Measurements of the Ultrasound Propagation Velocity in Different Materials

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***Abstract*—Most applications for underwater acoustics, nondestructive testing of materials and biomedical ultrasound require an accurate measurement of the ultrasound velocity in water and other materials since the velocity of ultrasound waves is used to determine the related distance. The objective of this work was to determine the velocity of ultrasound waves in different materials such as water, rubber and Plexiglas using piezoelectric transducer. The experimental techniques and system were developed to obtain ultrasound velocity in different materials in the unit of meter/second (m/s). The implementation of the ultrasound velocity measurement utilizes a pulse-echo technique using a set of acoustic transducers with three different resonance frequencies, 2.25 MHz, 3.50 MHz, and 5.0 MHz. To verify the performance of the experimental techniques and system, the measured ultrasound velocities were compared with the theoretical values. The results show that the experimental values were in good agreement with theoretical results. In addition, the results indicate that the velocity of ultrasound waves in water and in other materials is frequency-independent.**

Keywords—Ultrasound Metrology; Ultrasound Velocity; Biomedical Ultrasound

I. Introduction

Most applications for underwater acoustics, nondestructive testing of materials and biomedical ultrasound require an accurate measurement of the ultrasound velocity in water [1] and other materials since the velocity of ultrasound waves is used to determine the related distance [2].

The propagation velocity of traveling ultrasound waves in a medium varies with the physical properties of the medium. Normally, it is not dependent upon the other wave characteristics such as frequency, period and amplitude. In low-density media such as air and other gases, molecules may move over relatively large distances before they influence adjacent molecules. In these media, the velocity of an ultrasound wave is relatively low. In solids, molecules are constrained in their motion, and the velocity of ultrasound is relatively high. Liquids exhibit ultrasound velocities intermediate between those in gases and solids. With the notable exceptions of lung and bone, biologic tissues yield velocities roughly similar to the velocity of ultrasound in water. In different media, changes in velocity are reflected in changes in wavelength of the ultrasound waves, with the frequency remaining relatively constant. In ultrasound imaging, variations in the velocity of ultrasound in different media introduce artifacts into the image, with the major artifacts attributable to bone, fat, and, in ophthalmologic applications, the lens of the eye [3].

The basic principle behind the measurement of the ultrasound velocity in materials is to measure the time between the transmitted and the received ultrasound signals. In this research, the measurement of the ultrasonic transducer displacement is used since it is more convenient and accurate than the measurement of the transmitter/receiver or transducer/reflector distance. This technique is able to eliminate additional artifacts caused by the time delays from the transducers and attached electronics.

This paper describes experimental techniques capable of determining the velocity of ultrasound waves in three different materials, which are water, rubber and Plexiglas.

II. Methods

In this work, all ultrasound velocity measurements were made at room temperature (25°C). Three sets of unfocused ultrasonic transducers from Olympus NDT Inc., Waltham, MA, USA with operating resonance frequencies of 2.25 MHz, 3.5 MHz and 5.0 MHz were used to perform the measurement of the ultrasound velocity in different materials. The diameters of all transducers are identical at approximately 12.7 mm.

The methodology for measuring the velocity of ultrasound waves was organized into 2 parts. The first part is to measure the ultrasound speed in water, whereas the second part is to determine the velocity of ultrasound waves in materials, which are rubber and Plexiglas.

<u>Part 1:</u>

To measure the speed of ultrasound waves in water, the two methods of measurements were carried out. First method, a pair of ultrasonic transducers with an identical resonance frequency was utilized. A pulser/receiver (Panametrics Pulse/Receiver 5073 PR) was employed to generate the pulse echoes. While one transducer was connected to the T/R port on the pulser/receiver to use it as the transmitter and the other was connected to the R port to use as a receiver. Both transducers were placed in the deionized water inside the water tank with DAEDAL XYZ Scanning System (Rohnert Park, CA, USA). The dimensions (X, Y, Z) of the water tank are 800 mm x 900 mm x 350 mm. The experimental setup for measuring the ultrasound velocity in water (method 1) is shown in Figure 1.

