Investigation of focusing possibilities of convex and cylindrical phased arrays

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Abstract

This paper explores acoustic field simulation of 128 elements cylindrical phased array. The simulations were performed in a homogenous medium - water at several frequencies from 2.25 MHz to 7.5 MHz. Beam width versus the focal distance with a different number of active elements for chosen focal distance is simulated. To determine focusing efficiency of the cylindrical array the beam width of the main lobe was calculated at -6dB and -12dB levels while the array is operating in transmission mode. The influence of the array active aperture size to the beam width was analyzed.

Keywords: phased arrays, simulations, ultrasonic field.

Introduction

It is common that conventional ultrasound probes are replaced by phased arrays (PA) in specific areas because they best fit for specific tasks. The first commercial PA was introduced in 1970 while being used for medical purposes. Nowadays PA are used for non-destructive testing (NDT) in railroad industry, nuclear plants, for testing spot welds, pipelines, etc [1,2,6,7,8,13]. Difficulties for empowering of PA were limited by electronic resources needed for calculation and data visualization and small dimensions of ultrasonic probes. Nowadays the electronic industry supply us with tremendous speeds of analog digital converters and miniature PA systems were developed as well [9, 14].

The design of phased arrays is a complex task. Common geometries of PA probes are:

1) D linear: the beam can be steered only in one plane.

2) 2D matrix: the beam can be steered in the azimuth and elevation directions.

3) Circular arrays can be divided into 1D annular array and 2D sectorial annular array.

4) Custom design arrays, e.g. PA designed for special task like a flexible phased array which has been assembled with an active area able to deform its shape, a mechanical device pushing the elements on the surface and an instrumentation measuring the irregular profile met by the transducer [10]. As well PA can be designed like dual-element probes, made of separate transmitting and receiving probes over half wedges acoustically isolated. They are very efficient to remove the dead zone, and the possibility to use large apertures makes them suitable for inspection of thick objects. At last, both transmitting and receiving parts of the probe have been splitted into matrix arrays in order to focus and steer the beam both in the incidence and perpendicular plane [11].

The cylindrical shape‘s phased arrays are already used, but usually only annular scanning equivalent to 1D is exploited [17].

It is found that beam steering in a linear phased array is less complex than in a curved linear (convex) phased array, but with convex or cylindrical array it is possible to irradiate the object under a test from different angles. During simulation we investigated possibilities to focus a beam using cylindrical array. To decrease field complexity, we investigated beam widths dependency upon number of radiating elements.

In this case the spatial resolution in a lateral direction depends just on a beam width, which is defined by the dimensions and the frequency of array individual element.

In many cases it is desirable to have a better spatial resolution. It may be achieved by exiting a group of convex array elements with the delays enabling to obtain focusing of the resulting beam at the defined distance or position from the array. Annular scanning of the beam is obtained by consecutive shift of the exited group of elements in the array.

The purpose of the work presented in this paper was to find the optimal dimensions of the exited convex aperture and to determine the properties of focused ultrasonic beams.

It is clear that increasing number of elements improves directivity, so the number of radiating elements should be optimal. The operating frequency is the limiting factor in determining the inter-element spacing, element size, number of array elements. Therefore the simulations were carried at several frequencies. How to make full use of the existing channels to improve spatial and contrast resolutions is still an open question. The main-lobe and side-lobe characteristics of the pulse echo response are the optimization targets [12].

All array systems exhibit grating lobes and side lobe artifacts. Varying element pitch and a number of array elements these effects may be minimized. The element pitch – the gap between elements or kerf is equal to zero. It means that we minimize unwanted influence from array because gaps between elements acts like negative radiators. Depending from frequency probe diameter *D* was varied from 4.1 to 13.4 mm.

Table 1. **Element size and diameter for 128 element array.**

f, MHz	c, m/s	λ, mm	N	L, mm	d=a, mm	D, mm
7.5	1500	0.2	64	5	0.1	4.1
5	1500	0.3	64	5	0.15	6.1
3.5	1500	0.43	64	5	0.21	8.1
2.25	1500	0.67	64	5	0.33	13.4

Phased array design

The cylindrical PA is shown in Fig.1. In our case PA consists of N=128 rectangular elements with have fixed height L=5mm and the width, which is equal to the half wavelength $a=\lambda/2$, attached around the supporting cylinder surface, so the beam can be focused in all directions around the probe. In simulations was made assumption that inter element spacing d is equal to element width $a=d$.

