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DEVELOPMENT OF A LAUNCH VEHICLE CONTROL ALGORITHM AT THE INITIAL FLIGHT PART IN CASE OF ONE OF THE ENGINES' FAILURE

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Abstract

The object of study is the control system of the launch vehicle (LV) at the initial phase of flight when an emergency situation occurs due to failure of one jet engine. It is assumed that when the situation occurs, the LV has to be "allocated" from the launch pad in a horizontal direction along a certain trajectory to the pre-selected area, avoiding a collision with the of great importance constructions of the launch complex, to perform further procedures for the liquidation of the LV. The aim of the study is to develop an optimal regulator of the LV control system, providing the implementation of an emergency flight of the LV. For the formation regulator this paper proposes a modified version of the Letov's method of analytical design of regulators (ACOR) problem solution. The peculiarity of the formulation of the problem as the ACOR problem is the dependence of the system outputs from the input control variables. The efficiency of the control is evaluated using the integral-terminal quadratic criterion. The motion of the LV at the considered flight phase is described by simplified linearized equations. The performances of the proposed optimal regulator is confirmed by compareson of simulation results obtained with the simplified and the detailed spatial models of the LV controllable motion

Keywords

Launch vehicle, launch complex safety, engine failure, emergency displacement, optimal regulator, quadratic criterion

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Introduction. At present, the development of aircraft motion control algorithms when different types of failures occur on board is under attention [1–6]. This problem was called as fault-tolerant control [7]. There are different approaches to emergency control of the aircraft, including robust and adaptive control. For example, in [1, 2], failures of booster steering drives were considered, and adaptive control methods were developed to search for a solution. As an alternative to these approaches, an flight control system with variable structure control laws can be applied. The solution of the problem using this approach is given in the article.

When a manned LV starts and begin to move at the initial part of the flight, special attention should be paid to both the safety of astronauts and the safety of the launch complex when an emergency occurs on board the LV, in particular, if one of the engines fails. It is assumed that with such a failure, the capsule with astronauts using the emergency rescue system is shot off from the LV, and then descends by parachute to the Earth's surface in a given area near the cosmodrome [8].

The purpose of the LV control system in the situation of an engine failure is to drive the LV along a specific path to a predetermined area, upon reaching which further operations can be performed in accordance with the operation's program of the LV emergency flight. In the event of such a failure, the control law, which executes the nominal program of the LV motion, is switched to the emergency law to carry out the dislocation program of the LV. The task of implementing the vehicle launch program with using the control system can be called as the task of the LV emergency displacement.

After registering of a failure, the failed jet shuts down. As a result, disturbing forces and moments start to act on the LV, leading to a lateral displacement of the LV in the direction of the failed engine. When a LV is moving with the jet off, there is a possibility of LV collision with the umbilical tower located near the launch pad, which can lead to the destruction of the launch complex structures. Therefore, the requirement of non-impact flight should also be provided for to arrange of controlled motion of the LV along an emergency displacement path.

When one of the jets is switched off, the combustion chambers of other operating engines must be deflected to the balancing angles for balancing the LV, which implies that the main moment of their thrusts in respect to the center of mass of the LV is eguat to zero. In addition, to compensate for the loss of thrust of the failed jet and the emergency displacement of the LV from the structures of the launch complex, the thrust forces of operating jets have to be forced.

The purpose of this paper is to develop an optimal regulator of the control system of the LV in the event of engine failure, providing the implementation the flight emergency program for dislocation the LV. To find the structure and characteristics of the regulator, a modified version of the analytical design of regulators problem solution is used [9]. The modification of the method to form a law for controlling the motion of the first stage of the LV is presented in [10].

At the preliminary stages of solving the problem of emergency displacement, the motion of the LV can be described using the linearized equations with time variant coefficients. The position of the characteristic point of the LV body tail is considered. The command deflections of the LV in the pitch and yaw angles are considered as control actions. It is assumed that the control system of the LV angular motion of perfectly executes the command values of these angles.

The efficiency of control algorithms, formed using a simplified model of the LV motion, is confirmed by the simulation results obtained with use the detailed spatial model of the LV motion.

The task of controlling the LV motion at the emergency displacement phase is solved under the following assumptions.

1. Earth is flat and not rotating, the gravity field is homogeneous.

2. The influence of aerodynamic forces on the motion of the LV is neglected, since the velocity of the LV at the considered flight part is slow.

