HARMONIC ULTRASOUND BEAMS FORMING BY MEANS OF RADIATING SOURCE PARAMETERS

TAMARA KUJAWSKA, JANUSZ WÓJCIK

Ultrasound Department, Institute of Fundamental Technological Research
Polish Academy of Sciences, Warsaw, Poland
tkujaw@ippt.gov.pl

In the paper the investigation results of the influence of such parameters as shape and size of the radiating source, as well as waveform, frequency and amplitude of the propagating pulse on the non-linear ultrasonic beam forming are presented. The analysis was carried out on the basis of numerical simulations of the amplitude and harmonic field distributions, in space and time, of two-dimensional beams propagating in water. The applied software (numerical solver), describing the nonlinear propagation of the ultrasonographic pulse wave radiated by the axially symmetrical source in the layered lossy medium for given boundary conditions, was used as the tool to predict the behavior of the ultrasound beam. The algorithm of the above numerical solver, proposed by the second author, is based on the frequency-domain numerical solution of the non-linear wave equation for finite amplitude sound beams. It takes into account the influence of the effects of diffraction, non-linearity and thermoviscous absorption on the propagation of the finite amplitude acoustic beam in attenuating media.

INTRODUCTION

The ultrasonic imaging is widely used in clinical practice. Recently a technique of the Tissue Harmonic Imaging (THI), utilizing acoustic non-linear propagation effects, has attracted major interest in biomedical ultrasonography. During propagation of high amplitude ultrasonic pulses which are generated by some medical ultrasound equipments, the transmitted waveforms are distorted resulting in the native generation of harmonics of the initial frequency components. The main aim of the THI technique is to achieve the best possible resolution of the tested structures imaging in order to improve the image quality. It can be done first of all by the radiated beam cross-section decreasing within the whole penetration depth of the tested tissues. To optimize the harmonic beam dimensions it is necessary to study the influence of such radiating source parameters as shape and size, the transmitting pulse waveform, frequency and amplitude, the aperture apodisation function as well as non-linear properties of the investigated biological structures. In this paper, the results of numerical investigations of the influence of radiating source parameters on the spatial harmonic distribution of the two-dimensional (axially symmetrical) non-linear ultrasonic beam are presented. Numerical calculations were possible due to the powerful software (solver), compiled and tested recently in our laboratory, which made it possible to realize the fast simulations (for various boundary conditions) of the spatial distributions of the axially symmetrical ultrasound beams, propagating in the multi-layer liquids or biological structures. The additional advantage of this solver is an adaptability to work in the PC operating system environment. The boundary conditions parameters were the input data of the solver. The mathematical model and the numerical algorithm for the describing of the three-dimensional distributions (in space and time) of the non-linear acoustic beams, which are the basis of the above solver, were presented in previous publications [1, 3].

1. BOUNDARY CONDITIONS

Two-dimensional (2D) ultrasonic beams are generated by the circular piezoelectric transducers driven by short electrical pulses. Usually in clinical practice for diagnostic imaging of the soft tissues, probes with the transducer radius of $a = 5 \div 15$ mm and focal distance of $F = 8 \div 10$ cm are used. The pressure amplitude in those beams is limited by the American Institute of Ultrasound in Medicine (AIUM) as a patient security measure. For the diagnostic ultrasound, the maximum exposure in water from pulse-echo equipment [4] in form of the peak compression (positive pressure) is equal to 8.8 MPa, while in form of the peak rarefaction (negative pressure) is equal to 4.3 MPa. Therefore the standard value of the initial acoustic pressure amplitude, used in diagnostic medical systems, is contained within the range of $p_0 = 0.1 \div 0.4$ MPa. The frequency range of pulses radiated by typical ultrasonic probes used for soft tissue diagnostic purposes is contained within the interval of $1 \div 4$ MHz. Taking into account the above boundary conditions, several numerical simulations of field distributions in water (the 1-st and the higher harmonics, the peak positive and the peak negative, the peak-to-peak) for the beams radiated by plane sources with radius $a = 5$, 7.5, 10, 15 mm and by focusing sources with the same radius and focus $F = 8$ cm were realized. Computations were performed for radiated in water acoustic pulse waves with the carrier frequency of $f_0 = 1$, 2, 3 MHz and the initial acoustic pressure amplitude $p_0 = 0.1$, 0.2, 0.3, 0.4 MPa. The cases of long (8-cycle) and short (4-cycle) acoustic pulses were calculated assuming a constant ratio (equal to 0.4) of the pulse duration to its repetition period for all the resonant frequencies. Numerical simulations were realized for initial acoustic pulses with the envelope in the form of a polynomial function (1). The value of the exponent m is selected usually to obtain the waveform of the analytical initial pulse best matched to the measured one. In this paper all numerical computations were performed for $m = 8$ (see Fig. 1).

