Directivity Pattern Measurement of Ultrasound Transducers

Sumet Umchid, Member

ABSTRACT

Both diagnostic and therapeutic ultrasound applications require an understanding of the directivity patterns on the transducers to design ultrasound equipment and faithfully characterize the acoustic output from medical ultrasound devices. Since each ultrasound transducer has its own specific directivity pattern, the measurement of the directivity pattern is necessary. The objectives of this work were to determine directivity patterns analytically and measure directivity patterns experimentally. An experimental method was developed to obtain the directivity patterns for circular ultrasonic transducers. The implementation of the experimental method 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 measure the beam patterns of the transducers. The results of the measurement are 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. However, our comparison also indicates some differences between experimental and theoretical plots, and possible reason for this behavior is due to the reflection of the ultrasound waves within the water tank.

Keywords: Ultrasound Metrology; Ultrasound Transducer; Ultrasound Beam Pattern; Ultrasound Directivity Pattern; Biomedical Ultrasound

1. INTRODUCTION

Medical diagnostic ultrasound has become the primary noninvasive imaging modality because it does not employ ionizing radiation such as X-rays and also provides real-time information of the anatomical structures. In addition, the applications of ultrasound energy for therapeutic treatment purpose have also grown significantly in the past few years [1] [2] [3]. However, under certain conditions ultrasound exposure in general may introduce undesirable biological effects [4]. Therefore, the output acoustic characterization of the medical ultrasound devices, such as directivity patterns, needs to be determined in order to design ultrasound probes [5].

The acoustic output of the ultrasound transducer can be obtained under any given electrical excitation. The ultrasound pressure will propagates into free space, and form an intensity field in front of it. Transducers can be designed to radiate ultrasound waves in many different types of patterns. For a transducer with a circular radiating surface, as is most commonly used in ultrasonic sensor applications, the transducer aperture is a lot bigger than the ultrasound wavelength and the acoustic field has a shape similar to flashlight beam, so is called ultrasound beam. For ultrasound imaging or High Intensity Focused Ultrasound (HIFU) application, a narrow beam is needed regarding to a good ultrasound image resolution [6]. In some special cases, a more uniformed beam is required. Normally, a large aperture is required to achieve strong focus, and thus better resolution since the narrowness of the beam pattern is a function of the ratio of the diameter of the radiating surface to the wavelength of ultrasound waves at the operating frequency. The larger the diameter of the transducer as compared to a wavelength of ultrasound waves, the narrower the sound beam.

Each ultrasound transducer has its own specific directivity pattern. The directivity pattern, also known as beam pattern or radiation pattern, is an important far-field characteristic of a transducer. Directivity pattern consists of a main lobe and side lobes. Radiation intensity is dominant mainly in the front region of the transducer source, so the main lobe is directly in front of the ultrasound transmitter, followed by side lobes sidewise with null region in between these lobes. In general, the directivity patterns are the same whether the transducer is used as a transmitter or as a receiver.

Directivity pattern is a dimensionless and a relative parameter of a transducer as a function of spatial angle, which it is mainly determined by factors such as the frequency of operation and the size, shape and acoustic phase characteristics of the vibrating surface. The mathematical expression for the normalized directivity pattern of the plane circular piston transducer ($H(\theta)$) is given in equation (1) [7].

$$H(\theta) = \left| \frac{2J_1(ka\sin\theta)}{ka\sin\theta} \right| \tag{1}$$

Manuscript received on March 26, 2009 ; revised on July 9, 2009.

S. Umchid is with Department of Industrial Physics and Medical Instrumentation, Faculty of Applied Science, King Mongkut's University of Technology North Bangkok, Bangkok, 10800 Thailand

E-mail address: sumetu@kmutnb.ac.th (Sumet Umchid)

where k is the wave number. 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).

When describing the beam patterns of transducers, two-dimensional plots are commonly used. They show the relative sensitivity of the transducer vs. angle.

This paper describes both analytical and experimental techniques capable of determining directivity patterns for circular ultrasonic transducers.

2. STATEMENT OF THE CONTRIBUTION/METHODS

Three pairs 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 directivity patterns during this work. The diameters of all transducers are 12.7 mm. Two transducers with the same resonance frequency were set up and 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 × 900 mm × 350 mm. The experimental setup for measuring the directivity pattern is shown in figure 1. LabVIEW 8.2 virtual instrument (VI) presented in figure 2 was employed for extreme precision in movement of the stepper motors of the Scanning System at 10^{-4} mm per step. This allows for the displacement of the transducers from one position to another to occur accurately and rapidly.

