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Повышение возможностей испытательной баллистической ракеты по разведению объектов испытаний

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Предметом исследования настоящей работы являются траекторные характеристики испытательной баллистической ракеты (ИБР) дальнего действия.

Цель исследования – повышение возможностей ИБР по разведению объектов испытаний (ОИ). При этом в качестве обобщенной количественной меры данного повышения принят запас топлива ступени разведения (СР), расходуемого на разведение ОИ.

Поставлена и численно-аналитически решена проектно-баллистическая задача рационализации распределения имеющегося топлива СР ИБР между следующими основными характерными участками её полета: компенсации недолета последней маршевой ступени; разворотов с последующей угловой стабилизацией, отхода и увода; отделения ОИ (участок разведения).

В результате показано, что без снижения качества выполнения задач пусков ИБР допустимо перераспределение расходуемого топлива СР между данными участками относительно распределения для штатной баллистической ракеты (ШБР), приводящее к существенному увеличению его запаса, расходуемого на участке отделения ОИ (при полете по баллистической вертикали).

При этом достигается цель исследования – повышаются возможности ИБР по разведению ОИ, что, при непосредственном планировании пусков, может выражаться в увеличении количества и / или суммарной массы ОИ и/или увеличении скоростных или временных интервалов в порядке последовательного отделения ОИ.

В приведенных численных примерах (использующих в качестве ИБР переоборудованную трехступенчатую ШБР) также прослеживается существенная зависимость количества приращения топлива СР, расходуемого на участке отделения ОИ, от следующих траекторных условий испытательных пусков (соответствующие исходные данные (ИД) для расчетов заимствованы из ранее опубликованной работы автора): протяженности трассы; кинематических параметров выведения в момент начала автономного полета СР, определяемых задачей пуска.

В ходе исследования применены методы теории полета и проектной баллистики ракет дальнего действия.

В качестве заключения можно отметить, что рассмотренные задача и методы её решения могут быть полезны (естественно, с учетом проведения необходимых специализированных доработок) в работах уровня исполнительной баллистики при планировании и оценке результатов пусков ИБР.

Ключевые слова: рациональное распределение количества топлива, ступень разведения, испытательная баллистическая ракета.

Increasing the capabilities of a test ballistic missile to separate test objects

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The subject of this study is the trajectory characteristics of the long-range test ballistic missile (TBM).

The purpose of the study is to increase the capabilities of TBM in separating test object (TO). At the same time, as a generalized quantitative measure of this increasing, the post-boost vehicle (PBV) fuel reserve consumed for separation of TO is studied.

The design-ballistic task of rationalizing the distribution of the available fuel of the TBM PBV between the following main characteristic section of its flight has been set and numerically and analytically solved: final sustainer stage undershoot compensation; turns with subsequent angular stabilization, retreats and lead away; TO disconnection (separation section).

As a result, it is shown that without reducing the quality of TBM launch tasks, it is permissible to redistribute the consumed fuel of the PBV between these section relative to the distribution for a standard ballistic missile (SBM), leading to a significant increase in its reserve consumed in the section of disconnection of the TO (when flying along the ballistic vertical).

At the same time, the purpose of the study is achieved – the capabilities of the TBM in the separation of the TO are increased, which, while direct planning of launches is evaluating, can be expressed in an increase in the number and/or total mass of the TO and/or an increase in speed or time intervals in the order of sequential disconnections of the TO.

The given numerical examples (using a converted three-stage SBM as a TBM) also show a significant dependence of the amount of fuel increment of the PBV consumed at the TO disconnections of the trajectory conditions of test launches (the corresponding initial data (ID) for calculations are borrowed from the author's previously published work): length of the route; kinematic parameters of launch at the moment of independent PBV flight beginning determined by the launch task.

During the study, methods of flight theory and design ballistics of LR (long range) missiles were used.

As a conclusion, it can be noted that the considered task and methods for its solution can be useful (of course, taking into account the necessary specialized improvements) in works of the executive ballistics level when planning and evaluating the result of TBM launches.

Keywords: rational distribution of fuel quantity, post-boost vehicle (PBV), test ballistic missile.

