The Synchronous Excitement and Convergence of the Weakly-Focused Acoustic Shock Waves in the Multi-Beam Electromagnetic Shock Wave Generator

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Abstract – In acoustic shock waves generators with focusing system such as a lens or reflector the nonlinear absorption of a spherical converging wave usually limits amplitude of a shock wave in focus at a level 70–80 MPa. In the multi-beam electromagnetic shock wave generator, described in report, several weakly focused acoustic shock waves propogate independenly and transverse only in the narrow region near the inersecton point of theirs spread directions. Because of small distance of synchronous shock waves superposition the nonlinear absorption is negligible and we can achieve essential more high pressure amplitude in focal region then in traditional devices. Presented computer simulation of shock waves propogation in linear approximation is useful for choice the geometrical parameters of multi-beam shock wave generator. Electromechanical simulation is used to analyse the cooperative transition procesis in discharge cercuit and mechanical motion of metalic membrane in generator. The role of cavitation on shock waves propogation in multi-beam generator is considered. Additional advantages of multi-beam method of shock wave localisation are discussed in connection with medical and biology applications.

1. Introduction

The shock action of strong pulsed magnetic fields of microsecond duration on a thin metallic membrane or shell, which is in contact with a liquid medium, is used in the design of electromagnetic radiators of focused acoustics shock wave [1]. At present, three versions of such radiators are employed in the medical practice of noninvasive destruction of kidney stones and gall stones: a) a radiator in which a spherically converging acoustic pulse wave is produced by the action of a pulsed magnetic field on a membrane in the form of a spherical segment; b) a radiator in which a flat membrane placed on a plane spiral coil excites in a medium an acoustic pulse with a plane front, which is focused by an acoustic lens; c) a radiator in which a cylindrical metallic shell placed on a cylindrical spiral coil excites in a medium an acoustic pulse with a cylindrical front, which is focused by a parabolic reflector. The latter is a body of revolution with a generatrix described in a polar coordinate system with the center at the reflector focus according the expression

$$R = \frac{\left(R_0^2 + f^2\right)^{0.5} + R_0}{1 + \sin\varphi},$$

where R_0 is the radius of the reflector exit hole.

2. Design, Electrical Scheme and Singularity of Maltibeam Electromagnetic Shock Wave Ganerator

In shock waves generators with focusing system such as a lens or reflector the nonlinear absorption of a spherical converging wave usually limits amplitude of a shock wave in focus at a level 70–80 MPa. In the multi-beam generator of shock waves the new principle of a focalizing to an electromagnetic type generators is used on the basis of addition of several weakfocusing shock waves. In result the heightened efficiency of kidney destruction is provided at the minimum traumatic factor because of magnification of a shock wave amplitude in focus, localization of pressure allocation in a longitudinal direction and plateaulike allocation of pressure in a transverse direction.

Practically the multi-beam method of shock wave focusing was realized in a design of the three beam generator [6]. Fig. 1 shows an experimental device consisting of three electromagnetic shock wave radiators with convergent shock waves.

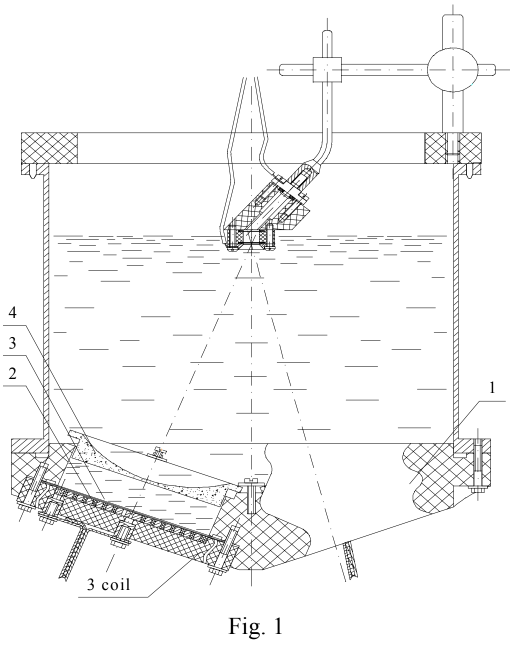

Fig. 1

Three electromagnetic-type radiators of shock wave are symmetrically mounted on a common base *1* so that the axes of the radiators intersect at their common focal point. The intersection angles between the radiator axes and the symmetry axis of the generator is $\alpha = 20°$. Each radiator consists of a planar spiral coil *2*, a metal membrane *3*, and an acoustic lens *4* made of an organic glass. The output diameter of the radiator lenses is equal to 100 mm, and the focal lenght $f = 170$ mm. The distance from the intersection point of the radiator axes to the base plan (the effective focal length of the three-beam generator) $F = 140$ mm. Measurement of the pressure field of each radiator has shown that the focal sport diameter of the radiators $2r_0 = 8$ mm, and the longitudinal dimension of the focal area (the distance between the points on the radiator axes at which the pressure amplitude equals half its maximum value at the focus) is equal to 70 mm. At the summing up three beams the longitudinal dimension of focal zone is 10–15 mm.

