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ACOUSTICS OF LIVING SYSTEMS. BIOACOUSTICS

The Possibility of Generating Focal Regions of Complex Configurations in Application to the Problems of Stimulation of Human Receptor Structures by Focused Ultrasound

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Abstract—Studies of the stimulating effect of ultrasound on human receptor structures have recently become more intensive in connection with the development of promising robotic techniques and systems, sensors, and automated control systems, as well as with the use of taction in the design of a human–machine interface. One of the promising fields of research is the development of tactile displays for transmission of sensory data to a human by an acoustic method based on the effect of radiation pressure. In this case, it is necessary to generate rapidly changing patterns on a display (symbols, letters, digits, etc.), which may often have a complex shape. It is demonstrated that such patterns can be created by the generation of multiple-focus ultrasonic fields with the help of two-dimensional phased arrays whose elements are randomly positioned on the surface. The parameters for such an array are presented. It is shown that the arrays make it possible to form the regions of action by focused ultrasound with various necessary shapes and the sidelobe (or other secondary peak) intensity level acceptable for practical purposes. Using these arrays, it is possible to move the set of foci off the array axis to a distance of at least ±5 mm, which corresponds to the display dimensions. It is possible, on the screen of a tactile display, to generate the regions of action with a very complex shape, for example, Latin letters. This opportunity may be of interest, for example, for the development of systems that enable a blind person to perceive the displayed text information by using the sense of touch.

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This paper proposes a way to develop a new acoustic device implementing the effect of stimulation of human receptor structures with the help of the stimulating action of focused ultrasound. The paper consists of two parts. The first of them briefly considers the basic results obtained from the studies of the stimulation by focused ultrasound and, first of all, the available information on the mechanisms of this effect. The second part gives the necessary parameters for a device intended for the transmission of sensory information to a human with the help of focused ultrasound and presents the results of calculations for the spatial distribution of acoustic fields generated by this device.

Approximately 30 years ago, in the studies carried out by us together with experts in the field of reception physiology, it was demonstrated for the first time that it is possible to produce local stimulation of human receptor structures with the help of short (up to units or fractions of a millisecond) pulses of focused ultrasound [1–3]. It turned out that it is possible to reproduce on the skin surface all the sensations experienced by a human in everyday life while interacting with the surrounding world: tactile, temperature (warmth and cold), tickling, itching, and also various kinds of pain, including in-depth ones [1–7]. Since, in various diseases (for example, skin and neurological diseases, etc.), the thresholds for different sensations (for example, tactile or pain) differ essentially from the thresholds for persons with normal sensitivity, the indicated method was used to diagnose a series of diseases accompanied by a change in skin and tissue sensitivity [6].

To efficiently use the stimulating effect of ultrasound in practice, it is important to understand its mechanism. In the course of previous studies, attempts were made to reveal the factor responsible for the stimulation of neural structures [2–5, 7]. The purpose of these studies was to determine which of the ultrasonic parameters varies to the minimal extent under variation of ultrasonic frequency, which was varied within the range from 0.5 to 2.7 MHz. The parameter formally most independent of frequency was the amplitude of displacement (i.e., an alternating-sign factor), although it seemed logical that such a parameter should be not an alternating-sign but unidirectional mechanical effect of ultrasound that would be related to demodulation of high-frequency ultrasonic oscillations [3–5, 7]. It is evident that such a parameter could be the radiation force, which, as it is known, is proportional to the acoustic power. However, the values of the threshold acoustic power depended on frequency to a somewhat greater

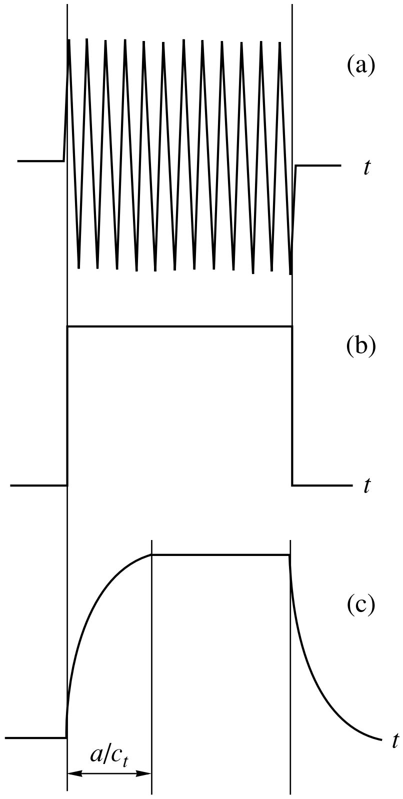

Fig. 1. Diagram illustrating the shape of (a) an acoustic signal, (b) acoustic power, and (c) shear displacement of the medium.

extent than the displacement amplitude, and, therefore, at the initial stage of investigation, the radiation force was not treated as the major factor of action. The doubts concerning the determining role of the radiation force were also increased by the fact that the area of the focal region (or, in other words, the area of application of the radiation force) changed at the frequencies indicated above by a factor of more than 30, which, nevertheless, affected in no way the values of the threshold radiation force.

Later, in [8], tactile sensations were produced in a human with the help of a nonfocusing ultrasonic source. In this case, a plastic disc was placed on the skin of a person, which cut off ultrasonic transmission through the tissue. Both ultrasonic stimuli with a length of 5–100 ms and series of pulses with a repetition frequency from 50 to 1000 Hz were used. The radiation force was recognized to be the main acting factor responsible for the rise of tactile sensations. In the case of single pulses, the threshold radiation force necessary to generate tactile sensations for probationers with normal skin sensitivity varied within the interval 1–2 gf [8]. It was one order of magnitude smaller in the case of a series of pulses. The threshold values in the presence of a reflector or in its absence, i.e., under the direct ultrasonic effect on the skin, almost did not change. The essential difference of this approach from the one described above consisted in the fact that, in our studies, focused ultrasound was used for a direct stimulating action on tissues, including the in-depth ones, while, in the method by Dalecki et al. [8], the direct ultrasonic effect on tissues was excluded.

