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ON THE POSSIBILITY OF REDUCING THE PENETRATION CAPABILITY OF SHAPED-CHARGE JETS IN A MAGNETIC FIELD

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The possibility of reducing the penetration capability of shaped charges by producing a magnetic field ahead of the target with flux lines parallel to the charge axis is considered. The problem is studied on the basis of results of experiments in which a magnetic field was produced in a shaped-charge liner before firing, resulting in a sharp reduction or elimination of penetration. The variation of the magnetic induction in the shaped-charge liner moving in the magnetic field is calculated using the model of two conducting coaxial cylindrical shells corresponding to the charge case and liner and assuming constant induction-current density over the shell thickness. A longitudinal magnetic field is specified on the surface of the outer shell as a function of the spatial distribution of the field ahead of the target and the charge velocity. The magnetic-field intensity that can provide a considerable reduction in the penetration capability of shaped charges of various diameters is estimated.

Key words: *explosion, shaped charge, penetration, magnetic field.*

Introduction. In experiments [1], a significant reduction in penetration was achieved by producing an axial magnetic field in a shaped charge (SC) liner directly before firing. The experiments were performed with 50-mm diameter charges which had a copper conical liner with a cone angle of 50°. The penetration into a steel target decreased by a factor of two or more when the initial field induction in the liner was a few tenths of a tesla. At somewhat higher initial field intensities in the liner (approximately 0.5 T), the charge did not exhibit penetration capability. This effect is apparently due to a sharp amplification of the magnetic field in the jet-formation region [2]. The disturbance of SC action by preliminary production of a magnetic field in its liner may result from an amplification of the field in the liner cavity, as is the case in the operation of magnetocumulative generators — devices for producing ultrahigh magnetic fields. Magnetic cumulation can lead to powerful thermal and mechanical effects capable of influencing SC action. In addition, according to the magnetic-field freezing-in effect [3], field amplification can result from rapid motion of a conducting medium, which is accompanied by stretching deformation in the direction of the magnetic flux lines. In this case, with neglect of the compressibility of the medium and the diffusion of the field due to the finite electric conductivity of the material, the variation of the magnetic induction $\boldsymbol{B}$ in the medium should be proportional to the variation of the length of the material fibers initially oriented along the flux lines. Diffusion processes in the medium, which smooth field inhomogeneities and speed up with decreasing electric conductivity of the medium obviously weaken the field generation. Therefore, to achieve a significant amplification of the magnetic field, it is necessary that its rate of pumping due to the deformation of the medium far exceed the rate of magnetic field diffusion.

During the formation of a shaped charge jet (SCJ), the liner material, ceasing to move in the radial direction upon impact on the charge axis, undergoes huge stretching deformations in the axial direction, i.e., in the direction of the magnetic induction lines of the field produced in the liner. In this case, the freezing-in effect should lead to the

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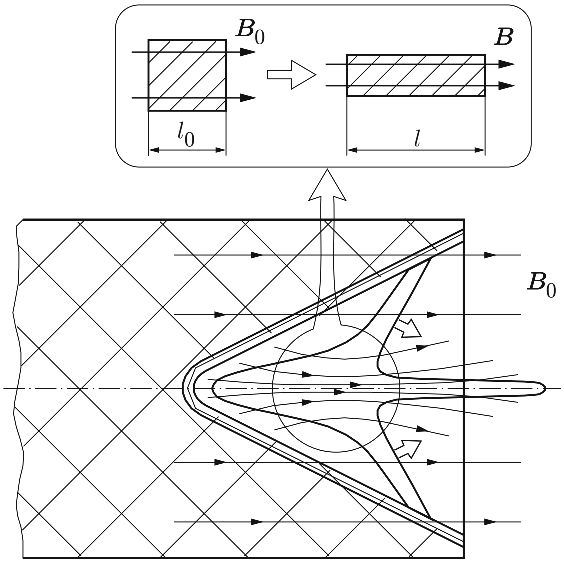

Fig. 1. Mechanism of magnetic-field amplification in the jet-formation region during shaped-charge liner collapse.

