Development of a Scanning System for Ultrasound Property Measurement

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ABSTRACT

Medical ultrasound is widely used in both therapeutic and diagnostic applications. However, ultrasound may cause some biological effects to the patients such as thermal effects and mechanical effects. Therefore, the objective of this work is to design, develop and construct a scanning system to accommodate for the measurement of the ultrasound properties such as pressure, intensity or other physical properties of ultrasound waves (i.e. ultrasound velocities in different materials) in order to ensure that the ultrasound waves from the transducer are not harm to the patients. The developed scanning system for ultrasound property measurement was designed to move on 4 axis (X, Y, Z and A) by using computer program to control. The resolution of the movement on the X, Y and Z is 1 mm. Also, the movement on the A axis can be adjusted from -90 to 90 degrees with 0.1-degree resolution. To verify the accuracy of the movement distances and angles on each axis, the movement distances and angles were compared with the distances and angles measured from the ruler and goniometer. From the tests, it shows that there was no error of the movement on the X, Y and Z axis. However, small errors were found to be less than 4.44% on the A axis. In addition, the developed ultrasound property measurement system was used to perform the measurements of the ultrasound velocity in water and directivity pattern in order to test the ultrasound property measurement of the system. The results of the ultrasound velocity measurement show that the velocity measured from the developed system is comparable to theoretical value. The differences are within 0.96%. The results of the directivity pattern measurement are also presented in comparison with the theoretical results as a function of spatial angle on both linear and logarithmic scales. Comparison between experimental and theoretical results indicates similar general behavior. These measurements confirm that the scanning system can accommodate for the measurement of the ultrasound properties.

Keywords: Ultrasound Metrology; Ultrasound Scanning Tank; Ultrasound Properties; Biomedical Ultrasound

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1. INTRODUCTION

Medical ultrasound has been used extensively in both diagnostic and therapeutic applications [1-5] during the past decades since medical ultrasound devices do not give ionizing radiation such as X-ray and can offer real-time information of the anatomical structures. However, other undesirable biological effects associated with ultrasound exposure such as thermal or mechanical effects may be introduced under certain conditions [6, 7]. For this reason, the acoustic output of the medical ultrasound devices should be determined and strictly regulated [8, 9].

The ultrasonic hydrophone probe is a standard tool used to acquire the acoustic output of the medical ultrasound devices. The acoustic pressure obtained by ultrasonic hydrophone probes can be used to determine the values that fulfill the labeling and reporting requirements of certain standards [7-10], such as the acoustic intensities and power. In addition, the Mechanical Index (MI) and Thermal Index (TI) of the medical transducer as defined by the Output Display Standard (ODS) [7, 9, 10] are values calculated from the acoustic pressure. The MI and TI have been used to evaluate the potential harm to a patient from a medical diagnostic ultrasound transducer. Reliable assessments of these calculated values can be obtained only when the ultrasonic hydrophone probes have been aligned in the proper position. Since the ultrasound measurements are performed in a confined space such as a finite-size water tank, there are several signals present, comprised of the desirable direct signal and undesirable echoes. The direct signal normally has the shortest traveling distance, which is related to the maximum signal received at the receiver. Therefore, the manipulation system that is able to find the optimize positions of the ultrasound source and the ultrasound receiver are significant.

In addition, the ultrasound field mapping for both diagnostic and therapeutic ultrasound applications are needed to fulfill the safety issue [11]. However, it is time consuming and quite hard to manually conduct the ultrasound field measurement. Performing the ultrasound field measurement automatically will save time and enhance productivity of the measurement.

In view of the above, it is clear that there is a well-defined need for a scanning system for ultrasound property measurement. This system will be able to accommodate for the movement of the ultrasound source and receiver to determine the ultrasound properties such as pressure, intensity or other physical properties of ultrasound waves (i.e. ultrasound velocities in different materials) in order to ensure that the ultrasound waves from the transducer are not harm to the patients.

