UDC 623-4 DOI: 10.18698/0236-3941-2020-2-76-87

INFLUENCE OF GEOMETRIC FEATURES OF THE PERIPHERAL PART OF THE THIN-WALLED SPHERICAL SEGMENT ON THE EXPLOSIVE THROWING PROCESS

M.A. Baburin[1]
V.D. Baskakov[1]
S.V. Eliseev[2]
K.A. Karnaukhov[1] karnaukhov93@mail.ru
V.A. Tarasov[1]

[1] Bauman Moscow State Technical University, Moscow, Russian Federation
[2] Mechanical Engineering Research Institute named after V.V. Bahirev, Moscow, Russian Federation

Abstract

The main factors controlling the formation of the stern of explosively formed projectiles are investigated using numerical calculations in a three-dimensional formulation of a problem. To form folds in the stern, it is proposed to use thin-walled spherical segments with a peripheral thickness deviation in terms of decreasing or increasing with respect to the thickness in the central part. The configurations of explosively formed projectiles with inclined folds in the stern are shown, and it is proposed to describe the fold inclination by two angles of its position. The effect of folds in the stern on the change in aerodynamic coefficients for a wide range of angle of attack is numerically studied. The angular velocity of the axial rotation of explosively formed projectiles with inclined folds in the stern is estimated based on the Newton method and considering the angles of its position. The results obtained are of interest to specialists working in the field of physics of explosion and high-speed impact, as well as those dealing with aerodynamics of aircrafts, mainly of axisymmetric shape

Keywords

Spherical segment, liner, explosive throwing, explosively formed projectile, folded stern

Received 04.09.2019
Accepted 17.09.2019

Introduction. Explosive throwing of a thin-walled spherical segment (liner) is widely used in various fields of technology to form an explosively formed projectile (EFP), capable of retaining kinetic energy and shape when it moves in air over long distances. The physics of the EFP formation is described in fundamental works [1, 2]. However, the effectiveness of their use is reduced by the disturbing effect of technological factors, which results in a change in the interaction angles of the EFP with the obstacle [3]. Moreover, the EFP trajectory become curved due to angular impact of aerodynamic forces.

EFP flight stability can be enhanced by designing a developed conical stern [3–5]. However, the techniques to control the geometry of the EFP stern are poorly studied. At the same time, the developed stern causes intense braking in the air and the loss of kinetic energy.

In some studies, an increase in flight stability was provided by the creation of a folded stern. Such an EFP stern can be formed due to the multipoint initiation or corrugation of the peripheral part of the spherical segment [5–8].

However, the EFP asymmetry leads to its radial drift. Axial rotation is used to counter this phenomenon [2]. Within the problem of increasing the stability of EFP flight, axial rotation can be ensured by the creation of inclined folds, but the formation of them requires special study, since the folds should not be in the shadow zone of the midsection and protrude too far beyond the EFP head. In [4], inclined folds were proposed to be formed by cover plates. However, the cover plate is an additional source of technological disturbances; therefore, it seems rational to form folds in the EFP stern by changes in the geometric parameters of the liner.

The purpose of this paper is to study the factors controlling the formation of the EFP stern and the impact of these factors on the EFP braking in the air.

Numerical analysis of the formation process of a developed folded stern. The study of the EFP formation process during explosive throwing of the liner was carried out by the finite element method in a three-dimensional Lagrange formulation in the LS-DYNA software package [6–10]. The system of resolving equations considering the laws of conservation of mass, momentum and energy was taken in the classical form [8, 10]. The material state equations that close this system and also mesh elements in numerical calculations for the LS-DYNA software package were taken in accordance with the recommendations in the works [9, 11–17].

The performed calculations showed that the shape of the EFP stern significantly depends on the geometry of the forming liner thrown by the explosion. It was determined that using liner of variable curvature at the base forms an EFP with a developed stern (Fig. 1), but at that the EFP length decreases [17].

The formation of folds in the EFP stern was studied on liners of variable curvature (Fig. 2). The body of the laboratory charge for explosive throwing and liners are made of plastic steels, and the composition TG-40/60 was taken as an explosive. The initiation point was located on the axis of the charge [9].