1. Introduction

The research provides the substantiation of the rational distribution of the amount of fuel consumed by the post-boost vehicle (PBV) of a long-range test ballistic missile (TBM) (converted from the standard ballistic missile SBM [1]) in the distinctive sections of its flight.

The purpose of such work is to increase the capabilities of the TBM for separating typical ballistic test objects (TO)[2] (separation capabilities are understood as the number and/or total mass of test objects (TO) and/or intervals in the order of sequential separation of TO. The desire to increase these capabilities is naturally linked to the desire to maximize the economic return from the use of TBM [1]).

The intended goal is achieved under the following basic provisions and limitations:

– an increase in the available post-boost vehicle capabilities is understood as an increase in the mass of fuel consumed during separation of test objects in the section separating the test objects from the post-boost vehicles [3];

– considering the fundamental differences between the ideology of constructing the trajectories of a standard ballistic missile (SBM) (ensuring that it hits a given targeting point (TP) with a given accuracy and at a given time) and a test ballistic missile (TBM) (ensuring that the test objects TB are launched with the planned levels of mechanical or thermal loads in the atmospheric passive section of the trajectory [4]), this paper develops the idea of saving fuel in the stage of the TBM PBV while compensating for the undershoot of the final sustainer stage relative to the TP);

– this idea is realized by means of incomplete compensation for the above-mentioned undershoot (in the general case, possibly overshoot) by compensating it only in the projection onto the λ-direction with the expansion of the set on the Earth's surface, to which the PBV is guided [2], from the generally accepted TP [5] to a certain targeting line (TL), oriented along the axis of the natural range of the target coordinate system [6], with the center at the AP (in this case, the permissible length of the TL is determined based on the requirements for safety and information content of the launch, taking into account the placement of trajectory means of obtaining information on the ground [7]; conditions for ensuring the required accuracy of operation of these trajectory means [8; 9]; the vastness and accessibility of territories subject to mandatory inspection and notification before launch [7]).

The author of this article is not aware of any previous publications by other authors presenting similar studies.

Further, the article contains the following information:

– section 2 provides a description of the used model ID (initial data) and mathematical models;

– section 3 states the problem and describes the methods of its solution;

– section 4 provides examples of solutions to the stated problem;

– section 5 provides a conclusion to the research.

2. **Used ID and mathematical models**

The research is more related to the direction of design ballistics than to the direction of launch support ballistics (in the terminology of [10; 11]), due to this, the use of relatively simple mathematical flight models is intended to increase both the clarity of the research (without introducing unnecessary complexities of a purely technical nature into the perception of the material) and the generality of the results achieved. For this purpose, the article provides numerical examples. If desired, the reader can independently increase the level of detail of the mathematical models used.

2.1. Description of model ID based on SBM:

– maximum effective firing range 10000.0 km [12];

– maximum undershoot (of course, at some fairly high level of probability [6]) of the final sustainer stage in apparent speed ΔW_{Guar} = 70.3 m/s [12];

– PBV separates all TOs at one section of movement in the direction of the ballistic vertical (ν-direction) [6] (in this case, three-parameter terminal guidance to the planned geodetic TPs and the full flight time is carried out [2]);

– the set of TOs has a total mass m_{TO};

– the total fuel reserve of the PBV propulsion system with an initial mass m_{PBV} = 525.5 kg [12] is ω_{comp} = 25.62 kg [12] and is represented as the sum [10; 12]

$$\omega_{comp} = \omega_{Guar} + \omega_{boost\ turn+backout} + \omega_{SS}\ , \tag{1}$$

where the guaranteed fuel reserves [6; 12] spent on compensation ΔW_{Guar} are calculated by the formula

$$\omega_{Guar} = \frac{\Delta W_{Guar} \cdot m_{PBV}}{J_1 \cdot \cos(\alpha)}, \tag{2}$$

the consumption of PBV turning to the ν-direction, its stabilization, departure and removal of PBV from the last separated TO are set constant and equal to $\omega_{boost\ turn+backout}$ = 4.49 kg [12];

– the consumption of ensuring the separation of the TO in a given order ω_{SS} [12] are calculated by the formula (1);

– the PBV mass is represented as a sum [12]

$$m_{PBV} = 1{,}1 \cdot (m_{TO} + m_{DK} + m_{NCS} + m_{PBVS} + m_{PSS} + \omega_{compl}). \quad (3)$$

