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Features of Ultrasonic Application for Non-Invasive Massage

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Abstract

The proposed method of non-invasive massage with the implementation of surface scanning with an ultrasonic beam of high -intensity parts of the human body is described. Discrete emitters were located on the matrix in concentric circles. The ultrasound field was calculated as the sum of the contributions from individual sources, taking into account the phase delay introduced. The electronic beam forming unit controlled from a computer made it possible to realize the focusing of ultrasound and scanning in the interval of angles 0-450, providing a radiation pressure of 57 Pa at a distance of 204 mm. The calculations of the characteristics of the focused field, the results of computer visualization, theoretical and experimental studies are given.

Keywords:Control beam, force action of ultrasonic,noninvasive massage,therapeutic treatment.

Introduction

The use of ultrasound for non-invasive massage is one of the main methods of therapeutic treatment [1] for patients with borderline skin conditions associated with an exacerbation of chronic skin diseases, such as, for example, psoriasis, or treatment of focal lesions due to burns. The most common ultrasonic vibrating massagers contain piezoemitters that come into direct contact with the surface of the human body, and the presence of additional covers in the form of dressings significantly weakens the intensity of the ultrasonic wave acting on the affected or requiring massage area. At the same time, the processes of generation of intense ultrasound in air have been studied in sufficient detail [2-4].

The concentration of ultrasonic exposure while providing various focusing devices, such as lenses, reflectors, emitters in the form of segments of a spherical surface [5]. Using of ultrasound in surgery associated with the use focused ultrasound [6, 7]. Unlike the methods presented in the previous section, this approach is a qualitatively new way used for tissue dissection. The idea of the method is to focus acoustic waves in focal region within which the intensity of the acoustic disturbance will be maximum. The appeal of this method is that it allows gets a strong enough damaging effect in the depth of the fabric without causing harm to the upper layers of the skin. The easiest way to get focused ultrasound is use of collecting acoustic lenses. For this, the ceramic radiator in the form of a fragment is most often used ellipsoid rotation. According to diffraction theory, the focal region is lenses will have the shape of an ellipsoid of rotation. But actually, depending on properties of the irradiated matter, the form will change quite strongly. Moreover, making an accurate calculation of the position of the focal area is also non-trivial, since the acoustic properties of the materials that make up the human body are strong enough are changing. For this reason, in order to exercise an accurate impact on any point of the brain, often requires trepanning of the skull. Also it should be noted that the theoretical calculation shows that in the case of using spherical transducer in a non-absorbing medium in the focal area will be get only 84% of the radiated energy. The main problem of using spherical reflector is that changing the focal length of the system difficult.

The processes of scanning by high-frequency ultrasound of soft tissues with the purpose of visualization by applying an acoustic radiation force pulse were investigated, however, only thermal effects [8] were realized in the frequency range of a few unit or ten megahertz. Also known examples [9, 10] of the application of scanning ultrasound beam to determine the flow rate of fluid, in closed shells, for example in blood flow measurement focusing on the sensory part in the frequency range of hundreds of kilohertz. The disadvantages of such devices include a fixed position of the focus. To move the focused beam along the surface, a mechanical drive is usually used, which is associated with the use of complex mechanical components and control circuits. The most promising are matrix emitters with program-controlled ultrasonic beam. They provide selective in space effects of ultrasound and have high speed. Known to develop devices focusing ultrasound in the air using computer technology modeling and processing of experimental data [11, 12].

It is necessary to evaluate the capabilities of the ultrasonic beam focusing device, which creates a forceful effect on a plane or relief surface, causing intense movement of muscle tissue or a tactile sensation. For this, it is necessary to analyze the capabilities of the device, consisting of an array of ultrasonic transducers, an electronic ultrasonic beam generating unit controlled from a personal computer. The calculation of the focused acoustic field of the matrix can be carried out according to the method proposed in the articles [12, 13].

Tactile Effect of Ultrasound

An ultrasonic focusing device is analyzed to create a pressing pressure, called tactile pressure or tactile impact. A tactile impact (from Latin *taktilis, tangere* — to touch) is any influence of an external force on an object's surface, causing deformation of its surface or another type of reaction to the action of this force. For example, a tactile effect on a person's skin of a certain size causes a corresponding reaction of the nervous system and a corresponding reaction in a person.

