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Investigation of the complex scanning method for the cylindrical ultrasonic array

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Abstract

This paper explores scanning method for the cylindrical array. To determine steps of the scanning sequence, ultrasonic fields of the cylindrical array were simulated while number of exited elements and the focal point varies. The width and the length of the main beam lobe at the arbitrary focal points were calculated, while beam is focused or steered. The investigation answers the question to what extent we can steer focused beam and how the beam steering influences resolution and scanning time, while the distance of defects from the probe is not a constant. The scanning method can be used with ultrasonic convex and cylindrical arrays while object under investigation has axial symmetry and task is to cover the area of investigation with the same probability.

Keywords: phased arrays, simulations, ultrasonic field, scanning algorithm.

Introduction

Arrays are widely used in radar, sonar applications, medical, seismic systems and non-destructive testing. Ultrasonic arrays used in non-destructive testing and medical applications vary in shape. They can be linear (1D), matrix (2D) and annular (annular-sectorial) arrays and not so often met are cylindrical (Fig.1) arrays. Cylindrical arrays of huge dimensions (up 1500 kg) [5] are used to detect and measure cracks in gas pipes at in-line inspection while relatively small cylindrical probes are used for medical purposes like for transrectal high intensity focused ultrasound to treat prostate cancer [6]. One of the major advantages of the cylindrical array is that the beam can reach arbitrary point around the probe. The main shortcoming of such arrays is limited focusing possibility due to cylindrical geometry of arrays. They were investigated in previous studies of the focusing possibilities of cylindrical and convex arrays [4].

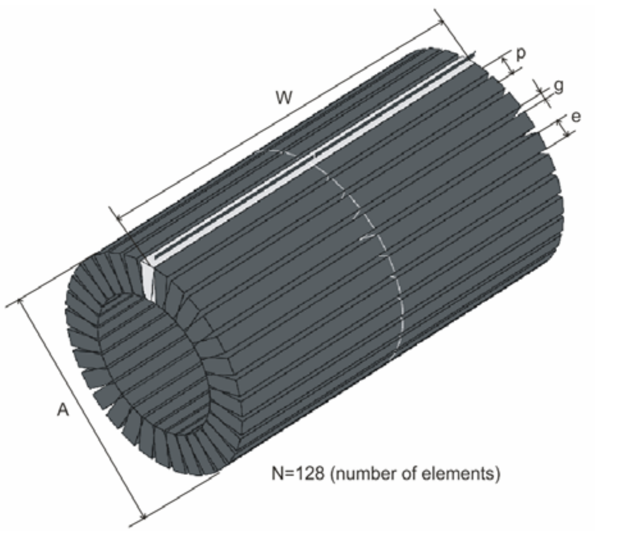

Fig.1. **Cylindrical array used in simulations. Element width *e*=0.15 mm, passive aperture *W*=10 mm**

There are several ways how to collect information about the inhomogeneities around the probe. Some authors use simple linear scanning exiting around the probe one element at sequence in immersion case [3], but the “dead zones” are found which are not covered and defects can be not detected in these zones. As well relatively small element of array has a wide main lobe which influences lateral resolution, the resolution which is transverse to the beam and it is determined by the width of the main beam lobe. To avoid this problem the only solution is to form a matrix of focusing points which guarantees that all area under the inspection is covered. The size of the matrix is determined by the amount of the focusing points or the resolution of inspection. Delays law for calculating focal point is easy calculated while amount of energy transmitted to the focal point (z_f) far away from the probe drops more in comparison with linear arrays. Changing the time delays it is possible to focus to any arbitrary point around the probe, but it is time consuming, so there is the need for an algorithm which optimizes scanning process.

Phased arrays allow to get beam steering as well as focusing. The objective of this investigation is the development of the scanning method for the cylindrical array which guarantees that any arbitrary point in the area around the probe is covered by the beam and is observed with the same spatial resolution. The method is based on switching the group’s of active elements around the probe while group size or active aperture is changed.

Approach

The investigation answers the following questions:

- at what circumstances we should use the beam steering or the beam focusing?

- how we will observe any arbitrary point with the fixed lateral resolution?

- how many elements will we use in the sequence?

- how much time will scanning take?

