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Simulations of ultrasonic fields of radial ultrasonic array

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Abstract:
Objective of this study was to develop an ultrasound probe small enough (diameter – less then 10mm, length less then 6mm) The probe must send and receive signals in 360 degrees, obtaining in this way the information needed for the software to generate a 2D image. In order to choose best suitable dimensions and frequency of the ultrasonic radial array, simulations of different array configurations were performed. The fields of elementary rectangular transducers were obtained by means of the impulse response method. Ultrasonic fields in a transmission mode of 10MHz and 5 MHz transducers with different dimensions (length 5 mm, width – 2mm, 1mm and 0.7mm) were simulated. The coverage of the field of the radial array with 16 and 32 elements, with different transducer frequencies were simulated. Performed simulations show, that the best results could be achieved using 5MHz 32 transducers array with dimensions of elementary transducers 5x0.7 mm.
Keywords: simulations, ultrasonic field, radial array, medical.

Introduction

Endoscopic ultrasonography - a combination of endoscopy and ultrasonography allows examination of tissue not only within the digestive tract, but also surrounding it. Traditional endoscopes use flexible tubes for examination of gastrointestinal tract. In recent years, capsule endoscopy has emerged as a very sensitive tool for diagnosis [1-3]. However, in most capsule endoscopes optical devices are used for capturing images, which allow to see just the surface of the digestive tract.

Objective of this work is to develop an innovative diagnosis system, based on an endoscope ultrasound capsule. This capsule should be used as a first line exam for investigation of diseases in the gastrointestinal tract, such as ulceration, Crohn's disease and cancers. Ultrasound capsule will be moving in the gastrointestinal tract by natural peristaltic movements of the stomach and intestines collecting ultrasonic data on its way.

Objective of this part of work - is to develop an ultrasound radial array small enough (D<10mm, l<6mm) to be inserted inside the capsule. In order to choose best suitable dimensions and frequency of the ultrasonic radial array, simulations of different array configurations were performed.

Ultrasound probe

In Fig.1 the possible geometry of the ultrasonic array consisting of 32 separate transducers is presented. In this work calculation for the arrays with 32 elements as well as with 16 were carried out. Separate transducers will be mounted on the supporting structure.

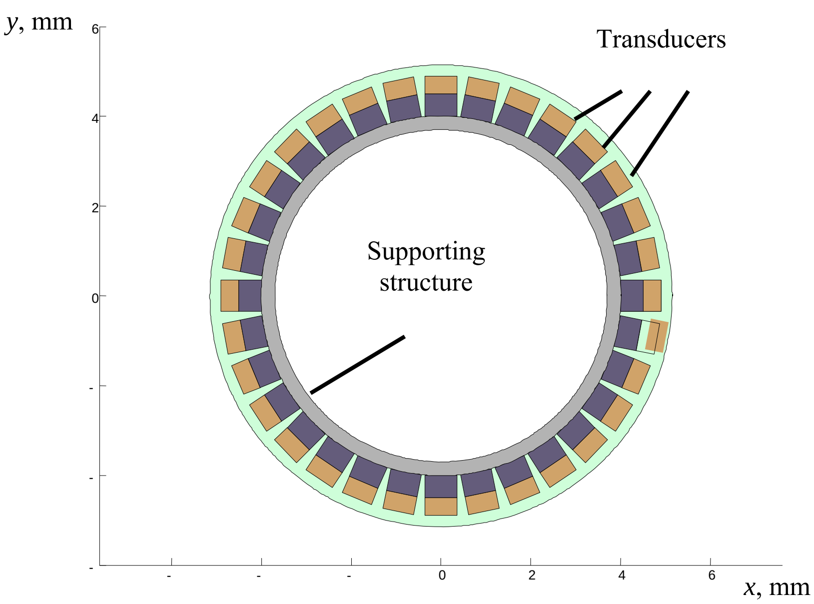


Fig.1 **Ultrasonic array consisting of 32 separate transducers**

In Fig. 2 geometry of the single array elements is presented. Single transducers in the array will have the rectangular form – height H and width Δl_t and they will be separated from each other by the gap Δl_g. In further calculations it was assumed, that the height of the elements was 5 mm and the width of the elements Δl_t was 1mm or 0.7mm. The gap between elements depends on the number of the elements.

