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ANALYSIS OF THE INFLUENCE OF THE LOADING COEFFICIENT AND GEOMETRIC CHARACTERISTICS OF FRAGMENT ELEMENTS ON THE PENETRATION CAPABILITY OF RADIAL-AXIAL HIGH-EXPLOSIVE FRAGMENTATION PROJECTILES

The article examines how the relative explosive charge (loading coefficient) and the fragment shape parameter affect the ballistic effectiveness of radial-axial high-explosive fragmentation shells, with a particular focus on their penetration capability.

The authors analyze existing models aimed at predicting fragment velocities and identify their limitations. They propose new analytical expressions for calculating initial and terminal velocities of fragments. These formulas are based on the uniform distribution of energy according to fragment masses, which offers a more physically justified approach.

The paper determines the critical value of the loading coefficient necessary to ensure the penetration of a standard steel obstacle (3 mm). It presents consideration of the dependence of the depth of a fragment immersion on the value of the loading coefficient, along with the influence of the shape parameter of the fragments. The research reveals a nonlinear nature of this relation and a significant decrease in the penetration capability for elongated fragments.

These results are key to optimizing the design of fragmentation-forming components of projectiles. The shell improvements can increase their lethality against manpower protected by modern means of armor protection.

Keywords: *radial-axial high-explosive fragmentation projectile, loading coefficient, fragment shape parameter, ballistic efficiency, initial fragment velocity, lethal fragment velocity, minimum explosive charge, obstacle penetration depth***.**

Statement of the problem. Despite significant progress in studying the kinetics of fragmentation and the ballistic effects of high-explosive fragmentation projectiles, several fundamental issues remain the subject of active scientific debate. Most existing studies focus on empirical or semi-empirical relationships between penetration depth and fragment mass and velocity. However, the functional connection between certain projectile parameters – such as the loading coefficient – and the characteristics of the shatter threads that determine its penetration capability has not been sufficiently explored.

In particular, the effect of the geometric configuration of fragmentation elements, quantitatively described by the shape parameter, on their ballistic efficiency remains understudied. Common design methodologies often overlook the complex nature of the interaction between fragment shape and the process of its penetration into the obstacle, which can result in suboptimal engineering solutions.

Moreover, traditional models for estimating initial and lethal fragment velocities often ignore the need to ensure a uniform distribution of kinetic energy among fragments of varying mass. This can lead to significant errors when predicting the minimum amount of explosive needed to guarantee target defeat [1]. Therefore, there is a need to develop more robust theoretical approaches that account for the energetic aspects of fragmentation and the ballistic performance of the fragment field. Together with that, it is important to consider mass distributions and geometric characteristics of the fragments.

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The influence of the relative elongation of fragments on their penetration capability has also been insufficiently investigated. Empirical models that include the shape parameter often have a limited range of applicability and require further theoretical substantiation from the standpoint of explosion physics and ballistics. Nevertheless, a quantitative assessment of the decrease in penetration capability for elongated fragments is essential for optimizing the fragmentation process. Such analysis is also crucial for enhancing the effectiveness of fragment fields in radial-axial high-explosive fragmentation (RAHEF) projectiles.

Analysis of recent research and publications. The results of the analysis of scientific literature indicate that, based on research on existing types of projectiles, artillery systems are currently considered the most probable means of engaging enemy personnel. This particular aspect has been thoroughly studied in recent years. Notable contributions to the study of explosive effects and the fragmentation of projectile casings i nto shrapnel fractions have been made by V. Yakovenko, Yu. Sydorenko, I. Chepkov, M. Vaskivskyi, and other researchers.

Scholars have also examined the influence of the loading coefficient and the geometric characteristics of fragment fields in radial-axial high-explosive fragmentation (RAHEF) projectiles. These factors significantly affect their ballistic efficiency, which is quantitatively assessed by the depth of obstacle penetration.

The purpose of the article is to provide a physical justification for a theoretical model that comprehensively describes the influence of the projectile's loading coefficient and the geometric characteristics of fragment fields on their ballistic efficiency, as measured by obstacle penetration depth. The paper also aims to establish quantitative relationships that describe how the loading coefficient and fragment shape parameter affect the penetration depth of a steel-equivalent obstacle by fragment fields of radial-axial high-explosive fragmentation projectiles.

Summary of the main material. When designing RAHEF projectiles, one of the main objectives is to optimize the transfer of energy released during the detonation of the explosive charge (EC) to the fragments. This is done to increase their ballistic efficiency, which directly determines the probability of striking a target. The loading coefficient $\beta = (m_{вр}/M)$ is a key characteristic that reflects the relative content of the EC energy-carrying aspect within the projectile and, accordingly, the potential energy that can be converted into the kinetic energy of the fragmentation field [3, 6]. However, the efficiency of this energy conversion is a complex function of multiple factors. These include the geometric configuration of the RAHEF projectile, the physical and mechanical properties of the shell material, the initiation of the detonation process, and the characteristics of the dynamic material failure, which govern the fragmentation process. Analytical models, such as the semi-empirical Pokrovsky formula, are used to estimate the initial fragment velocity, considering these factors [4, 7]:

$$v_0 = D\sqrt{\frac{\beta}{2+\beta}}, \qquad (1)$$

where D is the detonation velocity of the EC. While this parameter has found wide application in engineering practice, it has a number of fundamental limitations that reduce its predictive capability.

