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Выбор проектных параметров снарядов-пробойников активно-реактивного типа для движения в грунте

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Аннотация. Целью работы является расчетно-экспериментальное обоснование целесообразности применения (как на Земле, так и на поверхности других планет) снарядов-пробойников активно-реактивного типа (СПАРТ) для решения целого ряда научных задач, связанных с образованием скважин в грунте и доставкой полезных грузов на некоторую глубину. Методы исследования: рассмотрены различные схемы запусков (варианты организации процесса функционирования) СПАРТ. Произведен расчет глубины проникания СПАРТ в суглинок для случая, когда СПАРТ выстреливается из баллистической установки, расположенной таким образом, что скорость выхода снаряда равна скорости его входа в грунт, а тяга двигательной установки в два раза больше статического сопротивления грунта. Из множества вариантов произведен выбор трех конструктивных схем СПАРТ в зависимости от скорости горения используемого топлива для обеспечения нормального функционирования двигателя. В результате проведенных расчетно-экспериментальных исследований по определению глубин проникания в суглинок 152,4 мм снарядов-пробойников длиной 4,6 м, запускаемых с артиллерийской установки, использующей одинаковый пороховой заряд весом 18 кг, установлено, что с момента выключения двигателя до полного останова будет $L_{полн}^{ду} = 205{,}48$ *м, что более чем в два раза превышает глубину проникания такого же снаряда-пробойника, если бы он двигался в грунте только по инерции. Результаты, изложенные в статье, могут быть полезны для научных работников, аспирантов и инженеров, занятых созданием и эксплуатацией авиационной и ракетно-космической техники, а также студентов технических вузов, обучающихся по соответствующим специальностям.*

Ключевые слова: пенетратор, параметры и характеристики, снаряд пробойник активно-реактивного типа.

Selection of design parameters of active-reactive type penetrating projectiles for movement in the ground

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Abstract. The aim of the work is the calculation and experimental substantiation of the expediency of using (both on Earth and on the surface of other planets) active-reactive type penetrator projectiles (SPART) for solving a number of scientific problems related to the formation of wells in the ground and the delivery of payloads to a certain depth. Research methods: various launch schemes (options for organizing the functioning process) of SPART are considered. The depth of penetration of an active-reactive type penetrator projectile into loam is calculated for the case when SPART is fired from a ballistic launcher located in such a way that the projectile exit velocity is equal to the velocity of its entry into the ground, and the thrust of the propulsion system is twice as great as the static resistance of the soil. From a variety of options, three SPART design schemes are selected depending on the combustion rate of the fuel used to ensure normal operation of the engine. As a result of the conducted calculation and experimental studies to determine the depth of penetration into loam of 152.4 mm penetrator projectiles 4.6 m long, launched from an artillery mount using the same powder charge weighing 18 kg, it was found that from the moment the engine is turned off until it comes to a complete stop, $L_{full}^{ps} = 205.48$ *m, which is more than twice the penetration depth of the same penetrator projectile if it moved in the soil only by inertia. Conclusion: the results presented in the article can be useful for researchers, graduate 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 in the relevant specialties.*

Keywords: penetrator, parameters and characteristics, actin-reactive penetrator projectile.

Introduction

In modern human activities, there is a continual annual increase in the volume of earthworks involving the regulated disruption of soil masses.

On Earth, such operations are conducted in road and capital construction, the mining industry, geological surveying, land reclamation, civil engineering and military applications. On other planets of the Solar System, they are carried out for the purpose of subsurface exploration, borehole formation, and the delivery of payloads to specific locations within the soil medium. The labor intensity of working with soil, combined with a number of specific factors inherent in conventional technological methods, results in extremely high operational costs and significant consumption of material and human resources.

The projectiles considered in this study – Active-Reactive Penetrator Devices (SPART) – belong to a class of autonomous systems capable of rapid motion through soil, forming a borehole via compaction rather than excavation. These SPART are launched from a ballistic installation using a launch tube, from which they are propelled in the desired direction by a dedicated launching mechanism. Their movement through the soil is driven both by the kinetic energy imparted during launch and by the thrust of a rocket engine that is activated during the projectile's penetration into the ground.

Schemes of SPART Deployment into Soil

Various launch schemes (i.e., operational configurations) of SPART devices are possible. It is important to note that throughout all phases of the penetrator's movement, in addition to inertial forces and engine thrust, the gravitational force of the planetary body also acts on the system. This gravitational force depends both on the gravitational acceleration – whose magnitude varies across different planets – and on the angle of entry of the penetrator into the soil. The entry angle is defined by the orientation between the SPART's longitudinal axis and the tangent to the surface of the ground (or regolith). The gravitational force reaches its maximum when SPART enters and moves vertically through the soil. Conversely, during horizontal entry and motion, the gravitational component acting on the penetrator becomes zero.

