input section of the receiver.
- Use of single transducer for transmission as well as reception.
- Steps up the transmitted voltage at the transducer in secondary winding.
- Provides a differential (balanced) output signal for the receiver.
- Virtually acts as a switch between the transmitter/receiver and the transducer.

The center-tapped secondary winding of the circulator provides a differential output voltage, used to drive the high-gain differential amplifier. This differential amplifier provides balanced output. A single ended output is taken from this amplifier (NE592), which drives an active detector having a transistor in common collector mode and parallel *RC* element at emitter bias. This filters out the 10 MHz rf components from the received rf echoes. The detected echoes are further amplified by a stage of operational amplifier (op-amp) preamplifier and transistor amplifier stages and a transistor buffer at the final stage. The detected echo output is available at BNC to be fed out CRO for analysis.

B. Velocity measurement

Figure 3 shows the scheme of the time-of-flight (TOF) measurement using the time delay difference measurement technique. The detected echoes are fed to the noninverting terminal of both the comparators. The first comparator IC_1

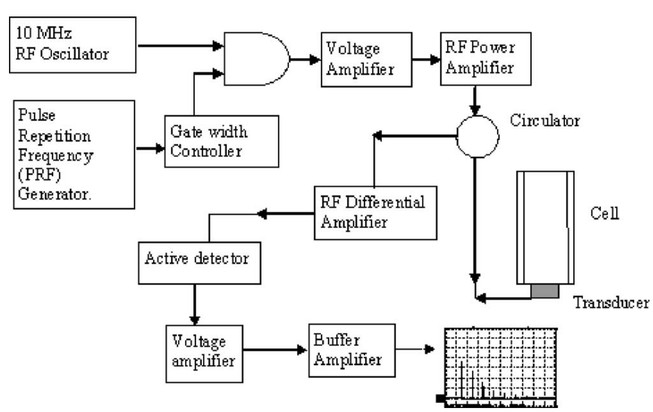

FIG. 2. Block diagram showing the major sections of the designed pulser-receiver module.

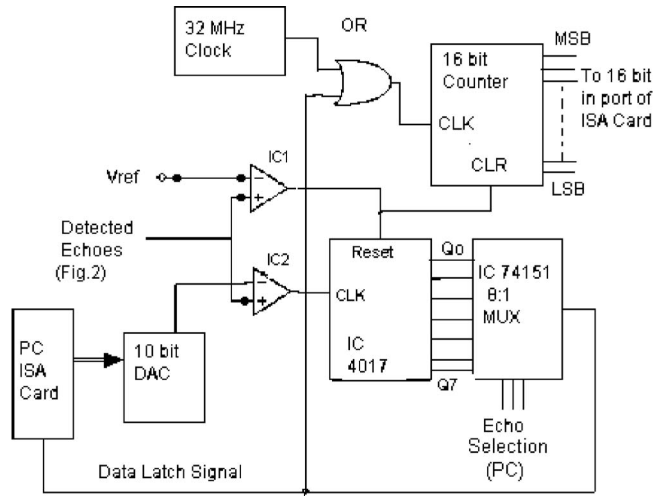

FIG. 3. Schematic of the velocity measurement.

(LM 311, ON Semiconductor voltage comparator) has inverting terminal at reference voltage of 4 V. The inverting terminal of the second comparator IC_2 is driven by a programmable reference voltage (V_{ref}), controlled by the PC. If V_{ref} from the PC is set at 4 V, then IC_1 generates a pulse only in response to the transmitted pulse of detected echoes to reset the counter and decoder (CD 4017: Fairchild Semiconductor decade counter with ten decoded outputs). The reference is reduced by a step of 4 mV and is again compared with the first echo amplitude. If the amplitude of the first echo is lower than V_{ref}, then IC_2 does not produce a second pulse.

The reference is further reduced by a step of 4 mV. This process continues until the programmable V_{ref} coincides with the amplitude of the first echo. At this amplitude level the comparator IC_2 will provide a second pulse related to the first echo. This pulse would be counted by IC 4017 which sets decoder output (Q_1) high. If the selected echo is the first (i.e., 001 is applied to select lines of multiplexer), then a high output produced by multiplexer (MUX) is sensed by the port of an ISA card, and hence the peak of the echo is detected. The 16 bit counter gives the delay from the transmitted pulse to the peak of the detected first echo. The same process is repeated for the subsequent echoes. Figure 4 shows the timing diagram of the comparator circuit.