To answer these questions and find the optimum scanning method for the cylindrical array we did simulations of the ultrasonic fields using CIVA-NDE software [1] while we varied following parameters:

a) *N* is the number of elements used in transmission sequence. *N* was chosen equal to 8, 12, 16, 24, 32, 48, 64 elements.
b) The position of the focal point z_{fi} (where *i*- 1,2..nth focal point) was set at following distances from the probe: 5, 10, 15, 20, 25, 30, 35, 40, 45, 50mm. The two neighborhood positions of the focal points define area under test in *z* direction from the probe or selects orbit in which scanning 360º around the probe is performed (Fig.4).
c) The width and length of the beam main lobe was calculated for 10º, 20º, 30º, 45º beam steering angles at the focal points described in b).
d) Scanning step (Fig.7) was calculated individually for each circumference which radius is defined by the focal point z_{fi} to satisfy the same resolution at all distances from the cylindrical array.

Let us analyse 1D cylindrical array immersed in water, which elements are rectangular and focusing and steering was performed in *x*0*z* plane. We can focus the beam in immersion case (coupling medium is water) to any focal point z_{fi}, while distance from the probe is up to 50mm, but the width of the main beam lobe D_{Fi} and the length of the main beam lobe L_{Fi} will be non constant if we shall use for radiation the same number of elements.

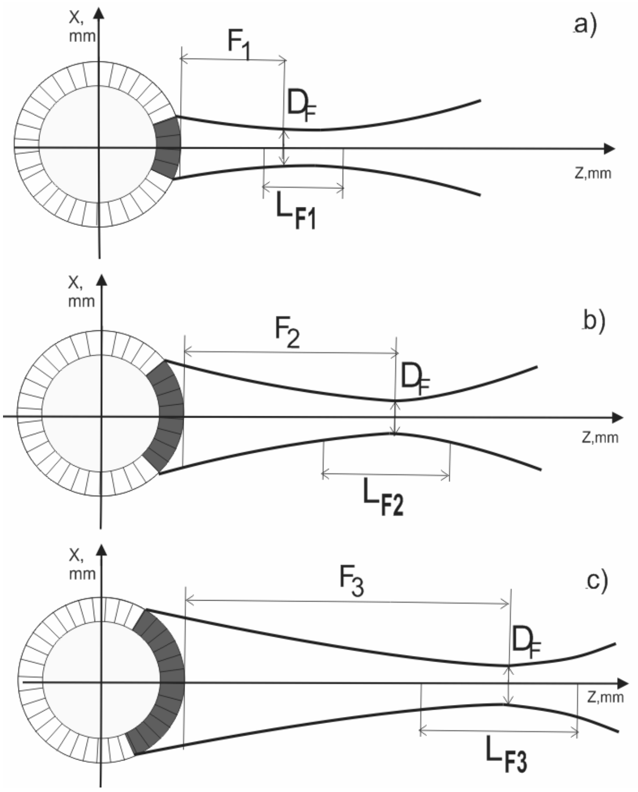

Fig.2. **The width main beam lobe D_F is constant while focal distances varies**

To maintain the condition that lateral resolution should be constant for any arbitrary point in *z* direction from the probe, we found that increasing the number of elements *N* used in the transmission sequence we can maintain the width of the main beam lobe D_F constant.

This approach is illustrated in Fig.2. In Fig.2 the beam is focused at a three different focal positions marked F_1, F_2, F_3. In a Fig. 2 we see that changing distances $F_1< F_2< F_3$ and exiting more elements we can keep the width of the main beam lobe D_F unchanged while the length of the focal spot will correspondingly increase $L_{F1}< L_{F2}< L_{F3}$. Dependency of number elements exited will be later used to determine scanning steps. In Fig.3 and 4 we see the simulated ultrasonic fields while the focal distance is set to z_f=20 mm and z_f=15 mm.