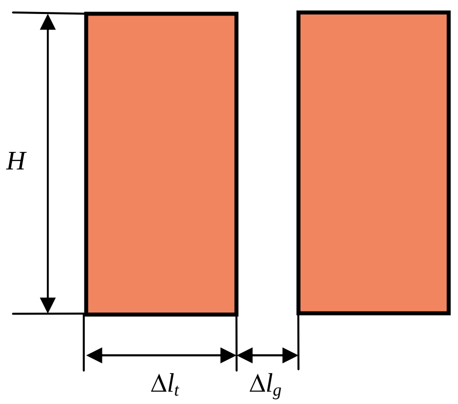


Fig. 2. **Geometry of the single elements (side view)**

Impulse response approach

The pulsed acoustic fields radiated by elementary rectangular transducers were calculated using impulse response method proposed by Lockwood and Willete [4] and taking into account observations for numerical calculations made by Reibold and Kažys [5, 6].

For any field point (x, y, z) its projection $O' = (x, y, 0)$ on the plane of the rectangular transducer is found (Fig. 3). The rectangular transducer is subdivided into four rectangles, each with the corner at O′. The field of the rectangular transducer is obtained by combining the field of the four rectangles. If O′ is outside the rectangular transducer, the rectangle is enlarged to include it and the added rectangles are subtracted.

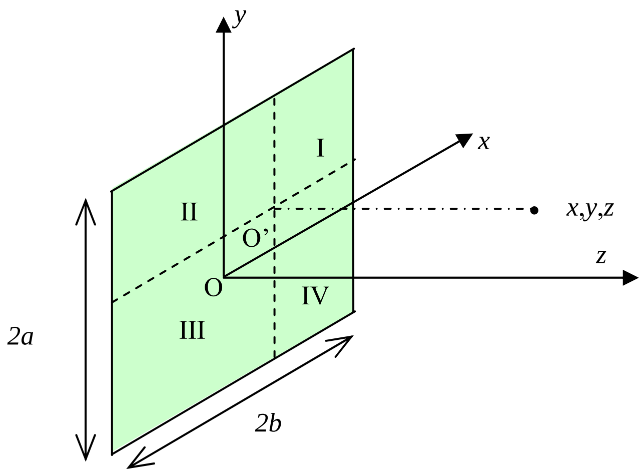


Fig. 3. **Subdivision of the rectangular transducer into four rectangles**

The spatial impulse response can be expressed as:

$$h(x,y,z,t) = -\frac{c}{2\pi}\sum_{k=1}^{4} \pm \left\{\frac{\pi}{2}\left[H(t-t_{1k}) - H(t-t_{4k})\right] - \right.$$
$$-\arccos\left\{\frac{s_k}{\sqrt{c^2(t-t_{2k})^2 - z^2}}\right\} \times \left[H(t-t_{2k}) - H(t-t_{4k})\right] -$$
$$\left. -\arccos\left\{\frac{l_k}{\sqrt{c^2(t-t_{3k})^2 - z^2}}\right\} \times \left[H(t-t_{3k}) - H(t-t_{4k})\right]\right\}, \quad (1)$$

where s_k is the length of the short side of the rectangle, l_k is the length of the long side of the rectangle, $H(t)$ is the Heaviside function, $t_{1k} = z/c$ - is the time of flight of the plane wave from the transducer to the observation point; $t_{2k} = \frac{\sqrt{z^2 + s_k^2}}{c}$ - is the time of flight of the signal from the nearest edge of the transducer to the observation point; $t_{3k} = \frac{\sqrt{z^2 + l_k^2}}{c}$ - is the time of flight of the signal from the farthest edge of the transducer to the observation point; $t_{4k} = \frac{\sqrt{z^2 + s_k^2 + l_k^2}}{c}$.

The acoustic field can be expressed:

$$p_i(x,y,z,t) = \rho\frac{\partial}{\partial t}\left[v(x,y,z,t) * h(x,y,z,t)\right]. \quad (2)$$

where ρ is density of the medium, v_i is the particle velocity, ∗ denotes convolution.