generation and amplification of the field $B = B_0 l/l_0$ directly in the material of the jet formed (Fig. 1). This process is accompanied by the occurrence of thrusting electromagnetic forces in the SCJ, which can lead to its destruction with radial dispersion of the material and a loss of the penetration capability. The effect of the magnetic field on SCJ formation during implosion of a shaped charge liner was studied by numerical modeling within the framework of the two-dimensional axisymmetric magnetic-hydrodynamic problem of the collapse of a conical liner, with a homogeneous axial magnetic field produced in it, on exposure to an external pressure corresponding to the loading of the shell by the detonation products of a HE charge (the liner material is assumed to be ideally conducting). Figure 2 shows the formation of a SCJ during dynamic implosion of a liner with a conical angle of 60° and a basis diameter of 60 mm in the absence of a magnetic field and for its initial intensity $B_0 = 0.2$ and 0.5 T. It is obvious that the presence of the magnetic field in the liner cavity leads to radial dispersion of the SCJ formed.

Experimental studies of the operation of shaped charges in an external magnetic field were performed using X-ray diagnostics. In the experiments, a 30-mm diameter SC having a copper conical liner 1 mm thick with a cone angle of 30° were used. The magnetic field in the liner was produced by a one-turn solenoid made from a copper wire 4 mm thick, with the SC placed inside. A capacitor bank of capacitance 3.2 to 6.4 mF was used as the power supply. The time delay between the switching of the discharge circuit and the firing of the SC was chosen such that by the beginning of liner collapse, the maximum field was reached at the center of the liner. The magnetic-field induction in the liner at the moment of SC firing was determined from experimental current curves taking into account the relationship between the solenoid discharge current and the magnetic field in the liner cavity established in calibration experiments. Figure 3 shows X-ray photographs of SCJs formed for field induction $B_0 = 0.84$ T (Fig. 3a) and $B_0 = 1.4$ T (Fig. 3b) at the center of the liner at the moment of liner collapse. The photographs were taken at the same time. The X-ray photographs of the disruption of the SCJ, which takes the shape of a hollow tube (Fig. 3a) up to its complete dispersion (Fig. 3b), indicate an "explosion" in the jet, obviously due to the "pumping" of a strong magnetic field.

The effect of disturbing the normal operation of SCs in a magnetic field of low intensity (a few tenths of a tesla) can be used for antiterrorist protection of various objects against the action of shaped-charge warheads by means of magnetic screening — the generation of a magnetic field (with flux lines mainly parallel to the axis of the approaching SC) ahead of the object to be protected.

Formulation of the Problem. To implement this method of protection, it is necessary that the magnetic field of the required intensity penetrate into the SC liner by the moment of SC firing. This process is hindered by the conducting case of the SC, in which, according to the electromagnetic induction law, eddy electric currents [3], screening the liner, are induced during motion in the magnetic field. The intensity of the magnetic field penetrating