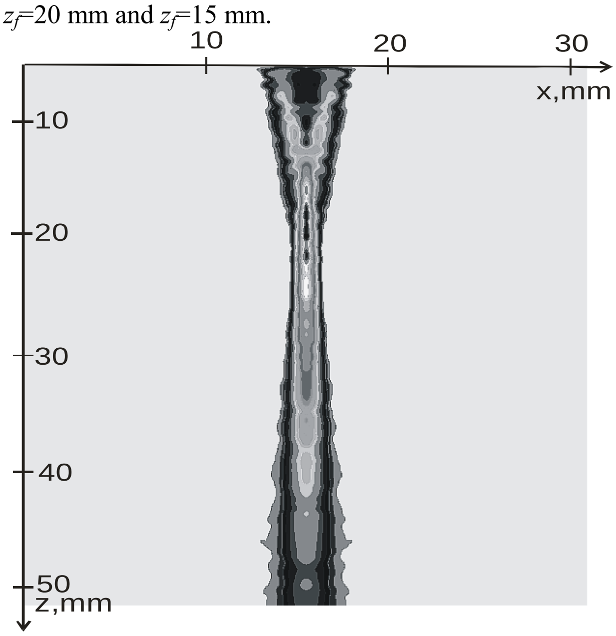

Fig.3. **Ultrasonic field of the cylindrical array in *x*0z plane. *N*=48 elements are exited at the center frequency *f*=5 MHz while the beam is focused at the focal distance z_f=20 mm**

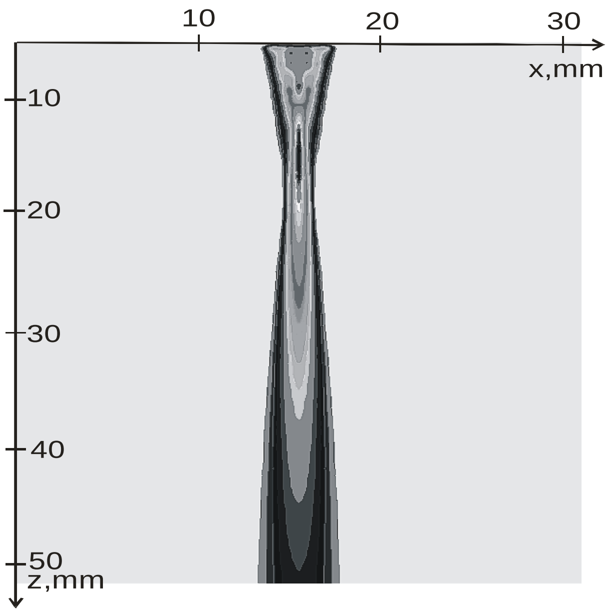

Fig.4. **Ultrasonic field of the cylindrical array in *x*0z plane. *N*=32 elements are exited at the center frequency *f*=5 MHz while the beam is focused at the focal distance z_f=15**

The width of the main lobe D_F while we focus *N*=48 elements to the focal point z_f=20 mm (Fig.3) at -3dB level equals to D_{F1} = 0.8 mm and D_{F2} =0.7 mm while we use *N*=32 elements.

To reach the point of interest using cylindrical arrays there are two ways: beam focusing and beam steering which are both limited due physical limitations and geometry of cylindrical array. The answer for selection the best way how the beam will be manipulated can be answered by choosing criteria like short scanning time or the required spatial resolution.

In Fig.5 we have two focal points z_{F1} and z_{F2} which are differently positioned in the $x0z$ plane (x coordinate varies, while z coordinate is constant). In Fig. 5a the focal point is perpendicular to the centre of the active aperture.

