International Journal of Electronics and
Communication Engineering (IJECE)
ISSN(P): 2278-9901; ISSN(E): 2278-991X
Vol. 4, Issue 5, Aug - Sep 2015, 9-20

International Academy of Science, Engineering and Technology
Connecting Researchers; Nurturing Innovations

MAPPING OF RADIATION PATTERN OF ULTRASONIC PHASED ARRAY FOR OBSTACLE LOCATION FOR VISUALLY IMPAIRED

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ABSTRACT

A real time beam steering characteristics of phased array transducer is implemented to detect and locate the obstacle for visually impaired. The steering performance can be characterized by the directivity pattern and the parameters that influence the wave propagation characteristics. The effects of various transducer parameters such as number of transducer elements, inter-element spacing, steering angle and array aperture are mathematically analyzed and optimal phased array is constructed. The Transmitter array of 6 elements with inter-element spacing of twice wavelength and receiver array with 4 elements of thrice wavelength is constructed with the 40 kHz piezo-sensors. The objective of this work is to determine directive pattern analytically and measure the pattern experimentally for the steering angle from -20 to 20 degrees. Radiation pattern of the array are mapped on the polar plot and the directivity of main lobe, grating lobes and side lobes are observed. These polar plots are simulated using LabVIEW (Laboratory virtual instrument engineering workbench) developed by National Instrument, is a graphical Programming environment suited for high-level or system level design. The obstacles are detected and located in the scanning area from distance of 15cm to 100cm.

KEYWORDS: Beam Steering, Grating Lobes, Radiation Pattern, Ultrasonic Phased Array

INTRODUCTION

The development and application of Ultrasonic Phased arrays, as a stand-alone technology reached a mature status at the beginning of the twenty-first century [1]. Phased array technology moved from medical field to the industrial sector at the beginning of the 1980's. The majority of the applications from 1985 to 1992 were related to nuclear pressure vessels (nozzles), large forging shafts and low-pressure turbine components. During the past three decades, several researchers have introduced devices that use sensor technology to improve the blind user's mobility in terms of safety and speed. Most of the devices rely on single beam, measuring only the distance to the obstacle. In order to locate the obstacle the user has to manually scan the area by pointing the device in relevant direction. This was a time-consuming task requiring a constant conscious effort by the user. New advances in Piezo-composite technology [2], micro-machining, microelectronics, and computing power, contributed to the revolutionary development of phased array technology by the end of 1990.

In 2006 Strakowski, Kosmowski, Kowalik, and Wierzba [3] introduced Ultrasonic obstacle detector that used Phased arraytechnique with receive beam forming using a single ultrasound source and an array of microphones. Phased array principles have not been completely applied for acoustic imaging in air.

A phased array system is based on the wave physics principle of phasing [4], varying the time between a series of outgoing ultrasonic pulses in such a way that the individual wave fronts generated by each element in the array combine with each other to add or cancel energy in predictable ways that effectively steer and shape the sound beam.

Here the aim in designing Ultrasonic Phased array is to build an Electronic Sensory aid for the visually impaired. In this work commercially available ultrasonic transducers of 40 kHz frequency of 16mm diameter are used to form transducer array.

DESIGN OF PHASED ARRAY

To design a phased array, it is very important to understand the wave propagation characteristics for various transducers parameters such as [4]

Number of Elements

As the number of elements in an array increase, so can the physical coverage area of the probe and its sensitivity, focusing capability and steering capability. At the same time, use of large arrays must often be balanced against issues of system complexity and cost. One of the key issues in designing an array transducer is to control the quality of the beam directivity and steer ability, so that the steered beams should be sharply defined and well-directed towards the desired steering direction. In the presence of obstacle, the reflected signal (echo) should be reproduced properly. The angular resolution required for proper reproduction of echo is considered to be 5 degrees.

Angular resolution = Half power beam width of main beam (HPBW)

HPBW of a phased array is given by [5][8]

$$\text{HPBW (degree)} = 50.8/a/\lambda \quad (1)$$

Where ‘a’ aperture size= Nxd,

N= number of elements, d= inter-element spacing

The size of transducer is 16mm or 1.9λ. So minimum spacing between the transducers of the transmitter array can be 17mm or 2λ. By substituting the values in equation (1) to get angular resolution less than 5^{o}

N = 5 gives angular resolution of 5.08 degrees.

N = 6 gives angular resolution of 4.23 degrees.