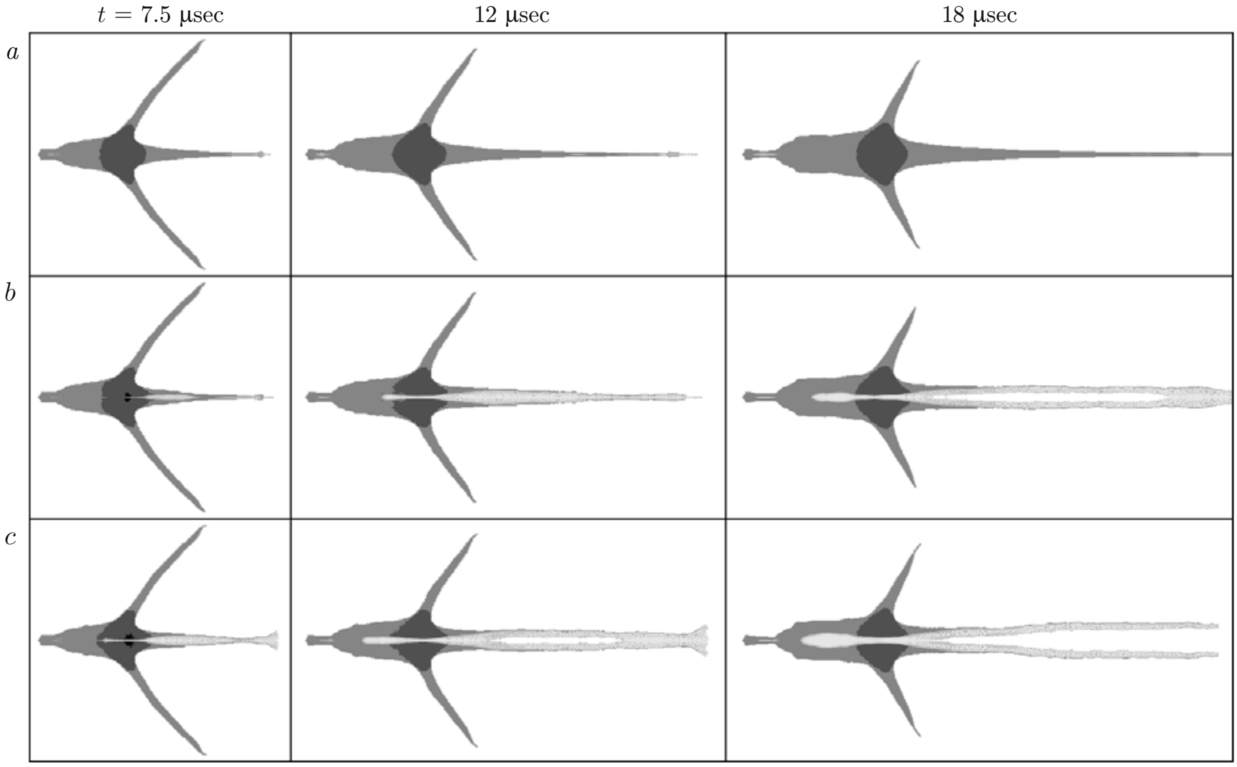

Fig. 2. Effect of the magnetic field on the formation of a shaped-charge jet: $B_0 = 0$ (a), 0.2 (b), and 0.5 T (c).

into the liner depends on the time of residence of the SC in it. Therefore, the process of penetration of the field into the liner is determined not only by its spatial propagation near the object being protected but also on the velocity of motion of the SC (the greater the extent of the region with the magnetic field along the trajectory of motion of the SC and the lower the SC velocity, the higher field intensity can be reached in the liner). The dimension of the region of space with the magnetic field depends on the dimensions of the field source placed on the object being protected, and, hence, on the dimensions of the object. To elucidate the fundamental possibility of magnetizing the SC liner as it approaches an object of specified dimension, we consider a model object (which is simultaneously a magnetic-field source) of spherical shape of radius R_0 (Fig. 4) which produces a stationary field. In the external (with respect to the object) space (in which other field sources are assumed to be absent), the magnetic field is potential. Introducing the scalar function $\varphi(\boldsymbol{r})$ of the field potential ($\boldsymbol{B} = \operatorname{grad} \varphi$) and assuming that the field produced by the spherical object is axisymmetric, we obtain the Laplace equation for the function $\varphi(r, \theta)$ in the spherical coordinates (r, θ) with origin at the center of the object:

$$\frac{1}{r^2}\frac{\partial}{\partial r}\Big(r^2\frac{\partial\varphi}{\partial r}\Big) + \frac{1}{r^2\sin\theta}\frac{\partial}{\partial\theta}\Big(\sin\theta\,\frac{\partial\varphi}{\partial\theta}\Big) = 0. \qquad (1)$$

The solution of the given equation has a simple form if on the surface of the sphere $r = R_0$ (Fig. 4), the distribution of the radial component B_r of the magnetic induction vector over the polar angle θ is given by the expression

$$B_r(R_0, \theta) = \frac{\partial\varphi}{\partial r}\Big|_{r=R_0} = B_s\cos\theta, \qquad (2)$$

where B_s is the magnetic induction at the pole of the sphere ($r = R_0$ and $\theta = 0$).