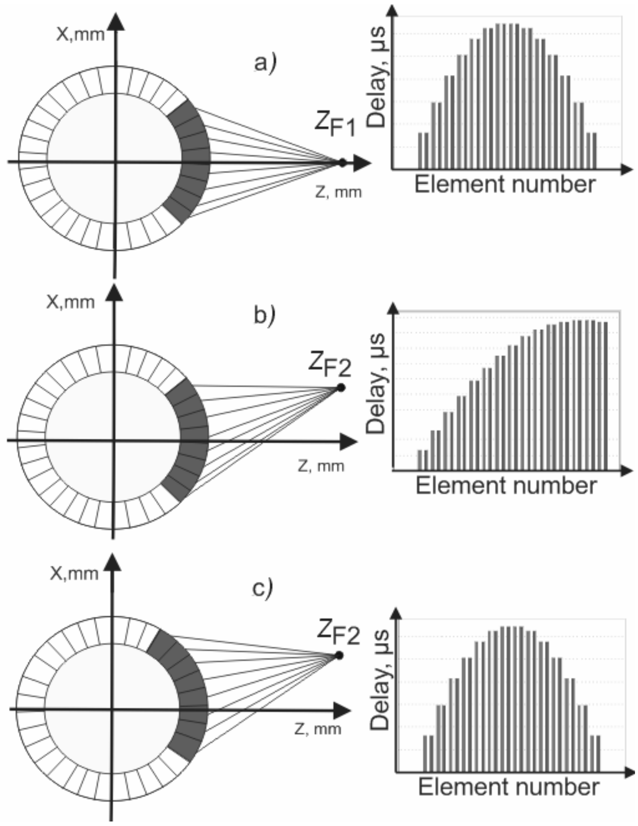

Fig.5. **Different positions of focal points z_f and applied delay laws to steer or focus the beam while: a) beam is focused only; b) beam is focused and steered to new focal point z_{f2} position c) elements of array is switch by the step of one element anticlockwise and beam is steered only to focal point z_{f2}.**

The active aperture consists of eight elements which are excited using different delays, so the beam is focused at the distance z_f. In the next picture (Fig. 5b) the focal point is deflected so that the x coordinate is not equal to zero. Using the same group of elements to reach the same focal point z_{F2} we need to steer and focus the beam simultaneously. In this case distances from the elements on the edges of the active aperture to focal point z_{F2} are not equal which require applying the delay law which is not symmetrical (Fig. 5b).

In the last picture (Fig.5c) the active aperture is turned anticlockwise by the certain step of elements (in our case one element) to align the centre of the active aperture perpendicularly to this centre. So in this case we will get a symmetrical delay law which guarantees the same resolution like in Fig.5a case. This approach allows us to use only beam focusing instead of beam steering and focusing simultaneously. This is very important when we need to keep the lateral resolution D_F constant and we do not want to increase the time of scanning.

In Fig.6 we have steered the beam by 30° angle and focused to the focal point z_f=15 mm. In this case the maximum applied delay to elements is 1.448 μs while the width of the main beam lobe at -3dB level is equal to 1.4mm. If we will employ only focusing (Fig. 7) we will

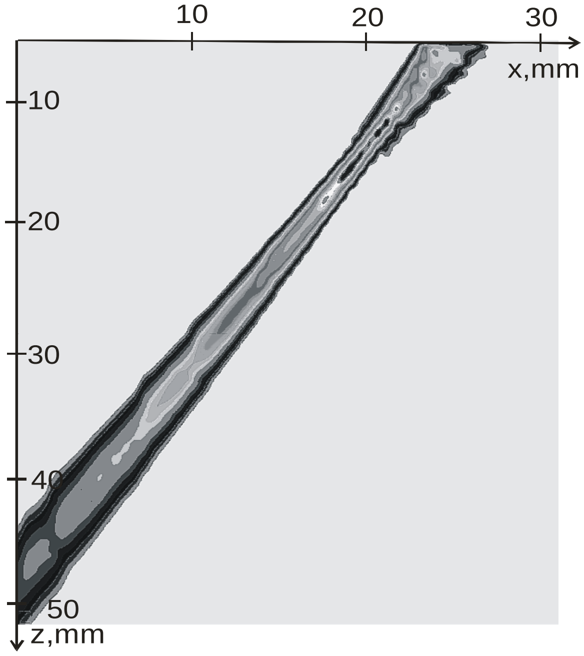

Fig.6. **Ultrasonic field of a cylindrical array in $x0z$ plane in the water, while N=32 elements are exited at the center frequency f=5 MHz and the beam is steered by 30° angle to z_f=15 mm focal point.**

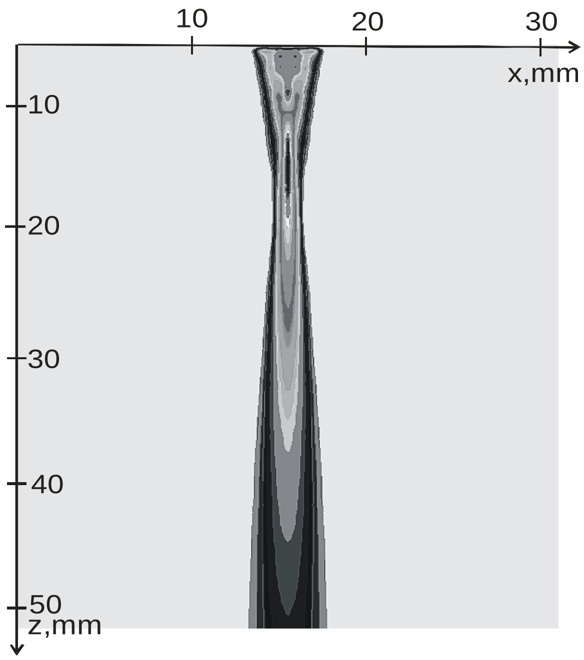

Fig.7. **Ultrasonic fields of a cylindrical array in $x0z$ plane in the water, while N=32 elements are exited at the center frequency f=5 MHz.The beam is focused at the z_f=15 mm focal point.**