2. METHODS

The developed scanning system for ultrasound property measurement was designed to move in 4 directions (X, Y, Z and A axis) by using computer program to control. Figure 1 shows a schematic diagram of the developed scanning system.

This scanning system is composed of the following parts:

A. Computer Program

A commercial CNC controller software is used in this work to control the motion of stepper motors by processing G-code. Basically, this software program will convert the personal computer into a fully functional 4 axis controller in X, Y, Z and A directions. In addition, this software program will be able to control both direction and speed of the motors.

B. USB Motion Card

A USB motion card model STB41000 is employed to use as an interface between the software program (via USB port) and drive motor units. This motion card can support for 4-axis linkage, which will be connected to four stepper motors. The step-pulse frequency can be up to 100 kHz.

C. Drive motor Units

The 4 units of oriental motor Vexta UDK2120A 2-Phase Stepper Motor Drivers are used to drive the 4 stepper motors after receiving the commands from the program. Each unit is assigned to drive each motor on each axis in four different axis (X, Y, Z and A directions).

D. Motors

The scanning system can be moved in 4 different directions, which are X, Y, Z and A axis by using 4 stepper motors as shown in Figure 2. This will accommodate for the movement of the ultrasound source or ultrasound receiver to the desired position.

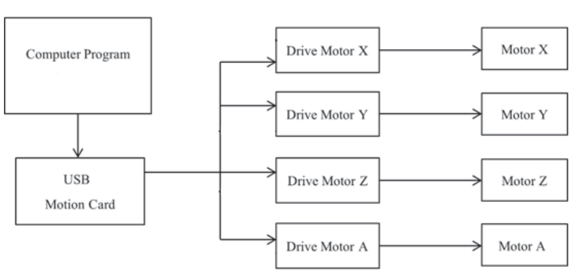

Fig.1:: Schematic diagram of the developed scanning system

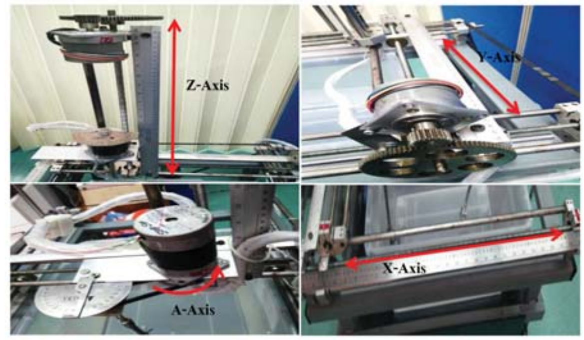

Fig.2:: The 4 stepper motors installed on 4 different axis

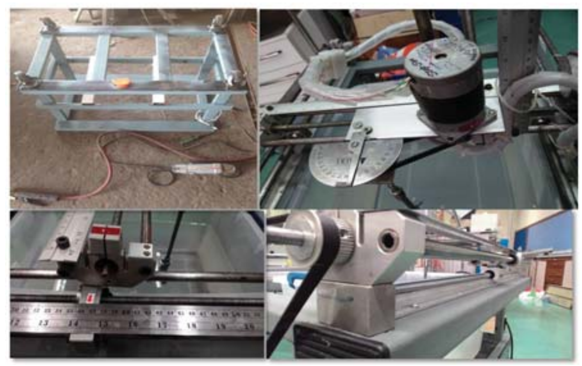

Fig.3:: The overall structure of the scanning system

E. Structure of the system

The overall structure of the scanning system was designed as shown in Figure 3. The gear systems of the X, Y, Z and A axis are presented in Figure 4, 5, 6 and 7, respectively.

After the scanning system was constructed, the system was tested with 3 different methods.

The first method was the testing for the accuracy of the movement distances on X, Y and Z axis and the movement angles on A axis. The movement distances would be compared with the distances measured from the ruler at 10 different locations (from 0.1 cm to 30 cm) for 3 times and the movement angles were also compared with angles measured from the goniometer at 10 different angles (from -90 degrees to 90 degrees) for 3 times. The results from the first test are presented in the results section.