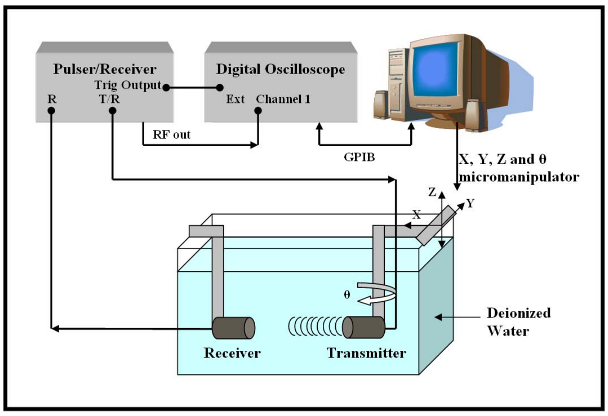

Fig.1: *The experimental set-up for the directivity pattern measurement of ultrasonic transducers*

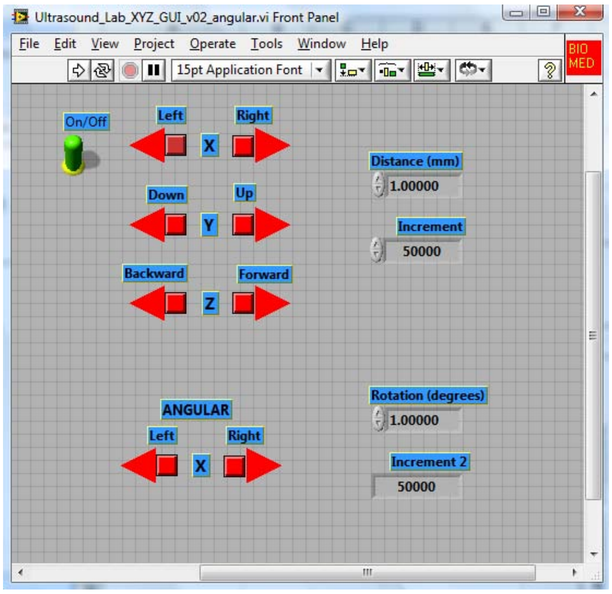

Fig.2: *Custom-made LabVIEW program for the alignment (x, y, z and θ directions) of the transducers*

used as a transmitter and the other as a receiver. A pulser/receiver (Panametrics Pulse/Reciever 5073 PR) was employed to generate the pulse echoes. 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 (Tektronix TDS220 Digital Oscilloscope with GPIB connection) 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.

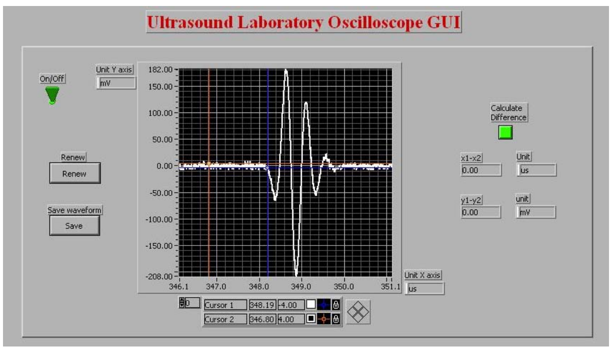

Fig.3: *Custom-made LabVIEW program for displaying and recording the waveforms from the oscilloscope*

All directivity pattern measurements here were made at room temperature 25 °C. A pair of transducers with an identical resonance frequency was used in each measurement. One transducer was

After the two transducers having the same resonance frequency were placed in the measurement system, the 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, 30 cm and 43 cm for the 2.25 MHz, 3.5 MHz and 5 MHz transducers, respectively. These distances were obtained using equation 2, which are the standard criteria for uniform circular piston [7].

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

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 θ directions. The alignment was based on the recording of the maximum amplitude of the received signal on the oscilloscope. Next, the directivity pattern measurement was carried out with the receiver fixed and the transmitter rotated using LabVIEW program in figure 2 from 0° to 10° in 0.1° increments (a total of 100 readings). For each angle, the peak-to-peak voltage of the received signal was recorded and the data were saved in the computer. The obtained data were normalized and then compared to theoretical results using the directivity pattern model provided in equation 1. This procedure was repeated for all three pairs of transducers, having resonance frequencies of 2.25 MHz, 3.5 MHz, and 5.0 MHz.