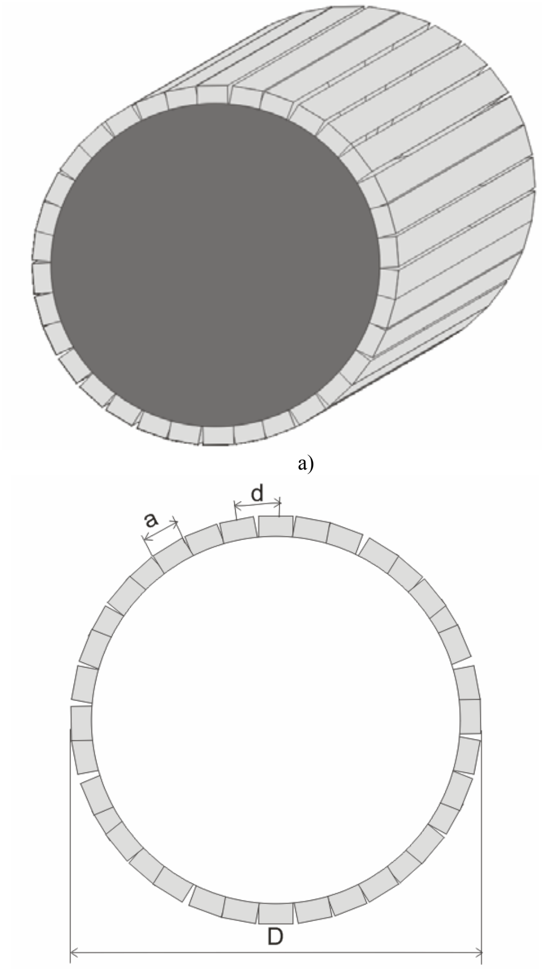

Fig.1. **Cylindrical array transducer –a); view from top – b)**

Simulations

Many authors use impulse response approach for calculating acoustic fields of PA [17, 19]. Some authors split arrays to rectangular, circular, elliptic or other aperture single element transducers of which radiation fields are well known. After that they sum contributions from each element and this way obtain equivalent field.

There is another approach which lets us to split each element from PA into elementary points. Possibility to subdivide any PA to elementary point type transducer enables us to simulate acoustic fields from an arbitrary transducer.

Calculations were carried out using Ultrasim – the Matlab toolbox for finding the sound field from transducers, by resolving Rayleigh integral [18]:

$$\phi(r,t)=\int_{S_t} d^2\underline{r_0}\,\frac{\rho(\underline{r_0})u_n(\underline{r_0},t-\left|\underline{r}-\underline{r_0}\right|/c)}{2\pi\left|\underline{r}-\underline{r_0}\right|}dS_t\,. \qquad (1)$$

where u_n is the particle velocity, $\underline{r}$ is the field point coordinate vector, $\underline{r_0}$ is the source point vector coordinate, ρ is the density of a medium.

The array beam profile was simulated in $x0z$ plane. So we can assume that we use linear curved array. Usually linear curved arrays consist of single row of elements. Elements are curved to produce a desired beam shape in a single plane. In our case array is bended in the opposite side (convex), so it has no geometric focus.

To find the minimum number N_r of required exited elements numerical calculations of the beam width at different focal distances z [5; 10; 15; 20; 25; 40; 50 mm] were performed. Active aperture D_a varies depending on number N_r of simultaneously driven channels, which each had N_r=64; N_r=32; N_r=16; N_r=8; N_r=4 respectively. Active aperture D_a can be determined by a number of the exited elements:

$$D_a = d(N_r - 1) + a\,, \qquad (2)$$

where d is the inter element spacing, N_r is the number of simultaneously driven channels (exited elements), a is the element size or width.

During simulation as a homogenous medium water was selected ($c\approx$1500m/s). PA elements were exited by the cosine-weighted pulse of two periods Fig.2. The pulse duration was chosen so short to keep grating lobe level low.