get the width of the main beam lobe at -3dB level equal to 0.7 mm while the maximum applied delay to elements is 0.652μs.

So it is clearly seen that beam steering increase width of the main beam lobe and the time needed for delay almost two times.

Our suggested scanning principle for the cylindrical array is based on switching the focused beam around the probe by certain step which matches that the focal point is perpendicular to the centre of the active aperture while its size varies to keep the lateral resolution constant.

For some reasons, like for investigation of "hook" type flaws, we can neglect the scanning time and use the beam steering together with the beam focusing. The maximum beam steering angle at -6dB level for linear phased array is given by [7]:

$$\sin\theta_{st} = 0.5 * \frac{\lambda}{d}, \qquad (1)$$

where λ is the wavelength and d is the inter element spacing. The width of the beam main lobe was calculated while beam is focused and steered, but in the suggested scanning method only the beam focusing is used.

Algorithm steps

The suggested scanning method consists of several steps while at each step different focal point and size of the active aperture is selected. The way how the switching of elements is performed for the cylindrical array and constant resolution is maintained at any point of interest are described in the algorithm steps below.

In the first algorithm step we should describe initial conditions: a) defect types, size, orientation; b) defect location (minimal, maximum distance from the probe); c) spatial resolution of non destructive evaluation or the maximum time of scan which can be used for inspection, while the scan resolution depends on number of scan paths; d) the object under the test or medium; e) parameters will be measured in the inspection (time, amplitude or both).

At this step we should set boundaries of the area under investigation. The geometry of area under investigation (Fig.8) is defined by the geometry of cylindrical arrays and has axial symmetry and can be divided into circles (orbits) by set step of radius by going from the probe in z direction. We selected that the radius of each circle increases in constant step which equals – 5 mm. The adios of the outer circle is limited due focusing capabilities of the phased array and we used it up to 25mm. The circle is divided into four quarters which each covers 90° of the scan area. The cylindrical shape of the arrays allows us to perform scanning in the first and second quarter and in the opposite quarters (third and fourth) simultaneously without crosstalks between elements which radiate to opposite directions.

Each area separated by circles can be subdivided into sectors with a defined area:

$$S_i = \frac{\alpha^\circ \pi R^2}{360^\circ}, \qquad (2)$$

where α° is the angular width of the sector, R is the radius of circle.

The sector area is limited by the width D_F and the length L_F of the beam main lobe.

The focused beam rotates around the probe (Fig.8) with a certain step which is equal to the width D_F of the main lobe at the estimated focal distance. To cover the area in the selected orbit around the probe the number of positions to be scanned can be determined:

$$N_{scan} = P_i / D_F, \qquad (3)$$

where P_i is the circumference of the i^{th} circle, D_F is the main lobe width at the focal point.

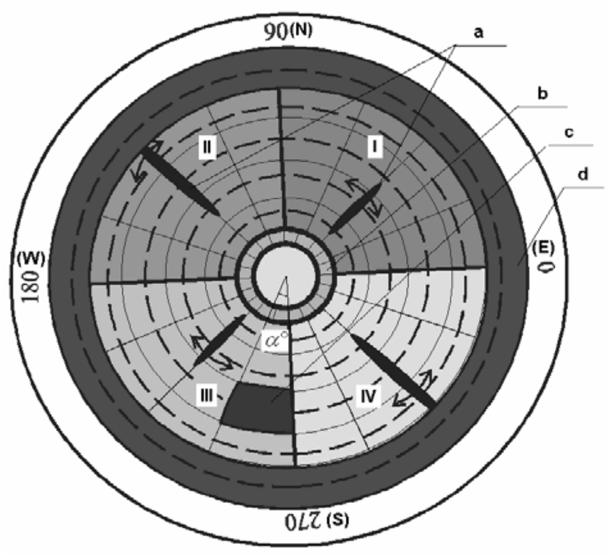

Fig.8. **Scanning area around the probe. View from the top: a - beam spots at variable focal distance z_f; b - probe; c - sector defined; d - defined orbit**

In the second step (coarse scanning) of the algorithm sectors or areas limited by the circles of certain radius where potential defects can be found are determined (Fig.9).