The next step in the investigation of the mechanism of the stimulating effect of ultrasound was described in [9]. One of its purposes was to clear out why the threshold value of the radiation force that is necessary to generate tactile sensations does not depend on the area of its application. The mechanism of the generation of shear waves with considerably large values of displacement amplitude under the effect of the radiation force was investigated. In the preceding paper [10], it was demonstrated that amplitude-modulated ultrasound with a carrier frequency of 3 MHz, a modulation frequency of 1 kHz, a velocity of shear waves in tissues equal to 3 m/s, and an intensity of 10 W/cm^2 at the axis of the ultrasonic beam generates the displacements in a tissue that are equal approximately to 30–40 μm. In [11], an expression was obtained for the maximum value of the displacement amplitude $u_{\max}$ in a medium in the case of the use of focused ultrasonic pulses with a length not exceeding the propagation time through the focal region:

$$u_{\max} = \frac{\alpha_0 a}{\rho c_l c_t} t_0 I \tag{1}$$

for short pulses ($t_0 \ll a/c_t$),

where a is the radius of the ultrasonic beam (i.e., of the focal region), α_0 is the ultrasonic absorption coefficient in the medium, t_0 is the length of action of the radiation pulse (i.e., the pulse length), ρ is the density of the medium, c_t is the propagation velocity of shear waves, c_l is the velocity of longitudinal waves, and I and W are the intensity and acoustic power averaged over the pulse length. One can see from Eq. (1) that the displacement under the effect of the radiation force is proportional to $t_0 I$; i.e., it depends not exactly on the ultrasonic intensity itself but on the pulse energy.

In our paper [9] this expression was modified for long pulses, when the pulse length is greater than its propagation time through the focal region, which corresponds to the case under consideration. In this case, the maximum value of the displacement amplitude is

$$u_{\max} = \frac{\alpha_0}{\rho c_l c_t^2} a^2 I = \frac{\alpha_0}{c_t \mu} a^2 I = \text{const}\, W \tag{2}$$

for long pulses ($t_0 \gg a/c_t$).

In Eq. (2), μ is the shear modulus of the medium and $c_t = \sqrt{\mu/\rho}$. Thus, the maximum value of the displacement amplitude is proportional to the acoustic power and, therefore, to the radiation force. Figure 1 shows a diagram illustrating the shape of an acoustic signal, the acoustic power, and the shear displacement of the medium under the action of ultrasound on it. One can see that the displacement of the medium (Fig. 1c) does not reproduce the shape of the acoustic signal (Fig. 1a) or the acoustic power (Fig. 1b). The displacement reaches its maximum value u_{max} after the time interval equal to the propagation time of a shear wave through the focal region ($t_0 = a/c_t$). This time is relatively small; for example, for $a = 1$ mm and $c_t = 3$ m/s, it is $t_0 = 0.3$ ms, which is much shorter than the length of an ultrasonic stimulus (commonly, from 1 to 100 ms). After this time, the value of the shear displacement remains constant up to the pulse end. This agrees well with our observations that pulses with the length from 5–10 ms to 500 ms cause tactile sensations as a response to the start and end of a stimulus, or that a person cannot distinguish a long pulse with a length, for example, of 400 ms from two short pulses separated by the same time interval [3, 4]. These data are the evidence in favor of the fact that stimulation of a neural structure is connected precisely with the gradient of the stimulating factor (the unidirectional displacement of the medium in this case).

Recently, the studies of the stimulating effect of ultrasound became more active (especially in Japan) in connection with the development of promising robotic techniques and systems, sensors, automated control systems, and also "human–machine" interfaces based on the use of taction. In this area of research, one of the most promising lines of work is the development of tactile displays for transmission of information to an operator by the acoustic technique based on the effect of radiation pressure [12–14]. In these studies, a human finger was affected by focused ultrasound and, methodically, the approach described by Dalecki et al. [8] was reproduced. A cap made of foamy silicon rubber was put on a probationer's finger. According to the data available to the authors, this rubber almost totally reflected ultrasound [13]. At first, the authors used focusing sources with a fixed focal distance as the radiator of focused ultrasound [12], and then, linear phased arrays, which allowed them to move electronically the focal region within a display [13]. The greatest technological achievement by this team up to now is the development of a two-dimensional tactile display, where the variation of the time–space structure on the surface was performed by a single focus moved in two orthogonal directions [14]. To generate a focus and move it along the display plane, a focusing system was used, which was a combination of eight linear phased arrays. The inclination angle of all arrays with respect to the system axis was 70 degrees, which provided an opportunity to combine electronic focusing with geometrical one. The transmission of ultrasonic energy was performed through water. The maximum dimension of the housing, in which all arrays were located, was 8 cm, and the focal distance was 3 cm. Each array was shaped as a trapezium and consisted of 40 piezoceramic elements with different lengths (from 3.3 to 20 mm). Thus, the total number of individually controlled electronic channels was 320 (a frequency of 3 MHz). The distance between the element centers was fixed (i.e., the arrays were regular) and equal to 0.5 mm. The required size of the tactile display was 1×1 cm [14]. The acoustic field measurements performed with a hydrophone demonstrated [14] that the focus diameter at the intensity level of 25% of the maximum value at the focus was 9 λ, where λ is the wavelength, and, at the level of 50%, it was about 5 λ, which is evidence of a very low spatial resolution of the system. The results of computer simulation for the acoustic field generated by this system demonstrated that the intensity in the secondary peaks was 13%, even for the case where the focus was located at the acoustic axis of the system. For the case of focus displacement off the system axis, the intensity in the secondary peaks unavoidably will be much greater than the indicated value (the authors do not give any quantitative data). Thus, the quality of the acoustic field generated by the system, at least at this stage of its development, needs considerable improvement. One more essential disadvantage of the system is the fact that it is intended for moving just one focus along the display area at a single time moment.