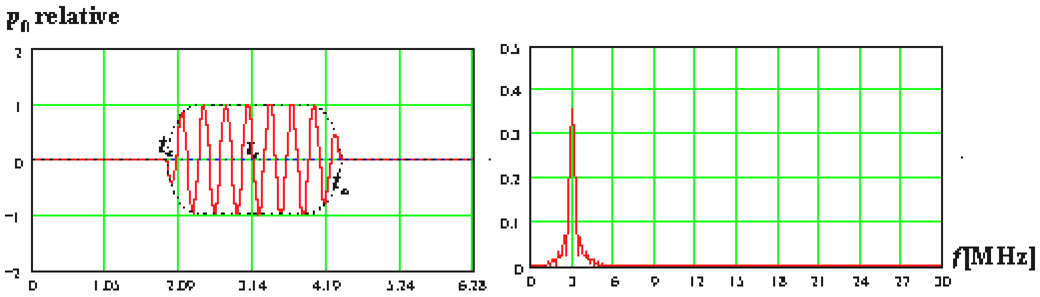

Fig. 1. The initial acoustic waveform containing 8-cycle sinusoidal pulse with the carrier frequency of 3 MHz, normalized with respect to the initial amplitude p_0 (left) and its spectrum (right). The pulse envelope is in the form of function (1) for $m = 8$.

$$f(t)=\left(1-\left|\frac{t-t_c}{t_e-t_s}\right|^m\right)\sin\left[\omega(t-t_c)\right] \quad \text{for } t_s \le t \le t_e \tag{1}$$

$$f(t)=0 \qquad \text{for } t \notin (t_s\,,\,t_e)$$

where t_s , t_c , t_e – dimensionless times corresponding to the start, the center and the end of the initial acoustic pulse.

The radial acoustic pressure distribution on the source radiating aperture (apodisation function), as the next input parameter of the numerical solver, is matched analytically by searching the initial function that settles the radial pressure distribution in the nearest vicinity of the radiating surface as close as possible to the measured one at the same distance. Fig. 2 presents the initial apodisation function described by the formula $f(r)=\left|1-(r/a_t)^8\right|$, used for numerical simulations, and the radial distribution computed very close to the radiating source. Here a_t is the source radius. This function was the best approximation of the measurement results [2].

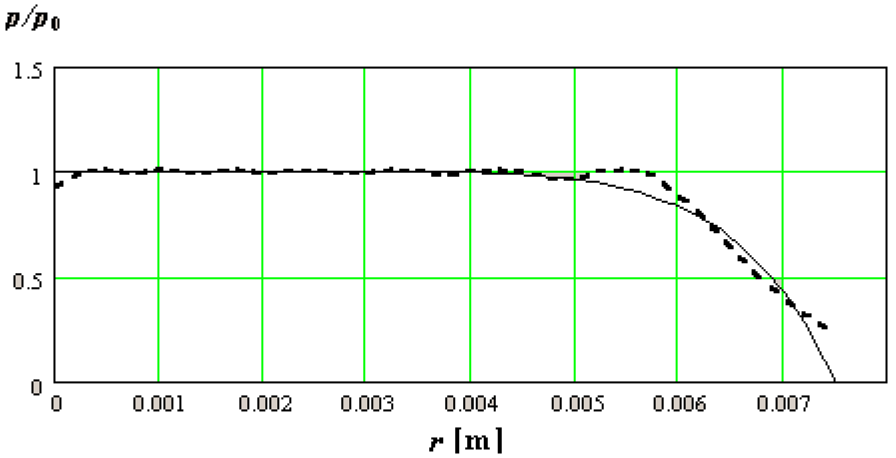

Fig. 2. The analytical apodisation function (normalized in respect to the initial acoustic pressure amplitude) of the plane source of radius 15 mm (solid line) and the computed radial pressure distribution at the distance $z = 5$ mm from the radiating surface (dashed line).

