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Влияние закрутки снаряда-пробойника активно-реактивного типа на глубину проникания его в грунт

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Аннотация. Целью настоящей работы является расчетно-экспериментальная оценка влияния закрутки вокруг собственной оси снаряда-пробойника активно-реактивного типа на параметры его движения и глубину проникания в грунт. Рассмотрены уравнения движения вращающегося снаряда-пробойника активно-реактивного типа (СПАРТ). Проанализированы особенности определения тяги двигателя, вращающегося СПАРТ и силы сопротивления при проникании СПАРТ в грунт с вращением. Проведен сравнительный анализ глубин проникания, вращающегося и невращающегося СПАРТ в суглинок. В результате проведенных исследований разработана математическая модель процесса внедрения снаряда-пробойника активно-реактивного типа в грунт. Показано влияние вращения СПАРТ вокруг собственной оси симметрии на рабочие характеристики двигательной установки. Проведена оценка влияния контактных сил трения между вращающимся СПАРТ и грунтом на параметры его движения и глубину проникания. Расчеты показывают, что за счет раскрутки СПАРТ вокруг собственной оси симметрии, глубина проникания вращающихся снарядов-пробойников активно-реактивного типа в грунт может быть увеличена на 8–10 %. Результаты, изложенные в статье, могут быть полезны для научных работников, аспирантов и инженеров, занятых созданием и эксплуатацией авиационной и ракетно-космической техники, а студентов технических вузов, обучающихся по соответствующим специальностям.

Ключевые слова: закрутка пенетратора, глубина проникания, снаряд-пробойник активно-реактивного типа, параметры движения, тяга двигателя, сила сопротивления.

The influence of the twist of an active-reactive type projectile-piercer on its penetration depth into the soil

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Abstract. The objective of this work is the computational and experimental assessment of the effect of twisting of an active-reactive type projectile-piercer around its own axis on the parameters of its motion and the depth of penetration into the soil. Research methods: the equations of motion of a rotating active-reactive type projectile-piercer (SPART) are considered. The features of determining the engine thrust, rotating SPART and the resistance force during penetration of SPART into the soil with rotation are analyzed. A comparative analysis of the penetration depths of rotating and non-rotating SPART into loam is carried out. As a result of the studies, a mathematical model of the process of penetration of an active-reactive type projectile-piercer into the soil is developed. The effect of SPART rotation around its own axis of symmetry on the performance of the propulsion system is shown. The effect of contact friction forces between the rotating SPART and the soil on the parameters of its motion and the depth of penetration is assessed. Calculations show that by spinning the SPART around its own axis of symmetry, the depth of penetration of rotating active-reactive type projectile-piercers into the soil can be increased by 8–10 %. Conclusion: the results presented in the article can be useful for researchers, postgraduate students and engineers involved in the creation and operation of aviation and rocket and space technology, and can also be useful for students of technical universities studying at the relevant specialties.

Keywords: penetrator twist, penetration depth, active-reactive type penetrator-projectile, motion parameters, engine thrust, drag force.

Introduction

A number of studies [1; 2] devoted to the choice of an effective means of delivering a payload to a given area of a ground half-space (the formation of boreholes) propose the use of an active-reactive type projectile-piercer (SPART), which is installed in the launch tube of a ballistic missile launcher and is ejected in the desired direction by a launching device. Movement through the soil is achieved both by the kinetic energy accumulated during the launch of the SPART from the launcher of the ballistic missile system, and by the thrust of a rocket engine activated as the SPAT penetrates the soil.

Regardless of the ballistic missile's relative soil position and the moment of engine activation, as the SPART passes through the launch tube, the pressure of the propellant gases causes it to move either without spinning or by acquiring rotation around its own axis, i.e., with spinning.

Studies [3–5] demonstrate that the presence of angular velocity of rotation of the SPART around its own axis will significantly affect the entire process of its penetration into the soil. Thus, due to the gyroscopic moment, the stability of the SPART will increase at all stages of its movement in the soil. The operation of the rotating engine will cause a twist in the gas flow emanating from its nozzle, which will ultimately affect the thrust of the propulsion system. Due to the interaction of the rotating structural elements (the head section) with the soil, the drag force of the SPART will change, and, consequently, the total depth of its penetration into the soil.