The solution of the external Neumann problem (1), (2) for the magnetic potential $\varphi(r, \theta)$ is given by the relation $\varphi = -0.5 B_s R_0^3 \cos\theta / r^2$ [4], which allows one to determine the components of the magnetic induction vector in the space surrounding the spherical object:

$$B_r = \frac{\partial\varphi}{\partial r} = B_s R_0^3\,\frac{\cos\theta}{r^3}, \qquad B_\theta = \frac{1}{r}\,\frac{\partial\varphi}{\partial\theta} = \frac{B_s R_0^3}{2}\,\frac{\sin\theta}{r^3}. \qquad (3)$$

a

b

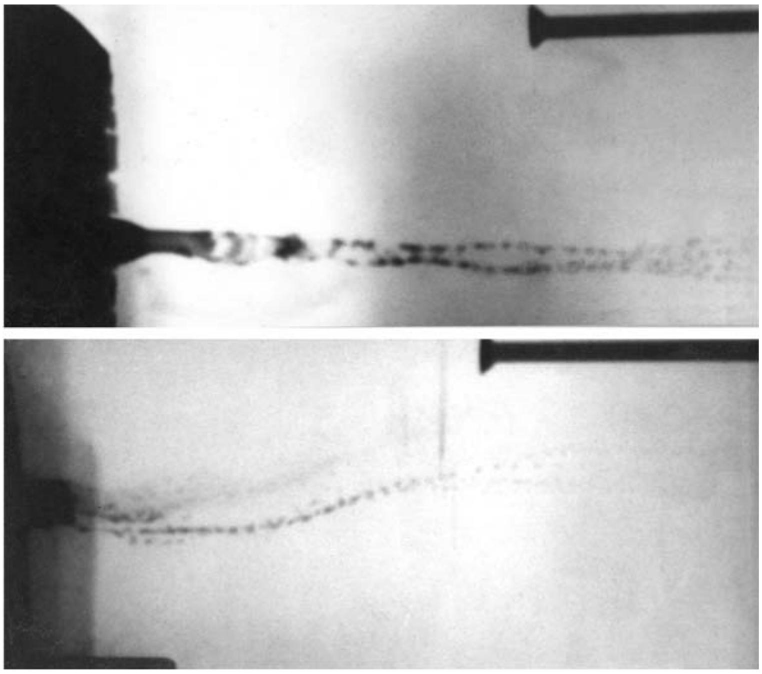

Fig. 3. X-ray photographs of shaped charge jets formed with the generation of a magnetic field in a shaped-charge liner: $B_0 = 0.84$ (a) and 1.4 T (b).

The magnetic field is mainly parallel to the axis of the SC approaching the object if the trajectory of its motion is parallel to the symmetry axis z of the field produced (Fig. 4). In the following, we shall consider exactly these approach trajectories. In view of (3), the distributions of the longitudinal component B_z and transverse component B_x of the magnetic-induction vector along the given trajectories have the form

$$B_z = \frac{B_s R_0^3}{2} \frac{2z^2 - x^2}{(z^2 + x^2)^{5/2}}, \qquad B_x = \frac{3B_s R_0^3}{2} \frac{xz}{(z^2 + x^2)^{5/2}}. \tag{4}$$

Here the axial coordinate z is reckoned from the center of the object and x is the radial coordinate in the cylindrical coordinates (x, z). From (3) and (4), it follows that the magnetic-field distribution around the examined spherical object is determined by two parameters: the radius of the object R_0 and the magnetic induction at the pole of the sphere B_s. On the surface of the sphere ($r = R_0$), the absolute value of the magnetic induction $B = \sqrt{B_r^2 + B_\theta^2}$ is maximal at the pole of the sphere ($\theta = 0$) and decreases monotonically as its equatorial plane is approached; on the equator ($\theta = 90°$), it is 50 % of the maximum value.

To determine the variation of the magnetic induction in the liner of a SC moving in the specified magnetic field of the spherical object, we use a simplified computational model of two conducting coaxial cylindrical shells of radii R_1 and R_2 and thicknesses δ_1 and δ_2 (Fig. 4), corresponding to the SC case and liner. The system of shells is assumed to be placed in an external axial magnetic field $B_e(t)$, whose variation with time t should obviously be determined by the distribution of the longitudinal component of the magnetic field B_z (4) along the trajectory of approach of the SC and the SC velocity v_0:

$$B_e(t) = B_z(z(t)) = \frac{B_s R_0^3}{2} \frac{2(z_0 - v_0 t)^2 - x^2}{((z_0 - v_0 t)^2 + x^2)^{5/2}}. \tag{5}$$