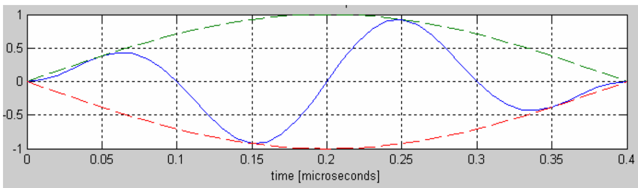

Fig.2. **PW signal of the center frequency 5 MHz**

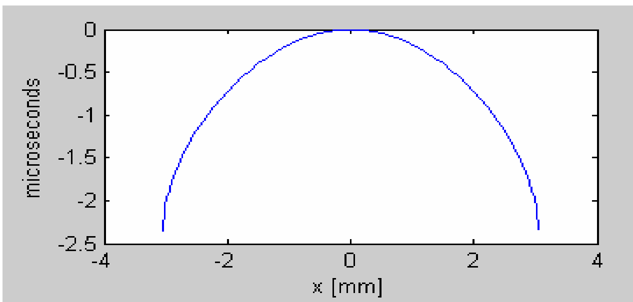

Fig.3. **Eexact delays of signal while focusing 64 elements at the focal point z=5mm (x=0; y=0)**

The pulse is sampled with a sampling frequency which is four times higher than the center frequency of pulsed wave (PW) signal.

Results

The beam pattern calculations were carried out and the beam width at the chosen focal distance (Fig.4) was determined at -6 dB and -12 dB levels as shown in Fig. 5.

Beam widths values were taken at maximum intensity at fixed focuses mentioned above.

The beam width dependences upon number of exited elements at different focal distances for different frequencies are shown. To get maximum field intensity and narrowest beam diameter the focal point should be closer to the transducer than a geometric focus [19].

The frequencies chosen used for simulations were 7.5 MHz, 5 MHz, 3.5 MHz and 2.25 MHz which are often used in commercially available probes. Corresponding to these frequencies the beam width versus the focal distance with a different number of active array elements is shown in Fig.6-9.

The focused beam at focal distance z=[5;10;15] mm from cylindrical array of simultaneously driven channels Nr=32 and Nr=16 is shown in x0z plane in Fig.10-13 when the two central frequencies (7.5 MHz; 5 MHz).

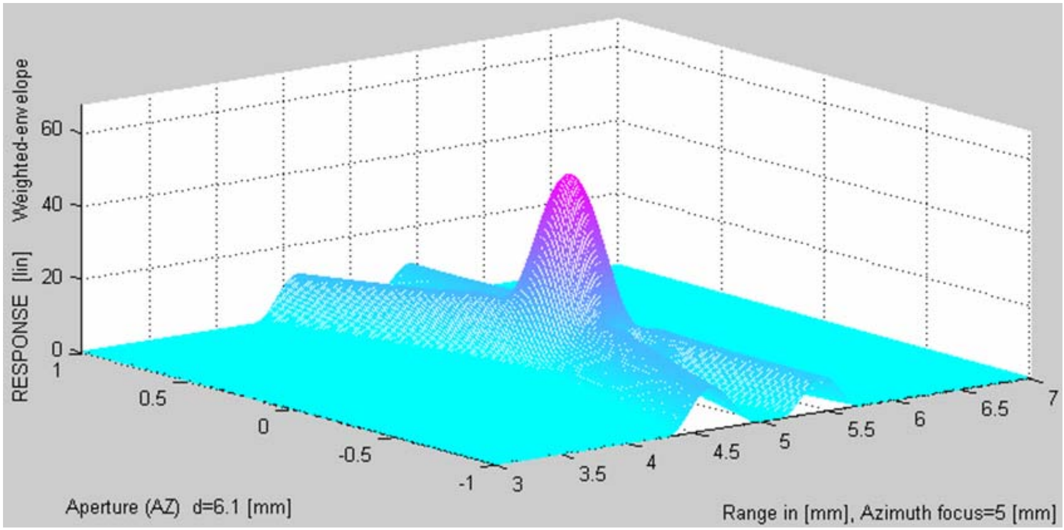

Fig.4. **Plot of a pulse field spatial distribution at the focal distance *z*=5 mm when 64 elements are excited at the center frequency f=5 MHz**