When using a ballistic launcher with a rifled launch tube to launch the SPART, upon entering thesoil, in addition to the kinetic energy of forward motion, the SPART also acquires torque due to its rotation around its own axis of symmetry. The angular velocity of the projectile upon exiting the artillery mount's barrel reaches its maximum value at the muzzle and is $\omega = 200 - 500$ 1/s (for a bullet $\omega = 3000 - 3500 \frac{1}{s}$). This value ensures stability in the projectile's flight, and the angular velocity then decreases along its trajectory.

In this case, approximately 0.1–0.5 % of the propellant charge's energy is expended on imparting rotational motion in rifled artillery systems. Rotation of the SPART around its own axis can also be achieved using special motors with a tangential component of the reactive force.

The aim of this study is to conduct a computational and experimental assessment of the effect of rotation of the SPART around its own axis on its motion parameters and penetration depth.

Equations of motion of a rotating SPART in the soil

The penetration of a rotating SPART around its own axis into the soil half-space can be represented as a system of two equations, one of which describes the forward movement of the center of mass, and the second describes the rotational motion of the SPART relative to the axis of symmetry passing through its center of mass.

The forward movement of the SPART's center of mass as it penetrates the soil with the engine running can be represented by an equation of the form

$$MV\frac{dV}{dx}=\left(1-k_{rot}\right)R+Mg\sin\theta-F,\tag{1}$$

where M is the current value of the SPART mass; R is the engine thrust; $k_{rot}=0{,}01-0{,}05$ – is a coefficient that takes into account the proportion of the reduction in thrust spent on the rotation of the SPART; V is the speed of movement of the SPART; F is the soil resistance; θ is the angle between the longitudinal axis of the penetrating projectile and the horizontal plane.

The equation of rotation of an active-reactive type projectile piercer around its own axis of symmetry passing through its center of mass has the form

$$I\frac{d\omega}{dt}=-M_{hp}^{br}+M_{ps}^{k},\tag{2}$$

where I,ω is respectively, the moment of inertia and the angular velocity of rotation of the SPART; M_{hp}^{br} is the braking moment from the rotating cone-shaped head part rubbing against the soil.

The magnitude of the braking moment from the rotating head part rubbing against the ground (rotational friction moment) M_{hp}^{br} is taken as proportional to the pressing force and is determined by the formula

$$M_{hp}^{br}=\mu F,\tag{3}$$

where μ is the coefficient of rotational friction, which has the dimension of length and depends on the coefficient of sliding friction μ_0.

For the case of a rotating head part in the form of a cone rubbing against the soil (with half the angle of the head cone β)), the coefficient of rotational friction can be determined by the formula [6]

$$\mu=\frac{\pi}{4}\mu_0\frac{1}{\cos\beta}\frac{D_{ext}}{2}.$$

In this case, the braking torque will be equal to

$$M_{hp}^{br}=0{,}39\frac{\mu_0 D_{ext}}{\cos\beta}F.$$

In the case of using the SPART propulsion system thrust for rotation around its own axis, the rotation moment can be represented by the product of the tangential component of the thrust force $k_{rot}R$ and the outer radius of the engine, $D_{ext}/2$ i.e.

$$M_{ps}^{k}=k_{rot}R\,D_{ext}/2.\tag{4}$$

In this study, the braking moment from the rotating cylindrical part of the SPART construction is not taken into account, since (at the considered forward motion speeds) only its conical part comes into contact with the soil.

The relationship between the speeds of rotation of the SPART around its own axis of symmetry ω and its penetration into the soil V is determined on the basis of Routh's hypothesis on the coincidence of the ratios of the tangential $I\omega$ and normal MV rotation impulses, as well as the tangential and normal components of the reaction forces during dry friction $I\omega = \mu MV$:

$$\omega = \mu \frac{M}{I} V = 0{,}39 \frac{\mu_0 D_{ext}}{\cos\beta} \frac{M}{I} V, \tag{5}$$

where M and I are the mass and moment of inertia of the SPART, respectively.