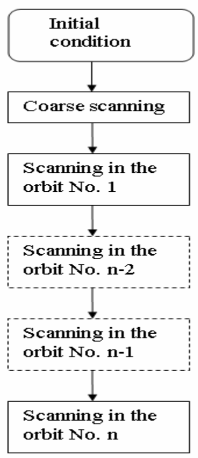

Fig.9. **Scanning sequence**

To prevent long inspection time we need to minimize the number of scanning positions, so at the first scanning step we use a coarse scanning in the circle defined by some radius for example in this particular case R=20 mm.

At this step we use N=32 elements which are exited by the delay law to focus at z_f=40 mm (Fig.10).

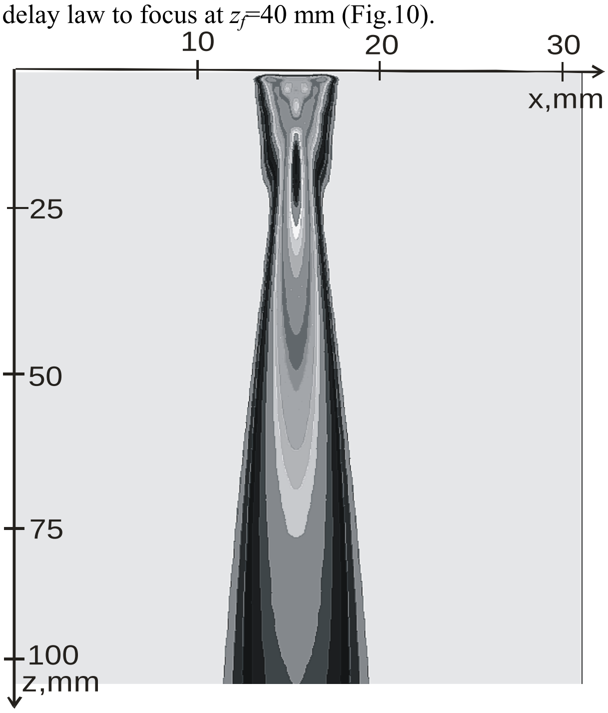

Fig.10. **Ultrasonic fields of cylindrical array in *x*0z plane. Elements are exited at the center frequency *f*=5 MHz. The beam is focused at the focal distance z_f=40 mm while *N*=32 elements are used**

As we see from Fig.10 the width of the main beam lobe is 3 mm and the length is 42.4 mm. The beam at -3dB level covers area from z=10 mm to z=40 mm, so at this step we will need to focus to 104 positions around the probe which is defined by the inner radius r=10 mm and the outer radius r=40 mm. At coarse scanning step we determine approximately areas around the probe with defects, but exact size of the defects and theirs position is not calculated at this time. This step makes sense to reduce the time consumption, when areas which have no defects can be skipped and no focused beams are transmitted to it. While we do not know the number of defects, the estimated time for scanning in algorithm will be calculated with assumption that all area from z_f [5; 40] is scanned.

In the next step we need to cover area in the next selected orbit. Depending on the defect distance from the probe various groups of exited elements are used. For example to scan area defined by the radius r=5 mm we will excite 16 elements at focus to z_f=10 mm (Fig.11).

The number of steps used in the scanning sequence will depend on how many orbits will be defined and how many elements will be used to focus the beam while increasing the number of elements we will narrow the width of the main beam.

The time t needed for transmission and reception of the pulse reflected from the target at the distance r is equal:

$$t = 2r/c, \qquad (4)$$

where c is ultrasound velocity .