Selection of Number of Elements in Receiver Array

Pitch is the distance between individual elements, and aperture is the effective size of the pulsing element that is usually comprised of a group of individual elements that are pulsed simultaneously. To optimize steering range pitch must be small. For optimum sensitivity minimum unwanted beam spreading, and strong focusing, the aperture must be large.

Grating lobes are undesirable and must be avoided. To avoid grating lobes $d/\lambda \leq 1/2$, or $d=\lambda/2$. This is not possible as the size of transducer is 1.9λ . ‘d ‘ can be written as

$$d = n\lambda, \; n= 1, 2,3 \quad (2)$$

For n=1 and n=2, spacing between receiver elements is not practically possible since transmitter width is greater than the wavelength, and if same spacing is placed between transmitter and receiver elements, grating lobes exist resulting in wrong location of obstacle. Therefore the minimum spacing can be for n=3,

$$d=3\lambda \quad (3)$$

Number of receiver elements can be calculated from half power bandwidth. From equation (1) N = 4 gives angular resolution of 4.23 degrees.The Transducer array is designed with transmitter of 6 element and receiver with 4 elements. “Figure 1” shows the transmitter array with spacing of 2λ at the top and receiver array below it with 3λ interelement spacing.

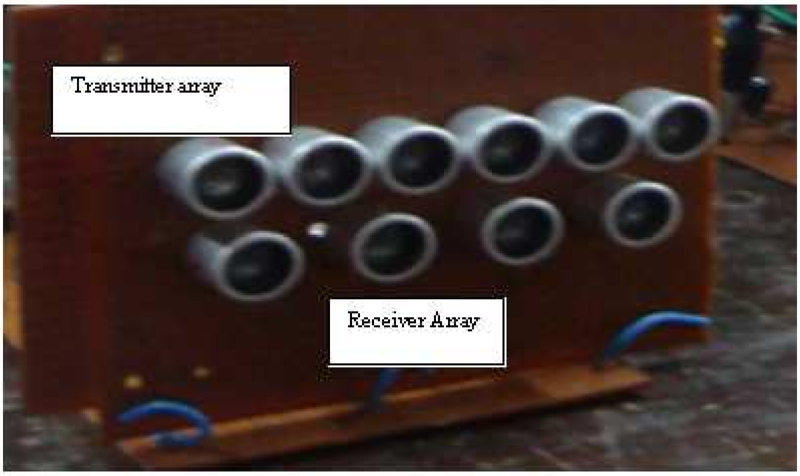

Figure 1: Designed Transducer Array

Beam Steering Characteristics

The method by which an array may be excited to produce a wave front which propagates in the desired direction is Steering. Each element is excited with a time delay for the steering angle θ is given by equation (4) [1]

$$\Delta t_n = nd/c\ (\sin\theta) + t \qquad (4)$$

where d is the interelement spacing, c = velocity of sound in air, n is the element number.

By varying the set of time delay the beam moves gradually and scans the entire detection area. The delay values required for driving the beam in particular steering angle is as shown in table I.

Table 1: Time Delay for 6 Element Transmitter Array

Sensors	4 degree	8degree	12 degree	16degree	20 degree
1	0	0	0	0	0
2	3.478 µsec	6.95 µsec	10.39 µsec	13.78 µsec	17.10 µsec
3	6.975 µsec	13.91 µsec	20.79 µsec	27.56 µsec	34.20 µsec
4	10.46 µsec	20.87 µsec	31.18 µsec	41.34 µsec	51.30 µsec
5	13.95 µsec	27.83 µsec	41.58 µsec	55.12 µsec	68.40 µsec
6	17.43 µsec	34.79 µsec	51.97 µsec	68.90 µsec	85.50 µsec

An FPGA based 10µsec clock pulse is generated to trigger the sensors of the transmitter array. The time delay pulse generated for steering angle 16 degree is as shown in "Figure 2".Here the first element from the right is excited which produces a circular wave front which propagates towards the focused angle. After 13.78µsec, the second element is excited which also propagates in the same direction. This process continues until the last element has been pulsed. All of the individual acoustic wave fronts will add to produce a maximum acoustic intensity along the direction of the steering angle. The direction of propagation of the effective transmitted wave is directly related to the time excitation sequence of the array elements, so that the acoustic beam may be oriented to any azimuth angle merely by altering the timing sequence of the excitation pulses.