3. If one of the jets fails at some time t_0, the thrust of this jet is instantly switched off, and operating jets are forced, their thrusts become to be equal to P_F.

4. After failure at any time $t \geq t_0$, due to the deviation of chambers of operating jets at angles δ_ϑ and δ_ψ in the pitch and yaw channel correspondingly, the LV is balanced, i.e., the main vector of the jets thrust forces LV is equal to zero.

5. At the emergency displacement phase, the LV motion in the horizontal plane is controlled by executing the programs for the command angles of pitch $\vartheta^*_C(t)$, yaw $\psi^*_C(t)$ and roll $\gamma^*_C(t) = 0$.

6. The actual angles $\vartheta(t)$, $\psi(t)$, $\gamma(t)$ of the LV axes at the flight phase under consideration are small and equal to the command angles.

Formulation of the problem. The paper deals with a hypothetical LV with five first-stage jets (Fig. 1). For concreteness, the jet number one fail is assumed (Fig. 1). Such a failure is one of the most unfavorable options for the LV control system.

The projection of the required trajectory of an emergency displacement of the LV onto a horizontal plane has a turn (Fig. 2), to pass at a certain distance from the landing area of the capsule with cosmonauts [8] and must not pass over critical structures of the launch complex.

If the LV characteristics, the time of jet failure t_0 and the LV required trajectory in a horizontal plane are known, it is necessary to develop an optimal law for controlling the LV motion, i.e., to select the structure and gains of the optimal regulator the motion of the vehicle along the desired displacement trajectory with desired accuracy.

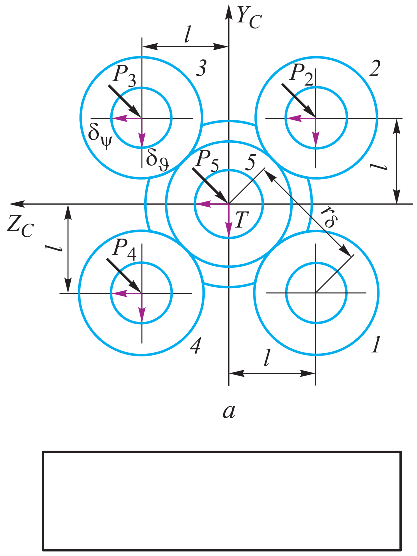

Fig. 1. The location of the failed (first) and operational (the remaining four) jets of the LV (*a*) relative to the umbilical tower (*b*) (top view)

As an output parameter of the LV motion, the position of a certain characteristic point T (Fig. 1 and Fig. 3) of the LV in projection on the horizontal plane is considered. The center of the nozzle of the central engine ($i = 5$) in a non-deflected position is taken as the characteristic point. This point was chosen in order to verify the requirement that the LV not collide with the constructions of the launch complex.

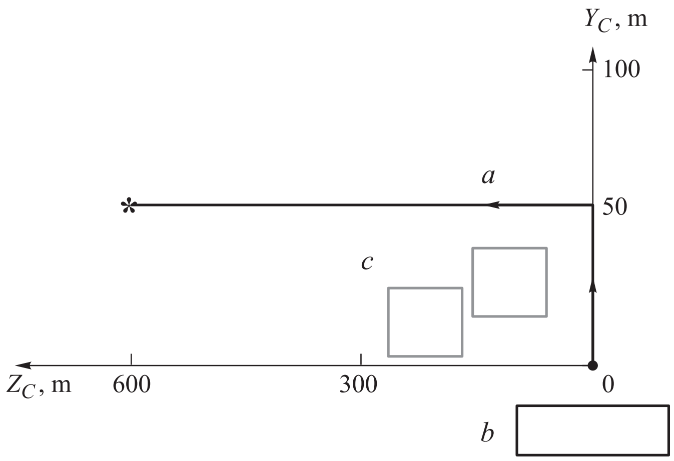

Fig. 2. Projection (top view) of the LV required trajectory (*a*) on the horizontal plane relative to the umbilical tower (*b*) and critical structures of the launch complex (*c*) when jet fails

