ISSN 1062-8738, Bulletin of the Russian Academy of Sciences: Physics, 2018, Vol. 82, No. 3, pp. 355–358. © Allerton Press, Inc., 2018.
Original Russian Text © I.A. Shvetsov, S.A. Shcherbinin, P.A. Astafiev, M.O. Moysa, A.N. Rybyanets, 2018, published in Izvestiya Rossiiskoi Akademii Nauk, Seriya Fizicheskaya, 2018, Vol. 82, No. 3, pp. 405–408.

Numerical Modeling and Optimization of Acoustic Fields and Designs for High-Intensity Focused Ultrasound Transducers

I. A. Shvetsov*, S. A. Shcherbinin, P. A. Astafiev, M. O. Moysa, and A. N. Rybyanets

Southern Federal University, Rostov-on-Don, 344090 Russia

**e-mail: wbeg@mail.ru*

Abstract—Recent advances in the fields of physical acoustics, imaging and imaging techniques, piezoelectric materials, and ultrasound transducer designs have led to the emergence of new methods and equipment for ultrasound diagnostics, therapy, and aesthetic medicine, and to the development of traditional and emerging new applications. Ultrasound transducers for medical diagnostic equipment, particularly high-intensity focused ultrasound transducers (HIFU), are one promising use of piezoceramic and composite materials. This work is devoted to the development of mathematical models, numerical modeling, and optimizing acoustic fields and transducers of this type made of porous ferroelectric piezoceramics.

DOI: 10.3103/S1062873818030267

INTRODUCTION

Studies of medical acoustic equipment operating at high powers of ultrasonic emission have been of considerable practical interest for the last several decades [1]. The influence of nonlinear effects has been debated even for diagnostic ultrasound levels [2]. Such effects are decisive in lithotripsy and therapy using high-intensity focused ultrasound (HIFU) systems, since acoustic pressures of 100 MPa or higher can be achieved in them. This is higher by two or even three orders of magnitude than ultrasound diagnostics.

Numerical modeling is often used to predict high-intensity acoustic fields. The possibility of calculating acoustic fields in both water and tissues is one advantage of this method. Numerical algorithms most commonly based on the nonlinear parabolic Khokhlov–Zabolotskaya–Kuznetsov (KhZK) equation have been developed and applied to the nonlinear fields of lithotripters; unfocused ultrasonic piston sources; diatonic ultrasound transducers operating in the mode of harmonizing tissue images [3]; focused ultrasound sources [4]; and HIFU sources [5, 6]. More comprehensive models based on full-wave nonlinear equations have also been developed, but calculating such models requires great computational power.

The KhZK equation and theoretical treatments using the Rayleigh integral are employed in this work to calculate ultrasonic fields of focused transducers.

OBJECT UNDER STUDY

The aim this work was to create a transducer in the form of a spherical segment with an aperture at the center that operates at frequencies of 1.6–2 MHz and is made of PKR-78 porous ferroelectric piezoceramics. The radius of curvature of the transducer is $F = 60$ mm, the outer diameter is 80 mm, and the diameter of the aperture is 40 mm (Fig. 1). Figure 2 shows this element in a frame filled with mineral oil to improve acoustic contact and cooling.

THEORETICAL

In [7], O'Neil obtained an analytical expression for the acoustic field of a focused source in the form of a continuous spherical segment in the linear acoustic approximation using the Rayleigh integral. It was assumed that the focusing angle was small and the radius of curvature of the emitting surface was much larger than the wavelength. Using O'Neil's results for the source with an aperture that is considered in this work, we can derive the following expression for the amplitude of the acoustic pressure:

$$P(z) = \left| \frac{2p_0}{1 - \dfrac{z}{F}} \sin\left(k\, \frac{R_{\min} - R_{\max}}{2} \right) \right|,$$

where p_0 is the amplitude of the acoustic pressure at the surface of the source, z is the axial coordinate, ω is the cyclic frequency of the ultrasonic wave, k is its wavenumber, and $R_{\max}$ and $R_{\min}$ are the distances from the point of observation to the outer and inner edges of the transducer, respectively.