To provide simultaneous switching on of all three radiators, their spiral coil were connected into a discharge circuit according the special scheme [5] shown in Fig. 2. The characteristic feature of this circuit consists in using a separate capacitor (typically 0.5–1 μF × 10 kV) for each coil, while the discharge of the capacitors through the coils is switched by a common discharge device. Such a circuit allowed us to avoid problems associated with synchronization of the switch-on of the radiators. The acoustic pulsed radiated by each radiator and focused by the lenses propagate independently up to the intersection space of the beams, which is located near the focus of the generator.

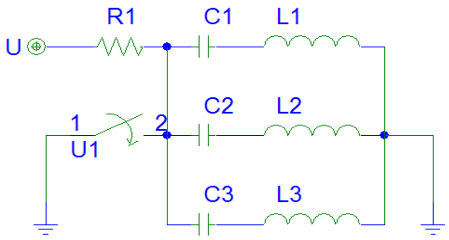

Fig. 2

In accordance with the equivalent circuit shown in Fig. 2, the radiating element operates in the following manner. When the capacitors C_1, C_2, C_3 with the capacitance C, which was preliminarily charged to the voltage U_0, discharges through the exciting coils L_1, L_2, L_3 with the inductance L_1, the discharge current $I_1(t)$ flows through the each coil. The full discharge current $I(t)$ is approximately N times higher than the current $I_1(t)$ (N – the number of radiators). The current $I_2(t)$ is excited in the metallic membrane, which forms the secondary turn of the transformer and is characterized by the inductance L_2 and resistance R_2. The current I_2 is approximately n times higher then I_1 (n – the number of the coil winding). Pulsed magnetic field exited in the gap between the coil and metal membrane accelerates membrane contacting with liquid and acoustical pulsed wave is formed in liquid.

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The simplest picture of wave propagation is shown in Fig. 3 at two moment: T_2, when waves are arrived to focus and T_1, when waves are on the middle distance from focus.

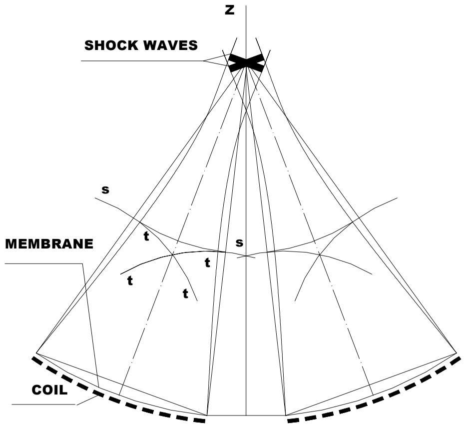


Fig. 3

For each radiator the radiated wave structure consists of the direct stress wave with front **s–s** and the edge wave which is stress wave outside focusing zone and tension wave **t–t** inside focusing zone. This tension wave has peculiarity on the axis of radiator, high tensile pressure in this peculiarity can cause cavitation. Early cavitation is favourable for decreasing the tension wave amplitude.

The diameter of focusing zone is defined by the caracteristic wave length $\Delta = c\tau$, τ – duration of shock wave impuls, c – sound velocity in liquid, and by the aperture θ of focusing system (lens or reflector) $d_r \sim \Delta/2\sin\theta$. The longitudinal size of focusing zone for classical focusing system is defined as $L \sim 1.8\Delta/(\sin\theta)^2$. From geometrical consideration of the shock wave intersection zone we can see that the longitudinal size of focusing zone in multi-beam shock wave generator $L \sim 0.5\Delta/(\sin\theta)^2$, that is less more then 3 times. On the analogy of previous consideration we can easy receive the evaluation of the pressure distributon width in transverse direction $D \sim c\tau/\alpha$.