2. NUMERICAL SIMULATION RESULTS

The influence of the radiating source shape and size as well as the propagating pulse frequency, amplitude and waveform on the non-linear acoustic beam forming was investigated. The numerical simulations of the 1-st and the 2-nd harmonic distributions in space and time were carried out for plane and focused (F = 80 mm) sources of radius a = 5, 7.5, 10, 15 mm, radiated long (8-cycle) and short (4-cycle) pulses. The pulse waveform and radial distribution function were described above. The frequencies of f_0 = 1, 2, 3 MHz and the initial acoustic pressure amplitudes of p_0 = 0.1, 0.2, 0.3, 0.4 MPa were considered. The obtained numerical results in the cases of axial distributions are presented in Figs. 3, 4, 5.

For the plane sources, as it can be noticed from Figs. 3, 4, 5 (A), the larger is the source size, the greater will be the distance of the 1-st and 2-nd harmonic maximum from the radiating surface. The same effect causes the driving frequency increase. The 1-st harmonic reaches its maximum value always earlier compared with the other harmonics. The higher harmonics for their growth take a part of the 1-st harmonic energy. When the maximum value of the 1-st harmonic is almost independent of the source size, the maximum value of the 2-nd harmonic grows faster with the source diameter increase. In extreme cases, for high radiating frequencies (see Fig. 4), the 2-nd harmonic amplitude is higher than a half of the 1-st harmonic. The resulting wave distortion can lead to shock-like waveforms.