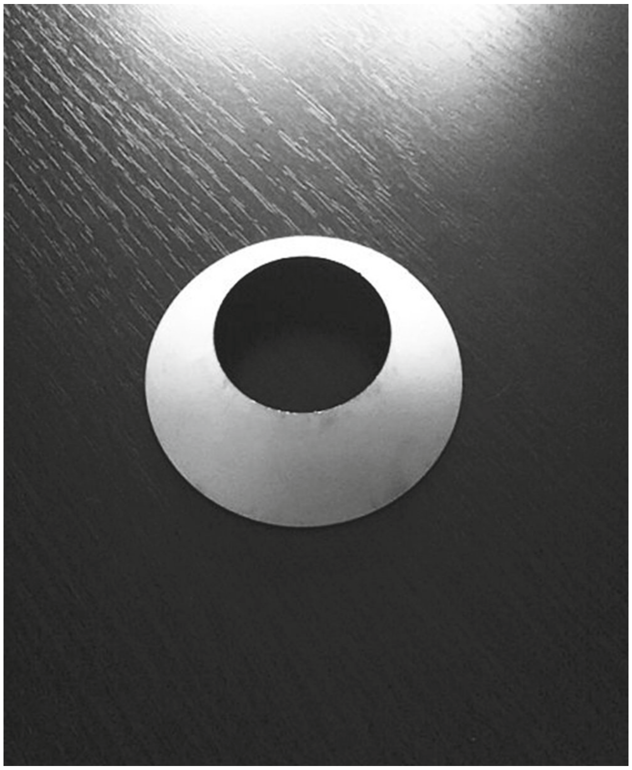

Fig. 1. Focused piezoelement.

Fig. 2. Focused element in a frame.

If the beam us focused in an absorbing medium, the damping of the wave can be described as

$$P(z) = \left| \frac{2p_0}{1 - \frac{z}{F}} \sin\left(k \frac{R_{\min} - R_{\max}}{2} \right) \right| e^{-\alpha z},$$

where α is the coefficient of absorption at the emission frequency. Values of α were given for some media in [8].

NUMERICAL MODELING

Since this transducer would be used to obtain high-intensity acoustic fields, the modes of its operation at high powers where nonlinear effects play a significant role and the linear acoustic approximation is no longer applicable are of great interest.

To consider the nonlinear nature of wave processes, we use the familiar Khokhlov–Zabolotskaya–Kuznetsov equation [5, 6] in this work. It has the form

$$\frac{\partial}{\partial \tau}\left[\frac{\partial p}{\partial z} - \frac{\beta}{\rho_0 c_0^3} p \frac{\partial p}{\partial \tau} - L_{\text{abs}}(p)\right] = \frac{c_0}{2} \Delta_\perp p,$$

where p is acoustic pressure; $\tau = t - z/c_0$ is time in the accompanying coordinate system; c_0 is the speed of sound in the medium; ρ_0 is the density of the medium; $\Delta_\perp$ is the transverse Laplacian; and L_{abs} is a linear operator characterizing the dispersive–dissipative properties of the medium. The classical form of the KhZK equation was derived for thermoviscous fluids, for which we have

$$L_{\text{abs}} = \frac{b}{2\rho_0 c_0^3} \frac{\partial^2 p}{\partial \tau},$$

where b is the dissipative parameter of the medium. The heating of the medium can be calculated as

$$Q = \sum_{n=1}^{\infty} 2\alpha_n I_n,$$

where $\alpha_n = \alpha(n\omega_0)$ is the coefficient of absorption of the n-th harmonic and $I_n = |C_n|^2/(2\rho_0 c_0)$ is the intensity of this harmonic.

RESULTS AND DISCUSSION

We performed theoretical calculations and computer modeling of the acoustic field of the considered transducer by numerically solving the KhZK equation. In both cases, we assumed the acoustic waves propagate in water.

Computer modeling of the acoustic field showed that even at a power level of 5 W cm^{-2}, nonlinear effects result in asymmetry of the pressure profile, which at an initial power of 20 W cm^{-2} is transformed into a shock wave at the focus, thus leading to extreme heating of the medium. The corresponding results are given in Figs. 3 and 4.

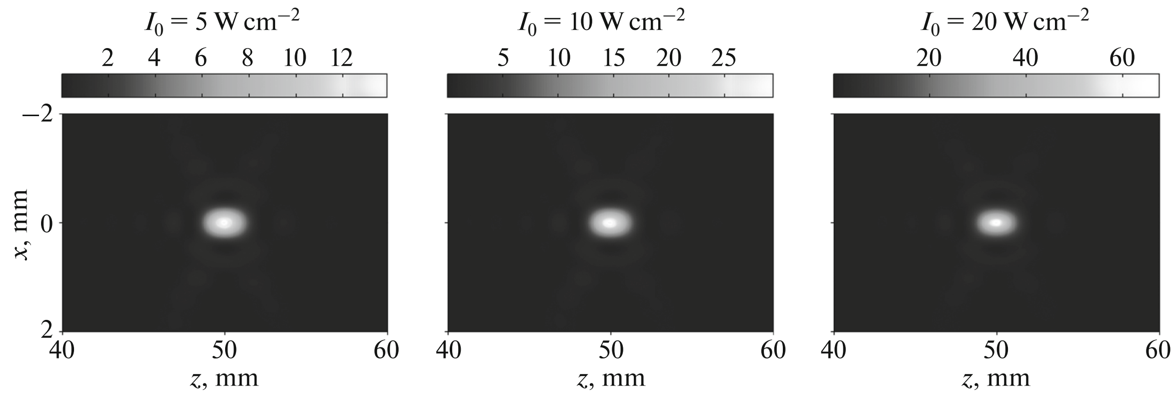

Fig. 3. Two-dimensional distributions of acoustic intensity in the focal plane of the transducer at a frequency of 2 MHz.