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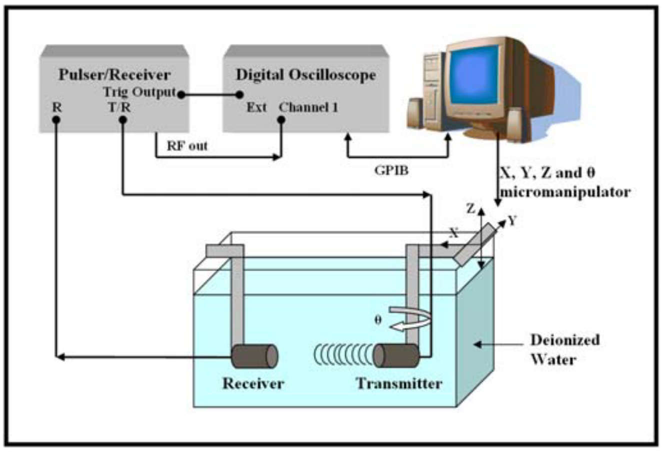

Fig. 1. The experimental set-up for measuring ultrasound velocity in water using two-transducer technique (method 1).

The placement of the transducers was controlled by the LabVIEW program presented in Figure 2.

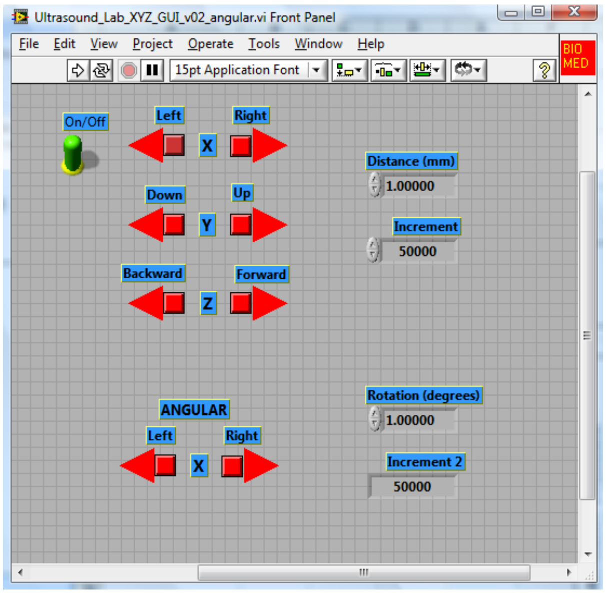

Fig. 2. Custom-made LabVIEW program for the alignment (x, y, z and θ directions) of the transducers

The precision of the stepper motors of the Scanning System is 10^{-4} mm per step, which allows for the displacement of the transducers from one position to another to occur accurately and rapidly. Proper alignment was signified by a maximum output voltage signal shown on the oscilloscope (Tektronix TDS220 Digital Oscilloscope with GPIB connection) when the transmitter was moved in the x, y, and z directions as well as in clockwise/counterclockwise (CW/CCW) rotation. The initial distance between the transducers and the initial time delay displayed on the oscilloscope at this initial alignment were recorded. Next, the transmitter was moved back (away from the receiver) by 50 mm increments to three different positions which were 50 mm, 100 mm and 150 mm. The results obtained for these positions were recorded and then later averaged. The external triggering of the oscilloscope is activated by the transmitted pulse from the pulser/receiver, which also sends the electrical energy to the transmitted transducer. While the transducer source transmits the ultrasonic pulses, the receiver transducer receives these pulses. This received ultrasonic signal is then converted to an electrical signal by the receiver transducer, and is amplified before it is finally transferred to the oscilloscope to observe and measure the corresponding signal. Another custom-made LabVIEW program was used for displaying and recording the waveforms on the computer from the oscilloscope for further analysis as shown in Figure 3. By measuring the time interval between two consecutive pulses on the screen of the oscilloscope and knowing the displacement of the transmitted transducer, the speed of ultrasound waves in water (c) can be calculated using equation 1.

$$c = \frac{x}{\Delta t} \tag{1}$$

where x is the displacement of the transmitter and Δt is the time interval between two consecutive received pulses.