First, these limitations do not account for the energy expenditure associated with irreversible processes of plastic deformation and material failure of the projectile casing during its fragmentation into individual fragments.

Second, they fail to reflect the statistical nature of energy distribution among fragments of varying mass and geometric shape, which is an inherent feature of the fragmentation process. Consequently, when considering the idealized case of complete conversion of detonation energy into the kinetic energy of the fragments, it becomes clear that formula (1) provides only an average estimate of the initial velocity and does not take into account the dispersion of velocities within the fragmentation field. Thus, to develop a more substantiated mathematical framework, it is necessary to examine the energy balance of the detonation and fragmentation processes [3, 4]. The energy released during the detonation of the EC can be expressed as $E_{det} = m_{вр}Q$, where Q is the specific detonation energy per unit mass of the EC. A portion of this energy is expended on the work required for breaking and plastic deformation of the casing material (W_{breake}), while the remainder is converted into the kinetic energy of the fragment field (E_{kin}), which, according to the law of conservation of energy, can be expressed as:

$$m_{вр}Q = W_{breake} + E_{kin}. \quad (2)$$

Since the kinetic energy of the fragment field is the sum of the kinetic energies of individual fragments, it can be expressed as follows [5, 9]:

$$E_{kin} = \sum_i \frac{1}{2} m_i v_{0i}^2. \quad (3)$$

Applying the statistical principle of uniform energy distribution across degrees of freedom (in this case, across fragment masses as a measure of inertia), one can assume that, on average, the kinetic energy assigned to each fragment is proportional to its mass:

$$\frac{1}{2} m_i v_{0i}^2 \approx \frac{E_{kin}}{M_{frag}} m_i, \quad (4)$$

where M_{frag} is the total mass of the fragments, which can be taken as 95–98 % of the mass of the fragment-generating part of the RAHEF projectile (M). From equation (4), the root-mean-square value of the initial velocity of the fragments can be derived:

$$\langle v_0^2 \rangle = \frac{1}{M} \sum_i m_i v_{0i}^2 \approx \frac{2E_{kin}}{M} =$$

$$= \frac{2(m_{вр}Q - W_{breake})}{M} = 2\beta Q - \frac{2W_{breake}}{M}, \quad (5)$$

while the mean value of the initial fragment velocity is given by:

$$\langle v_0 \rangle \approx \sqrt{2\beta Q - \frac{2W_{breake}}{M}}. \quad (6)$$

This formulation is more physically justified than Pokrovsky's equation, as it takes into account the energy expenditure required to fracture the casing, which depends on the material's strength and deformation rate.

To estimate the lethal velocity of an individual fragment, it is necessary to consider its interaction with biological tissue or personal body armor. This is typically done using the semi-empirical Rice model [7], which defines the lethal velocity as:

$$v_{leth} = C \frac{(h\varphi^n)^{1/2}}{m^{1/2}}, \quad (7)$$

where C is an empirical constant dependent on target characteristics (for personnel targets, C≈145);

h is the steel equivalent of the barrier;

φ is the fragment shape parameter;

n is the empirical exponent (usually set to 1/3 to describe penetration resistance or 1/2 to account for cross-sectional area);

m is the mass of the fragment.

The shape parameter φ is a dimensionless quantity that reflects the geometric configuration of the fragment and its orientation relative to the direction of motion. For fragments with complex geometry, this parameter can be determined empirically or based on approximation by a geometric figure with known properties. For a parallelepiped with characteristic dimensions of length a, width b and height c the shape parameter can be approximated by various formulas, one of which is:

$$\varphi \approx \frac{(abc)^{2/3}}{\sqrt{ab+bc+ca}}. \quad (8)$$

The shape parameter calculated by this formula decreases as l increases for elongated fragments characterized by a significant aspect ratio ($l = \sqrt{bc}$ >> 1). This trend indicates a potential reduction in the ballistic efficiency of such fragments, all other factors being equal.