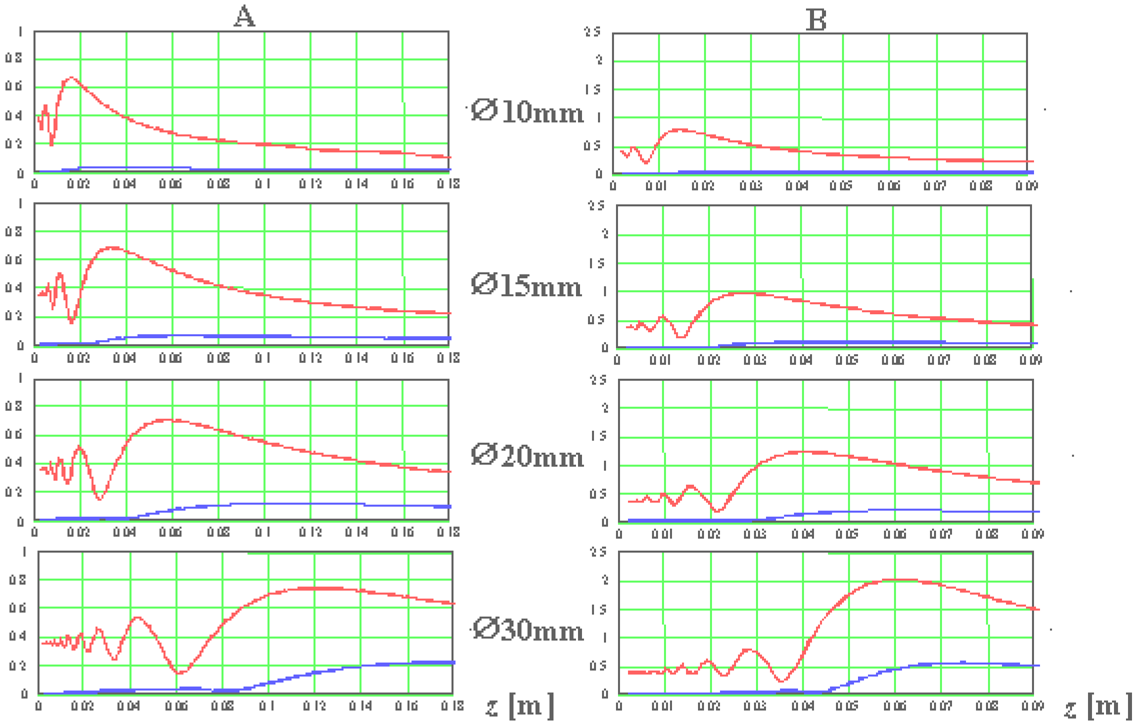

Fig. 3. The simulated 1-st (top lines) and 2-nd (bottom lines) axial harmonic distributions of the acoustic beam radiated in water by circular plane (A) and focused (B) sources of various diameters, driven by the 8-cycle sinusoidal pulse of 1 MHz and initial pressure amplitude p_0 = 0.4 MPa

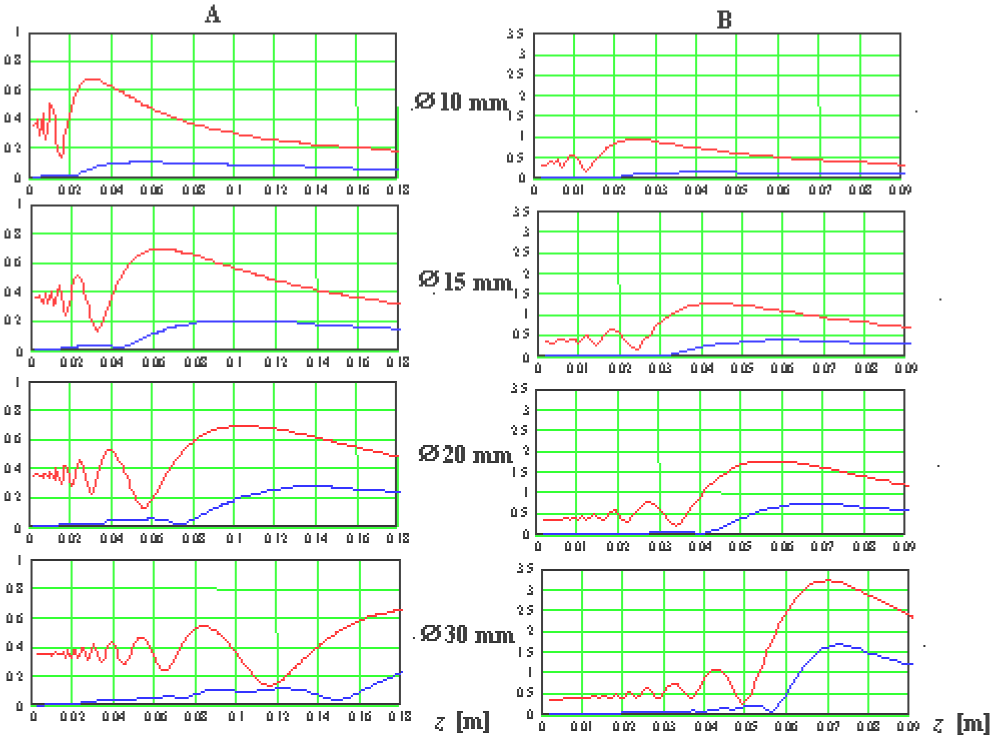

Fig. 4. The simulated 1-st (top lines) and 2-nd (bottom lines) axial harmonic distributions of the acoustic beam radiated in water by circular plane (A) and focused (B) sources of various diameters, driven by the 8-cycle sinusoidal pulse of 2 MHz and initial pressure amplitude $p_0 = 0.4$ MPa.