The complete field of the transducer is expressed as the sum of the fields of the rectangles:

$$p(x,y,z,t) = \sum_{i=1}^{N} p_i(x,y,z,t). \quad (3)$$

Simulation results

The pulsed acoustic fields were calculated using the above described approach. In order to choose best suitable dimensions and frequency of the ultrasonic radial array, simulations of different array configurations were performed. Ultrasonic fields in a transmission mode of 5MHz, 7 MHz and 5 MHz transducers with different dimensions (length 5 mm, width – 2mm, 1mm and 0.7mm) were simulated. It was assumed, that in all cases transducer is radiating into water (c=1500m/s), because the value of ultrasonic velocity in biologic tissues is similar to the ultrasonic velocity in water.

The transducer field was calculated in two perpendicular planes $x0z$ and $y0z$ (Fig. 4). The structure of the field of the rectangular transducer (which have different side lengths) is different in both planes because of asymmetry – the length of the near field depends on the transducer dimensions and differs in both planes.

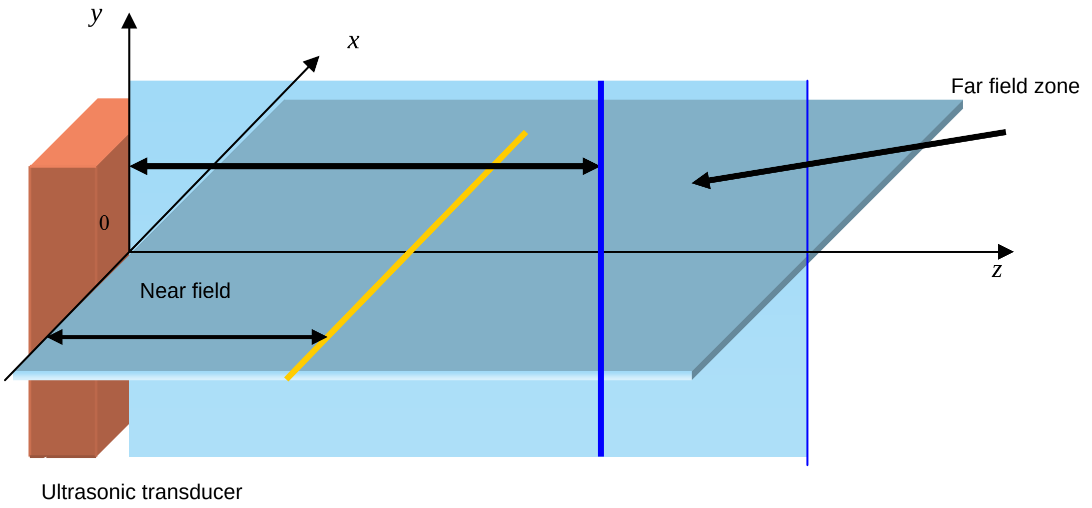


Fig. 4. **Ultrasonic field of rectangular transducer in *x*0z and *y*0z planes**

The simulated pressure fields are presented as $p_{CS}(x,z)=\max_{t}|p(x,z,t)|$. For better understanding, the presented fields are normalized with respect to the maximum value. Ultrasonic field of 5 MHz transducer with dimensions 2x5 mm is presented in Fig. 5. As can be seen the near field zone in *y*0z plane is longer if to compare with the near field zone in *x*0z plane. The acoustic field of the transducer with the same frequency, but with dimensions 1x5 mm is presented in Fig.6, and with dimensions 0.7x5mm is presented in Fig.7. Comparison of the acoustic fields of the transducers with the same frequency, but different dimensions shows, that when the dimensions of the transducer are decreased, intensity of the field is decreasing also.

For 10 MHz frequency acoustic fields of the transducers with the dimensions 2x5 mm (Fig.8) 1x5 mm (Fig.9) and 0.7x5 mm (Fig. 10) were calculated. Here, as in the case of 5 MHz transducer, it can be seen that when the dimensions of the transducer are decreased, intensity of the field is decreasing also.

It can be seen, that the near field zones of 10MHz transducer are longer if to compare with 5 MHz transducer.