3. RESULTS

Upon alignment and subsequent achievement of the highest peak-to-peak voltage value (V_{pp}), the readings were taken for each interval of 0.1 degrees. 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 done by dividing each value of (V_{pp}) obtained by the maximum value of (V_{pp}) obtained. Therefore, the first value will be 1 since it is expected to be the largest value after alignment. Subsequent values will drop off below 1 due to the induced angle between the two transducers.

After the completion of normalization, the scale was then 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 all the three sets of the transducers (receivers and transmitters) of resonance frequencies 2.5 MHz, 3.5 MHz and 5.0 MHz.

Consequently, two sets of the graphs were developed here; one set of the normalized (V_{pp}) vs. the angle (in degrees) as shown in figures 4-6 and the dB conversion of the normalized (V_{pp}) vs angle (in degrees) presented in figures 7-9. In both cases, the experimental or observed data were plotted alongside the theoretical results.

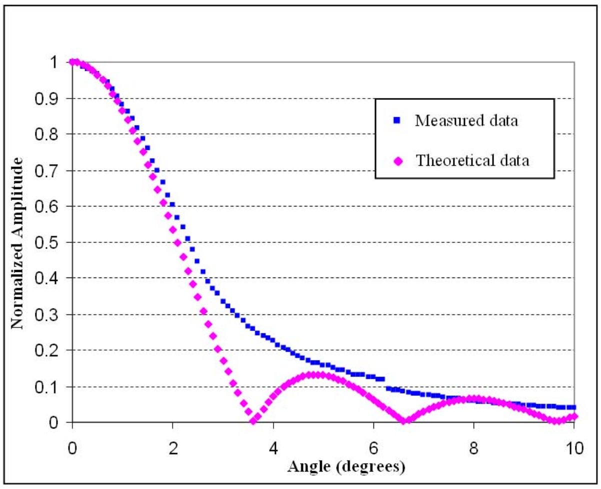

Fig.4: *Theoretical and measured (experimental) directivity patterns on a linear scale of the 2.25 MHz piezoelectric transducer*

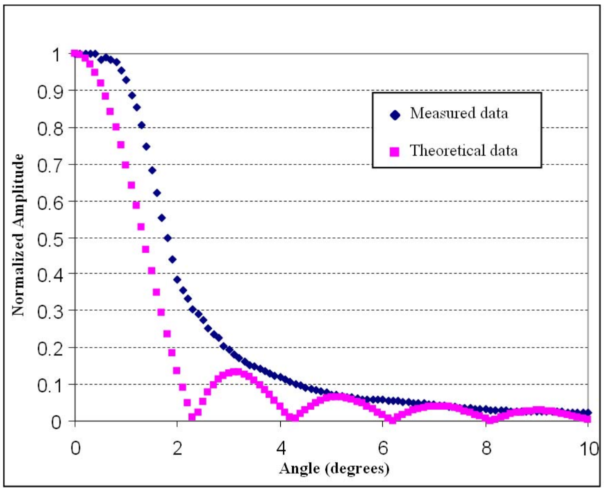

Fig.5: *Theoretical and measured (experimental) directivity patterns on a linear scale of the 3.5 MHz piezoelectric transducer*

4. DISCUSSIONS

The results of the directivity pattern measurement are presented in comparison with the theoretical results as a function of spatial angle on a linear scale as shown in figures 4-6. In figure 4, it could be observed that the blue squares indicate the normalized values of the measured directivity pattern for the 2.25 MHz resonance frequency transducer. These values were plotted against the magenta diamond theoretical values. Figures 5 and 6 represent the directivity patterns of the 3.5 and 5 MHz resonance frequency transducers, respectively. In each of these figures, the experimental values lie above the theoretical values. Comparison between experimental and theoretical results indicates similar general behavior. However, our comparison also indicates some differences