Scheme 1. The launch tube (barrel of the launching device) of the ballistic installation can be positioned at some distance above the soil surface. Using a propelling mechanism, the SPART is ejected from the tube in the desired direction, acquiring an initial velocity upon entry into the ground. In the case where the SPART is launched from a ballistic system mounted on a descent vehicle that is approaching the surface at a certain velocity, it is necessary to account for the deceleration effect exerted on the vehicle due to the recoil force generated by the projectile launch.

The propulsion system, in turn, can be activated under different conditions:

1.1. At the moment the propelling mechanism of the ballistic launcher is triggered. In this case, the engine operates both during the projectile's flight toward the interface between the atmosphere and the soil, and during its movement within the soil.

1.2. At the moment the penetrator enters the soil.

1.3. During its inertial movement within the soil. In both cases 1.2 and 1.3, the motion of the SPART through the ground is driven by both its kinetic energy and the thrust of the operating engine.

1.4. After the SPART comes to a complete stop during its inertial movement in the soil. In this case, the total penetration depth is composed of two segments: the initial inertial motion and the subsequent motion powered by engine thrust.

Scheme 2. The launch tube may be positioned in such a way that the penetrator's nose is in direct contact with the soil surface (impulse-driven insertion). As the propelling mechanism is activated, the SPART begins its motion into the ground due to the pressure exerted by the propellant gases.

In this case, the propulsion system may also be activated under several conditions:

2.1. Simultaneously with the activation of the propelling mechanism. In this scenario, the penetrator's motion through the soil is driven both by the expansion of gases within the launch tube and by the thrust produced by the operating SPART engine.

2.2. During the inertial phase of motion following the activation of the propelling mechanism, when the pressure of the propellant gases in the launch tube has dropped to zero. Here, the movement through the soil is sustained by both the kinetic energy of the SPART and the thrust from its engine.

2.3. After the SPART has come to a complete stop following its inertial motion in the soil, driven initially by the kinetic energy imparted by the propellant gases. The total penetration depth in this case consists of two phases: initial motion by inertia and subsequent advancement due to engine thrust.

Regardless of the configuration of the ballistic installation relative to the soil surface and the moment of engine activation, as the SPART passes through the launch tube, it may either move without rotation or acquire rotation around its own axis, i.e., with spin, due to the pressure of the propellant gases [1].

It is evident that the penetration depth of the active-reactive type penetrator will be influenced not only by the aforementioned operational configurations, mass and dimensional parameters, and characteristics, but also by the magnitude of thrust at each moment of the engine's operation.

In particular, if the thrust of the propulsion system is less than the static resistance of the regolith, the activation of the engine should be carried out either at the moment the SPART enters the soil or during its inertial motion. After the penetrator has come to a stop, activating the engine would no longer be meaningful.

The activation of the SPART propulsion system at the moment of the propelling mechanism's activation increases both the penetrator's entry velocity into the soil and the overloads acting on the penetrator's structure and its payload.

It is also known that to achieve the maximum penetration depth of the penetrator with an operating propulsion system, it must move through the regolith at an optimal speed, which is achieved when the engine thrust exceeds the static resistance of the medium by a factor of two [2].

Below is the calculation of the penetration depth of SPART into loam for the case where the SPART is fired from a ballistic installation positioned such that the exit velocity of the projectile is equal to its entry velocity into the soil, and the engine thrust is twice the static resistance of the ground.

Calculation of SPART Penetration Depth into Loam

As a result of laboratory tests aimed at achieving the same penetration depth when launching projectiles of different masses from a ballistic installation, it was established [3] that less energy and impulse are required when using heavier projectiles. Specifically, when $D_{ex} = 152.4$ mm projectiles were launched from a special artillery gun into naturally occurring loam, a 148 kg projectile reached a depth of L = 24 m, whereas a 612 kg projectile penetrated to a depth of L = 95 m. In both cases, the same gunpowder charge of weight ω = 18 kg was used (see table).