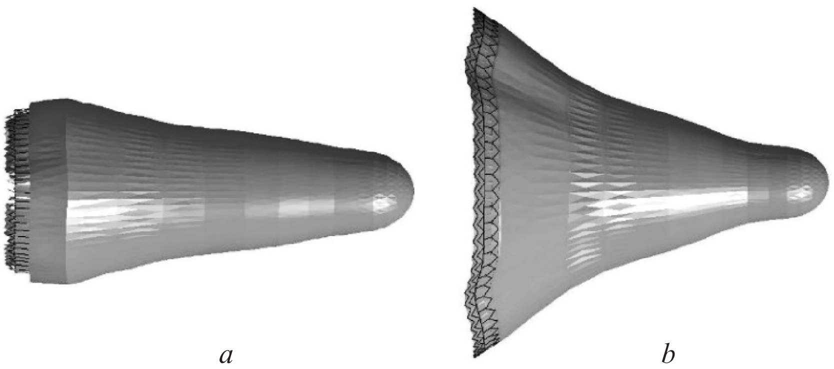

Fig. 1. Configuration of the EFP formed as a result of the explosive throwing:
a is liners of constant curvature; *b* is liners of variable curvature

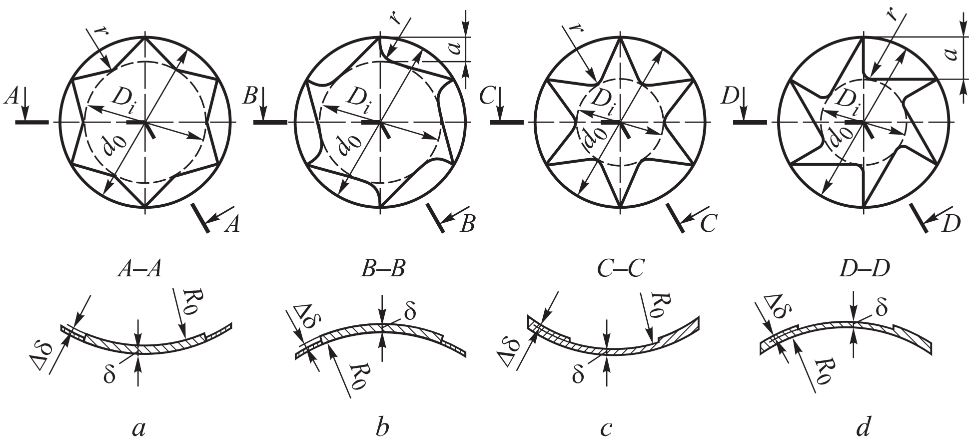

Fig. 2. Liner configuration variants with thickness deviations repeated in the circumferential direction in the form of symmetrical and asymmetric triangular sectors on the inner (*a*, *c*) and outer (*b*, *d*) surfaces; with a negative thickness deviation at $D_i = 3d_0/4$ (*a*, *b*) and a positive thickness deviation at $D_i = d_0/2$ (*c*, *d*); $a = d_0/8$ (*b*), $d_0/4$ (*d*); *r* are fillet radius; d_0, R_0, δ are geometric parameters of the liner

The liners had a diameter $d_0 = 65$ mm, a radius of curvature $R_0 = 50$ mm and a nominal thickness $\delta = 2.2$ mm. In the peripheral part of the liner, a thickness deviation $\Delta\delta = 0.1$ mm was created in terms of decreasing or increasing with respect to the thickness of the central part. Thickness deviation was created in triangular sectors located on the periphery of the liner. In accordance with [9], their number is taken equal to $n = 6$. Triangular sectors had a symmetric (Fig. 2, *a*, *c*) and asymmetric (Fig. 2, *b*, *d*) shape on the surface of the liner.

The diameter of the circle D_i inscribed in the contour of the sectors and the smaller side of the triangle a (for asymmetric sectors) was chosen as the geometric parameters of the triangular sectors.

Calculations showed that using such liners in explosive throwing causes the formation of the EFP with a developed folded stern that protrudes beyond the cross section of the element head (Fig. 3). From the symmetrical triangular sectors, the stern is formed with straight folds (Fig. 3, *a*, *b*, *e*, *f*), and from the asymmetric sectors — with inclined folds (Fig. 3, *c*, *d*, *g*, *h*). Thickness deviations in the peripheral part of the liner significantly affects the formation of folds in the stern: narrow folds and wide cavities between them are formed in triangular sectors from liners with positive thickness deviations, and vice versa, wide folds and narrow cavities — from liners with negative thickness deviations. This conclusion is universal and applies to liners with a thickness deviation in the region of symmetric and asymmetric sectors [9]. According to the stern diameter and length of the EFP with folds, they occupy an intermediate position between the EFP without folds from the liners of constant and variable curvature (Fig. 2, 3).