The second test was carried out by measuring the speed of ultrasound waves in water using the developed system. The experimental setup for this test is presented in Figure 8. An ultrasound transducer was placed in the deionized water inside the developed scanning system. A pulser/receiver (Panametrics Pulse/Receiver 5073 PR) was connected to the transducer to generate the pulse signals to the ultrasound transducer. This transducer would act as both the transmitter and the receiver. Since the ultrasound waves propagate in both directions – from

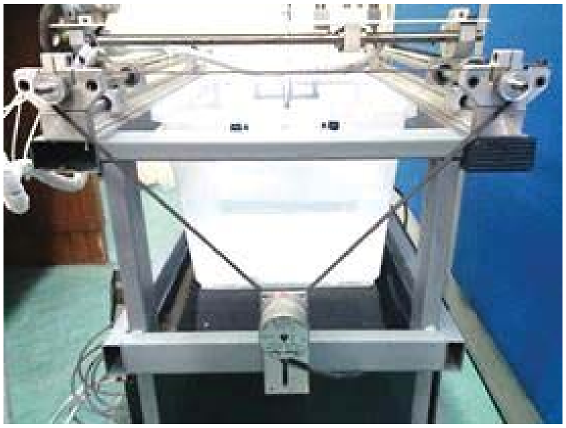

Fig.4:: The gear system on the X axis

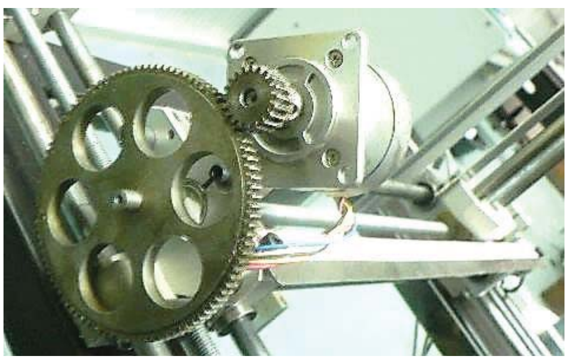

Fig.5:: The gear system on the Y axis

Fig.6:: The gear system on the Z axis

Fig.7:: The gear system on the A axis (clockwise/-counterclockwise (CW/CCW) rotation)

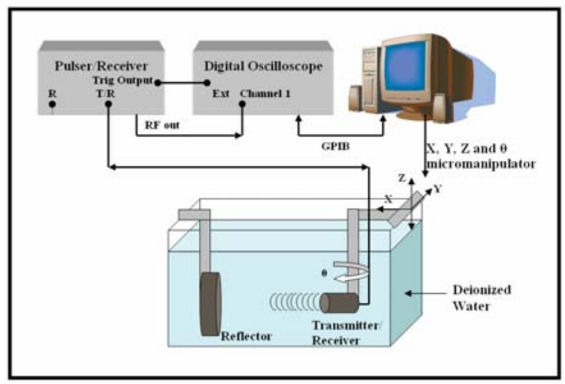

Fig.8:: The experimental set-up for measuring ultrasound velocity in water

the transducers, which acts as a transmitter, to the reflector and then back to the transducer, which act as a receiver.

When the transmitter was moved in the X, Y, Z and A directions, the suitable alignment was normally indicated by a maximum output voltage signal presented on the oscilloscope (Tektronix TDS220 Digital Oscilloscope). The initial distance between the transducer and the reflector, and the initial time delay displayed on the oscilloscope at this initial alignment were recorded. Next, the transducer was moved back (away from the reflector) by 50 mm increments to three different positions which were 50 mm, 100 mm and 150 mm. The results obtained for these locations were recorded and then later averaged. The external trigger of the oscilloscope was activated by the transmitted pulse from the pulser/receiver, which also sends the electrical energy to the ultrasound transducer. Then, the ultrasound signals would be sent from the transducer to the reflector and bounce back to the transducer. The received ultrasound signals were then converted to electrical signals by the receiver transducer, and was amplified before it was finally transferred to the oscilloscope to observe and

