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FLIGHT DYNAMICS AND CONTROL OF FLIGHT VEHICLES

On the Concept of Improving the Ballistic Efficiency of a Rocket Vehicle with the Dominant Midcourse Phase

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Abstract—A systemic set of methods and devices designed to increase the maximum range of flight is considered. The main attention is paid to evaluation of efficiency for new technical solutions related to integrating the ramjet rocket engines into rocket vehicles with active and reactive launch principles. According to the results of studies, comparative assessments are presented for attainable values of the range increase based on the technical solutions considered.

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INTRODUCTION

A conceptual approach to constructing the high-precision new generation rocket vehicles (RV) is now intensively formed [1]. In this paper, it is proposed as an object of study to consider a tactical surface-to-surface RV with a range of up to 200 km that is characterized by intense launch and a dominant midcourse phase. We distinguish two classes of RV, namely, of active launch (canon-launched guided projectile) [2] and of rocket launch (surface-to-surface missiles with the bicaliber scheme of bulk packaging) [3]. The substantially variable flight conditions (altitude to 50 km, speed up to 5 M) and severe restrictions on weight-dimension characteristics (WDC) are common to them. At the same time, there are differences in the principle of launch, namely, rocket vehicles of active launch from barrel systems have an initial speed of 2.5 – 3 M, whereas rocket vehicles of rocket launch have a low initial velocity at the moment of release from the launcher (20 – 100 m/s), and then accelerate intensively to 3 – 5 M. In terms of design, the differences are associated with mono- or bicaliber design scheme. By analyzing the trends in development of foreign counterparts, we can see that the emphasis is focused on the range increase with the fixed WDCs, i.e. on increasing the ballistic RV efficiency. This approach is considered in this paper.

A CONCEPTUAL APPROACH TO INCREASE THE BALLISTIC EFFICIENCY

A concept of increasing the ballistic efficiency is the specified conceptual framework, criteria of ballistic efficiency evaluation, structured set of methods and devices aimed at increasing the flight range, instruments for evaluating the ballistic efficiency as well as predictive estimates of the attainable range values, when new technical solutions are implemented.

We can distinguish two approaches to the assessment of ballistic efficiency, namely, to compare the solutions in the framework of product modernization at fixed WDCs and to compare the solutions for aircraft at significant differences in their WDCs.

In the first case, which is under consideration in this paper, it is rational to use as a criterion the relative increment of the range as compared to a certain basic option (prototype):

$$\Delta X_{rel} = \frac{X_{\max}^{new} - X_{\max}^{basic}}{X_{\max}^{basic}} 100\ \%$$

where $X_{\max}^{new}$, $X_{\max}^{basic}$ is the maximum range for advanced and basic RV options, respectively.

In the second case, it is desirable to consider the relative change in the coefficient of transport efficiency as a criterion.

In regard to the RV being considered, there is a vast range of methods and devices that provide the increased ballistic efficiency. It is proposed to systemize them based on a hierarchical classification (Fig. 1), the upper level of which includes two directions, namely, energoballistic and aeroballistic ones. The first one is focused on the effective operation of the airborne and launch power devices, and the second one on the rational use in the trajectory of the kinetic energy generated at launch. The specific ways to increase the flight range are singled out in the framework of these directions.