Experimental and Calculated Data on the Penetration of a 152.4 mm Diameter Projectile into Loam

Mg, kg	ω, kg	β, g	L, m	$v_0^э$, m/s	v_a, m/s	$k_θ$
148	18	90	24	482	787	0.61
148	23,9	36	34	640	908	0.70
612	10	36	76	191	285	0.67
612	10	36	69	191	285	0.67
612	18	36	95	274	384	0.71
612	18	36	90	274	384	0.71

We will calculate the possible penetration depth of $D_{ex} = 152.4$ mm projectile described above, with a length of l = 4.6 m and a mass of Mg = 612 kg, and with the nose cone angle $\beta = 36^0$ (if applicable), assuming it is fired from a special artillery gun into naturally occurring loam. Additionally, the projectile is equipped with a solid propellant rocket engine with a fuel mass of $M_f = 0{,}1Mg$, specific impulse of $I_{un} = 2620 \dfrac{\text{Ns}}{\text{kg}}$, and fuel density of $\rho_f = 1600\ \dfrac{\text{kg}}{\text{m}^3}$.

The natural soil used for testing is loam, into which artillery projectiles with the above-mentioned parameters were launched at various speeds.

Using the results of previous launches of these projectiles into the soil at different entry velocities, as presented in Table 1, we will substitute the values into the penetration depth equation for inertial motion

$$L = \frac{Mg_{artp}}{2B} \ln\left[\frac{F_0 + BV_{ent}^2}{F_0}\right] \tag{1}$$

using the two values of $v_0^э = V_{ent}$ and L from the third and fifth rows, respectively. As a result of the simultaneous solution of the system of two logarithmic equations for the unknowns F_0 and B we determine

$$F_0 = 27514.68\ \text{N} \quad \text{and} \quad B = 11.087\ \frac{\text{Ns}^2}{\text{m}^2}$$

in the formula for the soil resistance to the moving penetrator [2].

To achieve the maximum penetration depth into the soil due to the thrust of the operating engine, the projectile must move at an optimal speed, determined by the formula [4] $V_{opt} = \sqrt{\frac{F_0}{B}}$ which, for the values of F_0 and B calculated above, equals $V_{opt} = 49.816 \ \frac{\text{m}}{\text{s}}$.

In this case, the thrust of the propulsion system, according to the relationship $R^{opt} = 2F_0$, must be twice the static resistance of the soil, i.e., $R^{opt} = 55029.36$ N .

Given the total impulse of the solid propellant $I_{sum} = I_{un}M_f = 160344$ Ns and the known thrust R^{opt}, using the formula [2] $T = \frac{I_{un}M_f}{2F_0}$, we will determine the engine's operating time $T = 2.914$ s

Let us determine how the mass of the projectile with the given parameters will decrease by replacing the steel from which it is made with solid propellant, which has a lower density than steel. The volume of 61.2 kg of solid propellant is $W_f = \frac{M_f}{\rho_f} = 0.03825$ m^3. Let us assume that the free volume of the solid propellant rocket engine combustion chamber is $W_{fv} = 0{,}1W_f = 0.003825$ m^3. The total volume of the combustion chamber is $W_g = W_f + W_{fv} = 0.042075$ m^3.

Assuming the density of steel is $\rho_{st} = 7800 \frac{\text{kg}}{\text{m}^3}$, we will calculate how much the mass of the projectile casing has decreased:

a) by considering the difference in densities between the propellant and steel $\Delta Mg1 = W_f \left(\rho_{st} - \rho_f\right) = 237.15$ kg ;

b) by considering the free volume of the combustion chamber $\Delta Mg2 = W_{fv}\rho_{st} = 29{,}835$ kg ;

c) the total decrease in mass $\Delta Mg = \Delta Mg1 + \Delta Mg2 = 266{,}985$ kg .

The mass of SPART will be 267 kg less than the mass of a projectile of the same size, but made of steel and used in the experiment, i. e., $Mg_{artp} = 345$ kg .

Given the use of the aforementioned artillery system with identical powder charges ω = 18 kg, the entry velocity of SPART with a mass of $Mg_{artp} = 345$ kg will be $v_0 = 365 \ {}^{\text{m}}/_{\text{s}}$, while for a projectile with a mass of $Mg = 612$ kg , the entry velocity will be $v_0 = 274 \ {}^{\text{m}}/_{\text{s}}$. The penetration depth of the projectile with a mass of $Mg = 612$ kg into the soil by inertia is $L_{full} = 95$ m, while for a projectile with a mass of $Mg_{artp} = 345$ kg , if it were to move through the soil solely by inertia, the penetration depth would be $L_{full} = 62.26$ m.