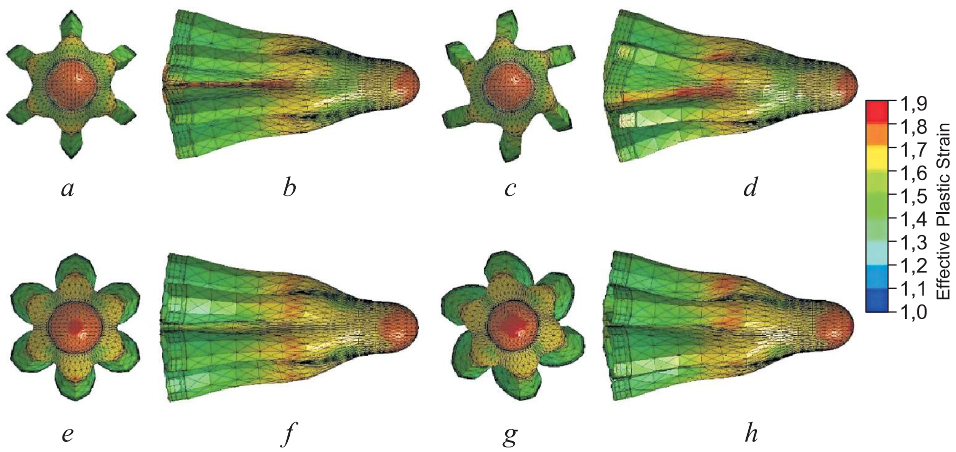

Fig. 3. The distribution of plastic deformation on the surface of the EFP formed from the liner with thickness deviations on the inner surface for a time t = 135 μs from the moment of initiation (Δδ = 0.1): with symmetric (*a*, *b*, *e*, *f*) and asymmetric (*c*, *d*, *g*, *h*, with $a = d_0/4$) triangular sectors and negative (*a*, *b*, *c*, *d*) and positive (*e*, *f*, *g*, *h*) thickness deviations; view from the toe (*a*, *c*, *e*, *g*) and from the cavities side (*b*, *d*, *f*, *h*)

The calculations also showed that with a negative thickness deviation in the peripheral region, a decrease in the diameter of the inscribed circle D_i leads to an increase in the plastic strain rate $\overline{\varepsilon}_p$, which can cause early fracture of the EFP in the axial direction, and also lead to a decrease in its length and an increase in the height of folds in the stern [9, 13, 14]. With a positive thickness deviation in the peripheral region, the opposite tendency is observed. The twisting of the EFP head relative to the stern with inclined folds leads to an additional increase in plastic deformations $\overline{\varepsilon}_p$, which can also negatively affect its integrity (Fig. 3). In addition, a difference in the axial initial velocities of the EFP movement is observed: the EFPs formed from the liners with a negative thickness deviation have a higher velocity than the analogous EFPs formed from the liners with a positive thickness deviation. When creating a thickness difference on the inner surface of the liner, higher folds are obtained [9].

The calculations showed that the use of asymmetric triangular sectors provides the appearance of the fold inclination angle α_c relative to the EFP symmetry axis and the fold inclination angle β_c relative to the contour of the EFP cross section (Fig. 4, *a*). With increasing side *a* in liners with a negative thickness deviation in asymmetric triangular sectors, the angle α_c increases, and the angle β_c takes a minimum value. In liners with a positive thickness deviation, the reverse trends in the change of the angles α_c and β_c are noted.