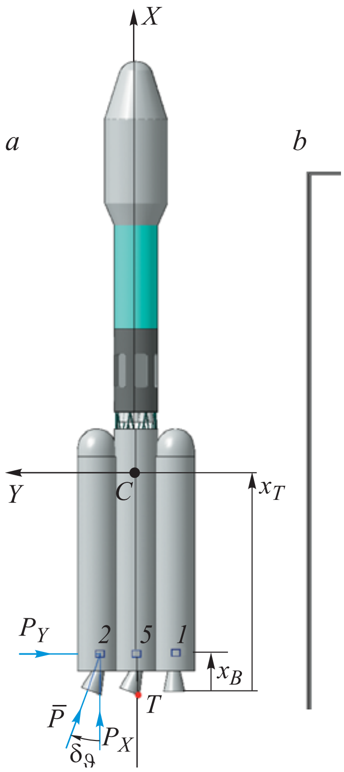

Fig. 3. Forces acting on the LV in case of engine failure (*a*) (side view) relative to the umbilical tower (*b*)

Model of the LV motion. To describe the angular motion of the LV, the body reference frame $CXYZ$ [11] is used. The position of the characteristic point on the launch pad is described in the inertial reference plane $OX_CY_CZ_C$. The origin O of this frame is located at the point of intersection of the LV longitudinal axis on the pad with the horizontal plane at the zero level of the pad. The OX_C axis is directed upwards along the longitudinal axis of the LV. The OY_C axis is located in the horizontal plane normally to the umbilical tower. The OZ_C axis complements the frame to the right-hand frame (Fig. 2).

The motion of the LV mass center is described by the following vector equations:

$$\dot{\vec{r}} = \vec{V}_K; \tag{1}$$

$$m\dot{\vec{V}}_K = m\vec{g} + \sum_{i=1}^{5} \vec{P}_i, \tag{2}$$

where $\vec{r}$ is the radius-vector of the LV mass center; $\vec{V}_K$ is the LV velocity vector; m is the mass of the vehicle; $\vec{g}$ is the acceleration of gravity; $\vec{P}_i$ is the vector of thrust force of the i-th jet.

It can be shown that to provide balancing of the LV $(\vec{M}_P = 0)$ after an engine failure, it is necessary that the angles of rotation δ_ϑ and δ_ψ combustion chambers of operating engines in the corresponding control channels are equal to:

$$\begin{aligned} \delta_\vartheta &= -l/4(x_T - x_B), \\ \delta_\psi &= l/4(x_T - x_B), \end{aligned} \tag{3}$$

where $l = r_\delta \big/ \sqrt{2}$ is the characteristic distance (r_δ is the distance between the axis of the LV and the axes of the side jets); x_T is the distance from the cutoff plane of the the side jet nozzles to the LV center of mass; x_B is the distance from the cutoff plane of the nozzles to the rotation centers of the combustion chambers of the jets (Fig. 1).

In the scalar form, taking into account (3), equations (1) and (2) can be represented as the following three independent groups of egations describing the longitudinal and lateral motions of the LV:

$$\begin{aligned}&\dot{x}_C = V_{xC},\\&\dot{V}_{xC} = 4P_F / m - g;\end{aligned} \tag{4}$$

$$\begin{aligned}&\dot{y}_C = V_{yC},\\&\dot{V}_{yC} = 4P_F \vartheta / m - P_F l / ((x_T - x_B) m);\end{aligned} \tag{5}$$

$$\begin{aligned}&\dot{z}_C = V_{zC},\\&\dot{V}_{zC} = -4P_F \psi / m - P_F l / ((x_T - x_B) m).\end{aligned} \tag{6}$$

It should be noted that the LV mass and coordinates of the vehicle center of mass are changing over time, i.e., (4)–(6) is time-variant eguations.

In system (5), which describes the lateral motion of the center of mass of the LV in the pitch channel, the control variable is the pitch angle ϑ, and the output is the position of the characteristic point y_{out} along the OY_C axis of the starting frame:

$$y_{out} = y_C - x_T \vartheta. \tag{7}$$

The deviation of characteristic point y_{out} from its program value $y_C^*(t)$ is a tracking error in the pitch channel

$$e(t) = y_{out}(t) - y_C^*(t). \tag{8}$$

The quality of control in the pitch channel can be evaluated using a terminal-integral quadratic criterion is written as follows:

$$J_\vartheta = \frac{1}{2} f_\vartheta \left[(y_C(t_k) - x_T \vartheta(t_k)) - y_C^*(t_k) \right]^2 +$$

$$+ \frac{1}{2} \int_0^{t_K} \left[q_\vartheta ((y_C(t) - x_T \vartheta(t)) - y_C^*(t))^2 + r_\vartheta \vartheta^2(t) \right] dt, \tag{9}$$

where $f_\vartheta, r_\vartheta, q_\vartheta$ are "weight" coefficients.