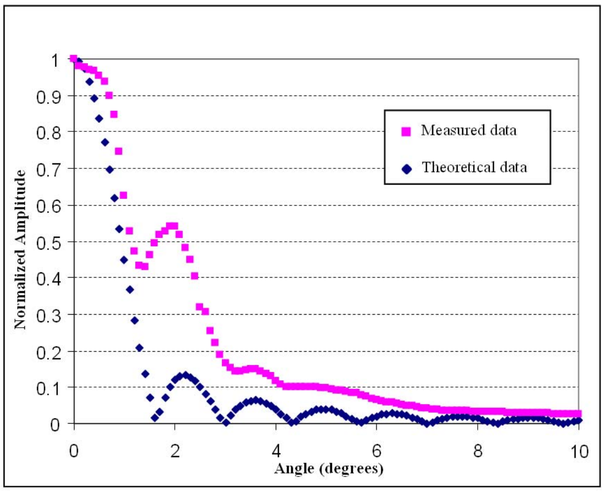

Fig.6: *Theoretical and measured (experimental) directivity patterns on a linear scale of the 5 MHz piezoelectric transducer*

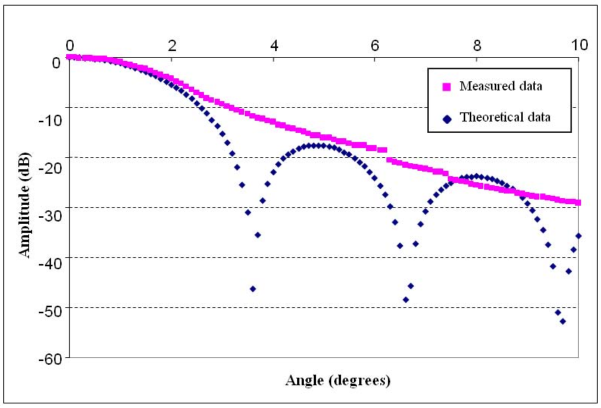

Fig.7: *Theoretical and measured (experimental) directivity patterns on a logarithmic scale (dB scale) of the 2.25 MHz piezoelectric transducer*

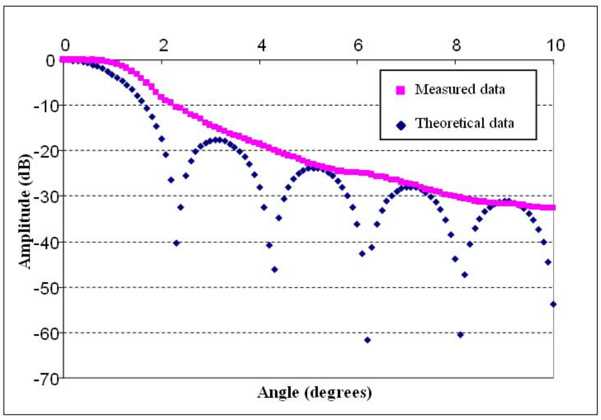

Fig.8: *Theoretical and measured (experimental) directivity patterns on a logarithmic scale (dB scale) of the 3.5 MHz piezoelectric transducer*

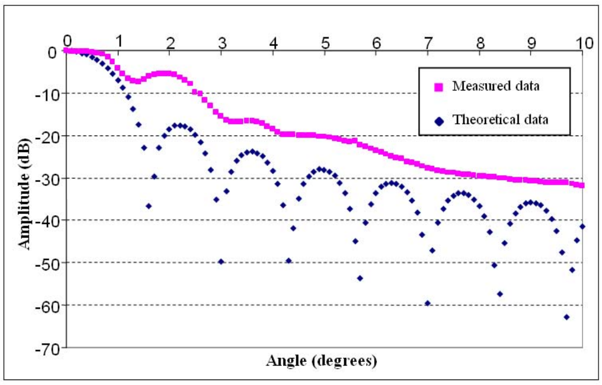

Fig.9: *Theoretical and measured (experimental) directivity patterns on a logarithmic scale (dB scale) of the 5 MHz piezoelectric transducer*

between experimental and theoretical plots, and possible reason for this behavior is due to the reflection 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 in which the pattern was observed. Each of the transducers also shows a decrease in the amplitude as the degree of the angle increased. The theoretical plots of the directivity patterns show the lobes of the directivity 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 experimental results again due to the finite constraints of the water tank.

By examining the main lobe size of the ultrasound beams in figures 4-6, it could be observed that the main lobe of the 3.5 MHz resonance frequency in figure 5 is narrower than that of 2.25 MHz resonance frequency in figure 4 but broader than that of 5 MHz resonance frequency in figure 6. This leads to another characteristic of the beam pattern, which varies with the ultrasound frequency. With increasing ultrasound frequencies, the directivity pattern gets sharper (an increase in resolution can be observed).