The major purpose of this work is to propose and study in model numerical experiments an alternative way for the development of such tactile displays on the basis of application of a two-dimensional array with elements randomly positioned on its surface (a so-called randomized array). Similar arrays were studied in detail in a series of previous papers [15–20], and, as was demonstrated, they have significant advantages over common and most popular regular arrays with equidistant positioning of elements [21–24]. We demonstrated in our previous papers [16–20] that irregularity in the element positioning at the array surface makes it possible to improve the quality of the acoustic and thermal fields generated by them, to reduce the level of secondary intensity peaks, and to increase the array capability to move the aggregate of a large number of foci off the array axis. The capability of the arrays to generate simultaneously and move in space a large number of foci is, perhaps, the major advantage of two-dimensional phased arrays [21, 23, 24], which, as it turned out, is implemented most effectively with the help of randomized arrays [16, 18–20]. As is demonstrated below, this property will be used also for the formation of focal regions with complex shapes corresponding to images of different symbols on the screen of a tactile display.

The calculation of the spatial distributions of acoustic fields was performed for the arrays with the surfaces shaped as a part of a spherical shell with a curvature radius of 60 mm. The array diameter was 65 mm. The ultrasonic frequency was 3.0 MHz in all cases. The arrays consisted of flat elements shaped as discs with a diameter of 2.5 mm (i.e., 5 λ at this ultrasonic frequency). Since the medium of ultrasonic propagation to the focal plane was water, the attenuation in the medium was ignored.

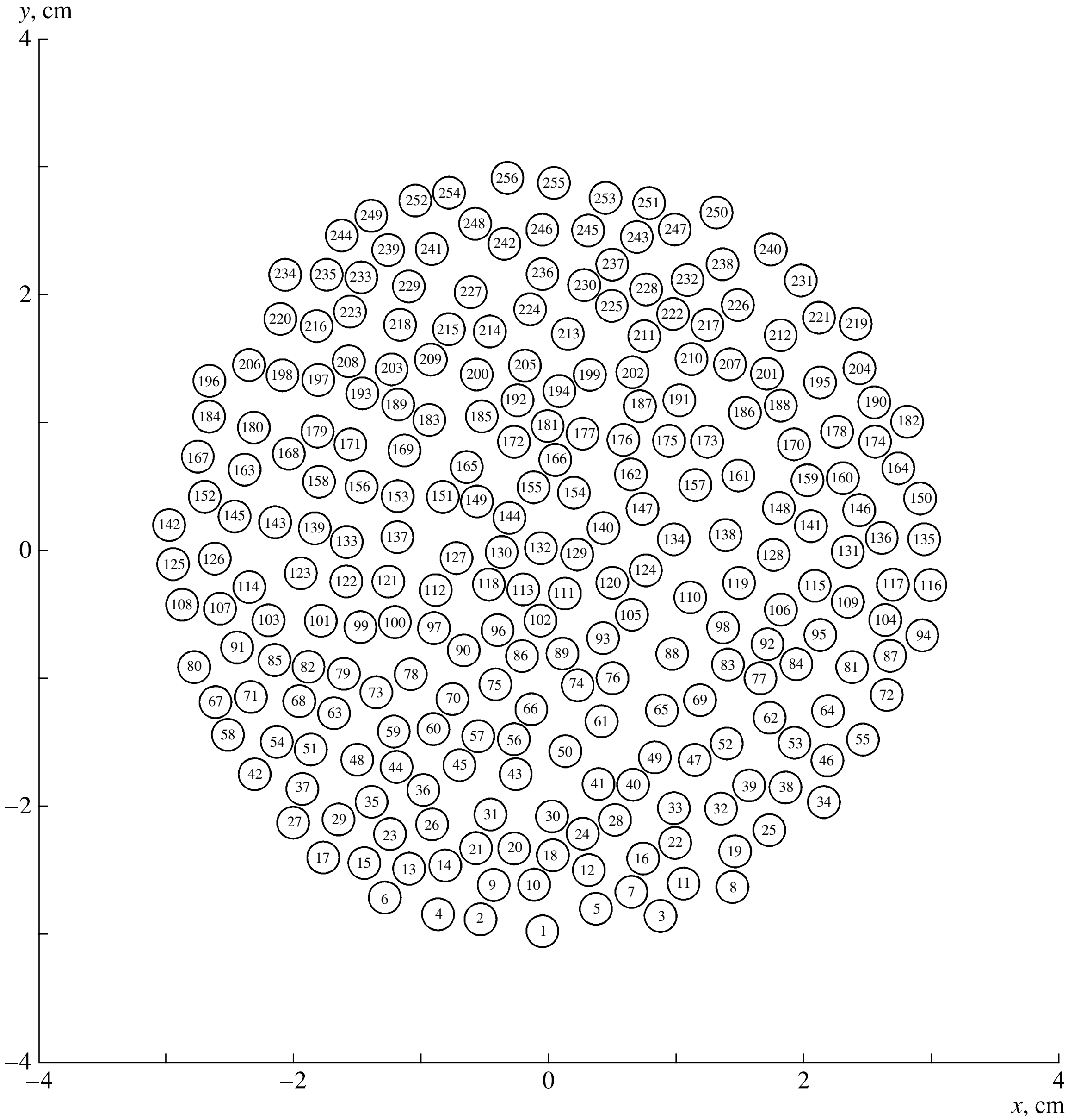

Fig. 2. Element positioning at the surface of a randomized array used for simulation.