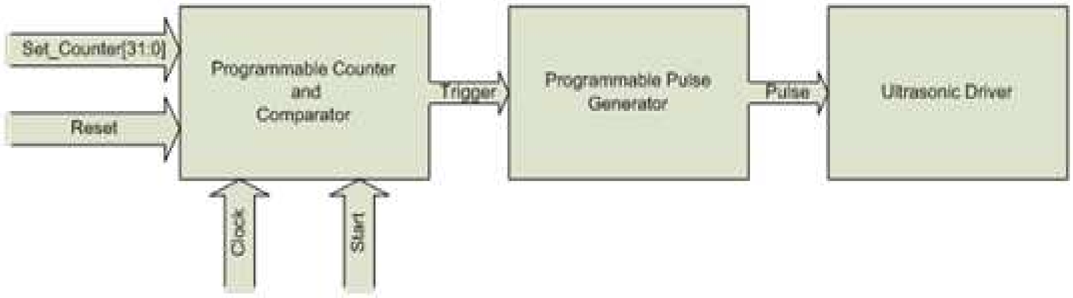

Figure 2: FPGA Based Pulse Generator

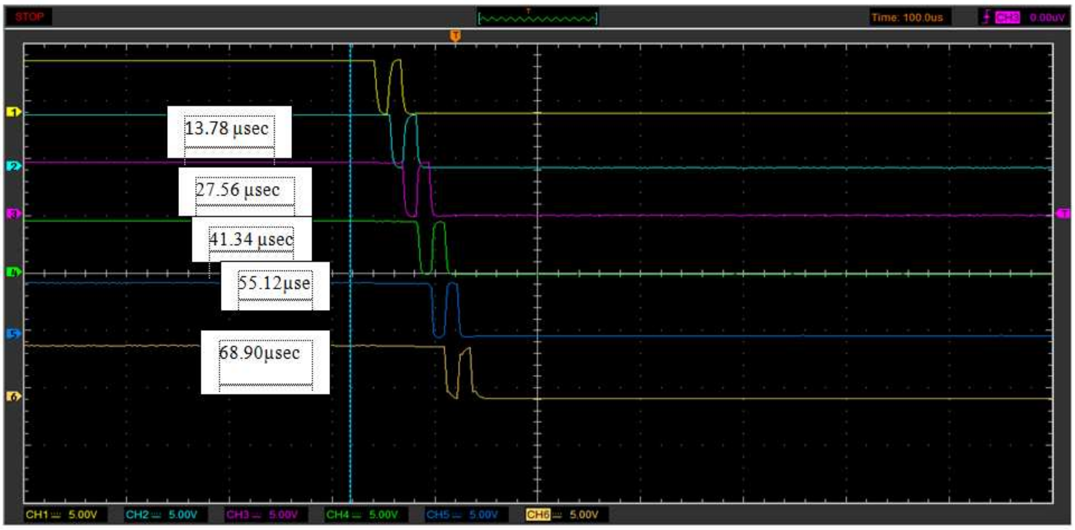

Figure 2: DSO Output Showing Time Delay for 16 Degree Steering Angle

EXPERIMENTAL SETUP

The pulse generator block diagram shown above in figure 2 is for single ultrasonic transmitter. The delays are implemented based on synchronous counters which operate at a frequency of 50 MHz, allowing a minimum counting period (delay) of 20 ns. This block is replicated for five transmitters. Clock, Reset signals, Start signals will be shared among six blocks. Initially system will be reset state. Counter will be loaded with specified delay values for individual sensors. Each element is excited with a time delay for the steering angle θ is given by equation (4) [10]

By varying the set of time delay the beam moves gradually and scans the entire detection area. The delay values required for driving the beam in particular steering angle is as shown in table I. Phase value changes for subsequent ultrasonic Transmitters. These values depend upon focusing angle. Here steering is performed from -20 degree to +20 degree with the angle resolution of 4 degree. The resultant signal strength is measured at specified angles on Digital storage oscilloscope. Based on these results radiation pattern is plotted. “Figure 4” shows the measurements for plotting radiation pattern.