In addition to the directivity patterns presented on a linear scale as shown in figures 4-6, the beam patterns of the transducers were plotted on a logarithmic scale (dB scale) in figures 7-9. The lobes are then clearly visible by the spikes observed in the dB scale plots. The introduction of a higher resolution with increasing resonance frequency of the transducer is evident from the increasing number of spikes as well as the observed bump in the 5 MHz experimental plot which is not observed in the other two frequencies. At the resonance frequency of 5.0 MHz in figure 9 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.

5. CONCLUSIONS

In conclusion, the directivity patterns were determined analytically and measured experimentally. Also, the results presented above confirmed that the beam pattern of ultrasound waves emitted from transducers of varying resonance frequencies is dependent on the frequency of the transducers. In addition, it was observed that the directivity pattern gets sharper as the frequency of the transducer increases. In terms of medical imaging, this means that there will be higher image resolution from an ultrasound test performed using higher frequencies. But since the observed Vpp (peak-to-peak voltage) values obtained were scrutinized, it was noticed that the Vpp values had lower amplitudes with increasing resonance frequencies of the transducers. This indicates that there is higher attenuation of the signal and its penetration will be hampered or reduced. Therefore, this translates to the understanding that the ultrasound signal will provide higher resolution images for tissue or organs being analyzed by higher frequency transducers, but the penetration of the signal will be lower and so only surface or sub-surface tissue can be clearly observed. For deeper investigation, a balance between the frequency and the associated attenuation would have to be found.

Ultrasound technology has varied applications in diagnostic and therapeutic medicine. By understanding the effect of frequency on the directivity patterns of ultrasound transducers, one can be able to better apply the right frequency transducer to the applicable tissue or organ for the perfect balance between resolution and penetration depth.

6. ACKNOWLEDGMENT

We gratefully thank Drs. Peter A. Lewin and Vladimir Genis for their guidance and providing the equipment used during this work.

References

[1] S. Umchid, R. Gopinath, K.Srinivasan, L. Bansal, P. A. Lewin, A. S. Daryoush, and M. El-Sherif, "100 MHz sub-millimeter size fiber optic pressure sensors: luxury or necessity?," *in IEEE International Ultrasonics Symposium New York, NY, USA: IEEE International Ultrasonics Symposium,* 2007, pp. 2013-2016.

[2] S. Umchid, "Frequency Dependent Ultrasonic Attenuation Coefficient Measurement," *in The 3rd International Symposium on Biomedical Engineering (ISBME 2008), Bangkok, Thailand,* 2008, pp. 234-238.

[3] S. Umchid, R. Gopinath, K.Srinivasan, P. A. Lewin, A. S. Daryoush, L. Bansal, and M. El-Sherif, "Development of calibration techniques for ultrasonic hydrophone probes in the frequency range from 1 to 100 MHz," *Ultrasonics,* vol. 49, pp. 306-311, 2009.

[4] C. Patton, G. R. Harris, and R. A. Philips, "Output levels and bioeffects indices from diagnostic ultrasound exposure data reported to the FDA," *IEEE Trans. Ultrason. Ferroelec. Freq. Contr.,* vol. 41, pp. 353-359, 1994.

[5] V. Khanna and R. X. Gao, "Design of ultrasonic transducers with controlled radiation patterns," *in Instrumentation and Measurement Technology Conference, 1997. IMTC/97. Proceedings. 'Sensing, Processing, Networking'., IEEE, Ottawa, Ont., Canada,* 1997, pp. 1466 - 1471

[6] T. Szabo, *Diagnostic Ultrasound Inside Out: Elsevier,* 2004.

[7] L. E. Kinsler, A. R. Frey, A. B. Coppens, and J. V. Sanders, *Fundamentals of Acoustics,* Fourth Edition: John Wiley & Sons, Inc., 2000.

S. Umchid was born in Bangkok, Thailand in 1978. He received the B.S. degree in Electrical Engineering from Mahidol University, Bangkok, Thailand in 1999, and M.S. and Ph.D. degrees in Biomedical Engineering from Drexel University, Philadelphia, PA, in 2003 and 2007, respectively. Currently, he is working in the Department of Industrial Physics and Medical Instrumentation, King Mongkut's University of Technology North Bangkok, Thailand as a lecturer. His main research interests include Biomedical Ultrasound, Ultrasound Metrology and Biomedical Instrumentation.