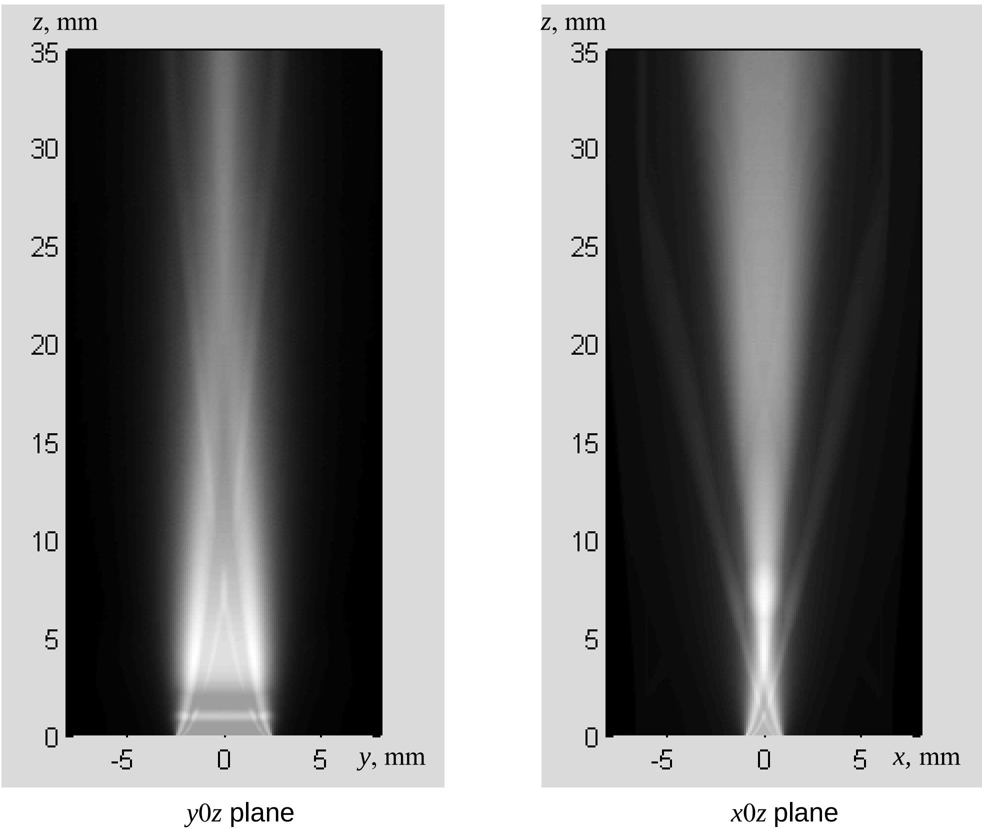


Fig. 5. **Ultrasonic field of 5MHz transducer with dimensions 2x5mm**

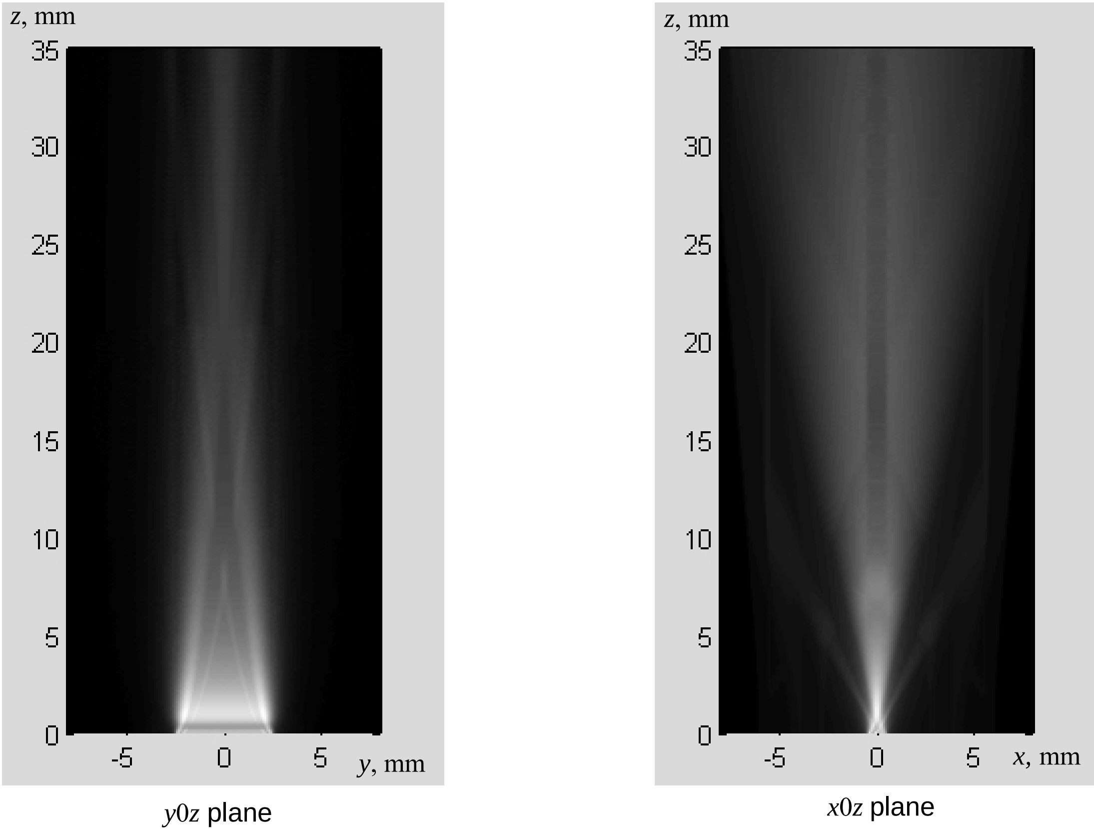