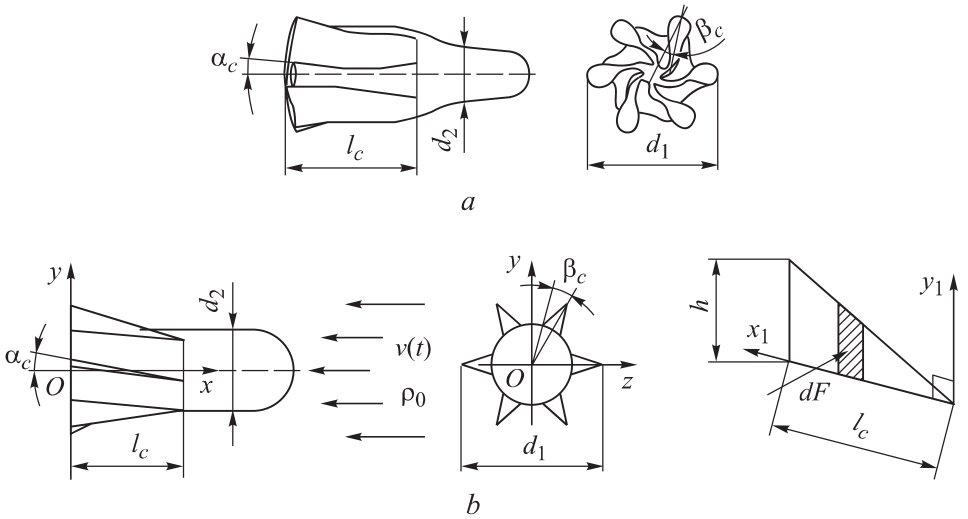

Fig. 4. EFP configuration (*a*) and its analytical model (*b*):
d_1 is stern diameter; d_2 is head diameter; ρ_0 is free air stream density; l_c is fold length; *h* is fold height; *dF* is elementary force acting on a fold

It should also be noted that the sign of the fold inclination angle α_c in the stern changes with the transition from negative thickness deviations of the liner to positive ones (Fig. 3, *c*, *g*).

Analysis of the EFP interaction with the free air stream. The aerodynamic forces that occur during the airflow around the EFP with folds in the stern, reduce the EFP oscillation in pitch and yaw, as well as reduce radial drift.

During research, the geometrical shapes of EFP obtained in the LS-DYNA software package were exported to the SolidWorks Flow Simulation software environment. Airflow around the EFP was described by a system including the continuity equation, the Navier — Stokes equations in the classical form of the three-dimensional Euler formulation (the gravitational acceleration value was neglected) [18]. To solve the system of equations, the finite volume method was used.

The origin of coordinates was located in the EFP tip, the system of equations was solved using the k–ε turbulence model, the free air stream velocity was taken to be v = 6 M, and the turbulence intensity was taken to be 1–2 % [19]. The standard air parameters loaded into the SolidWorks Flow Simulation software package were used. The selected software environment proved itself to be good for estimation of the aerodynamic characteristics of bodies with stream velocities $v \geq 4$ M, which is indicated by satisfactory agreement of the results of numerical calculations and experiments [19–21].

The aerodynamic coefficients were estimated for EFPs from liners with a negative thickness deviation in the region of triangular sectors with $D_i = d_0 / 2$ and $a = d_0 / 4$. Aerodynamic coefficients in accordance with [19–21] were determined as follows:

$$c_x = \frac{F_x}{q_\infty S_{\text{mid}}}; \; c_y = \frac{F_y}{q_\infty S_{\text{mid}}}; \; m_z = -\frac{M_z}{q_\infty S_{\text{mid}} L_{\text{ref}}}; \; CP = -\frac{m_z}{c_y}, \qquad (1)$$

where c_x is axial force coefficient; c_y is normal force coefficient; m_z is pitching moment coefficient; CP is relative coordinate of the pressure center; F_x, F_y are projection of elementary force due to excess normal pressure and acting on the EFP surface; q_∞ is impact air pressure; S_{mid} is EFP midsection area (the largest cross-sectional area of the body formed by a plane perpendicular to the reference axis of the body); L_{ref} is EFP reference length.

In numerical calculations, the position of the coordinate plane with respect to the EFP folds varied: in one variant, the position of the coordinate plane coincided with the fold, and in the other one — with the cavity. Aerodynamic coefficients were calculated as arithmetic mean values of these variants. The pitching moment coefficient in accordance with [20] was assumed to be negative, i.e., $m_z \leq 0$.

Figure 5 shows the calculated values of the aerodynamic coefficients for the EFP formed from the liner of variable (curves *2–4*) and constant curvature (curve *1*).