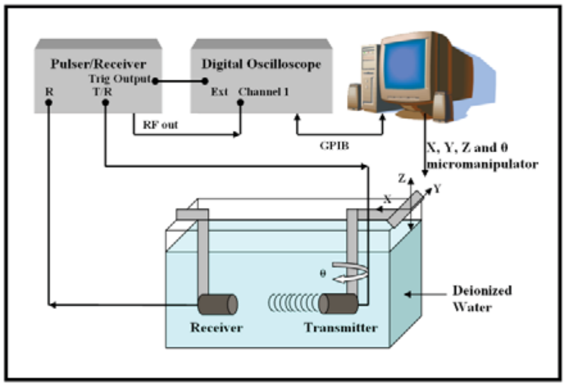

Fig.9:: The experimental set-up for measuring directivity pattern

measure the corresponding signal. By measuring the time interval between two consecutive pulses on the oscilloscope screen and knowing the displacement of the transmitted transducer, the speed of ultrasound waves in water (c) can be determined using equation 1.

$$c = \frac{2x}{\Delta t} \tag{1}$$

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

The measurements of the ultrasound velocity were then repeated with the two sets of the transducers, having resonance frequencies of 2.25 MHz and 5 MHz, and the results are presented in the results section.

Finally, the third test was the directivity pattern measurement from the ultrasound transducer. This measurement was performed by placing two transducers having the same resonance frequency in the developed scanning system as shown in Figure 9. The ultrasound transmitter and the receiver were separated by the minimum acceptable distance, called far-field distance, to minimize interference from reflections. The far-field distances were determined to be approximately beyond 20 cm and 43 cm for the 2.25 MHz and 5 MHz transducers, respectively. These distances were obtained using equation 2, which are the standard criteria for uniform circular piston [12].

$$X \geq \frac{\pi a^2}{\lambda} \tag{2}$$

where X is the far-field distance, a is the radius of the transducer and λ is the wavelength of the ultrasound waves in the medium.

Both transducers were then aligned in the x, y, z and A directions. As already mentioned, the proper alignment was based on the maximum amplitude of the received signal on the oscilloscope. Next, the directivity pattern measurement was performed with the receiver fixed and the transmitter rotated using the computer program from 0° to 10°. For each angle, the peak-to-peak voltage of the received signal was recorded. The obtained data were normalized and then compared to theoretical results using the directivity pattern model provided in equation 3. This procedure was repeated for both 2.25 MHz and 5 MHz ultrasound transducers.

$$H(\theta) = \left| \frac{2J_1(ka \sin \theta)}{ka \sin \theta} \right| \tag{3}$$

where $H(\theta)$ is the normalized directivity pattern of the plane circular piston transducer and k is the wave number. In addition, J_1 is the first order Bessel function and a is the radius of the transducer. It is good to note that the wave number is the ratio between the angular frequency of ultrasound waves (ω) and the speed of ultrasound waves in the medium (c).

3. RESULTS

The scanning system for ultrasound property measurement is developed as shown in Figure 10.

The movement distances on X, Y and Z axis were tested by comparing the movement distances with the distances measured from the ruler at 10 different locations (from 0.1 cm to 30 cm) for 3 times as shown on Table 1-3, respectively. In addition, the movement angles on A axis were compared with angles measured from the goniometer at 10 different angles (from -90 degrees to 90 degrees) for 3 times as shown on Table 4.

The results of the ultrasound velocity measurement in water with the resonance frequencies of 2.25 MHz and 5.0 MHz are presented on Tables 5 and 6, respectively.