2.2. Description of model ID based on TBM:

– the kinematic parameters of the trajectory at the moment $t_к$ at the end of the operation of the propulsion system of the last (3rd) cruise stage and the beginning of the operation of the propulsion system of PBV are set in the following volume:

V_{fin} – Earth velocity module;

θ_{fin} – the angle of inclination of the Earth velocity to the local horizon;

h_{fin} – height above the Earth surface;

φ_{fin} – angular range from the starting point to the sub-satellite point;

φ_{compl} – angular range from the starting point to the TP;

– the "impulse" approach [13] is used in the space of apparent velocities to calculate the final flight parameters of the PBV based on the specified final flight parameters of the last cruise stage;

– the value of $\omega_{boost\ turn\ +backout}$ is taken from the SBM;

– a new value of m_{TO} to the mass of the total TO is set.

3. Statement of the problem and its solution methods

3.1. For ID given in subsection 2.2, the task is to obtain a quantitative comparative estimate of ω_{yo}:

– with complete compensation for the shortfall of the last cruise flight stage (ideology for constructing the SBM trajectory);

– with incomplete compensation for the shortfall of the last cruise flight stage (ideology for constructing the TBM trajectory).

3.2. There are to methods to solve the stated problem:

– Method A – compensation for the miss of the last cruise flight stage of TBM is performed only in the projection on the λ-direction (that is two-parameter terminal guidance to the planned geodetic TP is carried out [2]);

– Method B – guiding PBV to the TL (more precisely, in relation to practical applications – for example, to the boundary point of the TL or the closest achievable point of the TL to the TP depending on the actual realized undershoot), as a result of which the magnitude of the compensated miss of the last cruise flight stage in the λ-direction is reduced.

It is natural, the rational application of these methods is consistent:

– first is method A;

– then method B is used (in combination with the previously applied method A).

When method A is applied:

– the calculation of the maximum undershoot of the last cruise flight stage is carried out in projection onto the λ-direction:

$$\Delta W_{Guar,\lambda} = \Delta W_{Guar} \cdot \cos(\theta_\lambda - \theta_к); \quad (4)$$

– the appropriate guaranteed fuel reserve is determined:

$$\omega_{Guar,\lambda} = \frac{\Delta W_{Guar,\lambda} \cdot m_{PBV}}{J_1 \cdot \cos(\alpha)}; \quad (5)$$

– a new value of the mass of fuel consumed in the separation section is determined:

$$\omega_{SS,\lambda} = \omega_{compl} - \omega_{compl,\lambda} - \omega_{boost\ turn+backout}. \quad (6)$$

When method B is applied:

– the admissible TL $[-L_{TL}; L_{TL}]$ with TP at point 0 is specified;

– it is calculated using the first formula (3.9) of the source [14] based on the values of V_{fin}, θ_{fin}, h_{fin}, φ_{fin}, and φ_{compl} is partial ballistic derivative $\partial L/\partial V_{fin}$ (in this paper it is used to estimate the range increment on the passive section of the trajectory. As it can be seen, this assumes a simplified accounting of its atmospheric part, which, however, is sufficient for the design-ballistic level of calculations. It is advisable to perform when preparing data for launches to perform a more accurate calculation of this derivative or a complete rejection of its use by performing direct integration of the equations of motion of the TO, taking into account the dependence of the meteorological parameters of the atmosphere on the geodetic coordinates and month of the year);

– the permissible value of the non-compensated miss of the last cruise flight stage is determined:

$$\delta W_{fin} = L_{TL} \Big/ \frac{\partial L}{\partial V_{fin\,fin}}; \tag{7}$$

– its projection onto the λ-direction is defined:

$$\delta W_{Guar,\lambda} = \delta W_{Guar} \cdot \cos(\theta_\lambda - \theta_{fin}); \tag{8}$$

– the compensated error in the projection onto the λ-direction is reduced by an acceptable value:

$$\Delta W^*_{Guar,\lambda} = \Delta W_{Guar,\lambda} - \delta W_{Guar,\lambda}; \tag{9}$$