Acoustic waves can have a tactile effect on the surface of the object. In this case, by the nature of the action, the tactile impact of the wave is no different from any other direct physical impact. The tactile effect [14, 15] of acoustic waves is associated with the appearance of the so-called radiation pressure (or sound pressure) on the barrier surface, which is determined by the sound pressure of the wave, as well as the parameters of the medium and the material of the object surface. The magnitude of the radiation pressure of sound for low-intensity waves is very small and does not because a tactile effect on objects, therefore, to create acoustic and ultrasonic tactile pressure, it is necessary to generate high-power acoustic waves.

The degree of tactile impact is determined by the magnitude of the force applied to the surface of the object. The force of tactile impact, referred to the unit surface area to which it is applied, is called tactile pressure (dimension g/sm^2). The amount of tactile pressure, which causes tactile sensations or other reactions of the object, is individual for each individual object and depends on the properties of the object. To describe the tactile sensations of a person, the concept of an absolute lower threshold of sensitivity is introduced, which corresponds to the minimum tactile pressure that causes irritation in a person [15]. This threshold is different for different parts of a person, but almost all of its values lie in the range from 0.2 to 25 g/sm^2. Tactile pressure values of 300 g/sm^2 cause pain in a person. Table 1 shows the lower thresholds of sensitivity for different parts of the human body.

Table 1. Minimum Tactile Pressure Causing Irritation In Humans

Part of Human body	Minimum tactile pressure [g/sm^2]
Fingertip	0.2
Back of the hand	0.5
Rear brush	0.8
Calf legs	1.5
Abdominal surface	2.6
Loin	4.8
Sole	25

Features of the Ultrasonic Field Analysis

The Rayleigh integral gives a fundamental possibility to calculate the potential of the field at any point of the half-space. The solution is obtained by representing the integral in the form of infinite power series, the convergence of which depends on the distance to the radiator. For the area near the radiator, the rows converge poorly. In the region remote from the emitter, the solution is found using the Fresnel integral. At large distances use asymptotic approximations. With the advent of computer technology, which allows for a large amount of computation, numerical methods for solving radiation problems have become effective. To calculate the focused ultrasound field, we will use the Cartesian coordinate system (X, Y, Z) located in the center of the radiating matrix with aperture D (see Fig. 1). The matrix consists of N * M discrete emitters of small wave size, located at the nodes of the coordinate grid. Step between radiators $\Delta x = \Delta y$. The oscillatory speed of discrete emitters V_{nm} is given by the distribution function W_{nm} relative to the value of velocity V_0 in the center of the matrix: Radiation occurs in a half-space with a characteristic impedance ρc. Focusing to a point in the space F (Xf, Yf, Zf). Ensured by the introduction of time delays in the excitation function of the emitters.

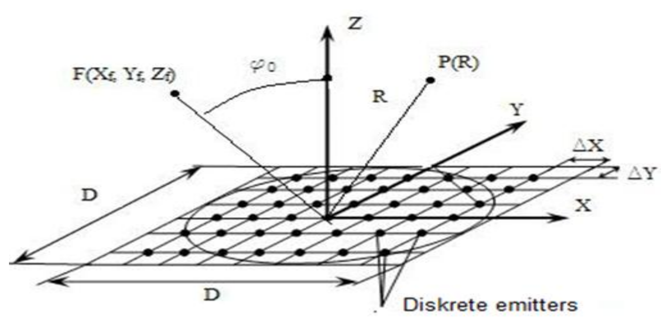

Fig. 1. Model of the matrix emitter

The spatial delay ΔR_{nm}, for an arbitrary discrete emitter with the number nm, is calculated as:

$$\Delta R_{nm} = R_{max} - R_{mn}, \qquad (1)$$

where R_{max} and R_{nm} are the maximum and current values of the distances to the focus point. The radiation pressure p (R) at an arbitrary observation point, normalized to $p_0 = \rho c V_0$, is determined numerically

$$p(R) = \frac{\Delta S}{\lambda} \sum_n^N \sum_m^M W_{nm} \frac{\exp(-jk\,(R_{nm}^* + \Delta R_{nm}))}{R_{nm}^*}. \qquad (2)$$

Where ΔS, λ - area of a discrete radiator and wavelength; R_{nm}* is the distance from the discrete emitter with the number nm to the observation point.