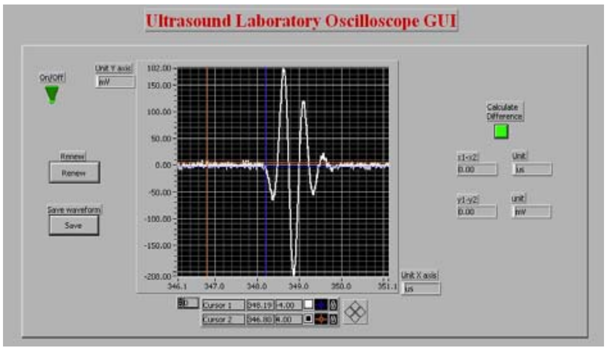

Fig. 3. Custom-made LabVIEW program for displaying and recording the waveforms from the oscilloscope

By using the second method to determine the ultrasound velocity in water, the procedure was practically the same as the first method. However, the receiver was replaced with the reflector. The experimental setup for the second method is presented in Figure 4. In this method, the same transducer acts as both the transmitter and the receiver. Since the ultrasound waves propagate in both directions – from the transducers, which acts as a transmitter, to the reflector and then back to the transducer, which act as a receiver, ultrasound velocity (c) can then be estimated as shown in equation 2:

$$c = \frac{2x}{\Delta t} \tag{2}$$

where x is the displacement of the transmitter/receiver and Δt is the time interval between two consecutive received pulses.

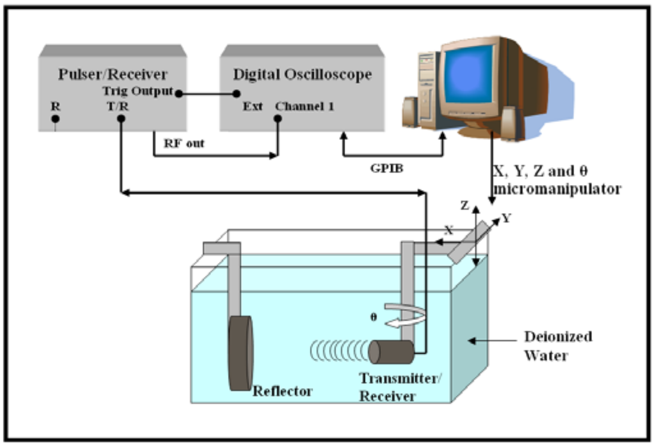

Fig. 4. The experimental set-up for measuring ultrasound velocity in water using one-transducer technique (method 2).

The measurements using both methods were repeated with the three sets of transducers, having resonance frequencies of 2.25 MHz, 3.5 MHz, and 5.0 MHz, and the results are presented in the results section.

Part 2:

The measurements of the ultrasound velocity in other materials were carried out in this part using three sets of transducers, having resonance frequencies of 2.25 MHz, 3.5 MHz, and 5.0 MHz. A Plexiglas plate and a rubber plate (polybutadiene) were employed for determining the ultrasound velocity in these materials based on the through-transmission configuration. The experimental set-up for measuring ultrasound velocity in materials is shown in Figure 5.

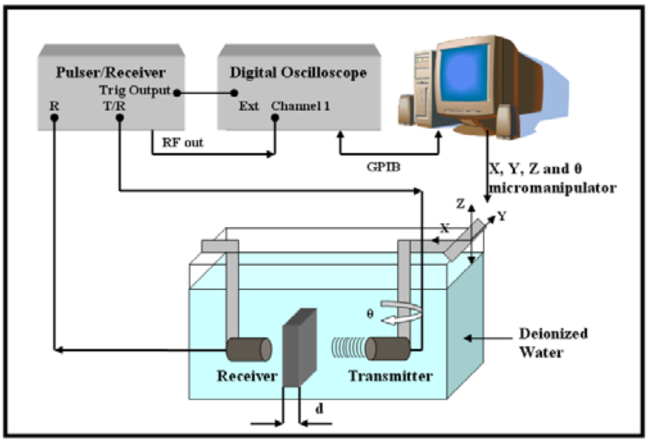

Fig. 5. The experimental set-up for measuring ultrasound velocity in materials using through-transmission technique.

The distance between transducers is larger than the thickness of the sample material, allowing a free alignment and positioning of the sample along the ultrasonic beam. The measurement system consists of a pair of coaxial transducers of similar frequency characteristics, denoted as a transmitter and receiver, and a sample material placed between them. A pulser/receiver (Panametrics Pulse/Receiver 5073 PR) was employed to generate the pulse echoes. While one transducer was connected to the T/R port on the pulser/receiver to use it as the transmitter and the other was connected to the R port to use as a receiver. The transducers and the sample material were placed in the deionized water inside the water tank as shown in Figure 5.