This form of the criterion allows to solve two problems together: to track the desired (program) trajectory of the LV and to reach a given final state with the enhanced accuracy, achieved through a rational choice of weights f_ϑ, r_ϑ, q_ϑ.

The expressions for the output variable, the tracking error, and the criteria in the yaw channel are similar.

Model of the LV motion in a vector form. The equations of the LV motion (1), (2) can be rewritten as a vector equations in the Cauchy normal form:

$$\frac{dX}{dt} = A(t)X(t) + B(t)\, U(t) + \xi(t); \tag{10}$$

$$Y(t) = C(t)X(t) + D(t)\,U(t). \tag{11}$$

For the pitch channel, the components of the system (10), (11) have the following components:

$$X = \begin{bmatrix} y_C & V_{yC} \end{bmatrix}^T_{2\times1} \text{ is the state vector;}$$

$$U = [\vartheta]_{1\times1} \text{ is the control vector;}$$

$$\xi = \begin{bmatrix} 0 \\ -P_F l/(x_T - x_B)m \end{bmatrix}_{2\times1} \text{ is the vector of disturbances;}$$

$$A = \begin{bmatrix} 0 & 1 \\ 0 & 0 \end{bmatrix}_{2\times2} \text{ is the dynamic matrix;}$$

$$B = \begin{bmatrix} 0 & 4P_F/m \end{bmatrix}^T_{2\times1} \text{ is the control matrix;}$$

$$Y = [(y_C - x_T\vartheta)]_{1\times1} \text{ is the output; } C = \begin{bmatrix} 1 & 0 \end{bmatrix}_{1\times2};\ D = [-x_T]_{1\times1}.$$

For the yaw channel these matrices are similar.

The tracking error is written as

$$E(t) = Y(t) - Z(t), \tag{12}$$

where $Z(t) = [y_C^*(t)]_{1\times1}$ is desired value of output variable.

The control guality criterion is

$$J(E,U) = \frac{1}{2}E^T(t_k)FE(t_k) + \frac{1}{2}\int_{t_0}^{t_k}\left(E^T(t)Q(t)\,E(t) + U^T(t)R(t)U(t)\right)dt, \tag{13}$$

where $F = [f_\vartheta]_{1\times1}$, $Q = [q_\vartheta]_{1\times1}, R = [r_\vartheta]_{1\times1}$ are weight matrixes. Similar expressions are formed for the yaw channel.

Mathematically, the task of analytic design of the regulators for the system under consideration is formulated as follows: find the optimal control law $U^*(t)$ for the linear dynamic system (10), (11) taking into account the disturbance vector $\xi(t)$ in the equation of state (10) and the term $D(t)U(t)$ in the equation of outputs (11), minimizing the criterion (13). The problem solution in this formulation will be called as the solution of the modified problem of analytical design of regulators.

The modified problem of analytical design of regulators. It was shown [12, 13] that the optimal control law for system (10), (11) with $D(t) = 0$ and $\xi(t) = 0$ has the form $U(t) = R^{-1}(t)B^T(t)[g(t) - K(t)X(t)]$.

However, such a statement of the problem is not general. When solving this problem of the LV emergency displacement, it is necessary to consider the system (10), (11) for the case when the right side of the equation of state (10) contains the vector of inputs $\xi(t)$ caused by the additional deviation of the combustion chambers of jets to provide the LV motion in the balancing mode, and the output vector Y explicitly depends not only on the state vector X, but also on the control U.

Optimal control for system (10), (11) can be obtained with use the method for solving a modified problem of analytical design of regulators in [10], taking into account the vector of inputs $\xi(t)$ in (10).