For the directivity pattern measurement, after the alignment and the highest peak-to-peak voltage value (V_{pp}) were obtained. The voltage values were then normalized to provide a better scale for comparison between the measured data and the theoretical data in a graph. This was basically calculated by dividing each value of V_{pp} obtained by the maximum value of V_{pp} obtained. Therefore, the first normalized value would be 1 because it is expected to be the highest

Table 1:: COMPARISON BETWEEN DISTANCES MOVED BY THE COMPUTER PROGRAM AND DISTANCES MEASURED FROM THE RULER ON THE X AXIS

Distances moved by the computer program (cm)	Distances measured by the ruler (cm)			Averaged distances measured by the ruler (cm)	Percentage Error (%)
	No.1	No.2	No.3		
0.1	0.1	0.1	0.1	0.1	0
0.5	0.5	0.5	0.5	0.5	0
1	1	1	1	1	0
3	3	3	3	3	0
5	5	5	5	5	0
10	10	10	10	10	0
15	15	15	15	15	0
20	20	20	20	20	0
25	25	25	25	25	0
30	30	30	30	30	0

Table 2:: COMPARISON BETWEEN DISTANCES MOVED BY THE COMPUTER PROGRAM AND DISTANCES MEASURED FROM THE RULER ON THE Y AXIS

Distances moved by the computer program (cm)	Distances measured by the ruler (cm)			Averaged distances measured by the ruler (cm)	Percentage Error (%)
	No.1	No.2	No.3		
0.1	0.1	0.1	0.1	0.1	0
0.5	0.5	0.5	0.5	0.5	0
1	1	1	1	1	0
3	3	3	3	3	0
5	5	5	5	5	0
10	10	10	10	10	0
15	15	15	15	15	0
20	20	20	20	20	0
25	25	25	25	25	0
30	30	30	30	30	0

Table 3:: COMPARISON BETWEEN DISTANCES MOVED BY THE COMPUTER PROGRAM AND DISTANCES MEASURED FROM THE RULER ON THE Z AXIS

Distances moved by the computer program (cm)	Distances measured by the ruler (cm)			Averaged distances measured by the ruler (cm)	Percentage Error (%)
	No.1	No.2	No.3		
0.1	0.1	0.1	0.1	0.1	0
0.5	0.5	0.5	0.5	0.5	0
1	1	1	1	1	0
3	3	3	3	3	0
5	5	5	5	5	0
10	10	10	10	10	0
15	15	15	15	15	0
20	20	20	20	20	0
25	25	25	25	25	0
30	30	30	30	30	0

Table 4:: COMPARISON BETWEEN ANGLES ROTATED BY THE COMPUTER PROGRAM AND ANGLES MEASURED BY THE GONIOMETER ON THE A AXIS

Distances moved by the computer program (cm)	Distances measured by the ruler (cm)			Averaged angles (degree)	Percentage Error (%)
	No.1	No.2	No.3		
10	10	10	10	10	0
30	31	31	31	31	3.33
45	46	46	46	46	2.22
60	61	61	61	61	1.66
90	94	94	94	94	4.44
-10	-10	-10	-10	-10	0
-30	-31	-31	-31	-31	3.33
-45	-46	-46	-46	-46	2.22
-60	-61	-61	-61	-61	1.66
-90	-92	-92	-92	-92	2.22

Fig.10:: The photograph of the developed scanning system

Table 5:: THE RESULTS OF THE ULTRASOUND VELOCITY MEASUREMENT IN WATER USING THE DEVELOPED SCANNING SYSTEM 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/Δt (m/s)**
0	0	185	-	-
50	50	252.6	67.6	1479.29
100	50	320.3	67.7	1477.10
150	50	387.8	67.5	1481.48
Average ultrasound speed in water				1479.29

Table 6:: THE RESULTS OF THE ULTRASOUND VELOCITY MEASUREMENT IN WATER USING THE DEVELOPED SCANNING SYSTEM 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/Δt (m/s)**
0	0	185	-	-
50	50	252.6	67.6	1479.29
100	50	320.3	67.7	1477.10
150	50	387.8	67.5	1481.48
Average ultrasound speed in water				1479.29