Fig. 6. **Ultrasonic field of 5MHz transducer with dimensions 1x5 mm**

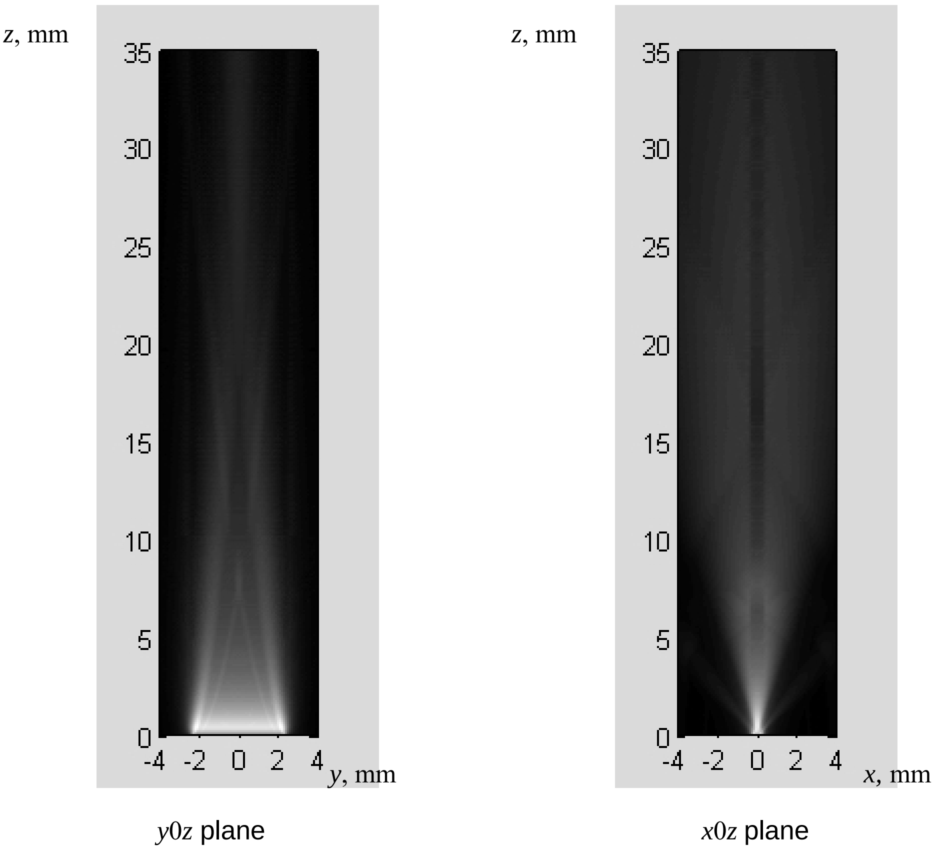