Features of determining the thrust of the engine, rotating SPART

As a part of the study conducted in the works [3; 5], it was established that for a single nozzle, the formula for the thrust force for a rotating engine can be written as follows:

$$P_{rot} = K_{thr} p_{rot} f_{crit} \varphi_1 \varphi_2 A_{rot}, \tag{6}$$

where K_{thr} is the thrust coefficient; p_{rot} is the pressure in the rotating engine chamber; f_{crit} is the nozzle critical section area; φ_1 = 0.95–0.98 is the nozzle coefficient; $A_{rot} = f\left(\alpha_{crit}\right)$ is the flow rate coefficient for rotating gas outflow; $\varphi_2 = \left(M^s_{\exp er} \big/ M^s_{theor} \right) < 1$ is the coefficient of agreement between the experimental gas flow rate per second through the nozzle $M^s_{\exp er}$ and its theoretical value M^s_{theor} for gas flow without twisting.

To determine the pressure in the chamber of a rotating engine p_{rot}, well-known equations for the balance of gas inflow and outflow are usually used, as in the case of a non-rotating solid propellant rocket engine (SPRE). The difference in the internal ballistics of a rotating SPRE is that the effect of rotation on the working process is taken into account [6] by the gas flow rate coefficient from the rotating engine chamber, the change in the erosive combustion rate of the solid propellant during SPRE rotation, and the heat loss coefficient.

Analysis of the above dependence for the thrust of a rotating engine allows to assert that the thrust of such an engine will be less than that of a non-rotating one, all other things being equal. The difference in thrust forces will be determined by the ratio

$$\frac{P_0}{P_{rot}} \approx \left(1 + \frac{k}{k-1} \alpha^2_{crit} \right)^{\frac{1}{1-\nu}}. \tag{7}$$

For real solid propellants, υ = 0.5–0.67 at α_{crit} = 0.1–0.15, the thrust ratios are in the range from $\frac{P_0}{P_{rot}}$ = 1.1–1.36, i.e., the thrust of a non-rotating engine is 10–36 % greater than the thrust of a rotating engine.

Experimental studies of rotating solid-propellant rocket engines equipped with multi-particle solid propellant charges have shown that, unlike solid-propellant rocket engines with a single charge, pressure non-uniformity in the combustion chamber is observed only in the volume just ahead of the nozzle block. Moreover, the more particles in the charge, the lower the degree of a twist, both in the channel of an individual particle and in the volume ahead of the nozzle as a whole.

Features of determining the resistance force during SPART penetration into soil with rotation

The results on penetration into the soil of rotating impactors with different speeds show the need to take into account the influence: a) contact friction forces on the interaction surface of the rotating piercer and the soil when determining the integral drag forces of the obstacle; b) rotational motion around the axis of symmetry of this piercer on its motion parameters and penetration depth.

In particular, in [6; 7], the problem of the motion of a perfectly rigid body in the form of a cylinder with a conical head rotating at angular velocity in the soil along the normal to its horizontal surface was solved. It was assumed that: a) cracks arise in both the longitudinal and transverse directions in the cone-soil interaction zone; b) the soil resistance force depends on the generalized velocity $(V + a\omega)$, which takes into account the contribution of each component to crack formation in the longitudinal direction. In this case, the coefficient *a,* has the dimension of length and determines what portion of the rotational force is spent on the formation of longitudinal cracks.

The drag force is determined by the formula [6]

$$F_{V,\omega} = F_V\left(2 - e^{-\alpha x}\right)\frac{V + \Delta}{V + b\left(V + a\omega\right) + \Delta}, \tag{8}$$

where F_V is the drag force of the medium for a non-rotating piercer; $2 - e^{-\alpha x}$ is one of the possible empirical laws of attenuation of the loss of soil strength when removing from the surface of the high-speed entry of the piercer into the soil; x is the immersion coordinate, which is calculated from the tip of the head part in the direction of movement of the SPART; α is a parameter determined experimentally; a, b, Δ are approximation coefficients determined experimentally [6].

Experimental data show [4] that the rotation of a body can significantly influence the process of its penetration into the soil – its forward component of motion–since the angular velocity ω will reduce the sliding friction force. This will lead, in particular, to an increase in the expected penetration depth into the soil of the piercers. Furthermore, the formula $F_{V,\omega}$ given for the resistance force implies a loss of soil strength and, consequently, the possibility of the SPART penetrating into the soil solely by rotational motion around its own axis, which indicates the simultaneous cessation of the SPART's forward and rotational movementss.