The object of investigation was the arrays of two types: (i) an array of 256 elements positioned regularly on the surface in squares (a typical element positioning for the majority of existing two-dimensional arrays); the minimal distance between the element centers was 3 mm; (ii) an array of 256 elements randomly positioned on the surface; in this case, the distance between the element centers varied and was ≥3.0 mm. The total active area of the array elements was 12.5 cm^2, which provides an opportunity to reach the required values of acoustic power (up to 20–30 W) at modest values of intensity at the element surfaces. Figure 2 shows the element positioning for a randomized array. The selection of element coordinates was performed as follows. A large (tens of thousands) two-dimensional aggregate of independent random coordinates (x, y) within the interval from –3 to 3 cm was created using a random-number generator (a uniform distribution). The coordinates within a circle with a radius of 3 cm were selected from this aggregate. The first point was selected arbitrarily, and then all other 255 points (element coordinates) were sequentially selected so that they were located no closer than 3 mm to all preceding ones. The coordinates inconsistent with this condition were rejected. It is necessary to note that the use of different sets of random coordinates for 256 elements could affect only the fine structure of the field generated by the array but in no way influenced the main result. The use of randomized arrays in all cases led to a considerable decrease in secondary intensity peaks caused by the regular discrete structure of an array.

Let us describe briefly the technique used for the calculation of the sound fields generated by an array. A more detailed description of the calculation technique for the acoustic fields and also the phases at the array elements, including the case of multifocus generation, is given in [20, 21]. The calculation technique includes three basic stages: the calculation of the field for a single array element, the determination of the optimal set of phases with further equalization of the absolute values of amplitudes at the elements, and the determination of the array field by summation of the fields of all elements with the determined amplitude-phase distribution. At the first stage, the distribution of the complex sound pressure of a flat element shaped as a disc was determined using the Rayleigh–Sommerfeld integral:

$$p(\mathbf{r}_i) = \frac{j\rho c k u_0}{2\pi}\int_S \frac{\exp((jk-\alpha_0)|\mathbf{r}-\mathbf{r}_i|)}{|\mathbf{r}-\mathbf{r}_i|}dS, \qquad (3)$$

where p is the complex pressure amplitude, $k = 2\pi f_0/c$ is the wave number, α_0 is the attenuation coefficient at the operational frequency of the array f_0, u_0 is the amplitude of particle velocity at the element surface, $|\mathbf{r} - \mathbf{r}_i|$ is the distance from the points $\mathbf{r}$ of the radiating surface S of a circular piston element to the ith point in space $\mathbf{r}_i$, ρ is the density of the medium (for example, tissue), and c is the sound velocity in the medium. Equation (3) was calculated numerically at the nodes of a sufficiently dense spatial grid. The size of the calculation region was $2 < z < 10$ cm in the longitudinal coordinate and $0 < r < 6$ cm in the transverse coordinate. The grid step in both directions was equal to 0.2 mm.

At the second stage, the values of complex amplitudes of particle velocity at each array element were determined, which should make it possible to form in space a set of a given number of foci (control points) with preset coordinates. This calculation can be performed using the so-called "pseudoinverse" method described in [21, 22]. According to this method, the values of the particle velocity u_n at the nth of N elements, which can be used to calculate the amplitude and phase of the signal at an element, are related to the complex sound pressure p_m at each of the M control points by the equation in the matrix form:

$$u = H^{*t}(HH^{*t})^{-1}p, \qquad (4)$$

where $u = [u_1, u_2, \ldots, u_n, \ldots, u_N]^t$, $p = [p_1, p_2, \ldots, p_m, \ldots, p_M]^t$, and H is an $M \times N$ matrix.

We used the matrix elements

$$h_{mn} = \frac{j\rho c k}{2\pi}\int_S \frac{e^{-ikr_{mn}}}{r_{mn}}dS, \qquad (5)$$

where r_{mn} is the distance from the mth control point to the center of the nth array element and S is the area of an array element; H^{*t} is the matrix conjugate to H, symbol t meaning the matrix transposition. In practice, the number M of selected control points (corresponding to localization of foci) is much smaller than the number of elements. To determine u_n ($n = 1, 2, \ldots, N$), it is necessary to select the phases and amplitudes of sound pressure at the control points p_m ($m = 1, 2, \ldots, M$). The amplitudes at the control points can be selected to be both equal and different. The method of choosing the phases at the control points depends on a specific problem. Here, we used optimization methods that provide an opportunity to obtain a preset number of foci at equal amplitudes at all elements, and, in this way, it was possible to achieve the maximum acoustic power of the array [21, 22].

The last calculation procedure is the determination of the array field by summation of the fields from all the elements with the amplitude–phase distribution determined earlier. The data given below correspond to the calculation performed in the focal plane of the array, i.e., at the distance $z = 60$ mm from it, in two orthogonal directions from 0 to ±20 mm. When it was necessary to investigate the field structure in more detail within the area of the tactile display, which was selected to be equal to 10×10 mm, as in [14], the dimensions of the field under investigation were limited by the indicated values.