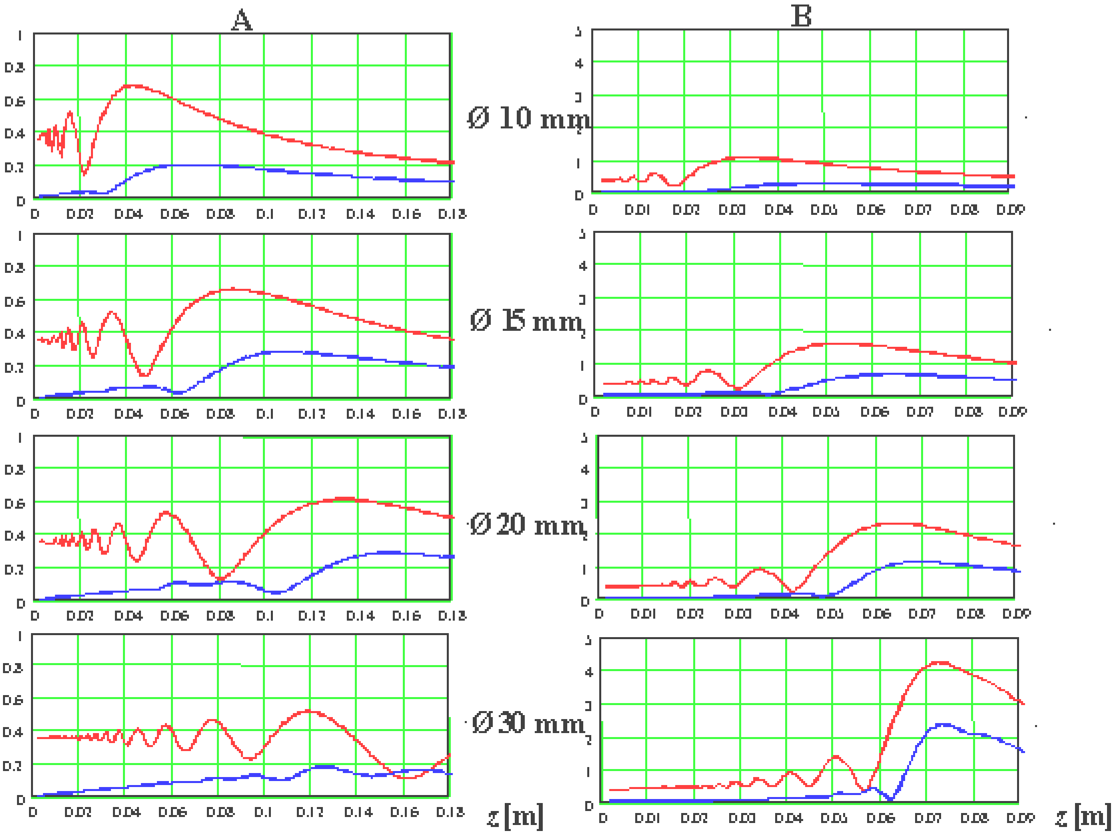

Fig. 5. The simulated 1-st (top lines) and 2-nd (bottom lines) axial harmonic distributions of the acoustic beam radiated in water by circular plane (A) and focused (B) sources of various diameters, driven by the 8-cycle sinusoidal pulse of 3 MHz and initial pressure amplitude $p_0 = 0.4$ MPa.

For the focused sources Figs. 3, 4, 5 (B) mentioned above dependences between the harmonic distributions and the plane radiating source parameters are the same however the non-linear effects are much more significant. Moreover, the harmonics reach their maximum values much closer to the source radiating aperture and their pressure amplitudes are several times higher.