C. Estimation of ultrasonic velocity

At every transmitted pulse, the 16 bit counter (modulus 65,536 counter designed by making use of two standard TTL IC 74LS393) resets by the pulse generated by comparator IC_1. After reset, the counter immediately starts counting until the reference amplitude coincides with the amplitude of the specified echo. Let the first echo, i.e., binary 001, be applied to the select lines of IC 74151 (TTL 8:1 multiplexer) by the PC. When the V_{ref} coincides with the amplitude of the first echo, comparator IC2 produces a pulse, which will be counted by IC 4017 and produces high at output Q_1. Hence, the output of 74151 becomes high, which disables the clock passing through the OR gate and the counter will stop counting. The number of counts specifies the delay between the

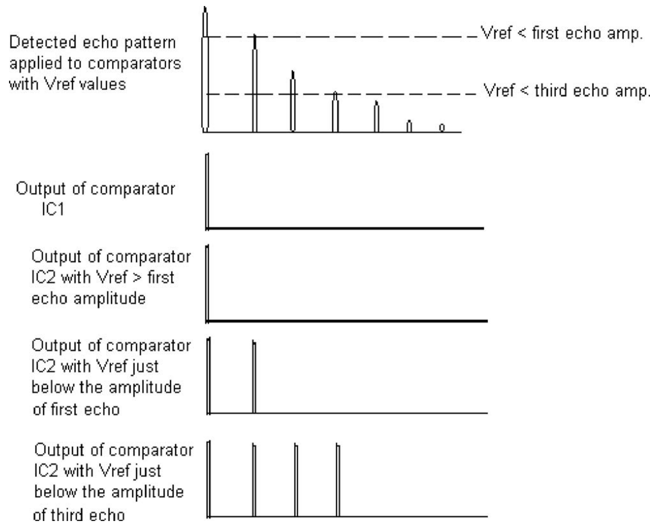

FIG. 4. Timing diagram of comparator circuit. Comparator IC_1 produces a pulse to reset the counter in response to the transmitted pulse. Comparator IC_2 detects the echo peaks.

transmitted pulse and the maximum of the first echo, given by

$$\tau_1 = N_1 \tau_{clk}, \tag{1}$$

where τ_1 is the delay between the transmitted pulse and the maximum of the first echo, N_1 is the number of counts in the counter between the transmitted and the first echo, and τ_{clk} is the time period of, the clock, i.e., 31.25 ns.

The same process is repeated for the second echo to give time delay between the transmitted pulse and the second echo τ_2. Hence, the actual time delay between the two echoes will be

$$\tau_{12} = (\tau_2 - \tau_1), \tag{2}$$

where τ_{12} is the time delay between echoes 1 and 2 in seconds.

Ultrasonic propagation velocity can be calculated using the formula

$$u = \frac{2d}{\tau_{12}}, \tag{3}$$

where d is the distance between the transducer and the reflector.

D. Software

A program has been written in C to display the following information on the user screen:

- the time delays of successive echoes from the transmitted pulse in microseconds,
- the time delays between two adjacent echoes,
- average time delay between two echoes, and
- propagation velocity in m/s.

III. RESULTS AND DISCUSSIONS

The precision in velocity measurement has been decided over 20 readings taken in the span of about 4 h, as shown in Fig. 5. The measurement was carried out at 34 °C. The standard deviation over this period was found to be 0.391 m/s. Better precision in measurement can be achieved by improv-