Here the initial coordinate SC z_0 ($z = z_0 - v_0 t$) is chosen at a sufficient distance from the object (where the magnetic field is nearly absent). Under the assumption of a uniform distribution of the azimuthal induction currents over the shells thicknesses [5], the current densities in the outer and inner shells (j_1 and j_2, respectively) are given by the formulas

$$j_1 = (B_1 - B_e)/(\mu_0 \delta_1), \qquad j_2 = (B_2 - B_1)/(\mu_0 \delta_2),$$

where $\mu_0 = 4\pi \cdot 10^{-7}$ H/m is the magnetic constant, and B_1 and B_2 are the magnetic induction in the gap between the shells and in the cavity of the inner shell, respectively (Fig. 4). Writing the Faraday of electromagnetic induction

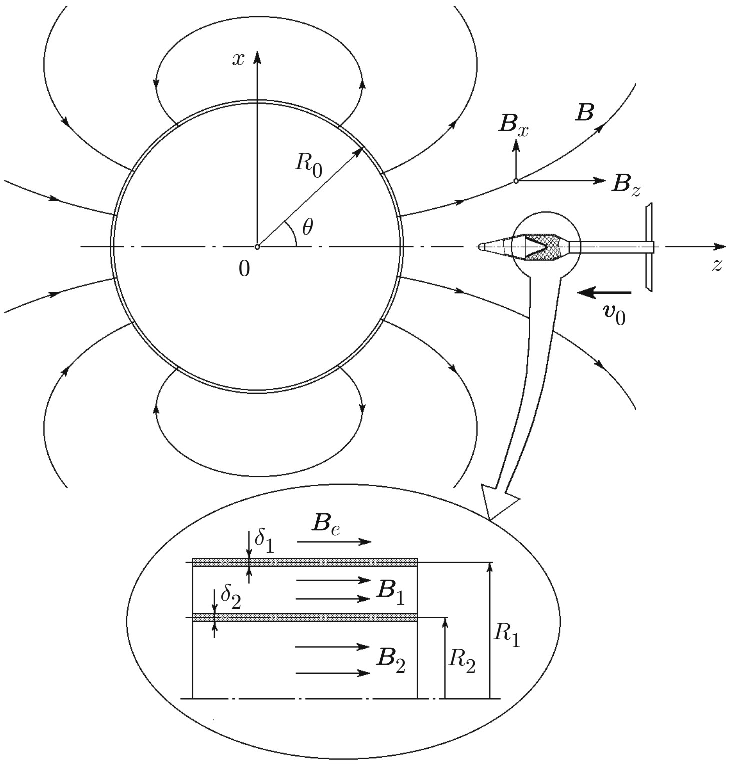

Fig. 4. Computational model for determining the magnetic induction in the liner of a shaped charge moving in a magnetic field.

law for each shell, we obtain the following system of ordinary differential equations for the evolution of the quantities B_1 and B_2:

$$\frac{dB_1}{dt} = \frac{2\eta_1 R_1}{\mu_0\delta_1(R_1^2 - R_2^2)}\,(B_e - B_1) - \frac{2\eta_2 R_2}{\mu_0\delta_2(R_1^2 - R_2^2)}\,(B_1 - B_2),$$

$$\frac{dB_2}{dt} = \frac{2\eta_2}{\mu_0\delta_2 R_2}\,(B_1 - B_2)$$

(η_1 and η_2 are the specific resistances of the materials of the outer and inner shells, respectively). For the further analysis of the calculation results, we write this system as

$$\frac{dB_1}{dt} = \frac{1}{1-\alpha^2}\Big(\frac{B_e - B_1}{\tau_1} - \alpha^2\frac{B_1 - B_2}{\tau_2}\Big),$$
$$\frac{dB_2}{dt} = \frac{B_1 - B_2}{\tau_2}, \tag{6}$$

where τ_1 and τ_2 are the characteristic times of diffusion of the magnetic field [5] for the outer and inner shells:

$$\tau_1 = 0.5\mu_0\delta_1 R_1/\eta_1, \qquad \tau_2 = 0.5\mu_0\delta_2 R_2/\eta_2, \tag{7}$$

$\alpha = R_2/R_1$ is the ratio of the radii of the inner and outer shells.