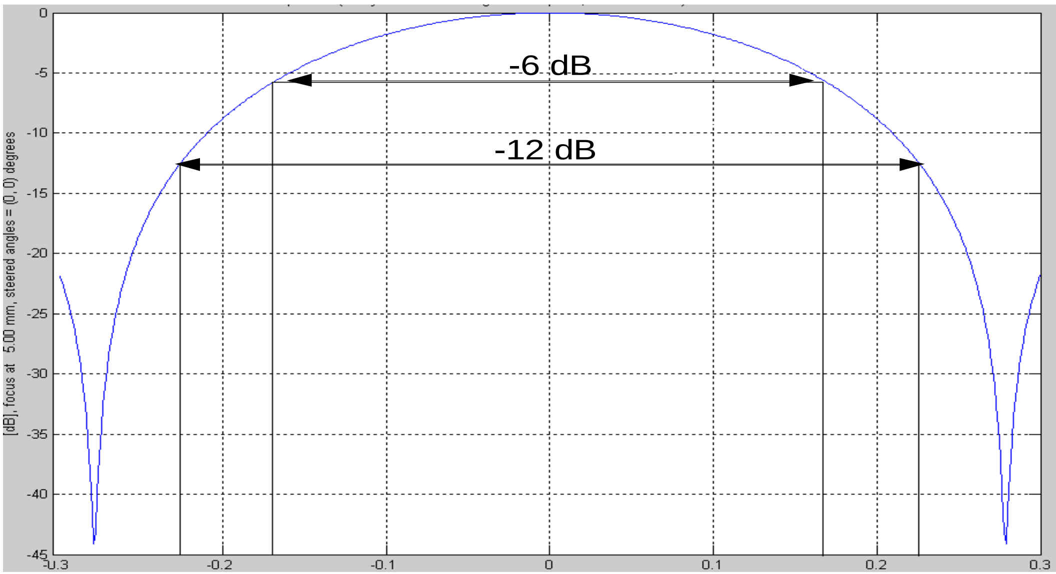

Fig.5. **Beam width at focal the focal point *z*=5 mm. Number of active array elements N_r=64. Central frequency f=5 MHz**

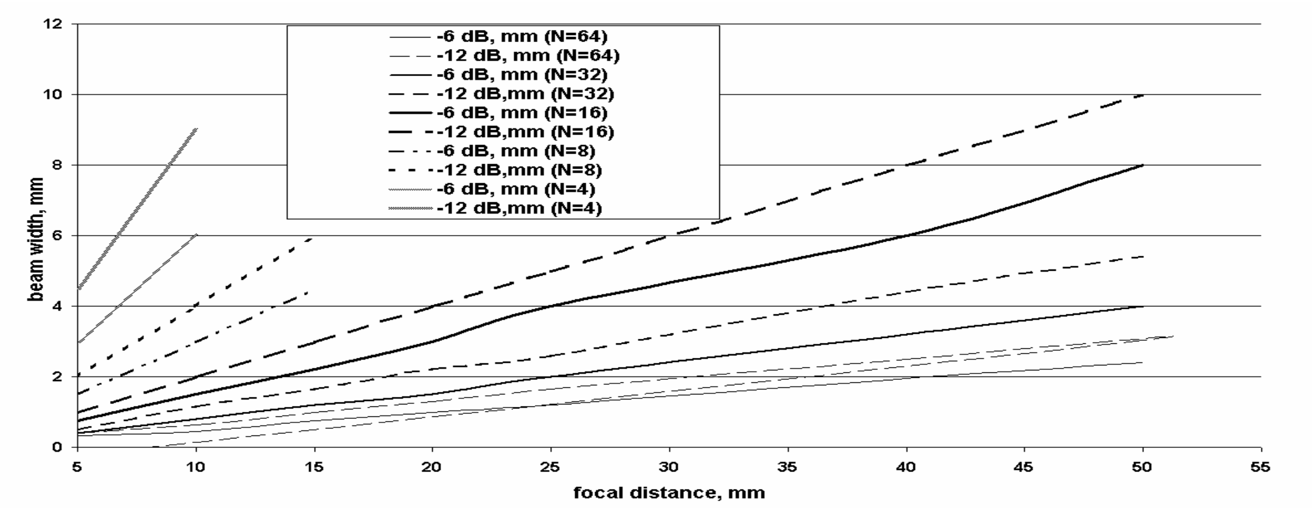

Fig.6. **Beam width versus the focal distance with a different number of active array elements when the central frequency f=7.5 MHz**