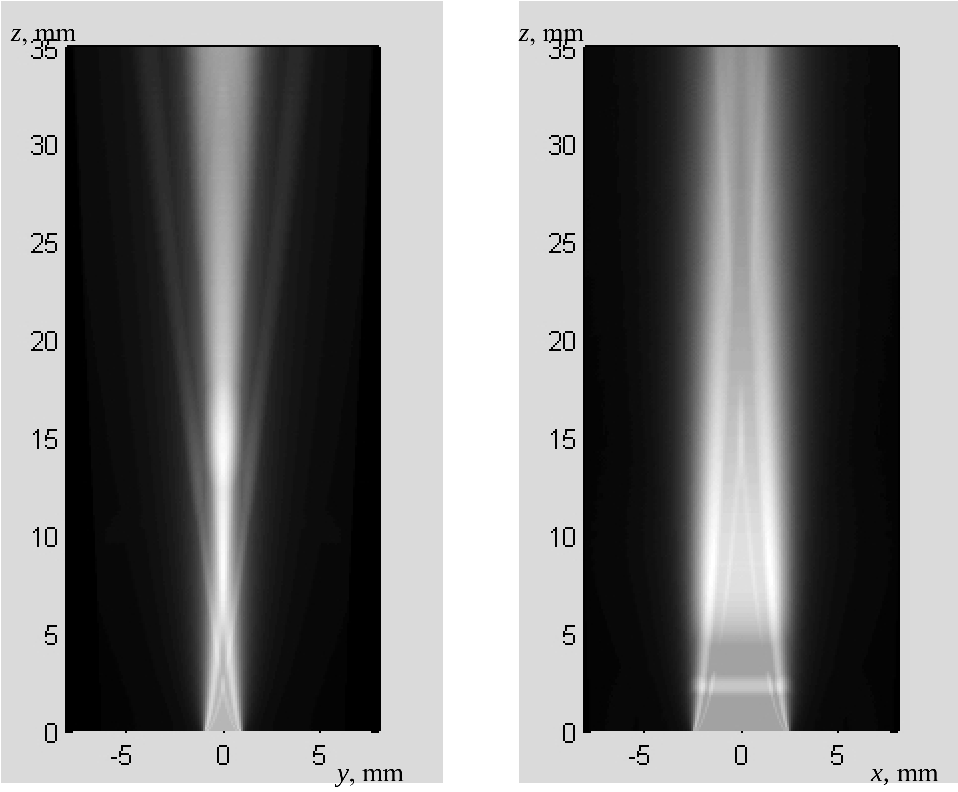


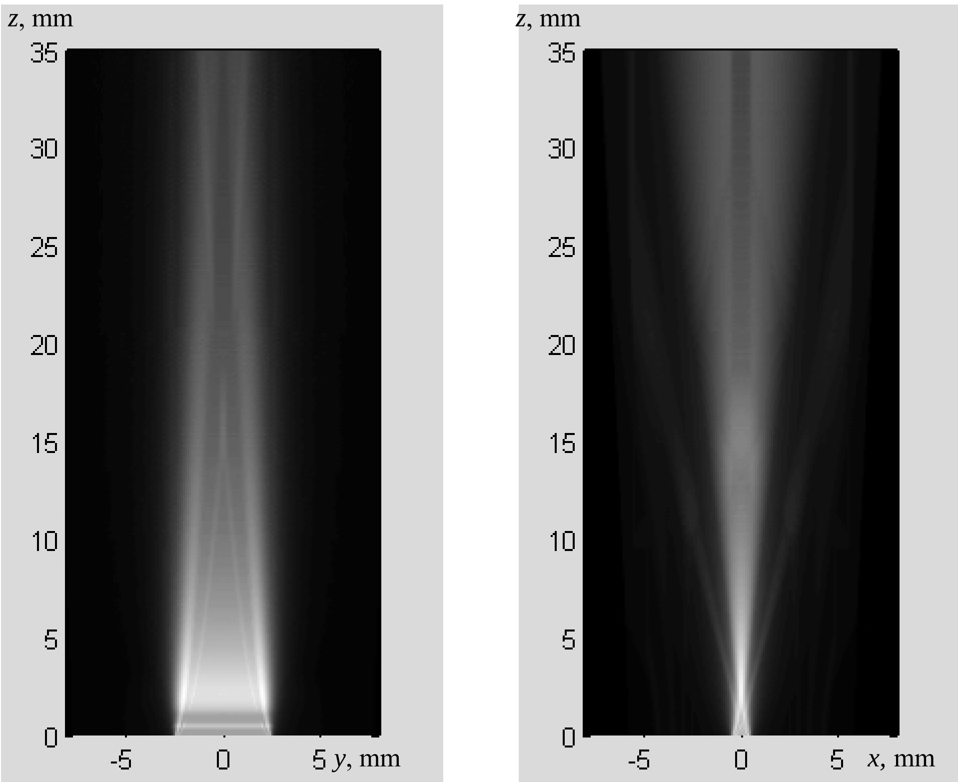
Fig. 7. **Ultrasonic field of 5MHz transducer with dimensions 0.7x5 mm**