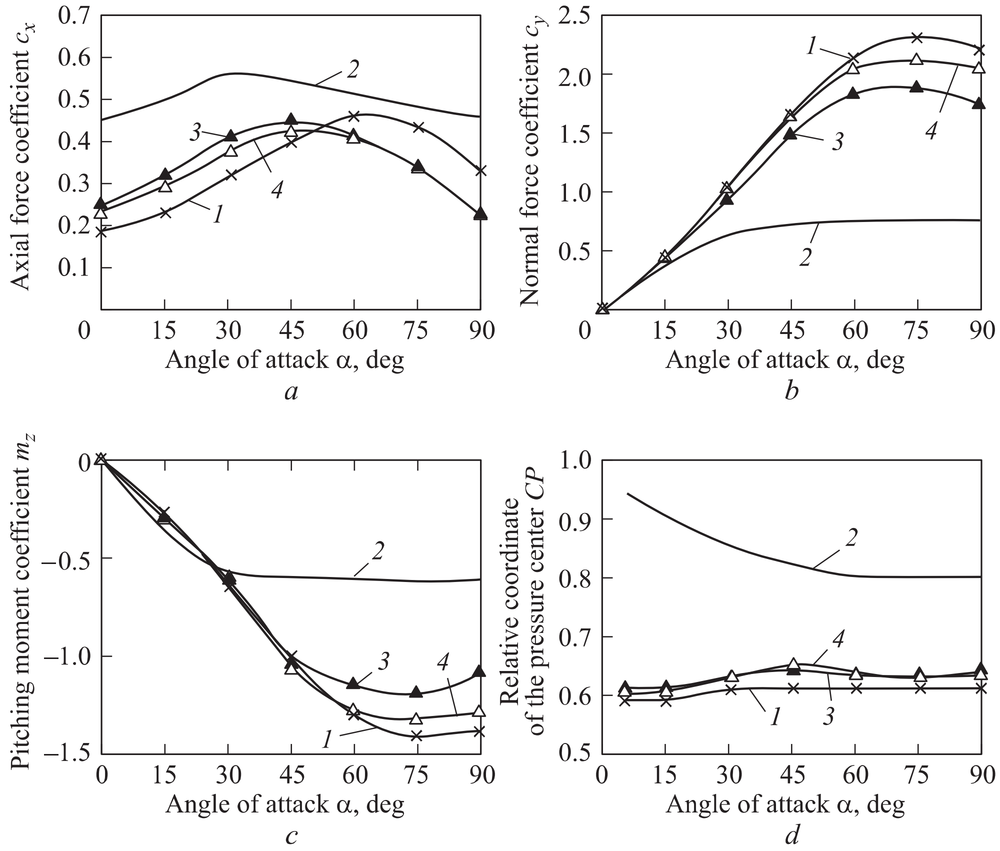

Fig. 5. Dependency graphs of aerodynamic coefficients on the EFP angle of attack:
1 and *2* are axisymmetric EFP formed from the liner of constant curvature and with a developed conical stern formed from the liner of variable curvature;
3 and *4* are EFP with inclined and straight folded stern formed from the liner of variable curvature with a negative thickness deviation in symmetric and asymmetric triangular sectors

All aerodynamic forces and force moments have the maximum values for the EFP formed from the liner of variable curvature. The minimum values of the aerodynamic forces and moments are characteristic of the EFP formed from a liner of constant curvature. However, the obtained values of the axial, normal force and pitching moment coefficients have a seemingly contradictory tendency for an angle of attack of more than 30° (curves *1*, *2*, Fig. 5, *b*, *c*). This phenomenon is related to the difference in the areas of the midsection of the considered EFP: it is much larger for EFPs formed from liners of variable curvature.

Folds forming is accompanied by a decrease in the area of EFP midsection. Therefore, in the range of angles of attack of 45–60°, the axial aerodynamic force of the EFP with folds turns out to be lower (curves *3*, *4*, Fig. 5, *a*) than the force of the EFP formed from the liner of constant curvature (curve *1*). At the same time, the surface area of the folds provides larger values of the normal force and pitching moment, and therefore, lower values of the aerodynamic coefficients of the EFP formed from the liner of constant curvature (curves *3*, *4*, Fig. 5, *b*, *c*). This phenomenon is also due to intense compression of the folded EFP stern (a decrease in the midsection area). Therefore, to increase the normal aerodynamic force and pitching moment, it is reasonable to increase the midsection area by increasing the height or width of the fold.

An important stage of the study is the analysis of the free stream interaction with the inclined folds of the EFP using the Newton method. As the main hypothesis, it was assumed that the medium flowing around the body consists of particles located at equal distances and not interacting with each other. When they collide with an element of the body surface, the particles change the normal to the element component of their momentum (Fig. 4, *b*), as a result of which the flow pressure force on the body arises. This approach made it possible to obtain the dependence of pressure at a surface point on the angle of the flow interaction with the streamlined surface [19–21].