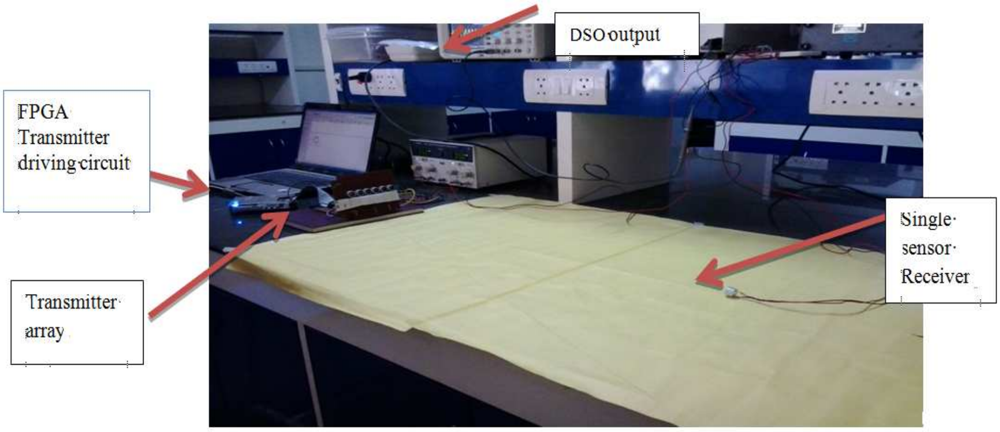

Figure 4: Experimental Setup

GRATING LOBES

In order to detect and locate the object properly the ultrasonic transmitter array should be sharply defined and well directed towards the desired steering direction. In the presence of obstacle, the reflected signal (echo) should be reproduced properly. The aimin implementing this design is to steer the beam at a given angle to investigate the object along the beam direction. The steering performance can be characterized by the directivity pattern and the parameters that influence the wave propagation characteristics. Directivity plots are featured by three kinds of lobes, Main lobe, side lobes and grating lobes. The main lobes appear exactly in the steering direction while the side lobes are present in many directions other than steering and grating lobes are third kind of lobes whose magnitude is exactly equal to the main lobe. In the optimum Transducer array design the side lobes and the grating lobes must be suppressed.

From the Antenna array theory, the presence of the grating lobe can be calculated from the equation shown below [7][8]

$$\boldsymbol{\theta_m = \sin^{-1}[\frac{1}{kd}(-\beta + 2m\pi)]} \quad (5)$$

for m= ± 0, 1. 2..., β= phasedelay between the elements and is calculated as $\beta = -\text{kdsin}\boldsymbol{\theta s}$ (6)

K is the wave number = 2π/λ, when m=0 corresponds main lobe, m= ±1 presence of first grating lobe. The table below shows the occurrence of the grating lobes for the transmitter array

Table 2

Steering angle in degrees	Main lobe in degrees	Grating lobes in degrees	Order of nulls (n)
4	4	-25.48	-6
8	8	-21.15	-6
12	12	-16.98	-6
16	16	-12.96	-6
20	20	-9.08	-6

The transmitter array of 6 elements with interelement spacing of two times the wavelength gives rise to grating lobes. For the steering angle 12 to 20 degree the unwanted lobes are present within the field of view, are to be eliminated. This can be minimized if the grating lobes of the transmitter array aligns with the nulls of the receiver array response. The nulls of the array[6] can be calculated from equation (6) given as,

$$\boldsymbol{\theta_n = \sin^{-1}\left[\frac{1}{kd}\left(-\beta + \frac{2n\pi}{N}\right)\right]} \tag{6}$$

where n= ±1, 2,3….., n≠N,2N,3N……

For the order n=-6, the nulls of the receiver occur which reduces the magnitude of the grating lobes to zero. Mathematically this design minimizes the grating lobes.

In the Practical setup the Radiation pattern of the transducer array is plotted as shown in "Figure 5a, 5b, 5c, 5d and 5e" for the steering angles 4, 8, 12, 16 and 20 degrees. The single sensor receiver is placed facing the transmitter array at a distance of 75 to 80cm from it. When the transmitter array is triggered for particular steeringangle, the receiver sensor is moved from -20 degree to +20 degree to measure the strength of the signal at each angle. The voltage levels should be maximum at the steering angle and then reducing at the other angles. From the polar plots main lobe in each of the plots have maximum amplitude and grating lobes are present with reduced magnitude than the main lobe.