To achieve maximum penetration into the soil due to the thrust of the operating engine, the SPART propulsion system must be activated at a depth of:

$L_{V_{opt}} = \frac{Mg_{artp}}{2B} \ln\left[\frac{F_0 + BV_{ent}^2}{F_0 + BV_{opt}^2}\right] = 51.42$ m at which the velocity of the projectile, moving by inertia, decreases to: $V_{opt} = 49.816 \ \frac{\text{m}}{\text{s}}$ [4].

The penetration depth of SPART due to engine thrust, assuming that the solid rocket motor thrust is $R = 2F_0 = 55029.36$ N and it is activated at a depth of $L_{V_{opt}} = 51.42$ m , will be determined by the formula $L_{ps} = V_{opt}T = 145.16$ m .

After engine shutdown, the SPART with a mass of $\left(Mg_{artp} = 283{,}8 \text{ kg}\right)$ will continue moving by inertia until it comes to a complete stop, covering a distance of $L_{V=0} = 8{,}9$ m.

The total penetration depth of the SPART with a mass of $Mg_{artp} = 345$ kg, assuming it moves through the soil in three stages – first, by inertia from the moment of entry to a depth of 51.42 m; second, with the propulsion system activated and operating at optimal thrust with 61.2 kg of fuel; and third, by inertia again after engine shutdown until coming to a complete stop – will be $L_{full}^{ps} = L_{V_{opt}} + L_{ps} + L_{V=0} = 205.48$ m.

When designing the propulsion system for SPART, it is necessary to take into account the overloads acting on both the projectile body and the propellant charge at the moment when the SPART's nose section is fully embedded in the soil. At this moment, SPART is moving by inertia, and the overload reaches its maximum value:

$$n_x = -\frac{F_0 + BV_{ent}^2}{Mg_{artp}\mathrm{g}} = -\frac{27514{,}68 + 11{,}087 * 365^2}{345 * 9{,}81} = -445.07 .$$

Let us assume that the operating pressure in the combustion chamber is $P_c = 25\,\text{MPa}$. The minimum wall thickness of the combustion chamber, according to shell theory, is determined by the formula [5]:

$$\delta_{\min} = \frac{P_c}{2\sigma_{st}} r\varepsilon = 1{,}6 \text{ mm},$$

where $\sigma_{st} = 6 * 10^8 \frac{\text{N}}{\text{m}^2}$ – tensile strength of the combustion chamber material; $r = \frac{D_{ex}}{2}$ – radius of the solid rocket motor; ε = 1.5 – safety factor.

Based on design and technological considerations, we will choose the wall thickness of the combustion chamber δ = 2.2 mm. In this case, the internal diameter of the combustion chamber will be $D_{cc} = D_{ex} - 2\delta = 0.148$ m.

For more efficient use of the combustion chamber's volume, it is advisable to use a poured solid propellant charge. In this case, the charge of a given mass and density will have a minimum length. For the case under consideration, when the internal diameter of the combustion chamber, the volume, mass, and density of the propellant are known, the length of the propellant charge will be determined by the formula $l_{fc} = \frac{4M_f}{\pi\rho_f D_{cc}^2} = 2.22$ m.

Selection of the Design Configuration of SPART

Depending on the burn rate of the propellant used, different design configurations of solid rocket motors can be applied to ensure the normal operation of the engine. Below, three design configurations are presented [6–7].

Scheme a. The burn rate of the selected (fast-burning) propellant at the given pressure in the chamber will be $U = 0{,}149 P_c^{0{,}53} = 744$ mm. The thickness of the burned layer over the total operating time of the engine will be $\Delta = UT = 2{,}168$ m.

To ensure the movement of SPART through the soil at optimal speed due to the operating engine, a motor with end-burning of the propellant (cigarette burn) can be used (see Fig. *a*).

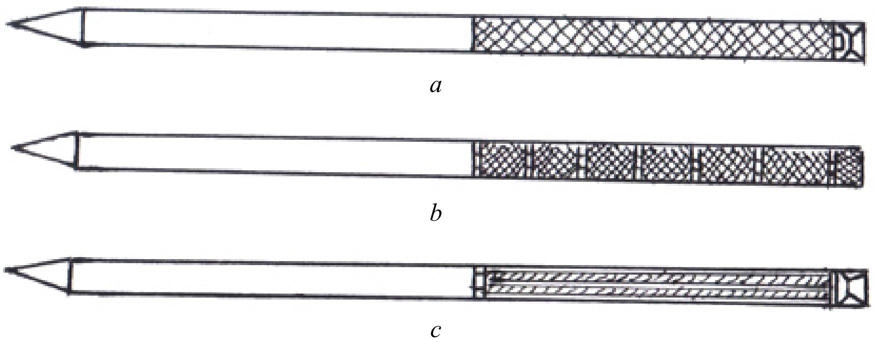
In this case, the surface area of the propellant burn will be $S_{full} = \frac{\pi D_{cc}^2}{4} = 0.0172$.