The moment of force acting on the inclined folds in the stern and rotating the EFP around the OX axis is determined in accordance with the model shown in Fig. 4, *b*, as follows:

$$M_n(t) = n\int_0^{l_c} P_0(t)y_1(x_1)\cos\alpha_c\cos\beta_c\left(\frac{y_1(x_1)}{2}\cos\beta_c + \frac{d_2}{2}\right)dx_1, \qquad (2)$$

where $P_0(t) = \rho_0 v^2(t)\sin^2\alpha_c\cos\beta_c$ is pressure acting on the fold of the stern; $y_1(x_1)$ is function describing the fold edge.

When constructing dependence (2), the fold thickness was not taken into account (Fig. 4, *b*). The time interval from the moment of the charge initiation to the formation of the steady-state EFP configuration was not taken into account.

The acting moment of aerodynamic forces causes the rotation of the EFP about its longitudinal axis with an angular velocity:

$$\omega(t) = \int_0^{t_e} \frac{M_n(t)}{J_0}dt, \qquad (3)$$

where t_e is end time, J_0 is axial moment of inertia.

Substituting (2) into (3) and assuming that the fold has a triangular shape, we finally obtain the expression for estimating the angular velocity:

$$\omega(t) = l_c h n \rho_0 \sin^2 \alpha_c \cos \alpha_c \cos^3 \beta_c \frac{2h \cos \beta_c + 3d_2}{12 J_0} \int_0^{t_e} v^2(t) dt. \quad (4)$$

Figure 6 shows the results of calculating the angular velocity under the assumption that the free stream velocity varies in time in a linear fashion and decreases from v_0 = 7 M to v_e = 6 M:

$$v(t) = v_0 - (v_0 - v_e) t / t_e, \quad (5)$$

where $t_e = 1750\, d_0 / v_0$ is adopted instant of time corresponding to the completion of the EFP flight; M is Mach number.

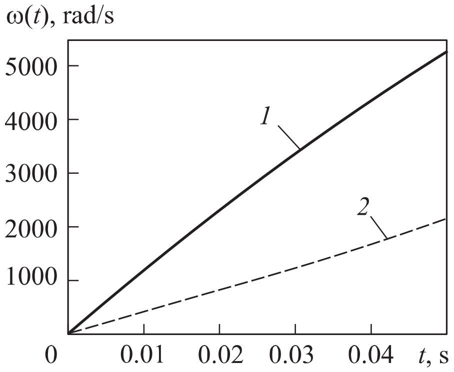

Fig. 6. Dependence of the angular velocity ω on time *t* of the EFP with inclined folds in the stern, formed from the liner with asymmetric triangular sectors with negative (curve *1*, $\alpha_c = \pi/15$; $\beta_c = \pi/30$) and positive (curve *2*, $\alpha_c = \pi/24$; $\beta_c = \pi/12$) thickness deviations

An analysis of the results showed that the EFP formed from liners with a negative value of thickness deviation in asymmetric triangular sectors is more strongly twisted by the free air stream than the EFP formed from liners with a positive value of thickness deviation. The difference in rotation speeds is due to the difference in the inclination angles α_c and β_c of the folds formed from different liners. With an increase in the angle α_c, the angular velocity of EFP rotation about the longitudinal axis increases, and an increase in the angle β_c leads to a decrease in the angular velocity. This is due to the fact that an increase in the angle α_c leads to an increase in the free air stream pressure on the surface of the inclined fold, and a change in the angle β_c causes a reverse effect.

The obtained estimated values of the angular velocity of the axial rotation ω (*t*) do not contradict previous studies and indicate the possibility of additional stabilization of the EFP during flight, which ultimately reduces the effects of the disturbing action of technological factors [4].

Conclusions. 1. The EFP with a developed stern, protruding beyond its head, is formed from the liner of variable curvature during explosive throwing.

2. The EFPs with straight and inclined folds in the stern are formed from the liner of variable curvature and thickness deviation in triangular symmetric or asymmetric sectors of the peripheral part.

3. The thickness of the folds in the EFP stern and the width between them can vary widely due to the configuration of the areas in the peripheral part of the liner with a deviation of its thickness from the nominal value.