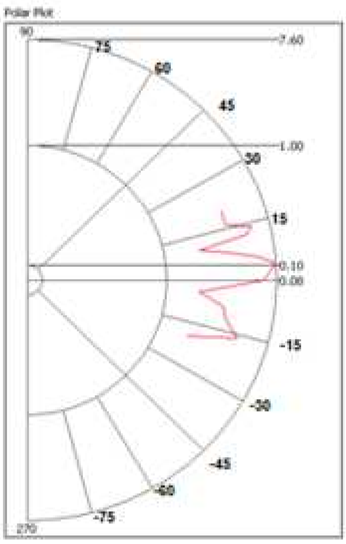

Figure 5a: Polar Plot for 4 Degree Steering Angle

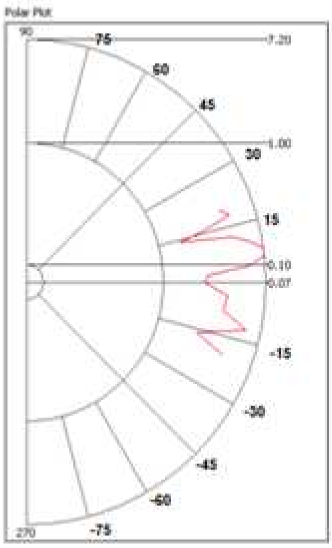

Figure 5b: Polar Plot for 8 Degree Steering Angle

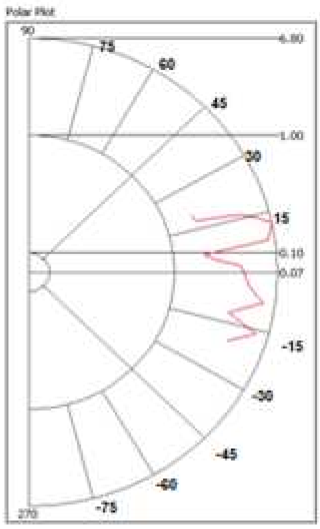

figure 5c: Polar Plot for 12 Degree Steering Angle

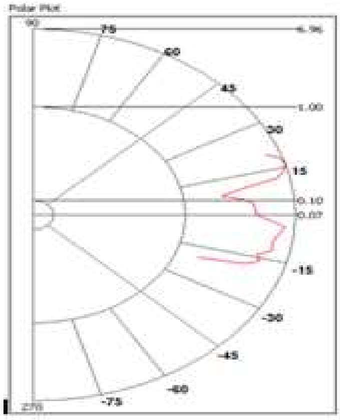

Figure 5d: Polar Plot for 16 Degree Steering Angle

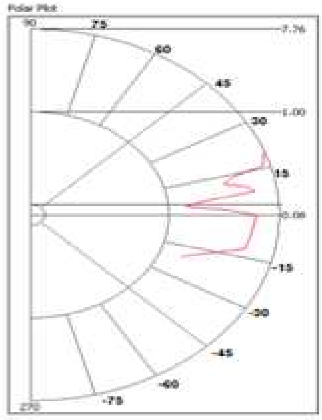

Figure 5e. Polar Plot for 20 Degree Steering Angle

OBSTACLE DETECTION AND LOCATION

The Block diagram of Ultrasonic phased array for obstacle detection is as shown in “Figure 6” below. The transmitter array is scanned to any angle from -20 to 20 degree by adjusting the time delay values. The Time taken by the ultrasonic wave to travel from the transmitter to the receiver after being reflected from the target is Time of Flight. The object distance from the transducer **R** can be calculated as[9]

$$R = C \times (T.o.F.)/2 \quad (7)$$

where **c**is the velocity of sound (air medium 340m/s) and T.o.F is Time of flight. Table IV shows the Time of Flight observed and calculated when obstacle was placed at different distance from the scanning array. The DSO output shows the transmitted pulse and the reflected echo at distance of 15 and 45cms.

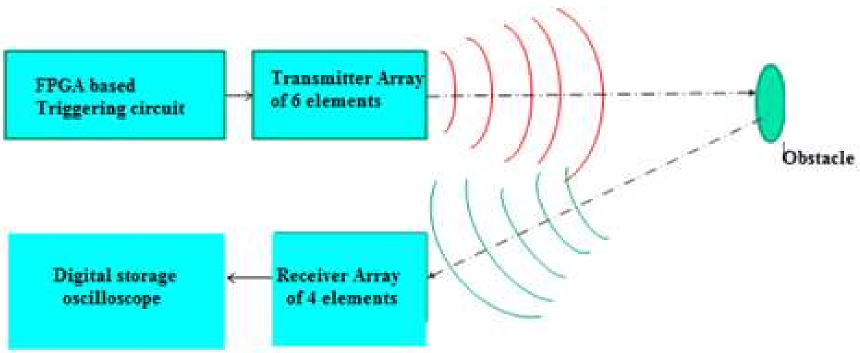

Figure 6: Block Diagram of the System

Table 4: Time of Flight Measurements

Distance in Centimeters	Time of Flight (Observed)	Time of Flight (Calculated)
15	820µsec	882.35µsec
30	1.8msec	1.76msec
45	2.6msec	2.647msec
60	3.52msec	3.529msec