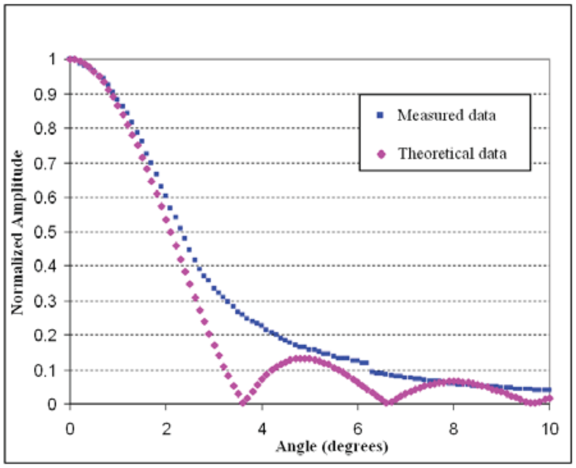

Fig.11:: Theoretical and measured directivity patterns on a linear scale of the 2.25 MHz ultrasound transducer

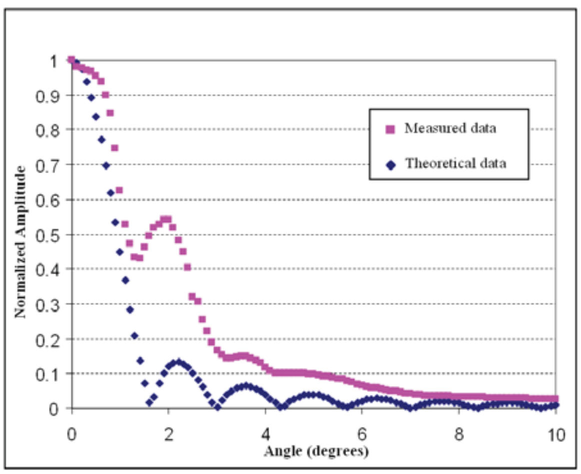

Fig.12:: Theoretical and measured directivity patterns on a linear scale of the 5 MHz ultrasound transducer

value after the proper alignment and subsequent normalized values would then drop off below 1 due to the induced angle between the two transducers.

After the normalization, the scale was also converted to the decibel scale (dB) by multiplying our linear calculations by 20 log base 10 to get a better visualization of the resolution of the curve. These procedures were performed for both 2.25 MHz and 5 MHz transducers. Consequently, two sets of the graphs were obtained here; one set of the normalized V_{pp} vs. the angle (in degrees) presented in Figures 11-12 and the dB conversion of the normalized V_{pp} vs angle (in degrees) as shown in Figures 13-14. In both cases, the measured data were plotted together with the theoretical results.

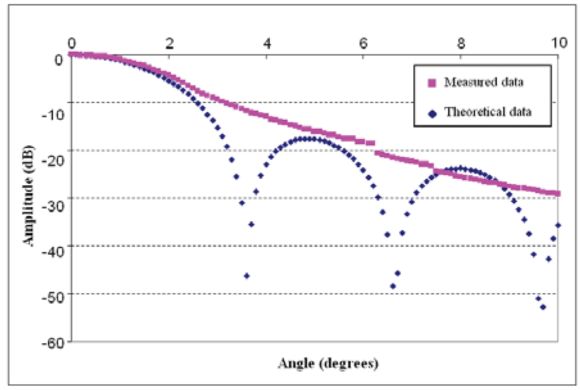

Fig.13:: Theoretical and measured directivity patterns on a logarithmic scale (dB scale) of the 2.25 MHz ultrasound transducer

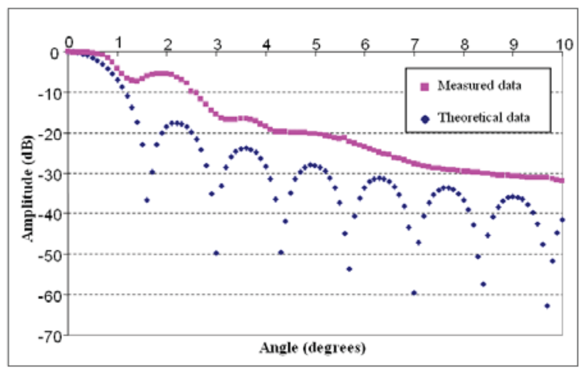

Fig.14:: Theoretical and measured directivity patterns on a logarithmic scale (dB scale) of the 5 MHz ultrasound transducer