In the process of solving a modified problem of analytical design of regulators in application to the system (10), (11), we obtain a differential Riccati-type equation for the matrix

$$\frac{dK}{dt} = -L^T K - KL + KMK - S, \tag{14}$$

and equation for vector

$$\frac{dg}{dt} = \left(KM - L^T\right) g + (KN - W)Z + K\xi. \tag{15}$$

In these equations

$$L = A - B\left(R + D^T QD\right)^{-1} D^T QC;\ M = B\left(R + D^T QD\right)^{-1} B^T;$$

$$N = B\left(R + D^T QD\right)^{-1} D^T Q;\ S = C^T QC - C^T QD\left(R + D^T QD\right)^{-1} D^T QC;$$

$$W = C^T Q - C^T QD\left(R + D^T QD\right)^{-1} D^T Q.$$

The matrix $K(t)$ and the vector $g(t)$ must to satisfy the boundary conditions

$$\begin{aligned} K(t_k) &= C^T(t_k)FC(t_k); \\ g(t_k) &= C^T(t_k)FZ(t_k). \end{aligned} \tag{16}$$

The optimal control U^* as a function of the state vector is written as follows:

$$U^* = \left(R + D^T QD\right)^{-1}\left(B^T g + D^T QZ - \left(B^T K + D^T QC\right)X\right). \tag{17}$$

When $D(t) = 0$ and $\xi(t) = 0$, equations (14)–(15) and expression (17) take the known form, considered in the standard version of solving the problem of analytical design of regulators [12, 13].

Thus, the solution of the modified problem of analytical design of regulators for a linear time variant dynamic system (10), (11) allows to find an optimal control $U^*(t)$ of the form (17) with criterion (13).

Numerical solution of the problem. To verify the efficiency of the solution obtained, a numerical calculation for the problem of regulator formation in the LV control system under consideration during the emergency displacement phase has been carried out. The required displacement trajectory in the horizontal plane is shown in Fig. 2.

In the considered problem, the optimal control laws (17) can be written separately for the pitch and yaw channels in the form

$$\begin{aligned} \vartheta(t) &= K_{yC}(t) y_C + K_{VyC}(t) V_{yC} + \vartheta^*, \\ \psi(t) &= K_{zC}(t) z_C + K_{VzC}(t) V_{zC} + \psi^*. \end{aligned} \quad (18)$$

The components of the equations (18) accordingly to (17) are the following:

$$\begin{aligned} &\left[K_{yC} \quad K_{VyC} \right] = -\left(R + D^T(t) Q D(t) \right)^{-1} \left(B^T K(t) + D^T(t) Q C(t) \right), \\ &\vartheta^* = \left(R + D^T(t) Q D(t) \right)^{-1} \left(B^T g(t) + D^T(t) Q Z(t) \right). \end{aligned} \quad (19)$$

For the yaw channel these expression are similar.

The first stage in the numerical solution the problem is calculation of coefficients of the control laws (18) by integrating the system (14), (15) in inverse time with the boundary conditions (16). The input data is the value of the vector $Z(t_k)$ at the end of the displacement trajectory. The second stage is the simulation of a closed control system of the LV using at each integration step previously calculated values of the coefficients K_{yC}, K_{VyC}, K_{zC}, K_{VzC}, ϑ^*, ψ^*.

Generally, the weight matrices F, R, Q (13) are unknown. In the considered problem, the elements of these matrices in the criterion (13) were determined heuristically taking into account the recommendations given in [14]

$$f_\vartheta = 1 \; [1/m^2], \; r_\vartheta = 1000, \; q_\vartheta = 0.1 \; [1/m^2]$$

for the pitch channel;

$$f_\psi = 1 \; [1/m^2], \; r_\psi = 1000, \; q_\psi = 0.01 \; [1/m^2]$$

for the yaw channel.

As a result of modeling, the dependences of the optimal control law coefficients for the pitch and yaw channels (18) and the coordinates of the characteristic point of the LV as a function of simulation time are shown in Fig. 4–9.