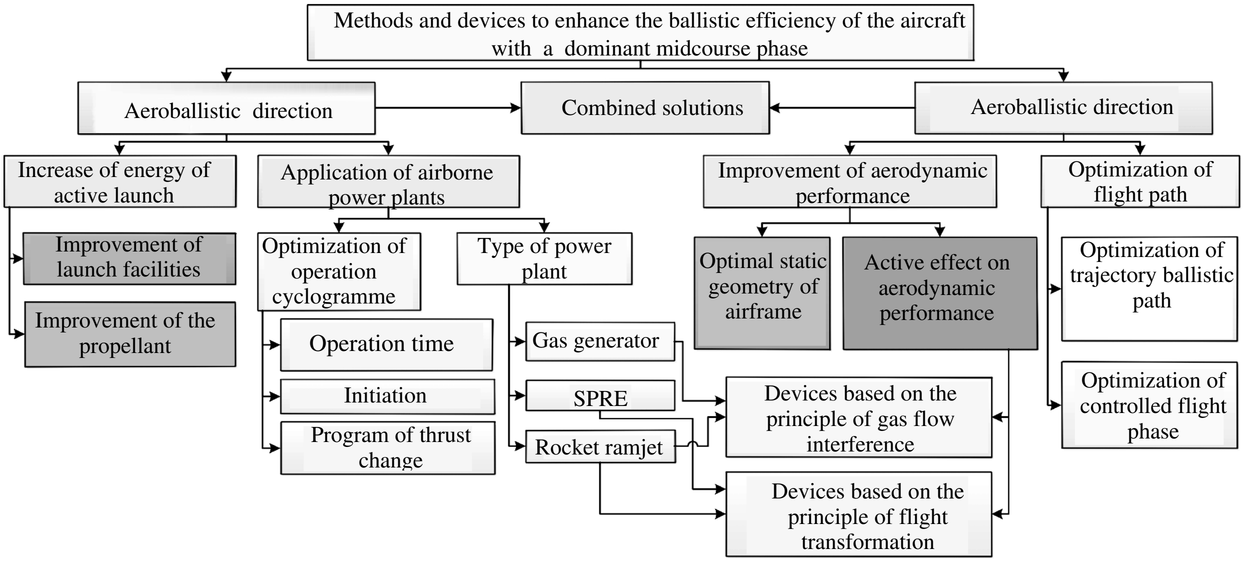

Fig. 1. Classification of methods and devices aimed at improving the aircraft ballistic performance with a dominant mid-course phase (bold type signifies the aspects discussed in this paper).

The ballistic efficiency of the solid propellant rocket engine (SPRE), base-bleed gas generator (BBGG) or their combinations, transformable aft dome (TAD) [4], and the program glide section on descending branch of the trajectory, can be estimated using the classical models of aircraft flight dynamics. At the same time, the availability of different methods and devices should be taken into account through the aerodynamic coefficients and the dependence of engine thrust on time.

In the case of new solutions for the RV type being considered that related to the implementation of ramjet rocket engines (RRE), the above approach becomes unsuitable since the rocket-ramjet thrust performance depend on external trajectory parameters, and those, in turn, are determined by the engine operation.

In combination with the significantly varying flight conditions this results in a need to construct the adequate models that permit us to describe in common the RV motion and the RRE operation. As a result, in order to obtain predictive estimates of ballistic efficiency of REE implementation to the RV being considered, it is necessary to solve the task of developing a relatively simple research tool that requires low computational resources and is focused on multiparameter optimization in the framework of structural parametric synthesis but it takes into account the main factors affecting the workflow and RRE thrust performance as well as the aircraft flight performance in general.

RESEARCH TOOLS

For substantiating the suitability for the RRE implementation into the aircraft being considered, it is proposed a set of known mathematical models of different granularity to be efficiently combined. The general structure of this toolkit includes two levels (Fig. 2). The first level is a set of models describing the combined RV and RRE operation and having a number of assumptions that allows the multivariate and optimization problems to be considered [5]. The second level is associated with the deeper studies of physical processes that are carried out using software, which is extremely sensitive to computational resources. The simulation results obtained in the form of coefficients and functional dependences serve as inputs to the first level models. At different development stages, the intensity of using the first and second level models is different. At the earliest stages in selecting a preferred option from the plurality being considered, the first level models are actively used with local inverse to the second level models that are configured to the valid rough estimates of the main coefficients. Further, when attention is focused on the specific embodiment, the capabilities of resource-intensive models of the second level are most completely used for the purpose of updating the coefficients and functional dependencies used in the first level models.