– the guaranteed fuel reserve is adjusted:

$$\omega^*_{Guar,\lambda} = \frac{\Delta W^*_{Guar,\lambda} \cdot m_{PBV}}{J_1 \cdot \cos(\alpha)}; \tag{10}$$

– the adjusted value of the mass of fuel consumed in the separation section is specified:

$$\omega^*_{SS,\lambda} = \omega_{compl} - \omega^*_{Guar,\lambda} - \omega_{boost\ turn+backout}. \tag{11}$$

Fig. 1 illustrates the comparison of the flight profiles of the SBM PBV and TBM PBV without TL use. Fig. 2 provides a flight profile of TBM PBV with targeting line (TL)

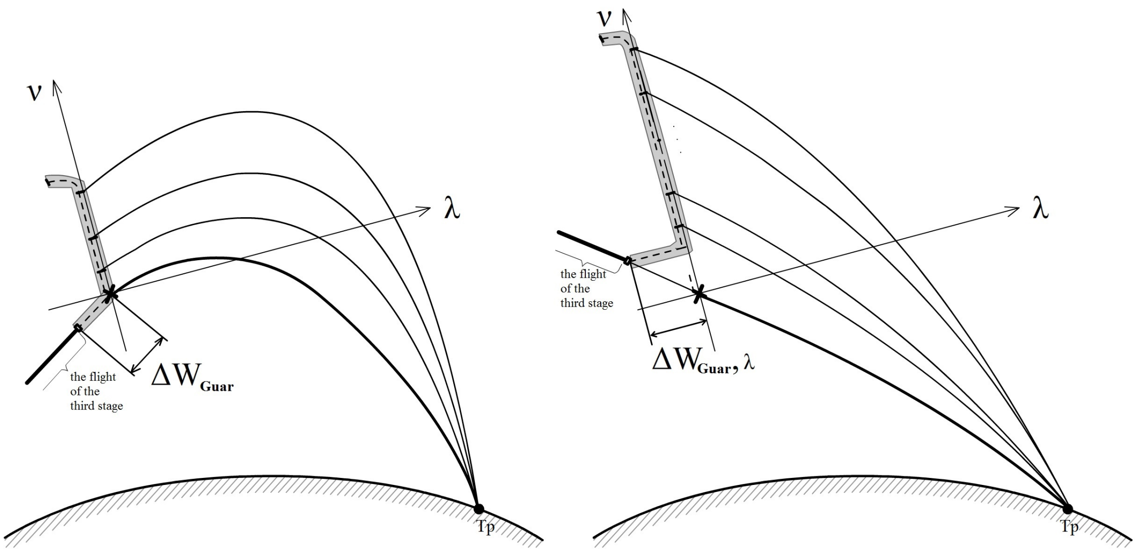

Рис. 1. Схемы полета СР (серым цветом) ШБР (слева) и ИБР (справа) без ЛПр

Fig. 1. Flight profiles of SBM (left) and TBM (right) PBV (grey) without targeting line (TL)

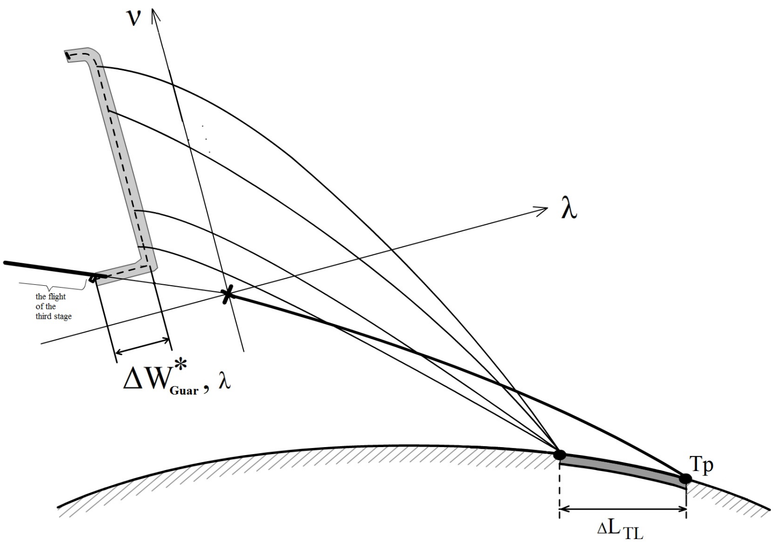

Рис. 2. Схема полета СР (серым цветом) ИБР с ЛПр

Fig. 2. Flight profile of TBM PBV (grey) with targeting line (TL)

4. Problem solution using the example of model ID

4.1. Example 1: firing an TBM at a range of 2000.0 km with trajectory parameters at the moment t_{fin} [15]:

V_{fin}= 5676.6 m/s;

θ_{fin}= –18.9°;

h_{fin} = 250847.1 m;

φ_{fin} = 12.39°;

φ_{compl} = 17.99°.