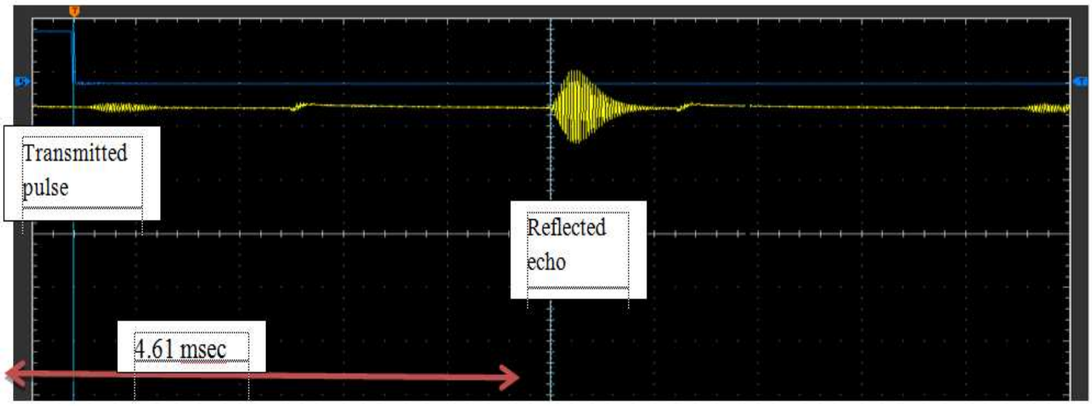

Figure 7a: DSO Output Showing Time of Flight Measurement for Object at 79 cm from the Array

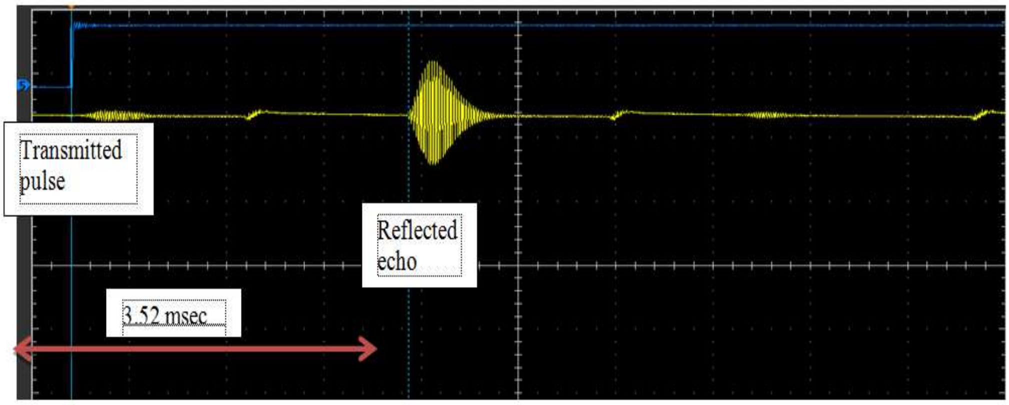

Figure 7b: DSO Output Showing Time of Flight for 60 cm

RESULTS

A. Radiation Pattern

The beam directivity pattern of the mathematical modeledTransducer array for different steering angles is as shown in Table III. The main lobe is in the steering direction and the grating lobes follow the main lobe by 29 degree. The receiver array is designed with 3 times wavelength spacing between them so that the nulls of the reciver align with the grating lobe of the transmitter. The complete Radiation pattern is given as the product of directivity of single element and directivity of the array [2]. “Figure 8a, b,c,d and e” shows an XY graph representing magnitude angle plot for 4 ,8,12,16 and 20 degree steering of the Practically designed Array. Table V shows the magnitude of the main lobe and the grating lobe. It is also observed that the grating lobe follows the main lobe by 20 degree. For 4 degree steering angle the main lobe is directed at 4 degree , and unwanted lobe present at -16 degree. Similarly for other angles 8,12,16,20 their exists reduced grating lobes at -12,-8,-4, and 0 degree.The main lobes appear at the steering direction with maximun signal strength. The reflected echo can be distinguished from the unwanted lobes. The signal can be reproduced and hence obstacle can be located.