Features of the Ultrasound beam scanning procedure

In the article [9] shown the dependence of the width of the beam on the aperture of the disk matrix focused on the point F (0, 0, Z_f). The beam section in focus is a circle whose diameter d is directly proportional to the wavelength λ and the focusing coefficient K_f

$$d = \lambda K_f. \ (3)$$

The width practically does not change with an increase in the matrix aperture for a fixed value of the focusing coefficient

$$K_f = \frac{Z_f}{D}, \qquad (4)$$

where Z_f is the focal length, D is the dimension of the radiating matrix.
When the beam is deflected during the scanning by an angle φ_0, the distance to the focus increases, the focusing ratio increases:

$$K_f = \frac{Z_f}{D \cos \varphi_0}. \qquad (5)$$

Authors in [12, 13] shown an increase in the focusing coefficient leads to an increase in the cross section and the length of the ultrasonic beam. The magnitude of the sound pressure in the focus is calculated through the amount of pressure on the surface of the radiator and it decreases with scanning [5].

$$p(F) = p_0 \frac{\pi D}{4\,\lambda\, K_f} = p_0 \frac{\pi D^2 \cos \varphi_0}{4\,\lambda\, Z_f}. \qquad (6)$$

In Fig. 2 and 3, as an example, raster images of the ultrasonic beam cross section in the axial plane are given for two scan angles $\varphi_0 = 0^0$, 30^0, respectively.

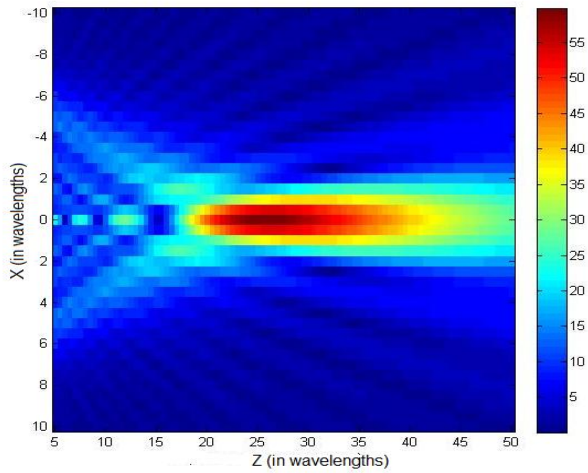

Fig. 2.The cross section of the ultrasonic beam in the plane perpendicular to the surface of the emitter and passing through its axis φ_0=0^0

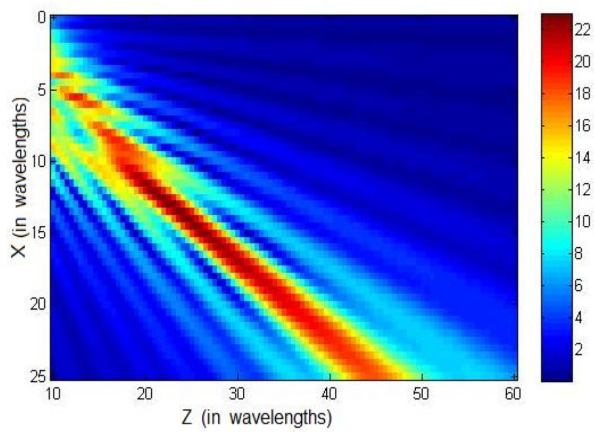

Fig. 3. The cross section of the ultrasonic beam in the plane perpendicular to the surface of the emitter and passing through its axis φ_0=30^0 .

In fig. 4 shown the pressure distribution curves for the initial value K_f= 2 depending on the scan angle φ_0=0^0, 30^0, 45^0. Increasing the angle leads to the expansion of the beam with a slight change in the level of side lobes. Estimate the width of the beam for the three values of the focusing coefficient K_f= 1,2,3 can be on the curves shown in Fig.5.

