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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

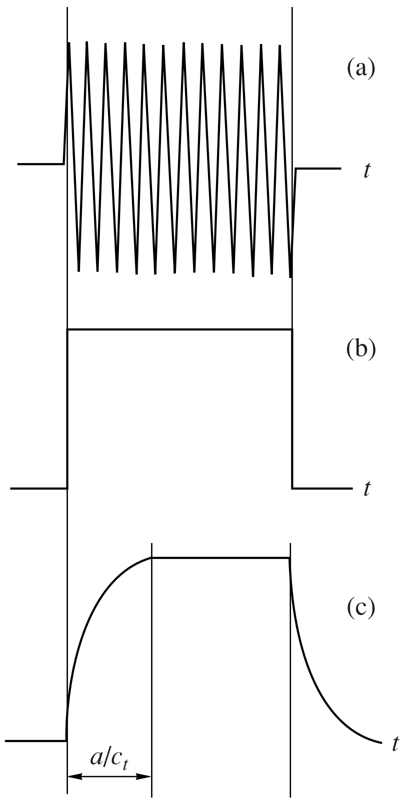

Fig. 1. Diagram illustrating the shape of (a) an acoustic signal, (b) acoustic power, and (c) shear displacement of the medium.

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