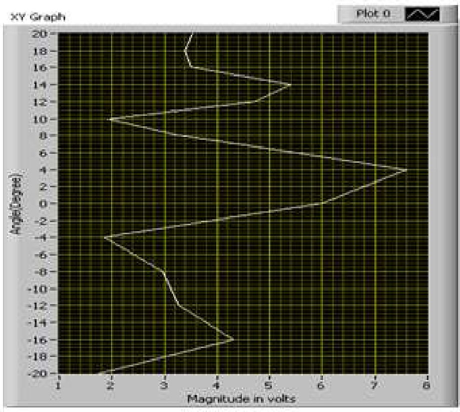

Figure 8a: 4 Degree Steering

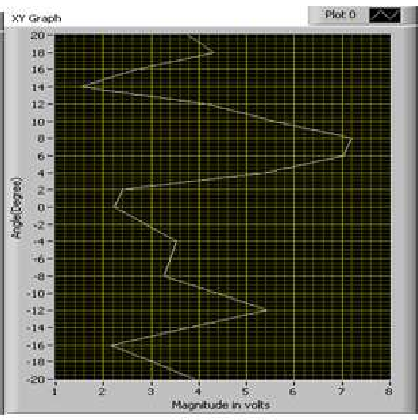

Figure 8b: 8 Degree Steering

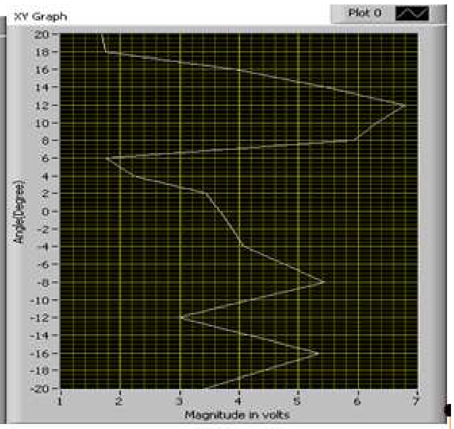

Figure 8c: 12 Degree Steering

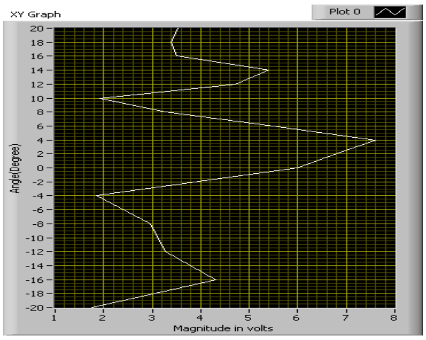

Figure 8d:16 Degree Steering

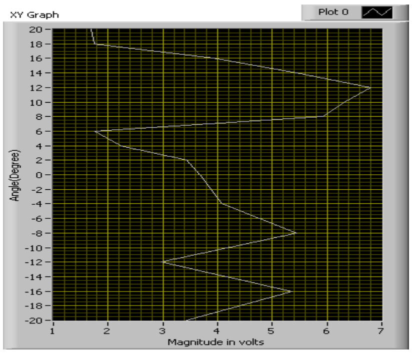

Figure 8e : 20 Degree Steering

Table 5: Magnitude of the Main Lobe and the Grating Lobe of the Practical Array

Steering Angle in Degrees	Magnitude of Main Lobe in Volts	Magnitude of Grating Lobe in Volts
4	7.60	4.32
8	7.20	5.44
12	6.80	5.40
16	6.96	5.84
20	7.76	5.04

Obstacle Detection and Location

The designed array can be used to detect obstacle at a distance of 15cm to 100cm. Two objects of dimension 19.7 x 9.5 cm and 27 x 20 cm are placed one behind the other at steering angle of 20 degree, first object is placed at 39 cm and second object is placed 50 cm . This system is able to distinguish between the objects and is shown in "Figure 9a".