To estimate the time t_s needed to focus to the fixed focal distance d_f=r we need to take into the account the duration of the transmitted pulse T_p and the time t_d needed for excitation of the elements:

$$t_s=t+T_p+t_d \qquad (5)$$

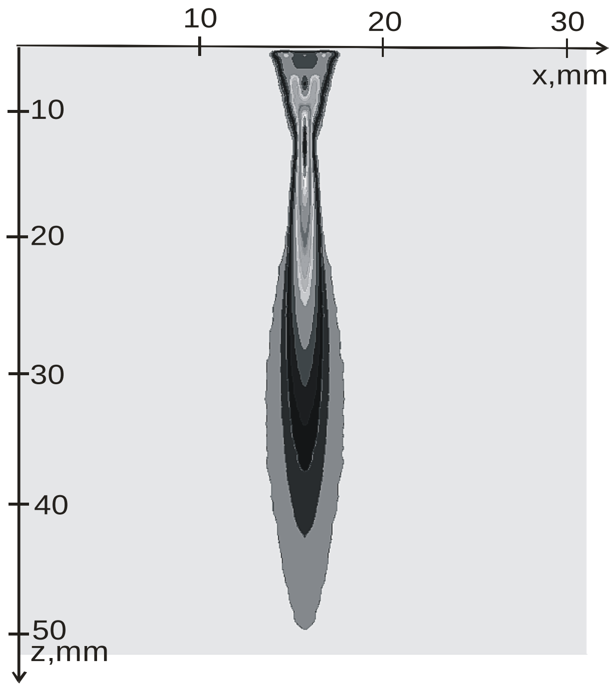

Fig.11. **Ultrasonic fields of cylindrical array in *x*0z plane. Elements are exited at the center frequency *f*=5 MHz. The beam is focused at the focal distance z_f=10 mm while *N*=32 elements are used.**

The time t_o for scanning of the selected orbit is equal to the number of the scan positions N_{scan} multiplied by the sum of the time t_s and the extra time t_{sw}, needed for switching groups of the active elements:

$$t_o=(t_s+t_{sw})*N_{scan} \qquad (6)$$

In Table 1 the time needed for scanning of the defined area (Fig8. d) is presented.

Table1. **Number of scanning steps N_{scan} and elements of the array *N* used in algorithm while focusing to different focal distances z_f.**

z_f, mm	P_i, mm	N	N_{scan}	t_s, µs	t_o, µs
5	62,8	8	138	10,67	736
10	94,2	16	130	17,33	1127
15	125,6	16	138	24,00	1656
20	157	24	144	30.67	2208
20	157	32	173	30,67	2653
30	219,8	32	186	44,00	4092
40	282.6	32	104	57.33	2981
40	282,6	48	239	57,33	6851
50	345,4	48	271	70,67	9575

The lateral spatial resolution at all focal distances was less than 5λ (λ =0.3 mm).

Conclusions

The scanning sequence described above is useful in time consuming approach while performing scans without *a priori* information about inhomogeneities around the probe. The provided algorithm allows scanning around the probe with a fixed spatial resolution at any arbitrary point in the region of the investigation. Inspection of the area around the probe takes two times less time while it is performed in the first and second and third and fourth sectors simultaneously. The fixed lateral resolution can be achieved by varying the number of exited elements, while the focus distance z_f can vary from 5 to 40 mm from the probe surface. The beam steering is undesirable for the arrays with cylindrical geometry, but can be used for certain tasks taking into account limitations arising from the steering angle. To maintain high speed of the inspection only the beam focusing was chosen in the scanning sequence provided in this article.

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Cilindrinės ultragarsinės gardelės kompleksinio skenavimo metodo tyrimas

Kaip parodė cilindrinės ultragarsinės gardelės kompleksinio skenavimo metodu gauti rezultatai, šis metodas pagerina skersinį skiriamumą ir užtikrina visišką tiriamos erdvės padengimą. Tyrimo metu buvo sumodeliuoti cilindrinės gardelės ultragarsiniai laukai, kai gardelės spindulys fokusuojamas skirtinguose erdvės taškuose. Siekiant optimizuoti skenavimą, buvo apskaičiuoti skenavimo laikai esant skirtingam žadinamų elementų kiekiui, kai skersinė skiriamoji geba fiksuota ir nekinta esant įvairiems fokuso atstumams. Aprašytasis skenavimo metodas tinkamas naudoti cilindrinėms ir išgaubtoms ultragarsinėms gardelėms, kai tiriamasis objektas turi ašinę simetriją ir darbo užduotis reikalauja, kad 360º tiriamosios erdvės aplink gardelę būtų padengtos.

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