*y*0*z* plane

*x*0*z* plane

Fig. 8. **Ultrasonic fields in a transmission mode of 10 MHz transducer (2×5 mm)**



*y*0*z* plane

*x*0*z* plane

Fig. 9. **Ultrasonic fields in a transmission mode of 10 MHz transducer (1×5 mm)**

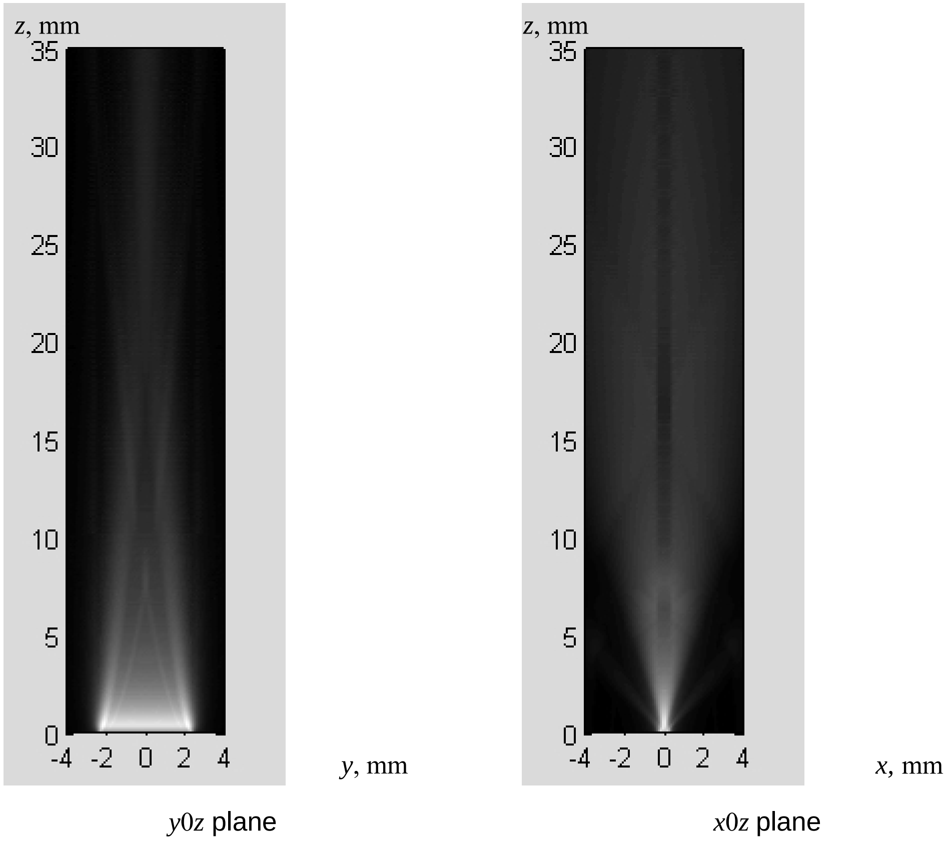


Fig. 10. **Ultrasonic fields in a transmission mode of 10 MHz transducer (0.7×5 mm)**

In order to visualize the field of the whole radial array, the coverage of the field of the radial array with 16 and 32 elements at different transducer frequencies was simulated. In Fig. 11 the coverage of the field of the 16 elements 5x1 mm 10 MHz radial array is presented. The dark zones in the image show, where there is almost no signal, or the signal is with a very small amplitude. That means, that in case of the 16 elements 5x1 mm 10 MHz radial array there are too many "dark zones", from which no information will be available.