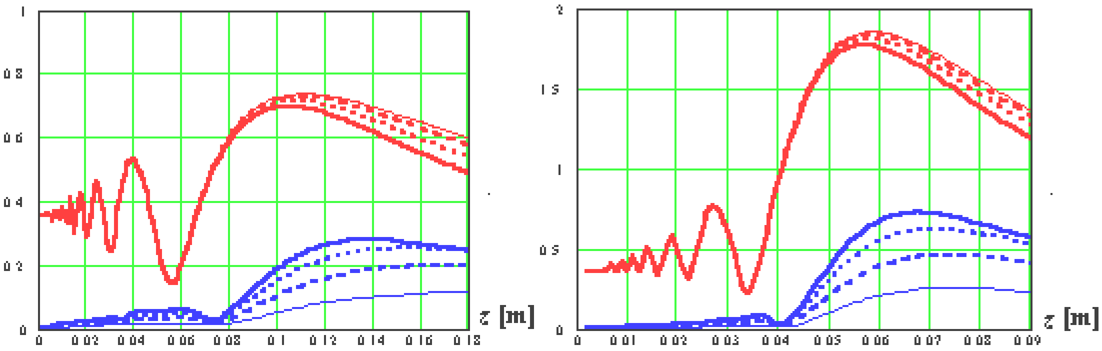

Fig. 6. The 1-st (top lines) and 2-nd (bottom lines) harmonic axial distributions for the case of 8-cycle acoustic pulse with the carrier frequency of 2 MHz, radiated by the plane (left) and focused (right) source with radius of 10 mm, when the initial acoustic pressure amplitude p_0 is equal to 0.1 (thin solid lines); 0.2 (dashed lines); 0.3 (dotted lines); 0.4 (thick solid lines) MPa.

The next stage of the investigations was to analyze the influence of the initial acoustic pressure amplitude p_0 at the source surface on the non-linear beam forming. Figs. 6, 7 demonstrates the influence of the p_0 value as well as of the focusing effect on the 1-st and 2-nd harmonic axial distributions.

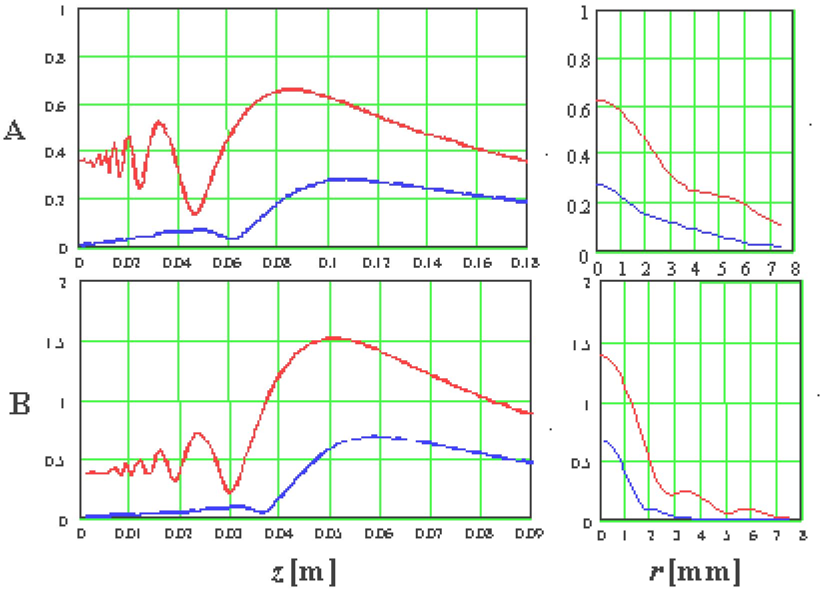

Fig. 7. The normalized 1-st (top lines) and 2-nd (bottom lines) harmonic axial (left) and radial (right) distributions for the case of 8-cycle pulse with the carrier frequency of 3 MHz and the initial amplitude of $p_0 = 0.4$ MPa radiated in water by the plane source of 15 mm in diameter (A) and the focused source with the same diameter and focal distance of $F = 8$ cm (B).

The distortion level of the initial acoustic pressure pulse during the non-linear propagation in water is shown in Fig. 8.