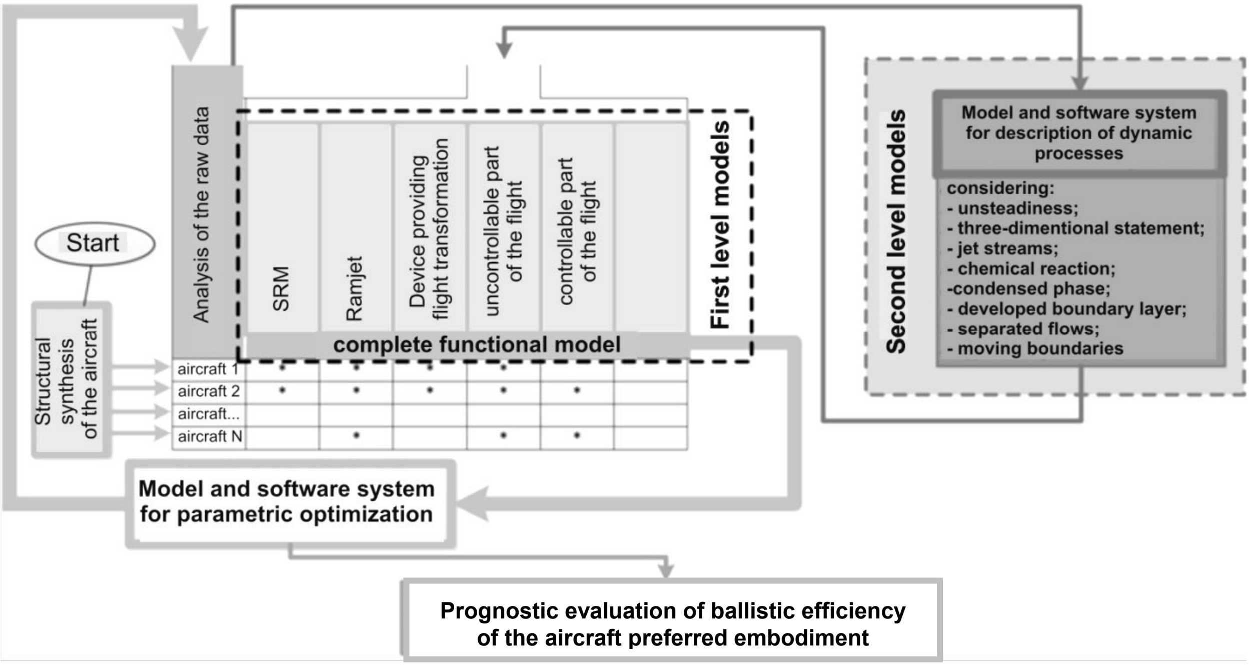

Fig. 2. Structural diagram of research tools.

The mathematical model of the RRE operation is based on the integral formulation of the following conservation laws:

1. The law of conservation of mass

$$G_g = G_a\left(1+\frac{1}{\alpha L_0}\right),$$

where G_g is the total mass flowrate of gas in the hot section of the afterburner; G_a is the mass flowrate of air, $G_a = \rho_\infty v_\infty F_{in}\varphi$ (ρ_∞ is the density of the undisturbed flow; v_∞ is the flight speed; F_{in} is the air intake area; φ is the air flow coefficient); α is the excess oxidant ratio; L_0 is the stoichiometric coefficient.

2. The law of conservation of momentum

$$J_{gg} + p_{0_d}\frac{\alpha L_0}{G_a} + \frac{\alpha L_0\left(k_a+1\right)a_{cr_a}}{2k_a}z(\lambda_d) = \frac{\left(\alpha L_0+1\right)\left(k_g+1\right)a_{cr_g}}{2k_g}z(\lambda_g),$$

where J_{gg} is the ideal specific impulse of the gas generator in a critical section; p_{0_d} is the braking pressure in the outlet cross section of intake, $p_{0_d} = \sigma p_{0_\infty}$ (p_{0_∞} is the braking pressure of the undisturbed flow; σ is the pressure recovery factor); k_a, a_{cr_a} are the adiabatic index and the critical speed of air; λ_d is the relative velocity at outlet section of the intake; k_g, a_{cr_g}, λ_g are the adiabatic index (function of temperature, pressure and excess oxidant), the critical and relative velocity of gas in the hot section of the afterburner.