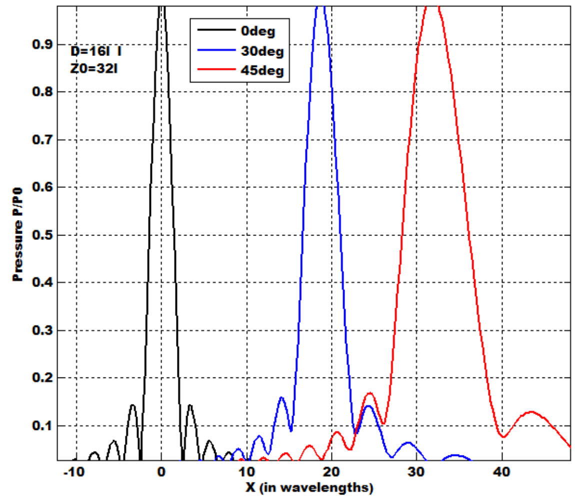

Fig. 4.Expansion of the beam during scanning.

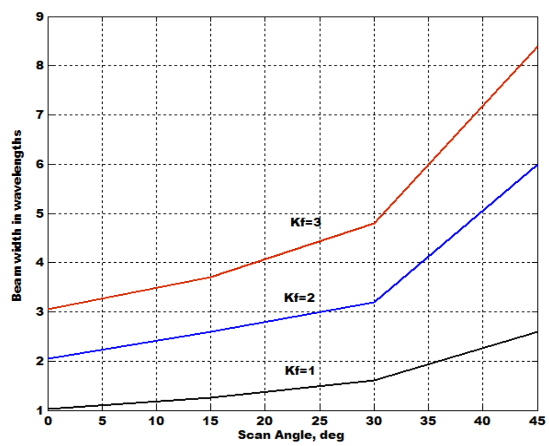

Fig. 5.Dependence of the beam width on the scan angle.

The radiation pressure can also be estimated from raster graphs (see Figs. 2 and 3). For example, for a coordinate, the pressure ratio in the focal area for angles $\varphi_0 = 30^0$ and $\varphi_0 = 0^0$ is estimated at 0,7 and corresponds to the cos φ_0 law. As follows from the expression for the value of radiation pressure [2] in the presence of a barrier, the radiation pressure is proportional to the square of the radiation pressure

$$P_r = (1 + \xi^2)I = 2\frac{p^2}{\rho\, c^2}, \qquad (7)$$

where p is the radiation pressure, I is the sound energy density, ξ is the pressure reflection coefficient in the presence of an obstacle, ρ is the specific density of the medium, c is the speed of sound in this medium, for air,

For example: ρ = 1,29 kg/m^3, c = 340 m/s.

The radiation pressure is calculated by equation above. This value is very small for creating a tactile sensation. It is known that the minimum pressure, perceived as a touch, is 0.2-0.5.

In Table 2, shown values of radiation pressure and the required ultrasonic pressure and its level, related by the ratio:

$$L = 20\,\lg(p/p_0)\ [dB]\,, \qquad (8)$$

where $p_0 = 2\cdot10^{-5}$ Pa.

Table 2. Radiation Pressure Values

Radiation Pressure P, [g/sm²]	**Ultrasonic Pressure p_0 [Pa]**	**Level of radiation L [dB]**
0,0055	0.2	140
0,055	0.5	150
0,55	0.8	160
5,5	1.5	170

To obtain pressure on the surface of the body, ultrasonic energy should be increased using a certain number of emitters. As an example, the number of radiators N is calculated with the radiation level

L_i = 120 dB to obtain the radiation level L_Σ = 160 dB

$$L_\Sigma = 20\,\lg\left(\sum_{i=1}^{N} 10^{0,05L_i}\right) = 20\,\lg\left(N10^{0,05L_i}\right) = L_i + 20\,\lg N, \qquad (9)$$

Where $N = 10^{0,05(L_\Sigma - L_i)} = 10^2 = 100$.