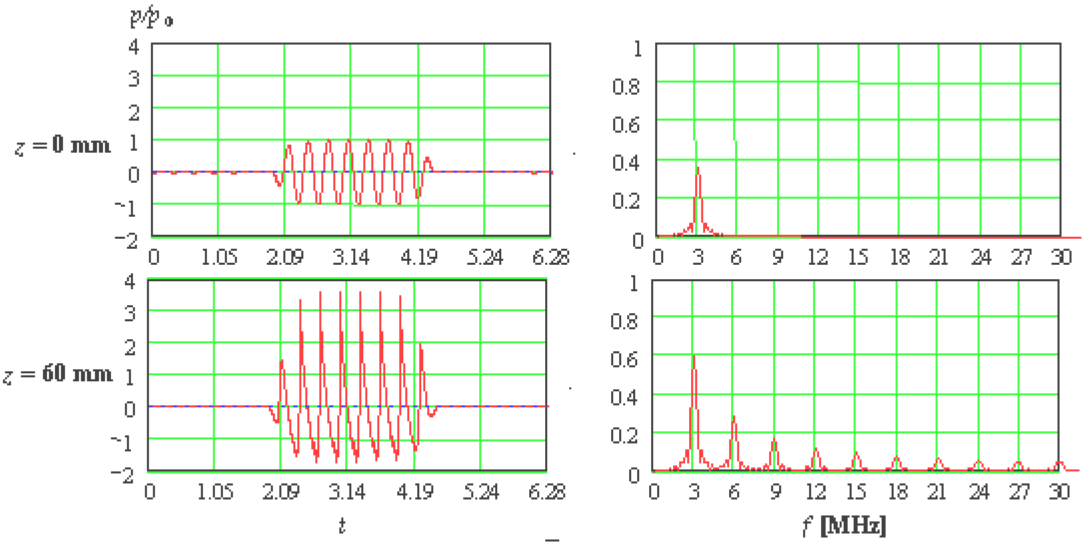

Fig. 8. The normalized (with respect to the initial amplitude) acoustic pressure waveform (left) and its spectrum (right) in water on the beam axis at the maximum pressure distance, when the 15 mm in diameter focused circular source radiates the 8-cycle acoustic pulse with the frequency of 3 MHz.

Fig. 9 presents the peak positive and the peak negative axial pressure distributions in water as well as radial pressure distributions at the distance *z* of the maximum acoustic pressure for the cases shown in Fig. 7.

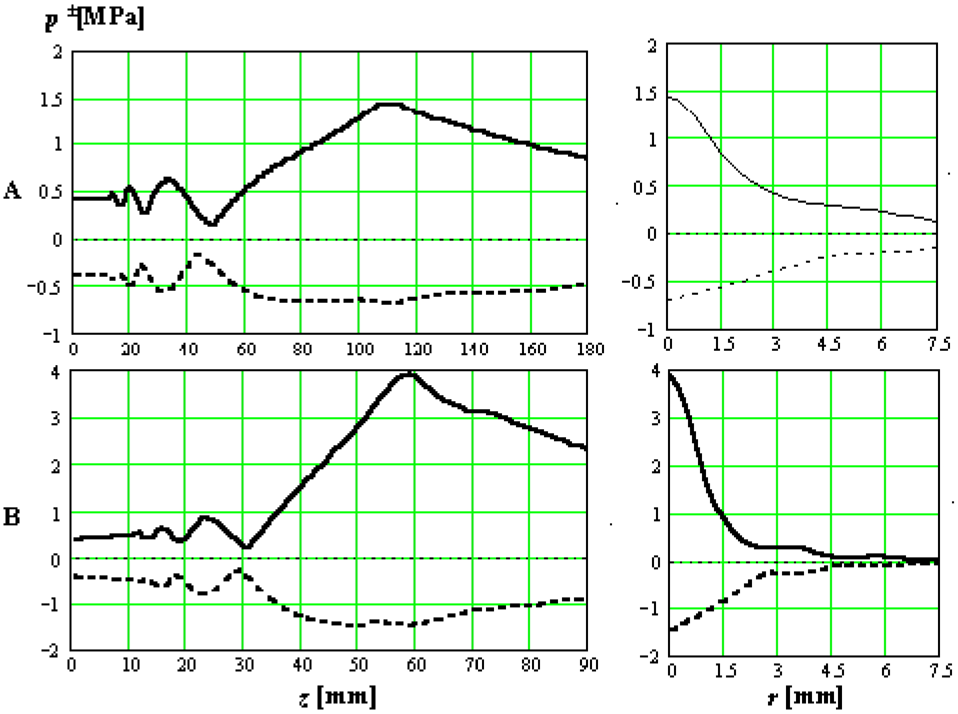

Fig. 9. The axial (left) and radial (right) pressure distributions in water: peak compression (solid lines) and peak rarefaction (dashed lines) for the cases shown in Fig. 7.