Before performing the ultrasound velocity measurement in the materials, the thickness of Plexiglas and rubber square plates were measured using a Vernier Caliper. The measured thickness distances were then taken an average of 8 measurements (2 on each side of the square) to obtain faithful values for the thickness. Two methods for measurements of the ultrasound velocity in the materials were used.

For the first method, the arrival time of the received signal, T_1, was recorded by the oscilloscope without placing the sample material between the transducers. Then, the sample material was placed approximately halfway between the transducers and the arrival time of the received signal, T_2, was recorded again. The ultrasound velocity in the sample material (c_m) could be easily obtained via the equation 3:

$$c_m = \frac{d}{\frac{d}{c} - \Delta T} \tag{3}$$

where c is the ultrasound velocity in water (m), which was previously determined, d is the thickness of the sample material (m), and $\Delta T = T_1 - T_2$ (s).

For the second method, the arrival time of the received signal, T_1, was also recorded by the oscilloscope without placing the sample material between the transducers. Then, the sample material was placed between the transducers and the receiver was moved back from the transmitter by the distance, which is equal to the thickness of the sample material. The arrival time of the received signal, T_2, was recorded again. The ultrasound velocity in the sample material (c_m) is able to determine by using the equation 4:

$$c_m = \frac{d}{\Delta T} \tag{4}$$

where d is the thickness of the sample material (m), and $\Delta T = T_1 - T_2$ (s).

It is worth mentioning that the second method for determination of ultrasound velocity in materials does not require the knowledge of the sound velocity in water, since the water path of the measurements remains the same and is eliminated in the calculations. The procedures described for both methods are repeated for both Plexiglas and rubber plates with the three sets of transducers, having resonance frequencies of 2.25 MHz, 3.5 MHz, and 5.0 MHz, and the results are presented in the next section.

III. RESULTS

To measure the speed of ultrasound waves in water, the two methods of measurements were carried out. The results of the ultrasound velocity measurement in water using two-transducer technique (method 1) with the resonance frequencies of 2.25 MHz, 3.5 MHz, and 5.0 MHz are presented on Tables 1, 2 and 3, respectively.

TABLE I. THE RESULTS OF THE ULTRASOUND VELOCITY MEASUREMENT IN WATER USING TWO-TRANSDUCER TECHNIQUE (METHOD 1) WITH THE RESONANCE FREQUENCY OF 2.25 MHZ

Position (mm)	Displacement or x (mm)	Measured time or t (μs)	Time interval or Δt (μs)	Ultrasound speed $C = x/\Delta t$ (m/s)
0	0	184.2	-	-
50	50	218	33.8	1479.29
100	50	252	34	1470.59
150	50	285.9	33.9	1474.93
Average ultrasound speed in water				1474.94

TABLE II. THE RESULTS OF THE ULTRASOUND VELOCITY MEASUREMENT IN WATER USING TWO-TRANSDUCER TECHNIQUE (METHOD 1) WITH THE RESONANCE FREQUENCY OF 3.5 MHZ

Position (mm)	Displacement or x (mm)	Measured time or t (μs)	Time interval or Δt (μs)	Ultrasound speed $C = x/\Delta t$ (m/s)
0	0	181.6	-	-
50	50	215.3	33.7	1483.68
100	50	249.1	33.8	1479.29
150	50	282.9	33.8	1479.29
Average ultrasound speed in water				1480.75

TABLE III. THE RESULTS OF THE ULTRASOUND VELOCITY MEASUREMENT IN WATER USING TWO-TRANSDUCER TECHNIQUE (METHOD 1) WITH THE RESONANCE FREQUENCY OF 5 MHZ

Position (mm)	Displacement or x (mm)	Measured time or t (μs)	Time interval or Δt (μs)	Ultrasound speed $C = x/\Delta t$ (m/s)
0	0	140.1	-	-
50	50	174	33.9	1474.93
100	50	207.9	33.9	1474.93
150	50	241.9	34	1470.59
Average ultrasound speed in water				1473.15