The total area of the critical sections of all nozzles can be determined based on the steady-state equilibrium between the gas inflow into the combustion chamber and their outflow, according to the formula [8–10]

$$F_{cr} = \frac{U\beta_p S_{full}\rho_f}{P_c} = 0.001146 \text{ m}^2,$$

where $\beta_p = 1400 \ \frac{\text{Ns}}{\text{kg}}$ – specific impulse of pressure.

For the selected design configuration of SPART, using a motor with end-burning of the propellant, either a single nozzle with a critical section diameter of 38 mm can be used, or a nozzle block with a total critical section area of 1146 mm² [11–12].



Constructive schemes of active-reactive type projectiles:
a – with a filled solid fuel charge; *b* – with a multimodule engine; *c* – with a nested tubular charge

Scheme b. The burn rate of the selected propellant at the given pressure in the chamber will be $U = 18 + 1.76 * 10^{-6} P_c = 62 \frac{\text{mm}}{\text{s}}$. The thickness of the burned layer over the total operating time of the engine will be $\Delta = UT = 180.668$ mm.

To ensure the movement of SPART through the soil at optimal speed due to the operating engine, a six-section multi-module engine with end-burning of the propellant charges can be used (see Fig. *b*). The length of each charge will be equal to twice the thickness of the burned layer, i. e. $l_{fc}^{1/6} = 2\Delta = 361.336$ mm.

In this case, the total surface area of the propellant burn will be [13–14]

$$S_{full} = \frac{\pi D_{cc}^2}{4} n = 0.206 \text{ m}^2,$$

where $n = 12 -$ number of combustion surfaces.

The total area of the critical sections of all nozzles can be determined based on the steady-state equilibrium between the gas inflow into the combustion chamber and their outflow, according to the formula [8]

$$F_{cr} = \frac{U\beta_p S_{full}\rho_f}{P_c} = 0.001146 \text{ m}^2.$$

For the selected design configuration of SPART, using a six-section multi-module engine with end-burning of the propellant charges, seven annular nozzles can be used. These nozzles should be placed at the ends of each of the six charges, with the five middle nozzles having identical critical sections with an area of 0.000191 m², and the outer nozzles having half the area, i.e., 0.0000955 m².

Scheme c. The burn rate of the selected propellant at the given pressure in the chamber will be $U = 0.001 P_c^{0,53} = 5.667$ mm. The thickness of the burned layer over the total operating time of the engine will be $\Delta = UT = 0.015$ m.

To ensure the movement of SPART through the soil at optimal speed, in this configuration, an engine with nested tubular propellant charges can be used (see Fig. c).

The main disadvantages of the SPART design using an engine with nested tubular propellant charges are the low degree of fuel filling in the combustion chamber and the need to ensure the stability of the fuel charges when SPART enters the soil (see Fig. c) [15–17].

Conclusion

As a result of the conducted computational and experimental studies to determine the penetration depth into loam of 152.4 mm probe projectiles with a length of 4.6 m, launched from an artillery system using the same gunpowder charge weighing 18 kg, it was established that:

1. The maximum total penetration depth of SPART, if it were moving through the soil:

– on the first stage from the moment of entry until a depth of 51.42 m by inertia;

– on the second stage with the engine turned on, using 61.2 kg of fuel and optimal thrust;

– on the third stage from the moment the engine is turned off until the projectile comes to a complete stop, $L_{full}^{ps} = 205.48$ m will exceed the penetration depth of the same projectile moving through the soil by inertia alone by more than twice.

2. The installation of the solid propellant rocket engine in the rear part of SPART (due to the shift in the center of mass forward caused by the difference in densities of the gunpowder and steel) significantly increases its static stability. This, when the probe projectiles move uncontrolled through the soil, allows for a more straight-line trajectory.

3. It is advisable to use SPART (both on Earth and on the surfaces of other planets) to solve a number of scientific tasks related to the formation of boreholes in the soil and the delivery of payloads to a certain depth.

4. For practical application of the formula that determines the soil resistance force when penetrating with probe projectiles, it is necessary to have a database of experimental values for the specific static resistances F_{0spec} and resistance coefficients *B*, depending on the shape of SPART and its speed through the soil.

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