System (6) was integrated numerically under zero initial conditions for the magnetic inductions B_1 and B_2 and the law of variation of the external field B_e in the form of (5). In the calculations, four types of systems of shells (Fig. 4) corresponding to real SCs were considered. In all cases, it was assumed that the outer shell (SC casing) was made of aluminum ($\eta_1 = 2.8\cdot 10^{-8}\ \Omega\cdot$ m) and the inner shell (shaped-charge liner) was made of copper ($\eta_2 = 1.75\cdot 10^{-8}\ \Omega\cdot$ m). The cross-sectional dimension of the inner shell corresponded to the average cross-sectional dimension of conical shaped-charge liners [in particular, the dimensionless parameter α in system (6) was set equal to 0.5]. The examined systems of shells were referred to four types of SC (below denoted as SC-1, SC-2, SC-3,

TABLE 1

Parameters of Equivalent Systems of Conducting Shells
for Various Shaped Charges

Type of SC	R_1, mm	R_2, mm	δ_1, mm	δ_2, mm	τ_1, msec	τ_2, msec
SC-1	35.0	17.5	1.1	1.2	0.86	0.75
SC-2	50.0	25.0	1.6	1.9	1.79	1.70
SC-3	65.0	32.5	2.0	2.2	2.92	2.57
SC-4	80.0	40.0	2.5	2.8	4.49	4.02