In the case when the SPART is used with a head in the form of a truncated cone, the cross-section of which is not circular, but in the form of an asterisk with a different number of ends, the formula for the soil resistance force is written as [6]

$$F_{V,\omega,\omega_1} = F_V\left(2 - e^{-\alpha x}\right)\frac{V + \Delta}{V + b_1\omega_1 + b\left(V + a\omega\right) + \Delta}. \tag{9}$$

In comparison with the formula $F_{V,\omega}$ for a smooth conical piercer penetrating the soil with rotation, the denominator of the expression for the drag force of a star-shaped piercer F_{V,ω,ω_1} contains a term $b_1\omega_1$ that determines the additional loss of soil strength. This term determines the continuous destructive effect of the sharp petals of the star-shaped piercer on the soil during penetration, depending on the current angular velocity of rotation ω_1, where b_1 is the coefficient of propotionality, which has the dimensions of length [6].

Analysis shows that a star-shaped piercer experiences a lower drag force and, consequently, a lower torque than a conical piercer. A star-shaped piercer, like a shaft of a drilling rig, continuously loosens the soil, which leads to a decrease in the strength of the adjacent contact layers [6].

Comparative analysis of the penetration depth, rotating and non-rotating SPART in the loam

Table 1 presents the calculated penetration depths of SPART using solid propellant rocket motors with different propellant charge masses M_{ch} and launched from the same artillery mount (with rotation and the same propellant charge) into naturally occurring loam.

The possible penetration depths are calculated for SPARTs with a diameter of $D_{ext} = 152,4$ mm, a length of $l = 4,6$ m, and a maximum mass $M_0^{SPART} = 612$ kg, with a warhead opening angle of $\beta = 36^0$. Solid fuel with single pulse $I_{\sin} = 2620\ \frac{\text{Ns}}{\text{kg}}$ and density $\rho_f = 1600\ \frac{\text{kg}}{\text{m}^3}$. is used in the calculations. In the formula for the total resistance of loam to a projectile-piercer $F = F_0 + BV^2$; moving without rotation, the coefficients $F_0 = 27514,68$ N and $B = 11,087\ \frac{\text{Ns}^2}{\text{m}^2}$.are determined.

It is assumed that 0.025 % of the propellant charge's energy (mass) is expended to spin the SPART up to an angular velocity of $\omega =$ 350 1/s. At the same time, the SPART's soil penetration velocity will decrease by 5 %. The proportion of the thrust reduction expended to maintain a constant angular velocity of the SPART during its penetration into the soil is accounted for by the coefficient $k_{rot} = 0,03$. The formula for determining the drag force (1) (SPART penetrates the soil with rotation) did not take into account the law of attenuation of the loss of soil strength when the head is removed from the surface, therefore $\left(2 - e^{-\alpha x}\right) = 1$.

The approximation coefficient a, in the first first approximation, is determined from the expression $I\omega = \mu MV$ and for this case is assumed to be $a = \frac{I}{\mu M}$ = 0.23. The coefficient Δ = 599.32 is determined by calculation based on the processing of experimental data. The parameter b is physically close to the coefficient of sliding friction, therefore in the calculation it is taken as $b = \mu_0 = 0,2$.

Table 1

Results of calculations of depths of penetration of the SPART into loam with rotation, depending on the mass of fuel used

M_0^{SPART}, kg	M_{ch}, kg	V_{ent}, m/s	L_p^{in}, m	L_{Vopt}, m	L_{ps}, m	$L_{V=0}$, m	L_{tot}, m	T_{ps}, s
612	0	260.3	102.4	–	–	–	102.4	0
533	18	280.2	94.8	75.8	46.5	17.6	139.9	0.94
453	36	304.2	83.3	67.9	93.9	14.3	176.1	1.89
345	61.2	340.5	6.4	56.1	158.3	9.8	224.2	3.19
178	122.4	484.5	41.14	34.9	319.3	2.4	356.6	6.38
101	42	0	0	0	108.5	4.29	112.7	2.145

In Table 1, in addition to the previously indicated masses of the SPART and solid fuel, the following designations are used: V_{ent} – SPART entry velocity into the soil; L_p^{in} – total penetration depth of the SPART during its movement in the soil only due to the kinetic energy acquired in the launcher channel; L_{Vopt} – SPART penetration depth due to inertia before engine activation; L_{ps} – SPART penetration depth due to engine operation in the optimal mode; $L_{V=0}$ – SPART penetration depth due to inertia after engine shutdown; L_{tot} – total penetration depth of the SPART during its movement in the soil (both due to inertia and to engine operation in the optimal mode); T_{ps} – engine operating time.