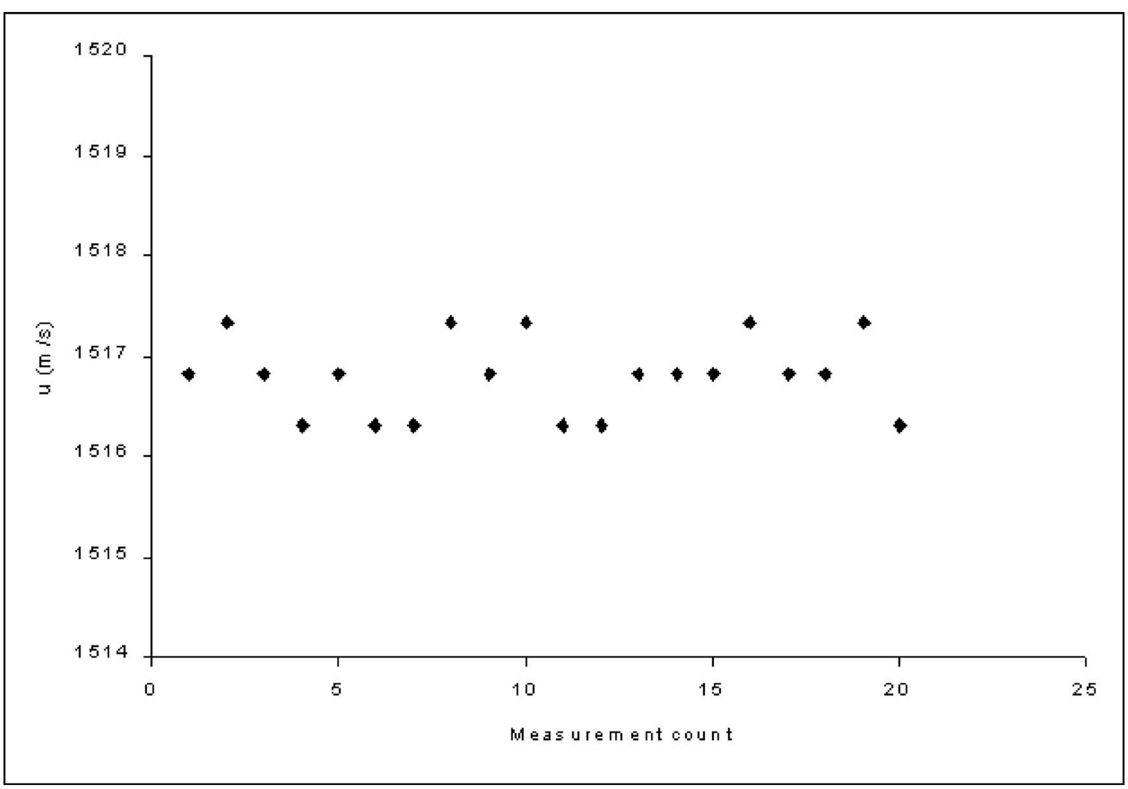

FIG. 5. Sound speed for distilled water at temperature 34 °C over 4 h.

TABLE I. Experimental data of ultrasonic propagation velocity in water, methyl alcohol, ethyl alcohol, and ethylene glycol at different temperatures.

Sample	Temperature (°C)	Velocity (m/s) (Expt.)	Velocity (m/s) (Refs. 17 and 18)	% Deviation
Water	30.0	1508.61	1509.12	0.033
	35.0	1519.40	1519.80	0.026
	40.0	1528.76	1528.86	0.006
	45.0	1536.66	1536.40	0.016
	50.0	1542.50	1542.55	0.003
	55.0	1547.67	1547.38	0.018
	60.0	1550.53	1550.98	0.029
Methyl alcohol	30.0	1086.66	1086.50	0.014
	35.0	1070.11	1070.00	0.010
	40.0	1053.07	1053.50	0.040
	45.0	1036.57	1037.00	0.041
	50.0	1019.52	1020.50	0.096
Ethyl alcohol	45.0	1079.43	1079.00	0.039
	50.0	1062.07	1062.50	0.040
	55.0	1045.31	1046.00	0.065
	60.0	1029.04	1029.50	0.044
Ethylene glycol	40.0	1627.94	1628.50	0.034
	45.0	1617.20	1618.00	0.049
	50.0	1606.83	1607.50	0.041
	55.0	1596.60	1597.00	0.025

ing the temperature stability, increasing path length, and using a higher counter clock frequency. Furthermore, the technique described here is not sensitive to the error introduced by the change in the shape of the echo pulse, which may occur by the improper bonding (in the case of a solid sample) and due to dispersion of the ultrasonic beam.

The designed instrument has been tested for its functionality on various standard liquids. The sample has been maintained at a desired temperature using a thermostat U_{10} with a stability of ±0.1 °C. Table I gives the experimental data of ultrasonic propagation velocity at different temperatures in some standard liquids. The measured experimental values closely match with literature. The variation in the measured values of ultrasonic propagation velocity due to counter resolution is ±1 count.

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