Fig. 11. **The coverage of the field of the radial array 10MHz, 5x1mm, N=16**

In Fig. 12 the coverage of the field of the 32 elements 5x0.7 mm 5 MHz radial array is presented. In this case coverage is much better in comparison with the previous case. The performed simulations show, that the best results could be achieved using the 5 MHz array consisting of 32 transducers with dimensions of elementary transducers 5x0.7 mm.

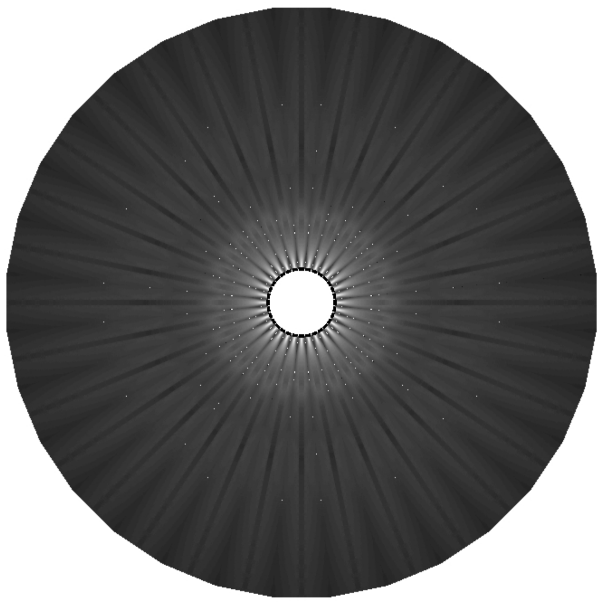


Fig. 12. **The coverage of the field of the radial array 5MHz, 5x0.7mm, N=32**

Conclusions

In order to choose the most suitable dimensions and frequency of the ultrasonic radial array, to be inserted inside the capsule with the dimensions of 11 mm x 26 mm, simulations of different array configurations were performed. The fields of elementary rectangular transducers were obtained by means of the impulse response method. Ultrasonic fields in a transmission mode of 10 MHz and 5 MHz transducers with different dimensions (length 5 mm, width – 2 mm, 1mm and 0.7mm) were simulated. The coverage of the field of the radial array with 16 and 32 elements, with different transducer frequencies was simulated. The performed simulations show that the best results could be achieved using 5 MHz 32 transducers array with dimensions of elementary transducers 5x0.7 mm.

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Apskritiminės keitiklių gardelės ultragarsinių laukų modeliavimas

Reziumė

Šio tyrimo tikslas – sukurti mažą ultragarsinį keitiklį (mažesnio nei 10 mm skersmens, mažesnio ilgio nei 6 mm). Keitiklis (keitiklių gardelė) turėtų siųsti signalus visomis kryptimis – 360 laipsnių. Tokiu būdu būtų gaunami duomenys, kurie leistų sugeneruoti 2 D vaizdą. Norint parinkti ultragarsinės keitiklių gardelės geriausius matmenis ir dažnį, buvo atliktas įvairių konfigūracijų keitiklio gardelių elementų kompiuterinis modeliavimas. Elementariųjų stačiakampių keitiklių laukams modeliuoti taikytas impulsinės reakcijos metodas. Buvo sumodeliuoti skirtingų matmenų (ilgis - 5 mm, plotis – 2 mm, 1 mm ir 0,7 mm) 10 MHz ir 5 MHz keitiklių siuntimo veikos ultragarsiniai laukai. Be to, buvo sumodeliuota 16 ir 32 elementų įvairių dažnių keitiklių gardelių lauko danga. Tyrimo duomenimis, geriausių rezultatų galima būtų pasiekti naudojant 5 MHz 32 elementų keitiklių gardelę, kai keitiklių matmenys 5x0,7 mm.

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