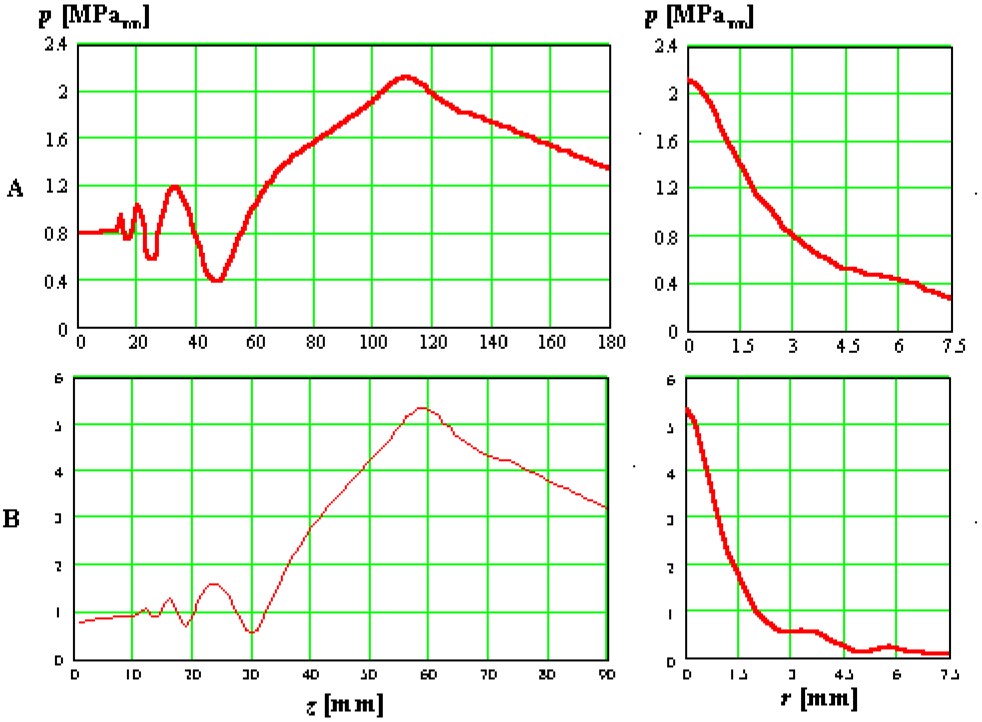

Fig. 10. The axial (left) and radial (right) peak-to-peak pressure distributions in water for the cases shown in Fig. 7.

3. CONCLUSIONS

The analysis of the realized investigations of the simulated harmonic beams, radiated in water by the axially symmetrical acoustic sources of various shape and size, driven by pulses of various amplitudes and carrier frequencies, produced the possibility of predicting the behavior of the harmonic beam, of forming the beam with maximum harmonic pressure at the fixed depth and of optimizing the acoustic source parameters. These investigations were the first step to establish the new method for determination of the acoustic non-linearity parameter in liquids and in biological media [2].

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REFERENCES

[1] L. Filipczyński, T. Kujawska, R. Tymkiewicz, J. Wójcik, Nonlinear and linear propagation of diagnostic ultrasound pulses, Ultrasound in Med. & Biol., 25, 285-299,1999.

[2] T. Kujawska, A new method for determination of the acoustic non-linearity parameter B/A in multi-layer biological media, Proc. of the World Congress on Ultrasound, 81-84, 2003.

[3] J. Wójcik, A new theoretical basis for numerical simulations of nonlinear acoustic fields, Proceedings of the 15th ISNA, Ed. Am. Soc. of Physics, 524, 141-144, 2000.

[4] M.C. Ziskin, P.A. Lewin, Ultrasonic exposimetry, CRC Press Inc., 320-323, 1993.