At the beginning, it was of interest to determine the resolution of a randomized array with the described parameters in the mode of multifocus generation; i.e., to evaluate the possibility of producing with its help the foci distinguishable from each other and controlled individually. It is known that the transverse spatial resolution of focused probe beams is determined by the wavelength and by the relationship between the depth of the received signal and the transducer aperture. The spatial resolution of a focusing transducer in the transverse direction at the focus is $1.02\,\lambda F$ at a level of –3 dB (here, F is the ratio of the aforementioned quantities) [25]. However, it is not evident that this relation automatically holds for a relatively high-power array with relatively large-size elements (~5 λ) used for the generation of multifocus ultrasonic fields. In this case, each of the array elements takes part in the synthesis of not a single focus, but a large number of foci simultaneously. The calculations performed for different configurations of foci, for example, positioned along a single line (a certain analog of wires in a tissue-like phantom, which is used for metrology of diagnostic devices) or in the form of an aggregate of compactly "packed" foci, demonstrated that an acceptable focus discrimination in space and an individual control of their amplitudes can be attained when the distance between the foci is no smaller than 1.3 λ, which is not much greater than the above value. If this distance is decreased, the foci merge, and if it is increased, the quality of their resolution improves (the results of this calculation are not given here for economy of space).

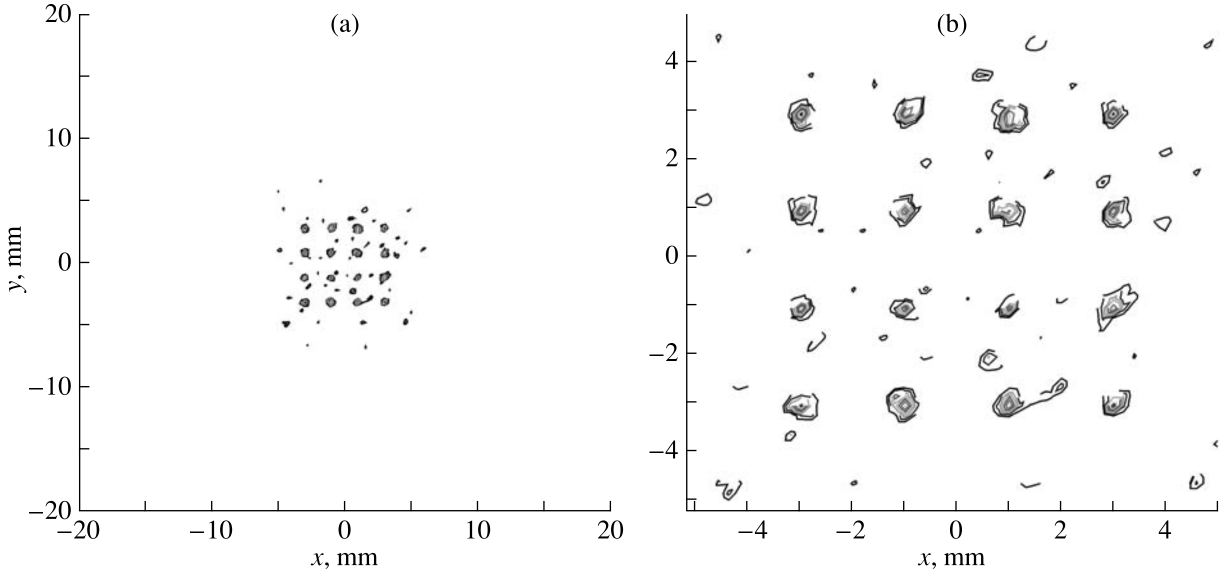

Fig. 3. Ultrasonic intensity distributions in the focal plane (the xy plane, $z = 60$ mm) for a randomized array in the case of 16 foci produced simultaneously. The dimensions of the calculation field: (a) from –20 to +20 mm and (b) from –5 to +5 mm. The distances between foci are 2 mm.

In the next numerical experiment, we examined the possibility to synthesize a certain symbol (for example, a square) with the help of a large number of foci produced simultaneously. Figure 3 demonstrates the contour distributions of ultrasonic intensity in the focal plane (the xy plane, $z = 60$ mm) for a randomized array in the case of 16 foci produced simultaneously. The figures differ in the dimensions of the field within which the computational results are presented: x and y vary from –20 to +20 for Fig. 3a and from –5 to +5 mm for Fig. 3b. The distances between the foci are 2 mm (4 λ for the selected ultrasonic frequency). In this and all subsequent figures, the contour distributions of intensity are given in the form of eight contours with the values from $0.2I_{max}$, where I_{max} is the peak value of intensity in the field under investigation, to $0.9I_{max}$ at a step of $0.1I_{max}$. The contour corresponding to the value of $0.1I_{max}$ is not given in the figures not to shade the field pattern and also in view of the fact that transmission of sensory information to a human is usually performed at the intensity values just slightly exceeding the threshold values. In this case, it is possible to assume that the intensity values slightly greater than $0.1I_{max}$ would unlikely distort considerably the perception of a symbol. From Fig. 3 it follows that the quality of symbol reproduction with the simultaneous use of a large number of foci (in this case, 16 foci) can hardly be considered acceptable.