Using 100 emitters, it is possible to obtain the radiation pressure Pr = 0.55 g/sm^2 at a distance equal to 300 mm, having fulfilled the condition of phase coincidence of oscillations coming from discrete emitters. A further increase in radiation pressure can be achieved by focusing the ultrasonic field created by a matrix of discrete emitters. As shown in [5, 12, 13], the magnitude of amplification of sound pressure in focus can significantly exceed the value obtained due to the in-phase interference of the contributions from the array of transducers.

However, it should be remembered that the characteristics of the near field depend on the geometry of the matrix, the wave distance between the elements and the focusing coefficient. The width and length of the main radiation lobe — the ultrasound beam — increases with increasing focusing coefficient, and the ultrasonic energy density and radiation pressure decrease. The dependence of the characteristics of the beam on the scanning angles in space has been studied using the example of a disk matrix emitter. Reducing the magnitude of ultrasonic pressure by 1.4 times leads to a decrease in energy density, and hence the radiation pressure by 2 times. As the scan angle increases, the cross section of the beam increases (see Fig. 4), which leads to a deterioration of the spatial force action. The graph shown in Fig.5 allows us to estimate the width of the beam, therefore, the size of the area of force action for different values of the focusing coefficient.

Moving the focus along the ultrasonic radiation axis

For three focal points F = 200 mm; 250 mm; 300 mm we calculate the numerical algorithm proposed in the same work, the distribution of ultrasonic pressure along the axis of the matrix emitter (see Fig. 6).

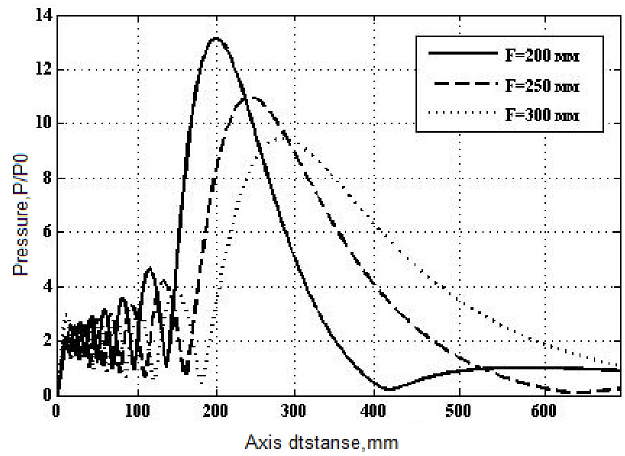

Fig.6. Pressure distribution along matrix disk emitter.

It should be noted that the maximum pressure (in focus) shifts towards the surface of the matrix emitter due to the diffraction of the waves and does not coincide with the position of the given points of focus. We will evaluate the level of ultrasound in the first focal point. The ultrasonic pressure in the focus P_F exceeds the average pressure on the surface of the radiator P_0 in (P_F/P_0) = 13 times equal to the increase in the pressure level by the value of ΔL:

$$\Delta L_r = 20\lg\frac{P_F}{P_0} = 22 \text{ dB}. \quad (10)$$

Let us assume for the average level of radiation on the surface of the matrix the level of ultrasound by the frequency (wavelength λ = 8,5 mm) of a discrete converter with a diameter d = 12,6 mm at the boundary of the Fresnel zone

$$r_F = 0{,}25(d^2\lambda^{-1}) = 4{,}7 \text{ mm}.(11)$$

Consider also the reduction of pressure in a spherical wave in proportion to the distance from the source. Knowing the level of the pressure of the discrete emitter Li = 115 dB at a distance Ri = 300 mm, we calculate the pressure level at the boundary of the Fresnel zone:

$$L_0 = L_i + 20\lg\left(\frac{P_F}{P_0}\right) = 115 + 20\lg\left(\frac{300}{4{,}7}\right) = 151 \text{ dB}. \quad (12)$$

Taking into account the focusing factor determined by the addition of ΔL, we find the L_F pressure level at the focus point

$$L_F = L_0 + \Delta L = 173 \text{ dB}.$$

The calculation of ultrasonic pressure for the other two focusing points is similar, with the use of a pressure distribution graph for different focal length values (see Fig. 6). The ultrasonic pressure in the second and third tricks exceeds the value on the matrix surface at 11 and 9 times, respectively. The results of calculations of the ultrasound level and the value of radiation pressure are given in Table 3. The difference between the experimental and calculated values can be taken into account methodical error of 6-7 dB.