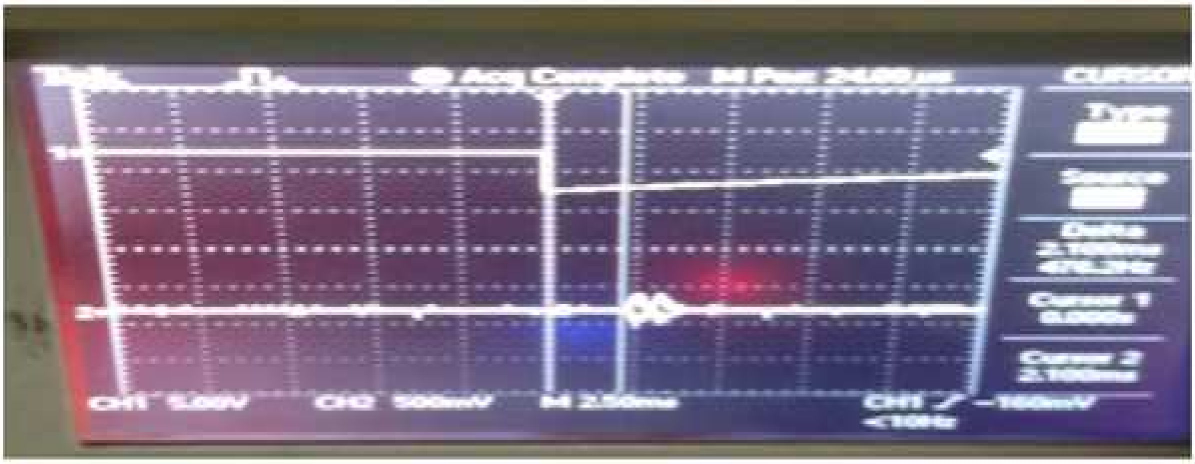

Figure 9a: Reflected Envelopes Placed at Distance 39cm and 50cm

To locate the obstacle, experiment was conducted by placing one obstacle in the steering area of 20 degree and the second object was placed at -16 degree at variable distance. From “Figure 9b” only envelope of the obstacle placed at steering angle 20 degree is detected.

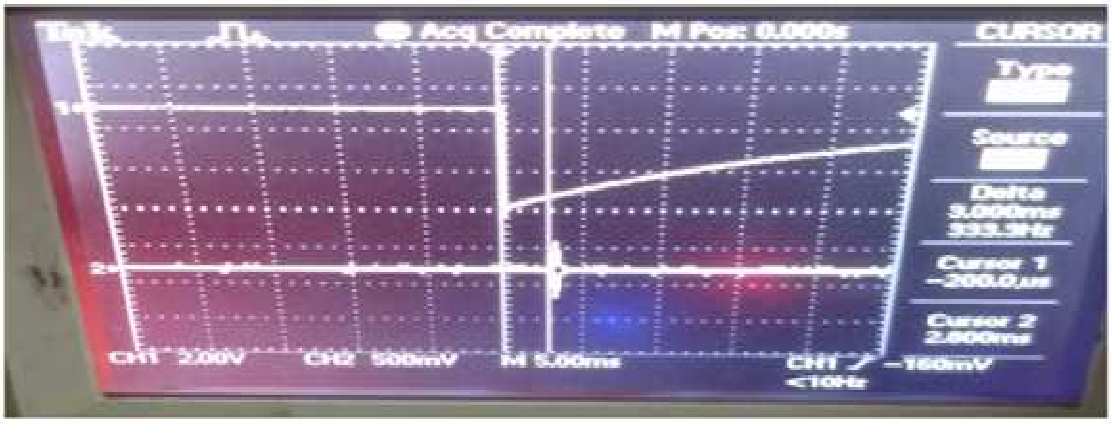

Figure 9b: DSO Output One Object Detected in the Steering Plane and Second Object not Detected Placed outside the Scanning Area

CONCLUSIONS

Ultrasonic phased array device to locate obstacle for visually impaired is designed with the phased array antenna concepts. The transmitter array of 6 elements with 2λ inter-element spacing and receiver array of 4 elements with 3λ spacing is found to be the most suitable configuration to realize the motive. The transducers used for construction are of 40kHz frequency and 16mm (1.9λ) in dimension. Since the width of the transducer is greater than the wavelength, grating lobes were sure to exist. The receiver array is selected such that the nulls of the receiver array response aligns with the grating lobe of the transmitter array.so that the model designed reduces the grating lobe and gives optimum steering characteristics. This design is mathematically analyzed and then practically implemented. The beam steering is performed for steering angles -20 to 20 degree. The designed device is simple,compact and has the ability to scan, which fulfils the conditions of developing a prototype device for visually impaired people and is able to detect and locate obstacle.

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