However, similar (and even more complex) symbols can be synthesized at a small distance between foci even with much better quality by using the approach described in a series of papers [23, 24, 19]. Its essence consists in the use of the fields of several configurations, which consist of a smaller number of foci and are switched electronically at a frequency of, e.g., 10–20 Hz instead of a static field with a rigidly fixed set of secondary intensity peaks, which is produced in the case of the generation of a large number of foci simultaneously. In this case, the secondary peaks are distributed more uniformly over the whole field under investigation, and the so-called "hot spots" vanish. We demonstrated in [19] that it is expedient to select the configurations consisting of an approximately equal number of foci. Figure 4 presents the intensity distributions obtained by using randomized arrays with the parameters described above in the xy plane, which correspond to the images of certain three conditional symbols demonstrated on the left-hand side of Fig. 4. The symbols in Figs. 4a and 4b are obtained with the help of four configurations of foci with four foci in each of them (16 foci totally, which are positioned at a distance of 1 mm from each other). The symbol in Fig. 4c is obtained using three configurations with eight foci in each of them (24 foci totally, which are positioned on a circle at a distance of 0.52 mm from each other; this value just slightly exceeds the wavelength). In the left- and right-hand columns, the intensity distributions in a relatively wide acoustic field (4 × 4 cm) are given. These distributions allow one to monitor the presence or absence of the secondary intensity peaks within the whole field under investigation (an important criterion for evaluating the quality of the acoustic fields generated by an array).The distributions in the left-hand and central columns are obtained for the case where multiple foci are not shifted off the array axis and, the distributions in the right-hand column for the case where the set of foci is shifted to a distance of 5 mm off the axis, which corresponds to the selected dimensions of the tactile display. The central

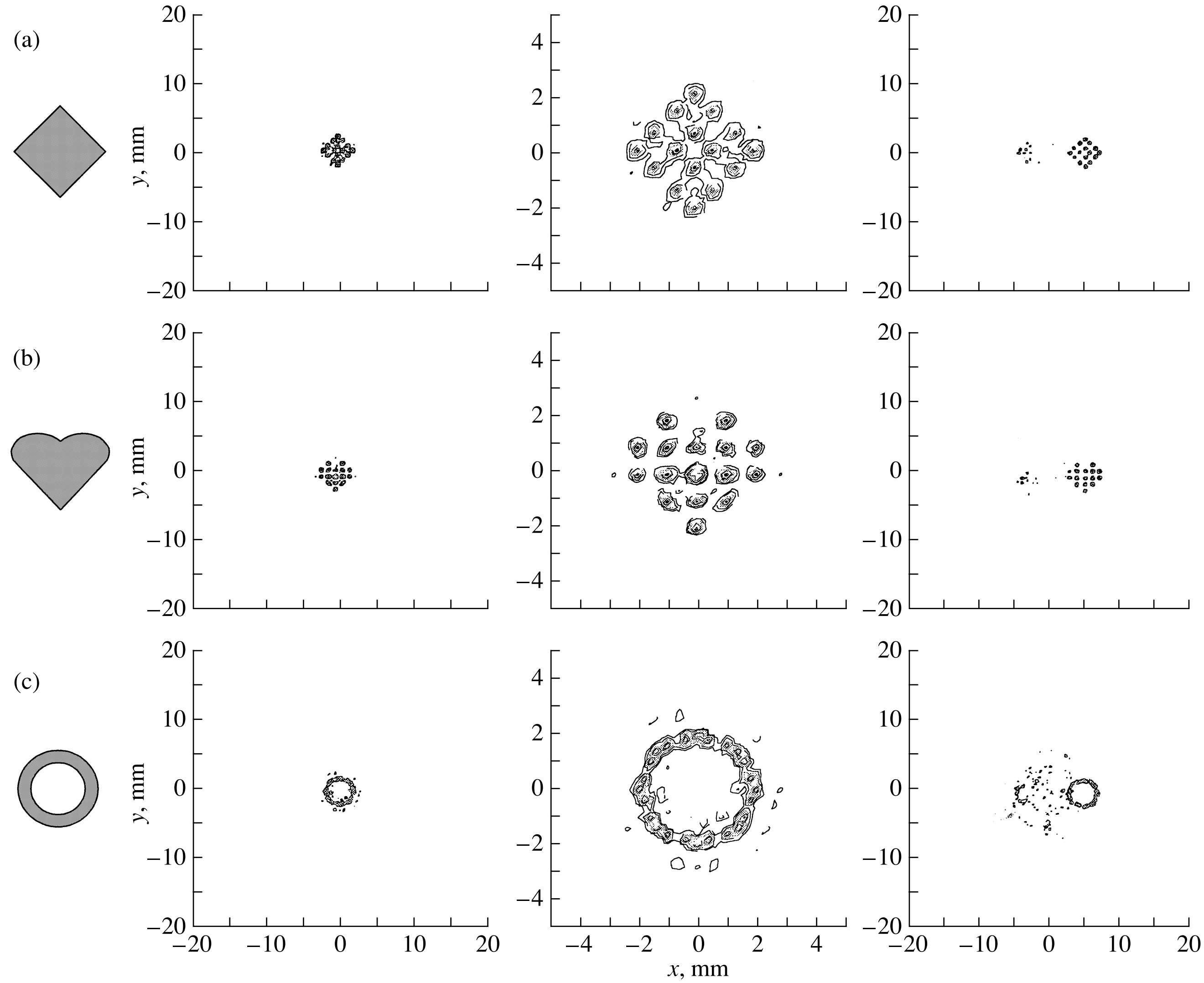

Fig. 4. Generation of regions of action by focused ultrasound in the form of different symbols (see at the left) with the help of a randomized array. Foci used: (a, b) 16 foci (four configurations with four foci in each) and (c) 24 foci (three configurations with eight foci in each). The dimensions of the field under investigation are 4 × 4 cm (the left- and right-hand columns) and 1 × 1 cm (the central column). At the left: the absence of the shift of the set of foci off the array axis. In the middle: the same but on an increased scale. At the right: the shift of the set of foci by 5 mm.

column gives the same distributions as those in the left-hand column, but in a much narrower field with the dimensions corresponding to the display dimensions. These distributions provide an opportunity to examine the field structure in more detail within the display area. From the distributions given in Fig. 4, it follows that, using randomized arrays, it is possible to generate complex-shaped regions of action by focused ultrasound. In this case, the symbols selected for imaging are reproduced with an acceptable quality (according to the criteria of the intensity level in the array sidelobes and in the secondary intensity peaks). One can also see that the displacement of the set of foci to a distance of 5 mm off the array axis does not noticeably deteriorate the distribution quality (especially in the cases of the symbols in Figs. 4a and 4b).