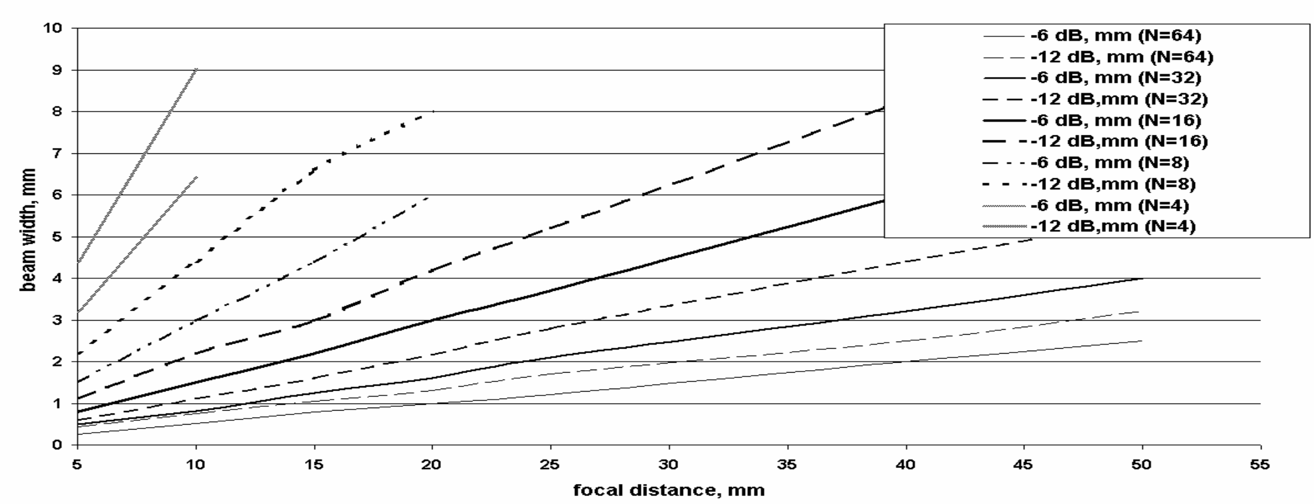

Fig.7. **Beam width versus the focal distance with a different number of active array elements when the central frequency f=5 MHz**