4. DISCUSSIONS AND CONCLUSIONS

In order to verify the performance of the developed scanning system, the movement distances on X, Y and Z axis were compared with the distances measured from the ruler at 10 different locations (from 0.1 cm to 30 cm) for 3 times as shown on Tables 1-3. The results indicate that there was no error of the movement on the X, Y and Z axis. In addition, the movement angles were also compared with angles measured from the goniometer at 10 different angles (from -90 degrees to 90 degrees) for 3 times. The small errors were found on Table 4 to be less than 4.44% on the A axis. The results here verified the accuracy of the movement distances and angles on X, Y, Z and A axis.

The average speeds of ultrasound waves in water using the developed scanning system with the resonance frequencies of 2.25 MHz and 5 MHz on Tables 5 and 6 were determined to be 1479.29 m/s and 1475.65 m/s, respectively. This measured ultrasound velocities in water were compared to the theoretical value of 1490 m/s at 25 degrees Celsius [13-14], the result indicates excellent agreement within the error of 0.96%. Thus, we can conclude that the developed scanning system is able to help finding an accurate value for measuring velocity of ultrasound in water. In addition, the results also shows that the speeds of ultrasound waves in water remained consistent independent of the frequency of transducers used.

The developed scanning system was also used to measure the directivity pattern measurement to prove that the scanning system can accommodate for the measurement of the ultrasound properties. The results of the normalized directivity pattern measurements for the 2.25 MHz and 5 MHz transducers are presented in comparison with the theoretical results as a function of spatial angle on a linear scale as shown in Figures 11-12, respectively. In both figures, the measured values lie above the theoretical values. Comparison between measured and theoretical results indicates similar general behavior. However, our comparison also shows some discrepancies between measured and theoretical plots, and possible reason for this behavior is due to the reflections of the ultrasound waves within the water tank. These differences could be accounted in the fact that the experiment was performed in a tank of finite dimensions, whereas the theoretical values were calculated using an infinite medium. The amplitudes of both transducers decreased as the degree of the angle increased. However, the theoretical plots of the directivity patterns clearly show the lobes of the beam patterns. In these regions, the pressure amplitude of the ultrasound wave decreases and then increases again as the pattern leaves the main lobe and enters the region of the side lobes. This type of behavior for the most part is not seen in the measured results again due to the finite constraints of the water tank. By examining the main lobe size of the ultrasound beams in Figures 11 and 12, it could be observed that the main lobe of the 2.25 MHz resonance frequency in Figure 11 is broader than that of 5 MHz resonance frequency in Figure 12. This leads to another characteristic of the directivity pattern, which varies with the ultrasound frequency. With decreasing ultrasound frequencies, the directivity pattern gets broader. In addition, the beam patterns of the transducers were plotted on a logarithmic scale (dB scale) in Figures 13 and 14. The lobes are then clearly visible by the spikes observed in the dB scale plots. The 5 MHz transducer generated more spikes than the 2.25 MHz transducer. For 5 MHz transducer in Figure 14, the first side lobe of the beam pattern can be observed at approximately 1.4 degrees of rotation. Also, at about 3 degrees of rotation, very small evidence of a second side lobe also exists. The existence of these bumps is purely because the pressure at the side lobe is not zero since the water tank in which the test was performed is small. This means that the dimension of the tank is not infinite which leads to the understanding that there is a finite pressure reflected within the water tank.

In conclusion, the scanning system for ultrasound property measurement was successfully developed. The precision of the stepper motors of the scanning system is 10-3 m per step on the X, Y and Z axis, whereas the A axis is 0.1 degree per step. This would allow for the movement of the transducers from one position to another position to occur accurately and rapidly. The results from the measurements of the speed of ultrasound in water and the directivity pattern also indicate that the scanning system can accommodate for the measurement of the ultrasound properties.

5. ACKNOWLEDGMENT

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