4. An increase in the area of regions with a negative thickness deviation from the nominal value leads to an increase in the plastic deformation $\overline{\varepsilon}^p$ of the EFP head, which can lead to its destruction in the axial direction. For a positive thickness deviation from the nominal value, the opposite tendency is observed.

5. The twisting of the EFP head relative to its stern during the formation of inclined folds leads to an additional increase in plastic deformation $\overline{\varepsilon}^p$ in the circumferential direction, which may cause its early fracture in the axial direction.

6. The inclined folds of the EFP stern are characterized by two angles — the fold inclination angle α_c relative to the EFP symmetry axis and the fold inclination angle β_c to the contour of the EFP cross section.

7. The axial force coefficient c_x of the EFP with a folded stern is 1.5–2 times less than that of an axisymmetric EFP with a developed conical stern, which reduces the loss of kinetic energy during the flight along the trajectory.

8. For the EFP with straight and inclined folds in the EFP stern, the normal force and pitching moment coefficients, as well as the coordinate of the pressure center, take close values in a wide range of the angle of attack variation.

9. An increase in the fold angle α_c and a decrease in the angle β_c leads to an increase in the EFP rotation speed about the longitudinal axis.

10. The folded stern provides the axial rotation of the EFP with velocities that allow to further stabilize their flight parameters.

Translated by A.E. Kurnosenko

REFERENCES

[1] Orlenko L.P., ed. Fizika vzryva [Explosion physics]. Moscow, Fizmatlit Publ., 2004.

[2] Selivanov V.V., ed. Boepripasy. T. 1 [Munitions. Vol. 1]. Moscow, BMSTU Publ., 2016.

[3] Baskakov V.D., Tarasov V.A., Kolpakov V.I., et al. Assessment method for impact of design errors in explosively formed penetrators construction on hits accuracy and penetration of elongated projectiles. *Oboronnaya tekhnika*, 2010, no. 1-2, pp. 90–97 (in Russ.).

[4] Bender D., Chouk B., Fong R., et al. Explosively formed penetrators (EFP) with canted fins. *Proc. 19th Int. Symp. Ballistics*, 2001, vol. 2, pp. 755–762.

[5] Liu J., Gu W., Lu M., et al. Formation of explosively formed penetrator with fins and its flight characteristics. *Def. Tech.*, 2014, vol. 10, no. 2, pp. 119–123.
DOI: https://doi.org/10.1016/j.dt.2014.05.002

[6] Asmolovskiy N.A., Baskakov V.D., Tarasov V.A. The impact of periodic disturbances on the formation of high-speed rod elements. *Izvestiya vysshikh uchebnykh zavedeniy. Mashinostroenie* [Proceedings of Higher Educational Institutions. Machine Building], 2013, no. 8, pp. 8–14 (in Russ.). DOI: http://dx.doi.org/10.18698/0536-1044-2013-8-8-14

[7] Asmolovskiy N.A., Baskakov V.D., Zarubina O.V. Research into the effect of technological imperfections of meniscus liners on explosive formation dynamics of high-speed rod elements. *Vestn. Mosk. Gos. Tekh. Univ. im. N.E. Baumana, Mashinostr.* [Herald of the Bauman Moscow State Tech. Univ., Mechan. Eng.], 2015, no. 5, pp. 72–86 (in Russ.).
DOI: http://dx.doi.org/10.18698/0236-3941-2015-5-72-86

[8] Asmolovskiy N.A., Baskakov V.D., Boyarskaya R.V., et al. Mathematical modeling of shock loading of the meniscus liner. *Matematicheskoe modelirovanie i chislennye metody* [Mathematical Modeling and Computational Methods], 2016, no. 1, pp. 52–67 (in Russ.).

[9] Baburin M.A., Baskakov V.D., Eliseev S.V., et al. Numerical analysis of the controlled loss of stability of meniscal form liners at high-speed collapse. *Herald of the Bauman Moscow State Technical University, Series Natural Sciences*, 2019, no. 4, pp. 22–39 (in Russ.).
DOI: http://dx.doi.org/10.18698/1812-3368-2019-4-22-39

[10] Babkin A.V., Selivanov V.V. Osnovy mekhaniki sploshnykh sred [Fundamentals of continuum mechanics]. Moscow, BMSTU Publ., 2004.