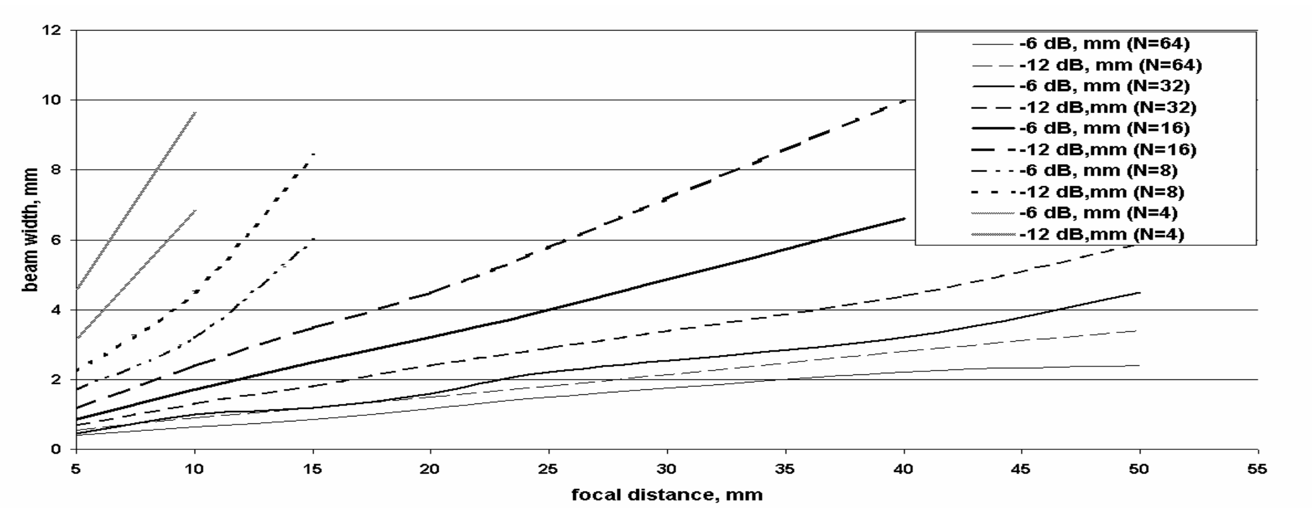

Fig.8. **Beam width versus the focal distance with a different number of active array elements when the central frequency f=3.5 MHz**

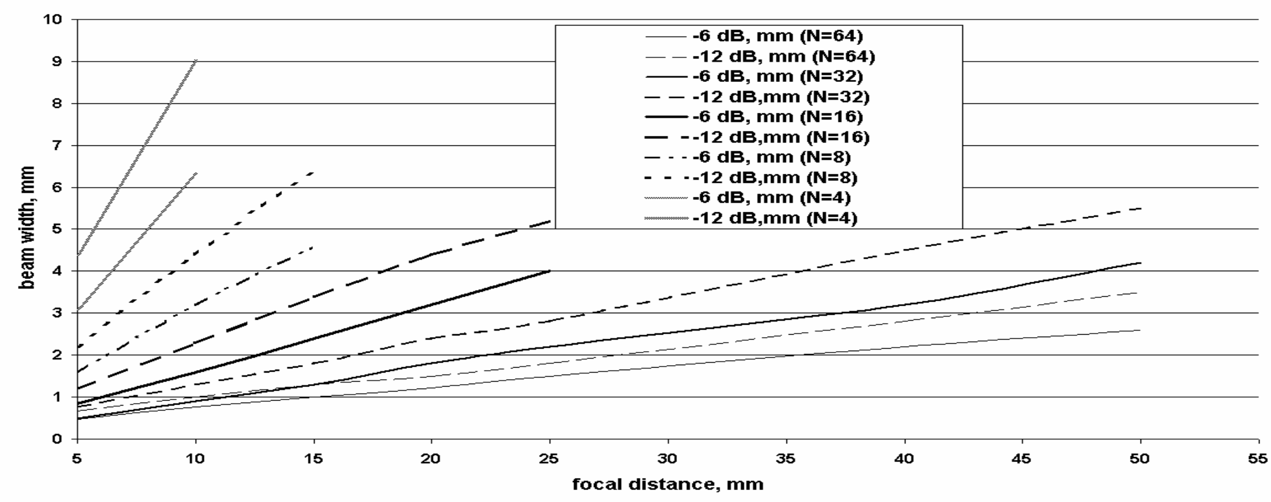

Fig.9. **Beam width versus the focal distance with a different number of active array elements when the central frequency f=2.25 MHz.**

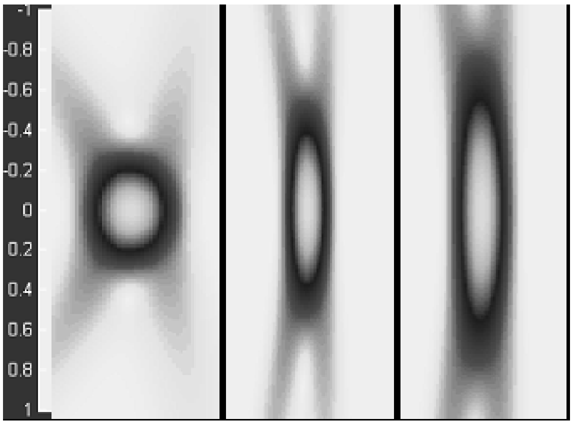

Fig.10. **The focused beam in *x0z* plane at the focal distance *z*=[5;10;15] mm when 32 elements are excited at the center frequency f=7.5 MHz**