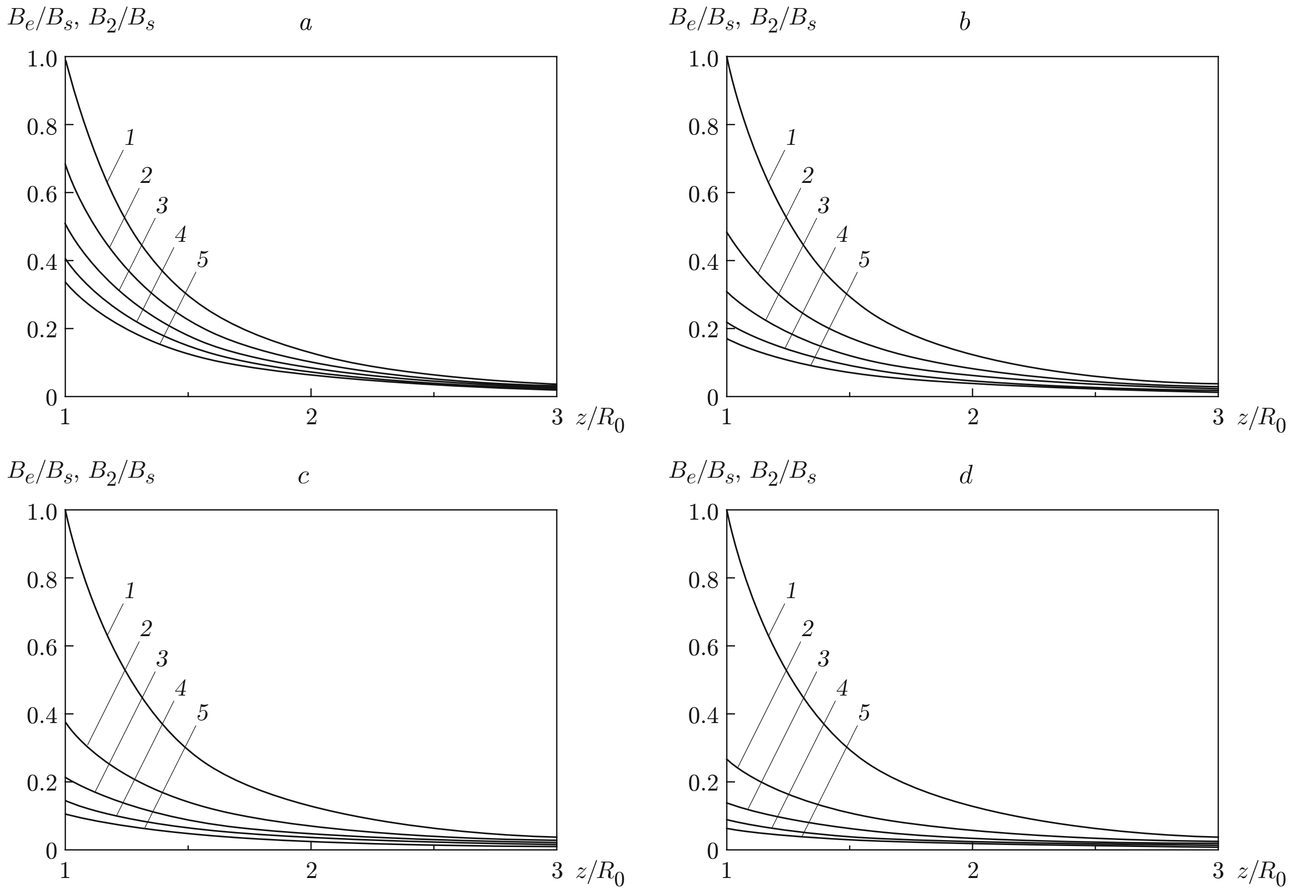

Fig. 5. Magnetic-field distribution along the symmetry axis in the liners of SC-1 (a), SC-2 (b), SC-3 (c), and SC-4 (d) approaching the spherical source: curves 1 refer to the B_e/B_s and curves 2–5 refer to the B_2/B_s for $v_0 = 100$ (2), 200 (3), 300 (4), and 400 m/sec (5).

and SC-4). Table 1 gives the geometrical dimensions of the shells used in the calculations for each type of SC and the characteristic times of diffusion of the magnetic field calculated by (7) (the dimension R_1 of the outer shell determines the diameter of the corresponding type of SC). For all SCs, the range of the velocities v_0 of approach to the object was 100–400 m/sec.

Figure 5 shows the variation of the external field B_e (5) and the field B_2 in the cavity of a shaped charge liner for approaching SCs of various types versus their current coordinate z relative to the center of the spherical object (see Fig. 4) for SCs moving along the symmetry axis of the field ($x = 0$). The radius of the spherical object R_0 (which determines the dimension of the region with the magnetic field) is set equal to 1 m. From Fig. 5, it follows that an increase in the SC velocity leads to a reduction in the induction of the field penetrating into the liner. However, for SC-1 (diameter 70 mm) over the entire range of approach velocities considered, the liner-field induction B_2 remains fairly close to the external-field induction (even at a velocity $v_0 = 400$ m/sec, the value of

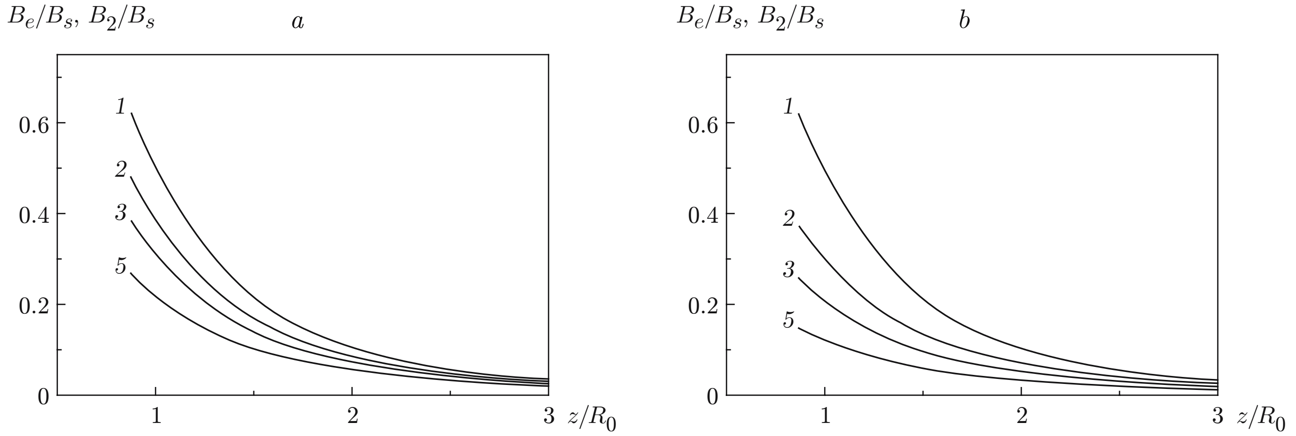

Fig. 6. Magnetic-field distribution in the liners of SC-1 (a) and SC-2 (b) approaching the spherical source along the straight line parallel to the symmetry axis and separated from it by a distance equal to half the radius of the source (notation the same as in Fig. 5).