The minimum loading coefficient (β_{msn}) required to achieve penetration of a barrier with a specified steel equivalent h, can be determined by ensuring that the kinetic energy of an average-mass fragment (m_{aver}), with an average initial velocity $\langle v_0 \rangle$, is sufficient to overcome the resistance of the obstacle [2, 3, 8]. The penetration criterion connects the fragment's kinetic energy with its effective work necessary for penetration. The coefficient can be calculated using the following relation:

$$\frac{1}{2} m_{aver} \langle v_0 \rangle^2 \geq A_w S_{aver} f(\varphi), \quad (9)$$

where A_w is the specific work of penetration for the obstacle material;

S_{aver} is the average cross-sectional area of the fragment;

$f(\varphi)$ is the function accounting for the influence of the fragment's shape on the penetration process.

Analyzing the influence of the shape parameter on penetration capability is a complex task. Shape affects both the aerodynamic properties of a fragment in flight (such as air resistance and stability) and the mechanism of its interaction with a barrier (including penetration depth and the nature of the breach). Thus, from equation (9), it is evident that, for effective damage against personnel, the minimum value of the loading coefficient – equivalent to the fragment's kinetic energy relative to its effective work – must exceed the resistance of the obstacle.

Conclusions

The theoretical study presented in this paper has made it possible to develop a more robust mathematical framework for analyzing how the loading coefficient and the geometric characteristics of fragment fields in radial-axial high-explosive fragmentation projectiles influence their effectiveness against targets. The proposed formulas for determining the initial fragment velocity consider the energy expended on casing fragmentation. The study also offers a general approach to calculating the minimum loading coefficient required to penetrate modern individual body armor.

Theoretical findings obtained here are significant for optimizing the design of radial-axial high-explosive fragmentation projectiles. A rational choice of the loading coefficient and ensuring the optimal fragment shape – while accounting for initial velocity, flight stability, and interaction with personnel – are key factors in enhancing the combat efficiency of these munitions.

However, the analysis of the influence of the fragment shape parameter on penetration capability remains a complex issue. The fragment's shape strongly affects both the aerodynamic properties in flight (such as air resistance and stability) and the mechanism of interaction with an obstacle (including penetration depth and the nature of the breach). Thus, elongated fragments, while generally having a smaller cross-sectional area, may demonstrate higher obstacle penetration due to wedge-like penetration mechanics if stable orientation is maintained. At the same time, excessive elongation increases the risk of losing stability, which can result in a cumulative effect and reduce penetration depth.

Future research will focus on further investigating ways to enhance the obstacle penetration capability of radial-axial high-explosive fragmentation projectiles.

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АНАЛІЗ ВПЛИВУ КОЕФІЦІЄНТА НАВАНТАЖЕННЯ ТА ГЕОМЕТРИЧНИХ ХАРАКТЕРИСТИК ОСКОЛКОВИХ ЕЛЕМЕНТІВ НА ПРОБИВНУ ЗДАТНІСТЬ РАДІАЛЬНО-ОСЬОВИХ ОСКОЛКОВО-ФУГАСНИХ СНАРЯДІВ

Досліджено вплив відносного заряду вибухової речовини, що кількісно визначається коефіцієнтом навантаження, та геометричних параметрів осколків природного дроблення, зокрема параметра форм осколка. Це має безпосередній вплив на балістичну ефективність осколкових полів осколкоутворюючих частин радіально-осьових осколково-фугасних снарядів, яка, як правило, проявляється у їхній здатності пробивати перешкоди.

Здійснено аналіз наявних теоретичних моделей, метою яких є прогнозування початкової та убійної швидкостей осколків, виявлено їхні обмеження, пов'язані з розподілом кінетичної енергії в осколковому потоці осколкового поля.

Запропоновано аналітичні вирази для розрахунків початкової та убійної швидкостей осколкових полів осколкоутворюючих частин радіально-осьових осколково-фугасних снарядів, що ґрунтуються на принципі рівномірного розподілу енергії осколків за їхніми масами, тому цей підхід є більш фізично обґрунтованим.

Визначено критичне значення коефіцієнта навантаження осколка, необхідне для забезпечення пробиття типової перешкоди зі сталевим еквівалентом 3 мм.

Проаналізовано залежність глибини занурення осколка відносно величини коефіцієнта навантаження для осколкоутворюючих частин радіально-осьових осколково-фугасних снарядів, включно з мінометними мінами та артилерійськими снарядами різного калібра. Особливу увагу акцентовано на дослідженні впливу параметра форми осколків на їхню пробивну здатність, у результаті чого подано нелінійний характер цієї залежності та виявлено суттєве зниження глибини занурення для осколків видовженої форми. Отримані результати мають значення для оптимізації конструкції осколкоутворюючих частин радіально-осьових осколково-фугасних снарядів з метою підвищення їхніх уражаючих можливостей під час впливу їхніх осколкових полів на живу силу, яка перебуває у сучасних засобах бронезахисту.

Ключові слова: *радіально-осьовий осколково-фугасний снаряд, коефіцієнт навантаження, параметр форми осколка, балістична ефективність, початкова швидкість осколка, убійна швидкість осколка, мінімальний заряд вибухової речовини, глибина пробиття перешкоди.*

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