Table 3. Numerical values of the ultrasound and the value of radiation pressure

Focal distance F [mm]	**200**		**250**		**300**	
	Calculation	*experiment*	*calculation*	*Experiment*	*calculation*	*Experiment*
Level L_F [dB]	173	166	172	165	170	164
Radiation pressure P_r [g/sm^2]	10,9	2,18	8,67	1,76	5,5	1,37

The calculated level of ultrasonic pressure in the three-step focusing, in accordance with Table 3, will allow radiation exposure $P_r \geq 1{,}37$ g/sm^2 to be sufficient for tactile effects on the surface of the human body and subcutaneous tissues and muscles.

Method and results of experiments

The experiment is based on the evaluation of the characteristics of the ultrasonic field, and not their measurement. The lack of accurate instruments for measuring the level of ultrasonic pressure over 160 dB only allowed to estimate its value. A Murata40T/R converter with a resonant frequency of 40 kHz and sensitivity in the reception mode of 5.6 mV Pa was used as the measuring microphone. On the top plate (see Fig. 7) a circular matrix with an aperture of D = 182 mm, were placed n = 172 ultrasonic emitters (DPU1240AOH9.5T/R, China). Diameter of each transducer is equal to d =12.6 mm. Emitters located at N=7 concentric circles.

Fig. 7. Ultrasonic matrix and control computer

Each group united in one electric circuit. The resonance frequency of the emitter is 40 kHz. The level of ultrasonic pressure developed by a separate radiator in the air, at a distance of R_i= 300 mm was L_i =115 dB, with the effective electrical voltage of 10V. Wavelength λ = 8.5mm. The beam control unit contains an Atmel mega128 processor board and an amplifier board. The processor is controlled by a PC via USB [16]. The array of emitters was mounted on a rotator (see Fig.8), providing rotation in sector $0\text{-}360^0$ with an angular step of 0.2^0.

Fig. 8.Installation for measuring the ultrasonic field.

The receiving transducer mounted on a tripod moved along the radiation axis of the matrix. The minimum distance of the receiver from the matrix was 140 mm, and was due to the design features of the device. The maximum distance selected is 380 mm. Stepwise moving the receiver along the centerline, a circular recording of the pressure distribution was made. Thus, line-by-line scanning of the acoustic field was implemented. The duration of the radiation pulse was 1 ms.

Conclusions

A method of non-invasive massage by creating a power action in the air using focused ultrasound is proposed. The calculations of the radiation pressure of ultrasound are given. The results of computer simulation of the ultrasonic field and computer processing of experimental data are presented. The description of physical experiments is given and the obtained results are analyzed. In the area of focusing, a radiation pressure of 57 Pa was obtained. The hand felt a tactile effect. The experimental characteristics of the ultrasound beam in the focal area - a length of 80 mm and a width of 11.2 mm, are in good agreement with the calculations. The differences in the raster field patterns obtained as a result of theoretical modeling and experimental studies are explained by the constructive inaccuracies of the location of the radiators on the matrix surface and the errors in the installation of the coordinates of the measuring stand. A high-intensity ultrasound generated by an emitter array in the air allows you to create radiation pressure that causes tactile stimulation. The magnitude of the pressure, its spatial localization depends on the characteristics of discrete emitters, the geometry of the matrix, the selected focusing coefficient.

Phase scanning in space leads to the expansion of the ultrasonic beam, therefore, reducing the radiation pressure, as well as increasing the focal length. The experimental part presents the results confirming the correctness of the hypothesis about the feasibility of using non-invasive massage of internal tissues with an ultrasonic focusing effect, and it is concluded that the proposed method is promising for conducting clinical trials. The results obtained in this work can be applied when developing devices for non-invasive massage of the affected areas of the body surface.

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