B_2 is more than 30% of the value of B_e). For SC-2 (diameter 100 mm), the liner field induction at the maximum velocities of motion decreases and is about 17% of the induction of the field produced by the object. As regards SC-3 and SC-4 (diameters 130 and 160 mm, respectively), at supersonic velocities of their approach ($v_0 = 400$ m/sec), the magnetic-field intensity in the liner is only 5–10% of the magnetizing-field intensity. At velocities of SC-3 and SC-4 close to $v_0 = 100$ m/sec, the intensity increases to values $(0.25–0.35)B_e$. Figure 6 shows the variation of the fields B_e and B_2 for SC-1 and SC-2 approaching the spherical object along the straight line parallel to the z axis and separated from it by a distance $x = 0.5R_0$. The induction of the longitudinal field B_e (5) produced by the object on this straight line is lower than that on the symmetry axis. As a result, at the time the charge approaches the boundary of the object, the liner-field induction B_2 for SC-1 is 25–50% of the maximum of the field B_s at the pole of the object, and for SC-2, it is 15–35%.

An analysis of the calculation results shows that the effectiveness of field penetration into the SC liner depends on the ratio of the characteristic time of field diffusion for the SC casing–liner system and the characteristic time τ_m of residence of the SC in the region with the magnetic field. For the spherical field source considered (see Fig. 4), the time τ_m can be determined from the formula $\tau_m = R_0/v_0$. For $R_0 = 1$ m and $v_0 = 100–400$ m/sec, we have $\tau_m = 2.5–10.0$ msec. If the sum of the times τ_1 and τ_2 is taken to be the characteristic time of field diffusion for the SC casing–liner system liner, then, from the of data of Table 1, it is easy to determine the required time τ_m of magnetization for various types of SC: for effective penetration of the field into a liner, it is necessary that the value of τ_m be several times larger than the characteristic time of field diffusion. This condition can be used to determine the necessary extent of the region with the magnetic field and, hence, the dimensions of the field source.

Information on the intensity of the liner field that neutralizes the SC action is important to determine the parameters of the field source intended to counteract concrete types of SC. As noted above, in the experiments with 50-mm diameter SCs [1], a factor of more than two decrease in the penetration of SCJ into a steel target is observed when the magnetic-field induction in the liner is a few tenths of a tesla. The calculations suggest that as the SC diameter increases, shaped-charge action will be absent at a weaker initial field in the liner (an increase in the liner dimensions leads to an increase in the rate of field pumping in the jet-formation region during liner collapse due to a decrease in the rate of diffusion processes). Therefore, for real SCs, the neutralization effect can be achieved by producing a field with an induction of a few tenths of a tesla in a shaped-charge liner at the moment of firing. If this assumption is valid (confirmed experimentally), the proposed method of magnetic protection of objects against shaped-charge warheads can be easily and effectively implemented by using electromagnets with ferromagnetic cores as magnetic-field sources. The maximum intensity of the magnetic field produced by such electromagnets is determined by the saturation induction of the core, which can reach 1.5–2.0 T [6]. Setting $B_s \approx 1.5$ T in the computational scheme, one finds that at a magnetic-sphere radius $R_0 = 1$ m, the magnetic induction B_2 in the liner for SC-1 and SC-2 approaching the sphere surface is not less than 0.4 and 0.3 T, respectively. As the sphere radius increases to $R_0 = 2$ m, the accompanying expansion of the surrounding magnetic region allows the liner of SC-3 to be magnetized to 0.3 T by the moment of contact, and the liner of SC-4 to 0.2 T even if the approach velocity of these SCs is at the level $v_0 = 400$ m/sec.

Conclusions. The calculations show the fundamental possibility of implementing the magnetic screening of objects against SC action. We note that the normal operation of a SC can be disturbed by producing not only a longitudinal (axial) magnetic field (considered in the present paper) but also a transverse field in the liner. If a magnetic field perpendicular to the liner axis is generated in the liner, the field can be amplified in the jet-forming layer of the liner during collapse, resulting in no jet formation. The indicated circumstance can significantly simplify the implementation of magnetic screening of objects since in the case of its experimental confirmation, there will be no need to trace the mutual orientation of the magnetic-induction lines of the protective field produced and the axis of the approaching SC.

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