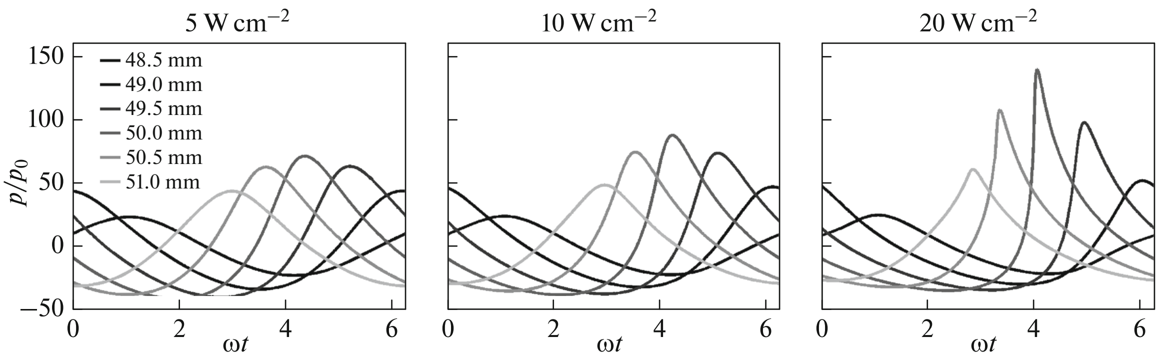

Fig. 4. Shapes of acoustic waves at the focus of the transducer, calculated for different powers at a frequency of 2 MHz.

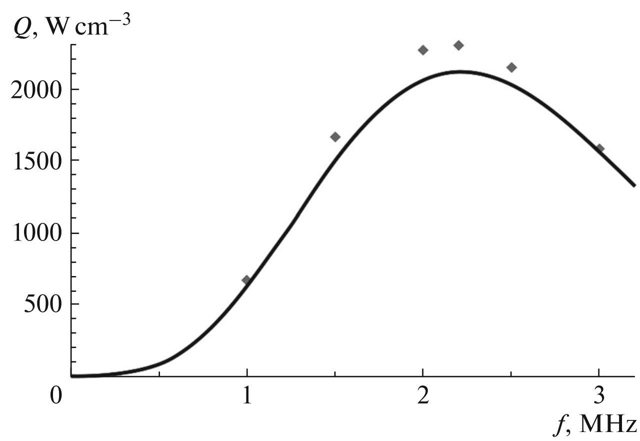

Fig. 5. Dependences of medium heating at the focus of the transducer, calculated using the Rayleigh integral (solid line) and computer modeling based on the KhZK equation (black dots).

For low levels of intensity (5 W cm^{-2}), we compared results on medium heating that were obtained in the linear acoustic approximation, and by numerically solving the KhZK equation (Fig. 5).

CONCLUSIONS

Spherically focused piezoelements were manufactured and studied. The acoustic fields of HIFU transducers were modeled, calculatied, and optimized.

Prototype models of diagnostic and high-power focused ultrasound transducers were developed and manufactured. Measurements were made for piezoceramic materials, piezoelements, and focused ultrasound transducers. It was established that using porous ferroelectric piezoceramics in HIFU transducers has significant advantages when compared to dense piezoceramics and other composite materials. These advantages are due to high processability, better acoustic matching with biological tissues, the absence of parasitic vibration modes, and high electromechanical efficiency.

ACKNOWLEDGMENTS

This work was supported by the Ministry of Education and Science of the Russian Federation: the basic parts of the state task, themes nos. BP0110-11/2017-44 (12.5425.2017/8.9), 3.8863.2017/ITW (3.8863.2017/7.8).

REFERENCES

1. Varslot, T. and Taraldsen, G., *IEEE Trans. Ultrason., Ferroelectr., Freq. Control*, 2005, vol. 52, no. 9, p. 1473
2. Zemp, R.J., Tavakkoli, J., and Cobbold, R.S., *J. Acoust. Soc. Am.*, 2003, vol. 113, no. 1, p. 139.
3. Hallaj, I.M. and Cleveland, R.O., *J. Acoust. Soc. Am.*, 1999, vol. 105, p. L7.
4. Ginter, S., Liebler, M., Steiger, E., et al., *J. Acoust. Soc. Am.*, 2002, vol. 111, p. 2049.
5. Zabolotskaya, E.A. and Khokhlov, R.V., *Sov. Phys. Acoust.*, 1969, vol. 15, p. 35.
6. Kuznetsov, V.P., *Sov. Phys. Acoust.*, 1971, vol. 16, p. 467.
7. O'Neil, H.T., *J. Acoust. Soc. Am.*, 1949, vol. 21, no. 5, p. 516.
8. Strohm, E.M. and Kolios, M.C., in *Proc. IEEE Int. Ultrasonics Symp.*, Orlando, 2011, p. 2368.

Translated by N. A. Berestova