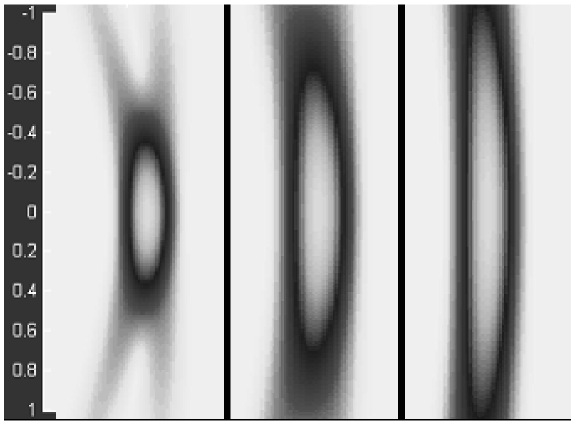

Fig.11. **The focused beam in *x0z* plane at the focal distance *z*=[5;10;15] mm when 16 elements are excited at the center frequency f=7.5 MHz**

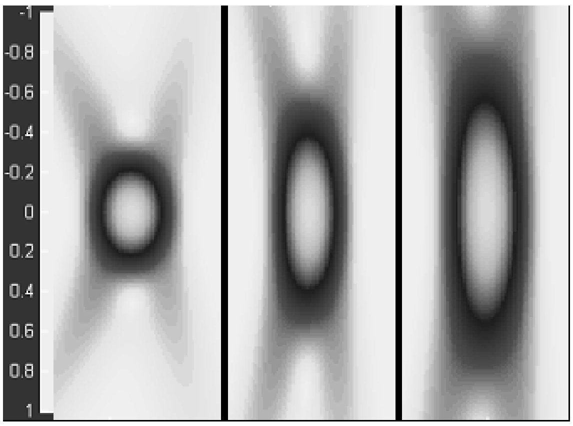

Fig.12. **The focused beam in *x0z* plane at the focal distance *z*=[5;10;15] mm when 32 elements are excited at the center frequency f=7.5 MHz**

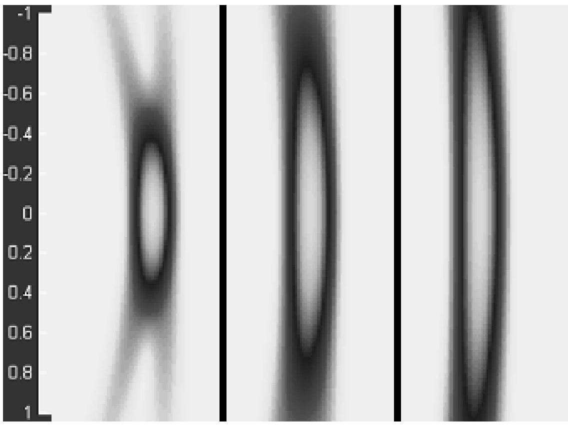

Fig.13. **The focused beam in *x0z* plane at the focal distance *z*=[5;10;15] mm when 16 elements are excited at the center frequency f=7.5 MHz.**

Discussions

Cylindrical probe construction allows us to use only dynamical focus to reach the point of our interest without need to steer a beam. It makes scanning algorithm less complicated so scanning can be performed in a real time.

The beam width depends strongly on the size of the active aperture or in our case on the number of simultaneously driven channels and partially on a focal range. The best array performance was achieved when the number of active elements was 32 at all focal distances while 4 and 8 simultaneously fired array elements give poor focusing not usable for practical applications. The cylindrical array is still acceptable for practical operations when the number of active elements is 16 while working in focal distance closer to array surface. It is clear seen in Fig.9-11 that the beam width increases and the focal depth decreases as the effective aperture decreases.

Numerical calculations enabled optimization of the cylindrical phased array, which will be used in future experiments.