TABLE IV. THE RESULTS OF THE ULTRASOUND VELOCITY MEASUREMENT IN WATER USING ONE-TRANSDUCER TECHNIQUE (METHOD 2) WITH THE RESONANCE FREQUENCY OF 2.25 MHZ

Position (mm)	Displacement or x (mm)	Measured time or t (μs)	Time interval or Δt (μs)	Ultrasound speed $C = 2x/\Delta t$ (m/s)
0	0	178.5	-	-
50	50	246.2	67.7	1477.10
100	50	314.1	67.9	1472.75
150	50	382	67.9	1472.75
Average ultrasound speed in water				1474.20

The results of the ultrasound velocity measurement in water using one-transducer technique (method 2) with the resonance frequencies of 2.25 MHz, 3.5 MHz, and 5.0 MHz are presented on Tables 4, 5 and 6, respectively.

TABLE V. THE RESULTS OF THE ULTRASOUND VELOCITY MEASUREMENT IN WATER USING ONE-TRANSDUCER TECHNIQUE (METHOD 2) WITH THE RESONANCE FREQUENCY OF 3.5 MHZ

Position (mm)	Displacement or x (mm)	Measured time or t (μs)	Time interval or Δt (μs)	Ultrasound speed $C = 2x/\Delta t$ (m/s)
0	0	192	-	-
50	50	259.8	67.8	1474.93
100	50	327.5	67.7	1477.10
150	50	395.2	67.7	1477.10
Average ultrasound speed in water				1476.38

TABLE VI. THE RESULTS OF THE ULTRASOUND VELOCITY MEASUREMENT IN WATER USING ONE-TRANSDUCER TECHNIQUE (METHOD 2) WITH THE RESONANCE FREQUENCY OF 5 MHZ

Position (mm)	Displacement or x (mm)	Measured time or t (μs)	Time interval or Δt (μs)	Ultrasound speed $C = 2x/\Delta t$ (m/s)
0	0	205.1	-	-
50	50	272.8	67.7	1477.10
100	50	340.6	67.8	1474.93
150	50	408.5	67.9	1472.75
Average ultrasound speed in water				1474.93

Two methods for measurements of the ultrasound velocity in the materials were used. The results of the ultrasound velocity measurement in the Plexiglas and rubber plates using the first method with the resonance frequencies of 2.25 MHz, 3.5 MHz, and 5.0 MHz are presented on Tables 7, 8 and 9, respectively.

TABLE VII. THE RESULTS OF THE ULTRASOUND VELOCITY MEASUREMENT IN THE PLEXIGLAS AND RUBBER PLATES USING THE FIRST METHOD WITH THE RESONANCE FREQUENCY OF 2.25 MHZ

Material Type	Thickness of material or d (mm)	Measured time or t (μs)	Time interval or Δt (μs)	Ultrasound speed $Cm = d/((d/C)-\Delta T)$ (m/s)
None (Baseline)	-	315.3	-	-
Plexiglas	11.885	311.6	3.7	2729.882
Rubber	6.785	315	0.3	1578.737

TABLE VIII. THE RESULTS OF THE ULTRASOUND VELOCITY MEASUREMENT IN THE PLEXIGLAS AND RUBBER PLATES USING THE FIRST METHOD WITH THE RESONANCE FREQUENCY OF 3.5 MHZ

Material Type	Thickness of material or d (mm)	Measured time or t (μs)	Time interval or Δt (μs)	Ultrasound speed $Cm = d/((d/C)-\Delta T)$ (m/s)
None (Baseline)	-	253.5	-	-
Plexiglas	11.885	249.8	3.7	2729.882
Rubber	6.785	253.2	0.3	1578.737

TABLE IX. THE RESULTS OF THE ULTRASOUND VELOCITY MEASUREMENT IN THE PLEXIGLAS AND RUBBER PLATES USING THE FIRST METHOD WITH THE RESONANCE FREQUENCY OF 5 MHZ

Material Type	Thickness of material or d (mm)	Measured time or t (μs)	Time interval or Δt (μs)	Ultrasound speed Cm = d/((d/C)-ΔT) (m/s)
None (Baseline)	-	174.1	-	-
Plexiglas	11.885	170.5	3.6	2668.587
Rubber	6.785	173.8	0.3	1578.737

The results of the ultrasound velocity measurement in the Plexiglas and rubber plates using the second method with the resonance frequencies of 2.25 MHz, 3.5 MHz, and 5.0 MHz are presented on Tables 10, 11 and 12, respectively.