Figure 5 shows for comparison the intensity distributions similar to those given in the right-hand column of Fig. 4 but obtained using a regular array with the parameters almost the same as in the case of the randomized array. The only difference is the positioning of elements on the array surface. The shift of the set of foci is 5 mm relative to the array axis in all cases. One can see that, in the case of the regular array, a side set of foci with almost the same values of peak intensity (up to $0.6–0.7I_{max}$) as in the main aggregate arises together with the main aggregate. This may lead to erroneous perception of one or another symbol. If the shift of foci increases, the peak intensity in the side set of foci may exceed the corresponding value in the main aggregate. As one can see from Fig. 4 (the right-hand column), this effect is absent in the case of the randomized arrays.

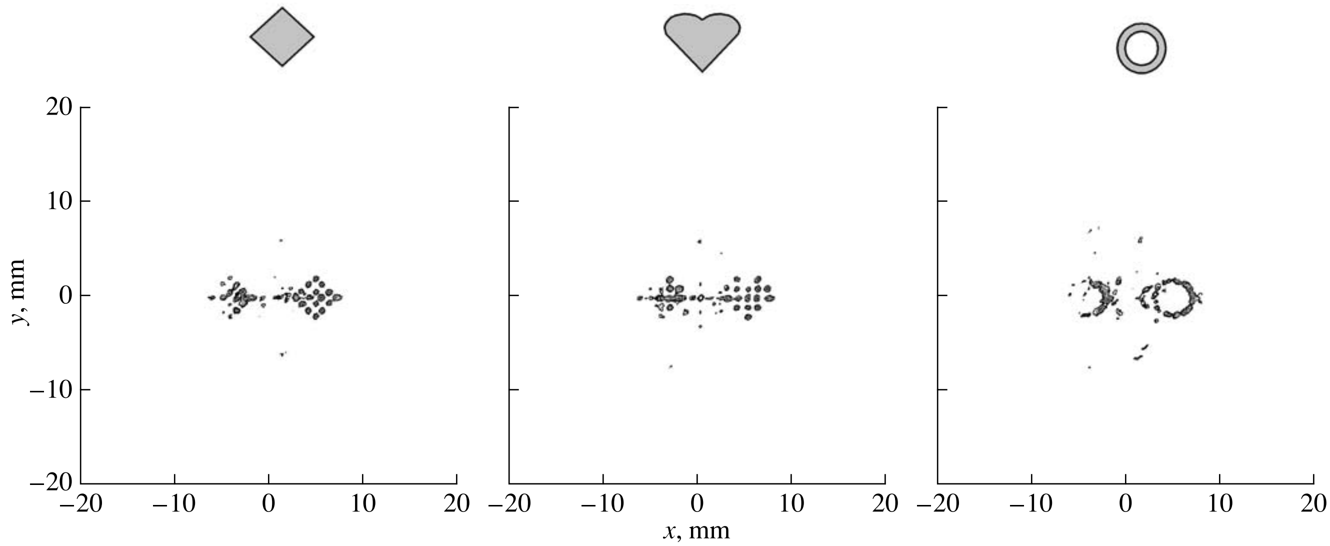

Fig. 5. Intensity distributions in the focal pane that are similar to those shown in the right-hand column of Fig. 4 but obtained using a regular array. The shift of all the focus aggregates is 5 mm with respect to the array axis.

Finally, Fig. 6 illustrates the possibility of "imaging" more complex symbols, for example, Latin letters with the help of randomized arrays. Figure 6 represents the intensity distributions in the focal plane that correspond to the letters S and W, which we considered to be rather difficult for imaging among the Latin letters. To synthesize these symbols, we used 24 and 25 foci, respectively, which consisted of three and five configurations containing a smaller number of foci (eight and five, respectively). The dimensions of the field where the calculation was conducted were 4×4 cm (Fig. 6a) and 1×1 cm (Fig. 6b). The absence of considerable secondary peaks within the field under investigation is the evidence of a quite acceptable quality of the intensity distributions obtained.

In connection with the images presented in Fig. 6, it is useful to discuss briefly one more field of application for the approach examined in this study. There are tactile displays, which allow a blind person and even a deaf and blind person to read a text displayed by a relief-dot font using his tactile sensation. Graphic tactile displays are developed as well. They allow a blind person to "see" two-dimensional pictures and images. Small pins are used in these devices. They are elevated or lowered following the image. The number of pins in graphic displays may reach several thousands. The Braille script is used to form images of letters, which makes it possible to produce an analog of a planar typed symbol with the help of 6–8 points (sometimes, such a symbol is imaged by two Braille symbols). It is much simpler to image the Braille symbols than Latin or Cyrillic letters. However, the existing displays have shortcomings and limitations. For example, the devices where the pins are moved mechanically are noisy, and they need a direct contact of probationer's skin with the pins, while the rate of "image" movement along a display or "frame" refreshment is very limited. From this point of view, ultrasonic tactile displays have certain potential advantages: they are noiseless, "noncontact," and have a high rate of information refreshment in the display screen. Although the expedience of practical application of ultrasonic displays for representation of planar typed symbols and not their Braille equivalents is an object for a separate study, the technological possibility of the development of such devices can be considered to be proved, as it is demonstrated in this paper.