References

1. **Ronald E., Mc Keighen Ph. D.** Design guidelines for medical ultrasonic arrays. Proc. SPIE. February 1998. Vol. 3341.P. 2.
2. **Meyer P. A.** Use of phased arrays for ultrasonic testing of railroad wheels. www.ndt.net. October 2002. Vol.7. No.10.
3. **Spies M., Rieder H**. A conclusive concept for three-dimensional imaging based on efficient steering and focusing of an ultrasonic 2D –array. Proc. ECNDT. September 2006.
4. **Meyer P. A., Anderson J. W.** Ultrasonic testing using phased arrays. Proc. WCNDT. October 2000.
5. **Denisov A. A.et all.** Spot weld analysis with 2D ultrasonic arrays. J. Res. Natl. Inst. Stand. Technol. March-April 2004. Vol. 109. No. 2.
6. **Erhard A., Schenk G., Hauser Th., Volz U.** New applications using phased array techniques. Nuclear engineering and design. June 2001. P.325-336.
7. **Bosch J., Hugger, A. Franz J., Falt erand S., Oberdörfer Y.** GE energy pipeline solutions and GE inspection technology systems phased array technology for automated pipeline. Proc. WCNDT. August 2004.
8. **Yamashita K., Murakami H., Fukunaga T., Okuyama M., Aoyagi S., Suzuki Y**. Ultrasonic micro array sensor using piezoelectric PZT thin film and resonant frequency tuning by poling**.** Proc. 13th IEEE International Symposium. May 2002. P.487 – 490.
9. **Casula O., Poidevin C., Cattiaux G.and Dumas Ph.** Control of complex components with smart flexible phased arrays. Ultrasonics. 2006. Vol. 44. P.647–651.
10. **Mahaut S., Godefroit J.-L., Roy O. and Cattiaux G.** Application of phased array techniques to coarse grain components inspection. Ultrasonics. 2004. Vol. 42. P.791–796.
11. **Otero R., Sánchez O., Ruíz A.** Characterization of ultrasonic array transducers. http://proton.ucting.udg.mx/somi/ REVISTA/ Vol_III/No6/artic2.pdf
12. **Yang P., Chen B., Shi K.-R.** A novel method to design sparse linear arrays for ultrasonic phased array. Ultrasonics. 2006. Vol. 44. P.717-721.
13. **Stepinski T., Wu P., Martinez E.** Ultrasonic inspection of cooper canisters using phased arrays. www.ndt.net. March 1998. Vol.3. No.3.
14. **Jain A.; Greve D. W.; Oppenheirn I. J.** A MEMS Phased Array Transducer for Ultrasonic Flaw Detection. Proc. IEEE. Sensors. 2002. Vol.1. P.515 – 520.
15. **Mendelsohn Y., Wiener-Avnear E.** Simulations of circular 2D phase-array ultrasonic imaging transducers Ultrasonics 39 (2002) 657–666.
16. **Kažys R., Jakevičius L., Mažeika L.** Beamforming by means of 2D phased ultrasonic arrays. ISSN 1392-2114 Ultragarsas. 1998. Nr.1(29).
17. **Jasiūnienė E., Kažys R., Mažeika L.** Simulations of ultrasonic fields of radial ultrasonic array. ISSN 1392-2114 Ultragarsas (Ultrasound). 2007. Vol. 62. No. 2.
18. Ultrasound field simulator home page.http://heim.ifi.uio.no/ultrasim/
19. **Bjorn A., Angelsen J.** Ultrasound imaging. Emantec. 2000. Vol 1.

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Išgaubtų ir cilindrinių fazuotų gardelių fokusavimo galimybės

Reziumė

Tyrimo tikslas - nustatyti išgaubtos cilindrinės gardelės fokusavimo galimybes esant pusei bangos ilgio atstumo tarp gardelės elementų. Šių elementų kiekis - 128. Gardelės skersmuo ir elementų plotis buvo parenkami išlaikant pusės bangos ilgio atstumą tarp elementų. Cilindrinės gardelės ultragarsiniai laukai buvo modeliuojami keičiant dažnį ir žadinamų elementų kiekį pasirinktam fokusavimo gyliui, kad būtų nustatytas minimalus spinduliuojančių elementų kiekis. Cilindrinės gardelės laukams modeliuoti taikytas impulsinės reakcijos metodas. Fokusavimui įvertinti buvo apskaičiuojamas pagrindinio lapelio plotis - 6 dB ir -12 dB lygyje, dirbant gardelei siuntimo režimu vandenyje. Geriausias fokusavimo rezultatas gautas esant 5 MHz dažniui.

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