A new value of m_{TO} is set to 331.3 kg (100.0 kg more than the original value for the SBM [12]).

The value of L_{TL} = 1.0 km.

The calculation results are in table 1.

Table 1

Calculation results for example 1

	SBM Ideology	TBM Ideology	
		Method A	Methods A and B
Compensated undershoot, m/s	ΔW_{Guar} = 70.3 (ID of section 2)	$\Delta W_{\text{Guar},\lambda}$ = 12.1 (formula (4))	$\Delta W^{*}_{\text{Guar},\lambda}$ = 8.5 (formulae (7, 8, 9))
Guaranteed fuel reserve of PBV, kg	ω_{Guar} = 19.75 (formulae (3, 2))	$\omega_{\text{Guar},\lambda}$ = 3.40 (formula (5))	$\omega^{*}_{\text{Guar},\lambda}$ = 2.39 (formula (10))
Fuel consumed per separation, kg	ω_{SS} = 1.38 (formula (1))	$\omega_{\text{SS},\lambda}$ = 17.73 (formula (6))	$\omega_{\text{SS},\lambda}$ = 18.74 (formula (11))

Table 1 demonstrates that for the accepted ID:

– applying method A allows to significantly increase ω_{SS} (by 12.85 times);

– additional application of method B allows to increase ω_{SS} by another 1.06 times.

4.2. Example 2: firing TBM at a range of 6000.0 km with trajectory parameters at the moment $t_{к}$ [15]:

V_{fin} = 5680.6 m/s;

θ_{fin} = 11.47°;

h_{fin} = 644904.6 m;

φ_{fin} = 9.08°;

φ_{compl} = 53.96°.

A new value of m_{TO} is set to 281.3 kg (50.0 kg more than the original value for SBM [12]).

The value of L_{TL} = 4.0 km.

The calculation results are in table 2.

Table 2

Calculation result for example 2

	SBM Ideology	TBM Ideology	
		Method A	Methods A and Б
Compensated undershoot, m/s	ΔW_{Guar} = 70.3 (ID of section 2)	$\Delta W_{Guar,\lambda}$ = 63.3 (formula (4))	$\Delta W^{*}_{Guar,\lambda}$ = 62.0 (formulae (7, 8, 9))
Guaranteed fuel reserve of PBV, kg	ω_{Guar} = 18.04 (formulae (3, 2))	$\omega_{Guar,\lambda}$ = 16.25 (formula (5))	$\omega^{*}_{Guar,\lambda}$ = 15.9 (formula (10))
Fuel consumed per separation, kg	ω_{SS} = 3.09 (formula (1))	$\omega_{SS,\lambda}$ = 4.88 (formula (6))	$\omega^{*}_{SS,\lambda}$ = 5.23 (formula (11))

Table 2 demonstrates for the accepted ID:

– applying method A allows to increase ω_{SS} by 1.58 times;

– additional application of method B allows to increase ω_{SS} by another 1.07 times.

5. **Conclusion**

Due to the above, it follows that the stated objective of the research has been achieved, namely:

– the design and ballistic problem of implementing rational distribution of the consumed fuel of the TBM PBV has been solved;

– a two-stage method to increase the TBM capabilities for separation of TOs has been developed.

The proposed two-stage method allows to significantly (up to several times) increase the available PBV stock of fuel intended for separating the TOs.

Considering the necessary specialized modifications (for example, taking into account the areas of fall of the detachable parts of the tested ballistic missile along a specific launch route [16, 17]), the researched problem and the proposed solution methods can be used in work at the level of executive ballistics to plan and evaluate the results of launches of the tested long-range ballistic missile.

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