TABLE X. THE RESULTS OF THE ULTRASOUND VELOCITY MEASUREMENT IN THE PLEXIGLAS AND RUBBER PLATES USING THE SECOND METHOD WITH THE RESONANCE FREQUENCY OF 2.25 MHZ

Material Type	Thickness of material or d (mm)	Measured time or t (μs)	Time interval or Δt (μs)	Ultrasound speed Cm = d/ΔT (m/s)
None (Baseline)	-	315.3	-	-
Plexiglas	11.885	319.7	4.4	2701.136
Rubber	6.785	319.6	4.3	1577.907

TABLE XI. THE RESULTS OF THE ULTRASOUND VELOCITY MEASUREMENT IN THE PLEXIGLAS AND RUBBER PLATES USING THE SECOND METHOD WITH THE RESONANCE FREQUENCY OF 3.5 MHZ

Material Type	Thickness of material or d (mm)	Measured time or t (μs)	Time interval or Δt (μs)	Ultrasound speed Cm = d/ΔT (m/s)
None (Baseline)	-	253.5	-	-
Plexiglas	11.885	257.9	4.4	2701.136
Rubber	6.785	257.9	4.4	1542.045

TABLE XII. THE RESULTS OF THE ULTRASOUND VELOCITY MEASUREMENT IN THE PLEXIGLAS AND RUBBER PLATES USING THE SECOND METHOD WITH THE RESONANCE FREQUENCY OF 5 MHZ

Material Type	Thickness of material or d (mm)	Measured time or t (μs)	Time interval or Δt (μs)	Ultrasound speed Cm = d/ΔT (m/s)
None (Baseline)	-	174.1	-	-
Plexiglas	11.885	178.5	4.4	2701.136
Rubber	6.785	178.4	4.3	1577.907

IV. DISCUSSIONS AND CONCLUSIONS

After completing Part 1 of the research, the average ultrasound velocities in water using two-transducer technique (method 1) with the resonance frequencies of 2.25 MHz, 3.5 MHz, and 5.0 MHz were found to be 1474.94 m/s, 1480.75 m/s and 1473.15 m/s, respectively. The results of the average ultrasound velocities in water using one-transducer technique (method 2) with the resonance frequencies of 2.25 MHz, 3.5 MHz, and 5.0 MHz were determined to be 1474.20 m/s, 1476.38 m/s and 1474.93 m/s, respectively. However, the theoretical value of the ultrasound velocity in water at 25 degrees Celsius in [4] is 1490 m/s. Therefore, our results indicate tremendous accuracy within the error of 1.2%.

In Part 2, the theoretical value for the ultrasound velocity in Plexiglas is reported as 2760 m/s in [5] whereas the average velocities of ultrasound in Plexiglas using the 2.25 MHz transducers were found to be 2729.882 m/s using method 1 and 2701.136 m/s using method 2. Our calculated velocities of ultrasound in Plexiglas using the 3.5 MHz transducers were found to be 2729.882 m/s using method 1 and 2701.136 m/s using method 2. Finally, when the 5.0 MHz transducer was used, the average velocities of ultrasound in Plexiglas using methods 1 and 2 were 2668.587 m/s and 2701.136 m/s, respectively. Therefore, our calculated values using both methods have percent errors within 3.5%.

The velocity of ultrasound wave in rubber using method 1 was found to be 1578.737 m/s for all three frequencies. However, the values of ultrasound velocities in rubber were found to be slightly different when we were using method 2 (1577.907 m/s for 2.25 MHz transducers, 1542.045 m/s for 3.5 MHz transducers and 1577.907 m/s for 5 MHz transducers). The theoretical value of the ultrasound velocity in rubber (polybutadiene) in [6] is 1610 m/s. Therefore, our measurement values using both methods have percent errors within 4.5%.

In conclusion, our techniques can provide an accurate value for measuring velocity of ultrasound. Also, the velocity of ultrasound waves in the materials is frequency-independent.

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