3. The law of conservation of energy

$$I_{0g} = \frac{1}{aL_0+1}\left(aL_0 I_{0a} - \left(1-\eta_{eg}\right)H_u + \Delta H_f\right),$$

where I_{0g} is the deceleration enthalpy of gaseous products in the hot section of the afterburner; η_{cg} is the combustion efficiency ratio; H_u is the lowest fuel efficiency; ΔH_f is the enthalpy of fuel formation.

4. The RRE thrust

$$P = \frac{\alpha L_0+1}{\alpha L_0}G_a v_{out} - G_a v_\infty + F_{out}\left(p_{out} - p_n\right),$$

where F_{out} is the area of the output section of the RRE nozzle; v_{out}, p_{out}, p_n are the speed, static pressure at the outlet nozzle section in the undisturbed flow.

The parameters φ, σ, η_{cg} are determined by means of computational gas dynamics. Numerical implementation of the model mentioned is implemented as a subroutine that is integrated into the software system to calculate flight path of the RV being considered.

The classical equations of motion [6, 7] are used for calculating the RV flight path in the air. The aerodynamic coefficients being required are determined using the second level models with consideration for the RRE availability both on the active and passive trajectory parts. The program, which realizes numerically the system of motion equations for a variable-mass body with the subroutine to describe the process of the RRE operation, is a module that integrates all of the models being used and is designed to generate a predictive estimate of maximum range.

In the framework of the research, the models of dynamic processes are the principal second level models. They are based on the motion equations for viscous heat-conducting gas. These equations are the Reynolds-averaged ones and closed by one of the turbulence models. In this research, use was made of relations for semi-empirical two-parameter dissipative k–ε turbulence model [8]. The mathematical model is numerically realized based on a modified method of large particles.

THE RESEARCH RESULTS

In the course of the research in the form of structural-parametric synthesis, the predictive estimates of maximum values of the range were obtained for all of the technical solutions mentioned above. In the framework of each of the RV class being analyzed, the weight-dimension characteristics were recorded, therefore, the assessment of ballistic efficiency was performed using the criterion of relative increment of the flight range ΔX_{rel}.

It is reasonable to consider the flight range increment for RV of active launch as a function of additional power inputs expressed through the increase in fuel mass or pyrotechnic composition (Fig. 3). As a base level to which the range is referred, we accept the flight range of the prototype that is not equipped with special devices to increase the range. Figure 3 presents the relative increment of the maximum range obtained by the parameter optimization relative to the other relevant parameters (firing angle, SPRE ignition time, characteristic cross-sectional areas of the RRE duct, etc.) for each of the relative masses of fuel.

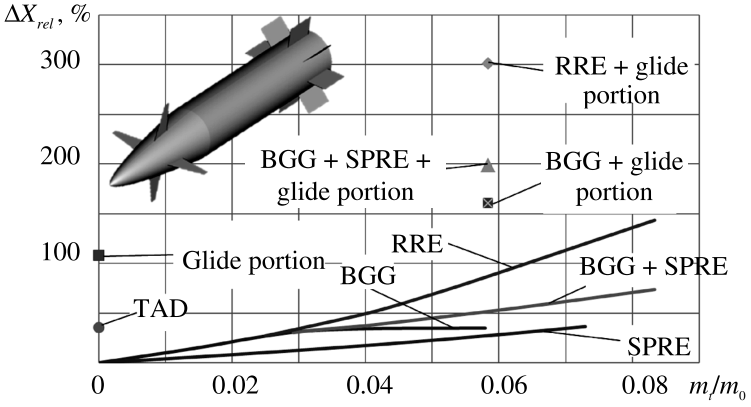

Fig. 3. Relative increment of the flight range for the RV of active launch for different ways to increase ballistic efficiency depending on the relative charge mass.

The results obtained show evidence that the use of solid propellant rocket engines is reasonable only if the fuel weight is in excess of 6% of the total RV weight. At smaller weights, it is more reasonable to use the base-bleed gas generator that can provide the range increment up to 35%. The transformable aft fairing can compete with the base-bleed gas generator as it provides a similar relative increment of the maximum flight range.

Considerable potential to increase flight range is concentrated in the realization of the aircraft gliding section on the descending branch of the trajectory, which allows the flight range to be increased by more than 100% as compared to the base aircraft.