In the offered way of addition several weakly focused crossed shock wave beams [5] at their imposing in focus it is possible essentially to reduce nonlinear absorption at the expense of reduction of distance run by a wave of total amplitude before focus. Everyone radiator thus should generate the weakly focused shock wave with amplitude in focus approximately in N of time smaller then required, where N – number of radiators. Additional advantages of multi-beam method are displayed in an opportunity of formation of a plateau pressure distribution in focus with sharp recession of pressure on borders of a beam, that results in increase of efficiency of destroying action on stones. Use weakly focused radiator allows also to reduce amplitude of a negative pressure half-wave in focus, as the cavitation trace in such beams resulting in absorption a half-waves of negative pressure, begins to be formed already on an exit of a focusing element, thus in a zone of crossing of beams the negative half-wave appears largely suppressed. At a rational choice of the geometrical sizes of the multi-beam generator it is possible appreciablly to suppress a negative half-wave of pressure up to border of a body of the patient and to exclude undesirable traumatic damage of soft tissue caused by stretching loading. In the multi-beam generator there is also opportunity of change (regulation) of focus location at the expense of simply change of an inclination of separate radiators axes.

3. Electromechanical and Geometrooptical Simulation

The Lagrangian L of the cylindrical radiator (cylindrical coil inside cylindrical metallic shell) can be written in the form

$$L = \frac{\left(L_S + L_1\right) I_1^2}{2} + \frac{L_2 I_2^2}{2} + M I_1 I_2 - \frac{Q^2}{2C} + T_S - U_S\,,$$

where $T_S = \frac{2\pi r_0 db\dot{r}^2}{2}\rho$; $U_S = \frac{\pi dbE\left(r - r_0\right)^2}{r_0}$; ρ, d, b, E – density, thickness, length and elastic module of the shell; r_0, r – initial and real at time t radius of the shell; $L_s + L_1$ – inductance of discharge circuit with coil, L_2 – inductance of the shell and M – mutual inductance; I_1, I_2 – currents in the coil and in the shell; Q – charge of capacitor C.

As the shell movies in the liquid, it produces the pressure P, which acts on the shell with the external force $F_{\mathring{A}} = 2\pi rbP$. The dissipation function of the system is written as $F = 0.5(R_1 I'^2{}_I + R_2 I'^2{}_2)$. Following a conventional procedure, we obtain the Lagrange equations for the radiator:

$$\left(L_S + L_1\right)\frac{dI_1}{dt} + M\frac{dI_2}{dt} + R_1 I_1 = \frac{Q}{C}; \qquad (1)$$

$$\frac{d}{dt}\left(L_2 I_2\right) + M\frac{dI_1}{dt} + R_2 I_2 = 0; \qquad (2)$$

$$\dot{Q} = -I_1; \qquad (3)$$

$$\ddot{r} = \frac{1}{2\pi r_0 db\rho}\left(I_2^2\frac{dL_2}{dr} + I_1 I_2\frac{dM}{dr}\right) - \frac{E\left(r - r_0\right)}{\rho r_0^2} - \frac{P}{\rho d}\,. \qquad (4)$$

If $r_0 \gg c\Delta t$ (c is velocity of sound in the liquid, and Δt is the characteristic discharge time), then the local relations between the liquid pressure and velocity at the shell boundary can be described by the plane wave approximation

$$P = \rho_L c\dot{r}, \qquad (1)$$

where ρ_L is the liquid density.

Equations (1)–(5) with the initial conditions $Q = Q_0$, $I_1 = 0$, $I_2 = 0$, $r = r_0$ and $r = 0$ at $t = 0$ give the complete solutions to the problem of radial motion of the shell during the capacitor discharge through the exciting coil at known expressions for $L_2(r)$ and $M_2(r)$ and specified values of L_1, L_S, R_1 and R_2. The system of equations (1)–(5) can be reduced to a dimensionless form similar to that in [2, 3] for a single-circuit discharge scheme of an acoustic-pulse radiator, and we can derive numerical solutions for wide ranges of the dimensionless parameters that characterize the discharge circuit, the mechanical characteristics of the shell, and the electromechanical relations between them. Similar to the cylindrical case we can obtain equations for flat or spherical radiator

It is of interest to enter into a discharge contour of the electromagnetic generator closing switch, included parallel to inductor coil or primary winding of the transformer and included at the moment of a maximum of a current in a contour (crowbar). The accounts show, that thus the duration of a pulse of the induced current in a radiating shell or plate is increased, the pulse of pressure is tightened and the efficiency of generation of a shock wave pulse is increased. The technical difficulties of realization of the circuit in a microsecond range apparently can be overcome.