Fig. 1 shows the curves for the change in the SPART entry velocity into the soil V_{ent} and the possible penetration depth if it were moving with rotation and only by inertia L_p^{in}, depending on the mass of the fuel used M_{ch}.

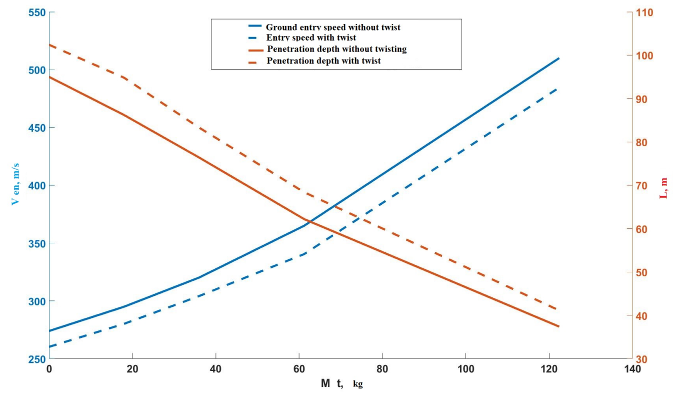

Рис. 1. Зависимости скорости входа и глубины проникания в грунт от массы используемого топлива

Fig. 1. Dependences of the entry velocity and depth of penetration into the soil on the mass of fuel used

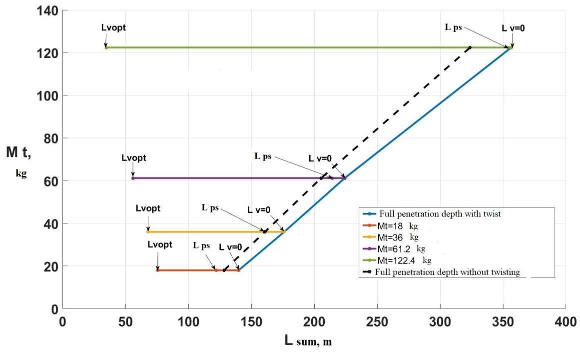

Рис. 2. Зависимость полной глубины проникания СПАРТ от массы топлива РДТТ

Fig. 2. Dependence of the total depth of penetration of the SPART on the mass of the solid propellant rocket motor fuel

Figure 2 shows the dependence of the total penetration depth of the SPART into loam L_{tot} as a function of the mass of fuel used M_{ch} for the case when the SPART, fired from an artillery mount, acquires an angular velocity of $\omega = 350$ 1/s and initially moves through the soil by inertia due to kinetic energy to a depth of L_{Vopt}, then penetrates to a certain depth at an optimal speed due to engine thrust L_{ps}, and after the solid propellant rocket motor is switched off, penetrates further into depth $L_{V=0}$.

Conclusion

As a result of the conducted research:

1. A mathematical model of the SPART penetration process into the soil is developed. This model includes a description of both the forward motion of the SPART's center of mass and an equation for its rotation around its own axis of symmetry, which passes through the center of mass, as the SPART moves through the soil with the engine running.

2. The impact of the rotation of the SPART around its own axis of symmetry on the operating characteristics of the propulsion system is demonstrated and the ratio is given, allowing to take into account the difference in the thrust of the non-rotating and rotating engine, in particular for the real solid fuels the thrust of the non-rotating engine is at 10-36% higer than that of a rotating one.

3. The impact of contact friction forces between the rotating SPART and the soil on its movement parameters and penetration depth is conducted. A correction was introduced into the formula for determining the soil resistance force of a SPART moving forward, taking in account the reduction in sliding friction due to its rotation around its own axis.

4. Preliminary calculations show that by rotating the SPART around its own axis of symmetry, all other things being equal, the penetration depth of rotating SPARTs into the soil can be increased by 8–10 %.

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