In the case of BGG + SPRE combination the range turns to be larger than that in the case of the separated SPRE or BGG at a constant total weight of the fuel and pyrotechnic compositions.

From the comparative analysis of the results obtained it is evident that the RRE application is the most efficient among all the solutions considered aimed at increasing the flight range for RV of active launch. It should be noted that due to the dimensional limitations of a prototype, the RRE option was considered based on the principle of flight transformation for organizing the afterburners of required size [9]. It is important to emphasize that the RRE in its operation combines both the properties of the engine focused on the thrust creation and the properties of BGG aimed at removing the most of the base drag.

The combination of glide section, at which the mission with optimal aerodynamic quality is realized, and the methods associated with the use of additional on-board power, allows us to attain a qualitatively new level of flight ranges. As evident from Fig. 3, the RRE application permits the base range to be increased by 87%, and the addition of glide section allows this value to be increased even by 213%, which ultimately leads to an increase in flight range of basic options by 300%.

When we consider a bicaliber aircraft of rocket launch, the solid propellant rocket, which flies a ballistic trajectory, is taken as a prototype. Considerable attention was paid to a promising scheme with the integral RRE [10]. In this regard, the calculation results are presented as a dependence of the relative increment of flight range on the RRE fuel weight proportion in the total on-board fuel weight (Fig. 4). In this case, each point corresponds to the optimum range for the other parameters (firing angle, cross-sectional areas of the straight-through duct).

According to the results obtained by using the integral RRE instead of the classical SPRE allows us to increase the range of ballistic flight by 75%. The similar result can be achieved by applying the glide section. In the case of combining the glide section and RRE application, we can provide the increase of flight range by 200%. It should be noted that in order to attain such a result, it is necessary to organize the fuel distribution between the RRE and SPRE in a ratio of 1/3.

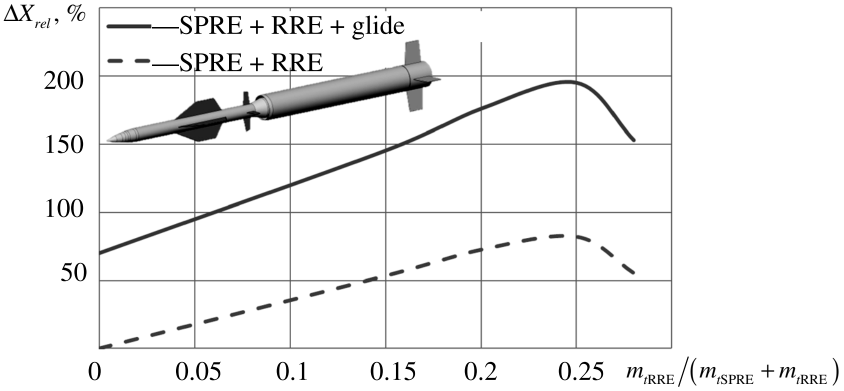

Fig. 4. Relative increment of the flight range for the RV of jet launch depending on the variants of the fuel redistribution between SPRE and RRE.

CONCLUSIONS

It should be noted that the research tools have been developed that have the two-level structure and are focused on multiparameter optimization in the framework of structural-parametric synthesis, which allow the predictive assessment of ballistic efficiency for technical solutions to be sequentially refined.

Using these research tools at the stage of conceptual design, we can distinguish two trends in the long-term future development of tactical aircraft with a dominant post-boost, namely,

—use of on-board engine assemblies based on RREs (transformable structures, integrated circuits) that permit the specific features of an aircraft under consideration to be efficiently realized with a view to increasing their power potential and flight range;

—reasonable combination of the best aeroballistic (realization of program flight section with optimal aerodynamic quality) and energoballistic (implementation of the RAP) solutions.

The results obtained demonstrate that using the combination of the RRE and glide section with optimal aerodynamic quality in comparison with the best of solutions used allow us to obtain a 50% increment of the maximum flight range for aircraft of active launch and increase by 670 % in flight range for bicaliber aircraft with the jet launch principle with the same weight-dimension characteristics.

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