For the simulation the pressure distributions in intersection zone of shock waves we used linear approximation and representation the shock wave as impulse with Gauss distribution in transverse direction and exponent decreasing in longitudinal direction with transformation from coordinate system of each radiators to coordinate system of generator:

$$\psi(i) = 2\pi i/K\,,\ i = 0, 1, 2, \quad K = 3\,;$$

$$x_i(x,y,z) = x\cos(\psi(i))\cos(\alpha) -$$
$$-y\sin(\psi(i))\cos(\alpha) + z\sin(\alpha),$$

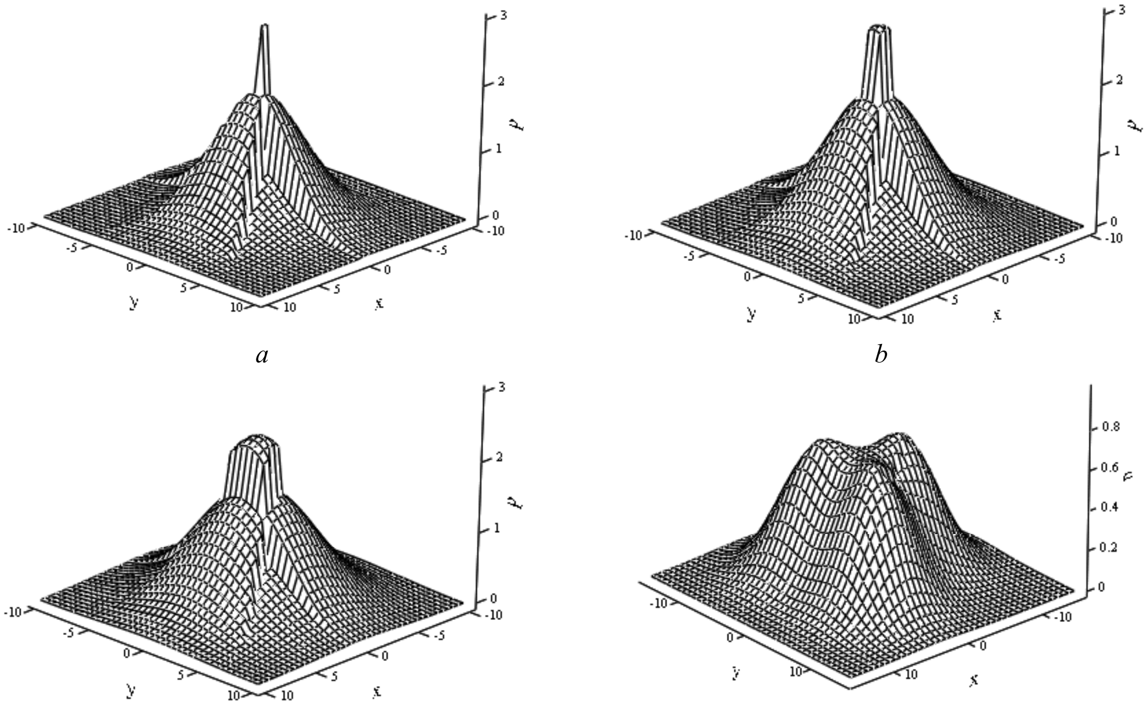
$$y_i(x,y,z) = x\sin(\psi(i)) + y\cos(\psi(i)),$$

$$z_i(x,y,z) = -x\cos(\psi(i))\sin(\alpha) +$$
$$+y\sin(\psi(i))\sin(\alpha) + z\cos(\alpha);$$

$$P(x,y,z) =$$
$$= \sum_{i=1}^{3}\exp\frac{x_i^2 + y_i^2}{r_0^2}\exp\frac{-z_i + z_f}{\Delta}\Theta(z_i - z_f\cos(\alpha)),$$

where x_i, y_i, z_i – coordinate system i-th radiator with axis z_i on the radiators axis with center in focus point; x, y, z – coordinate system of generator; $P(x, y, z)$ – resulting pressure; Θ – Theta functon; r_0 – caracteristic radius of pressure distribution of radiator; z_f – distance shock front from focus; Δ – caracteristic lenth of shock wave.

The results of calculations are shown in Fig. 4. The pressure distribution shown in Fig. 4*a* is near to geometrical focus of the three-beam generator. The pressure distribution shown in Fig. 4*b* is in 5 mm before to geometrical focus of the three-beam generator. The pressure distribution shown in Fig. 4*c* is in 10 mm before to geometrical focus of the three-beam generator. The pressure distribution shown in Fig. 4*d* is in 20 mm before to geometrical focus of the three-beam generator.



a *b*

c *d*

Fig. 4

4. Conclusions

The results of simulations are in quality coincided with our early experiments [6]. In the multi-beam generator of shock waves the new principle of a focalizing to the electromagnetic type generators is used on the basis of addition of several weak-focusing shock waves. In result the heightened efficiency of kidney destruction is provided at the minimum traumatic factor because of magnification of shock wave amplitude in focus, localization of pressure allocation in a longitudinal direction and plateau-like allocation of pressure in a transverse direction. Probably in the multi-beam generator we can overcome the limit for the pressure amplitude in focus 100–150 MPa in water medium which given nonlinear acoustical consideration for classical focusing devices.

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