The results obtained in this study demonstrate that arrays with random positioning of elements at the surface provide an opportunity to produce the regions of action by focused ultrasound with a preset and, if necessary, rather complex configuration. The use of the application of differently-shaped action regions (a cube, a torus, etc.) in surgery and therapy for destruction of biological tissues and hyperthermia was demonstrated in [26]. Together with other possibilities of their practical application, this capability may be useful for research in physiology and search for new methods of supplying information to a human. In particular, the method may be applied for the stimulation of human receptor structures by focused ultrasound in the process of the development of promising methods and systems for robotics, sensors, automated control systems, and also "human–machine" interfaces based on the use of taction. The approach proposed here may be also useful for the development of tactile displays for information transmission to an operator by an acoustic technique based on the effect of radiation pressure. A version of this device may be a tactile display for blind persons, which provides an opportunity to "read" the displayed text using a relief-dot font. This display can synthesize

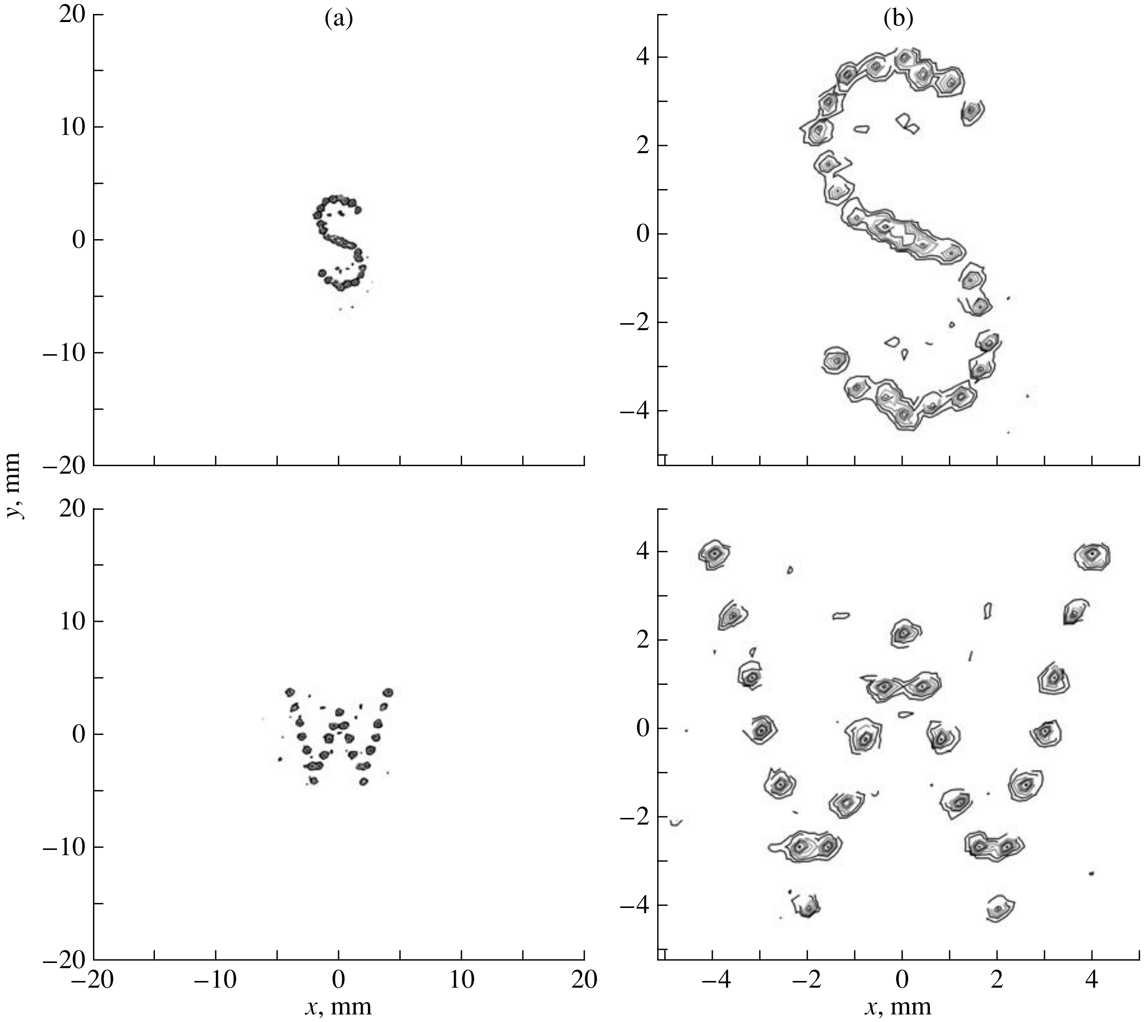

Fig. 6. Synthesis of more complex symbols, for example, in the form of some Latin letters, by a randomized array. The dimensions of the field under investigation are (a) 4×4 cm and (b) 1×1 cm.

rapidly changing patterns with complex configurations (letters, digits, punctuation marks, symbols, etc.). In this paper, it is demonstrated that arrays with randomly positioned elements on their surface provide a better quality of intensity distributions in synthesizing complex-shaped symbols, as compared to the arrays with regularly positioned elements.

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