[11] Johnson G.R., Stryk R.A. Some considerations for 3D EFP. *Int. J. Impact Eng.*, 2006, vol. 32, no. 10, pp. 1621–1634. DOI: https://doi.org/10.1016/j.ijimpeng.2005.01.011

[12] Liu J.F., Long Y., Ji Ch., et al. Numerical and experimental study on the formation and dispersion patterns of multiple explosively formed penetrators. *Lat. Am. J. Solids Struct.*, 2017, vol. 14, no. 4, pp. 685–699. DOI: http://dx.doi.org/10.1590/1679-78253385

[13] Hallquist J.O. LS Dyna theory manual. Livermore, LSTC, 2005.

[14] LS Dyna keyword user's manual. Livermore, LSTC, 2007.

[15] Baskakov V.D., Karnaukhov K.A. Research into the process of impingement of two plane jets of an ideal fluid with free boundaries. *J. Phys.: Conf. Series*, 2016, vol. 731, no. 1, art. 012002. DOI: https://doi.org/10.1088/1742-6596/731/1/012002

[16] Li V., Van S., Li V., et al. Research on the skirt tail explosively formed projectile stable shaping technology. *J. Appl. Mech. Tech. Phy.*, 2016, vol. 57, no. 5, pp. 894–899.
DOI: https://doi.org/10.1134/S0021894416050175

[17] Kruglov P.V., Kolpakov V.I. Mechanism of explosive formation of high-velocity elongated projectiles from steel segment lining. *Inzhenernyy zhurnal: nauka i innovatsii* [Engineering Journal: Science and Innovation], 2017, no. 12 (in Russ.).
DOI: http://dx.doi.org/10.18698/2308-6033-2017-12-1714

[18] Cengel Y.A., Cimbala J.M. Fluid mechanics. Fundamentals and applications. New York, McGraw Hill, 2014.

[19] Asmolovskiy N.A., Baskakov V.D., Tarasov V.A. Numerical and analytical evaluation aerodynamic coefficients of elongated bodies with irregular shape. *Vestn. Mosk. Gos. Tekh. Univ. im. N.E. Baumana, Mashinostr.* [Herald of the Bauman Moscow State Tech. Univ., Mechan. Eng.], 2014, no. 4, pp. 109–122 (in Russ.).

[20] Kalugin V.T., ed. Aerodinamika [Aerodynamics]. Moscow, BMSTU Publ., 2017.

[21] Kalugin V.T., Golubev A.G., Lutsenko A.Yu., et al. Raschet aerodinamicheskikh kharakteristik tel slozhnoy formy pri sverkhzvukovykh skorostyakh obtekaniya [Calculation of aerodynamic characteristics for a complex body at hypersonic ambient velocity]. Moscow, BMSTU Publ., 2012.

Baburin M.A. — Cand. Sc. (Eng.), Assoc. Professor, Department of Aerospace Engineering Technologies, Bauman Moscow State Technical University (2-ya Baumanskaya ul. 5, str. 1, Moscow, 105005 Russian Federation).

Baskakov V.D. — Dr. Sc. (Eng.), Professor, Department of Aerospace Engineering Technologies, Bauman Moscow State Technical University (2-ya Baumanskaya ul. 5, str. 1, Moscow, 105005 Russian Federation).

Eliseev S.V. — Cand. Sc. (Eng.), Head of the Bench Test Laboratory, Mechanical Engineering Research Institute named after V.V. Bakhirev (Leningradskoe shosse 58, Moscow, 125212 Russian Federation).

Karnaukhov K.A. — Post-Graduate Student, Department of Aerospace Engineering Technologies, Bauman Moscow State Technical University (2-ya Baumanskaya ul. 5, str. 1, Moscow, 105005 Russian Federation).

Tarasov V.A. — Dr. Sc. (Eng.), Professor, Department of Aerospace Engineering Technologies, Bauman Moscow State Technical University (2-ya Baumanskaya ul. 5, str. 1, Moscow, 105005 Russian Federation).

Please cite this article as:

Baburin M.A., Baskakov V.D., Eliseev S.V., et al. Influence of geometric features of the peripheral part of the thin-walled spherical segment on the explosive throwing process. *Herald of the Bauman Moscow State Technical University, Series Mechanical Engineering*, 2020, no. 2, pp. 76–87.
DOI: https://doi.org/10.18698/0236-3941-2020-2-76-87