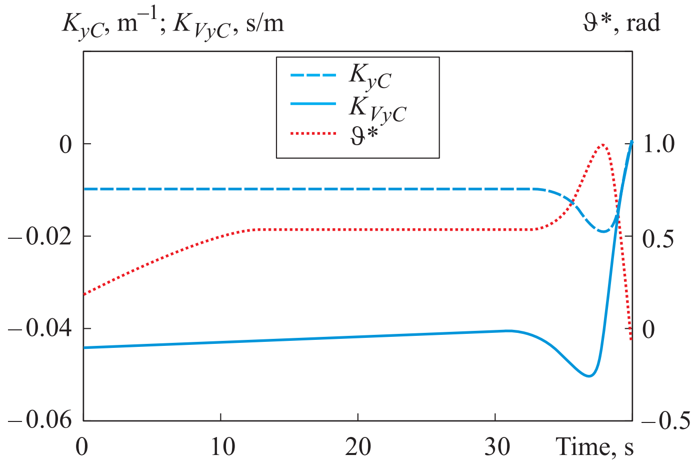

Fig. 4. The coefficients of the optimal control law in the pitch channel

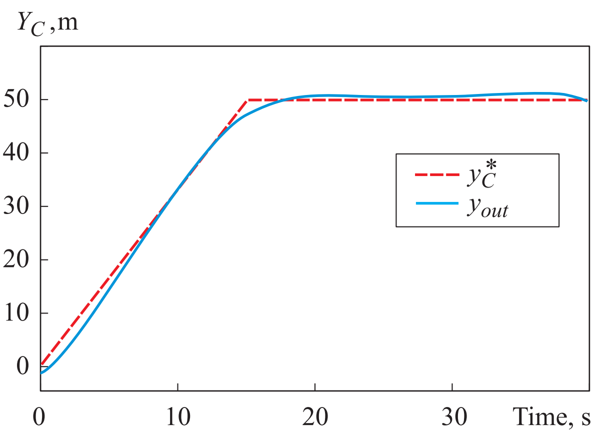

Fig. 5. Program (y_C^*) and executed (y_{out}) positions of the LV characteristic point in the pitch channel

To verify the optimal solution obtained using the simplified LV model of motion (1), (2), the control law (17) was investigated using the detailed spatial model. The projections of the LV characteristic point trajectory onto the horizontal plane, calculated using simplified and detailed models are shown in Fig. 9.

As it is seen from the plots, the optimal control laws, calculated using a simplified LV model, provide a satisfactory quality of control when considering the detailed spatial model of the LV motion along the displacement trajectory. Near the turning point, the trajectory calculated with the detailed model is even better than the trajectory obtained with the simplified model (Fig. 9).

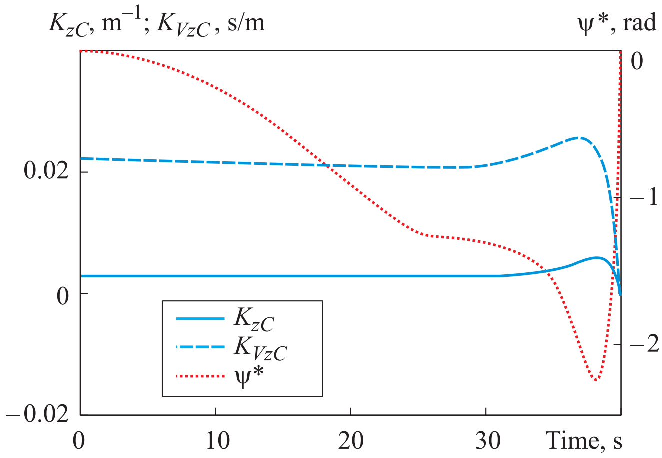

Fig. 6. The coefficients of the optimal control law in the yaw channel

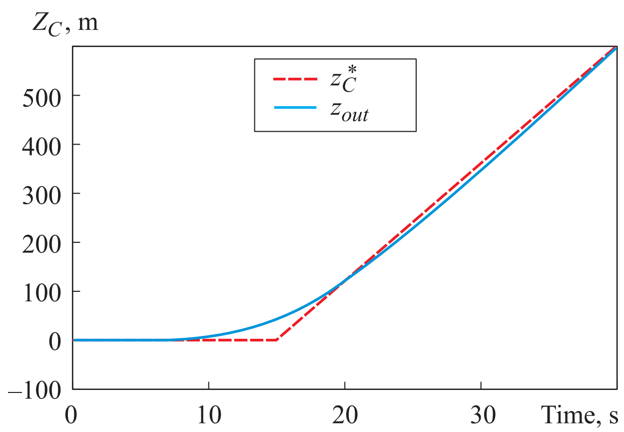

Fig. 7. Program (z_C^*) and executed (z_{out}) positions of the LV characteristic point in the yaw channel

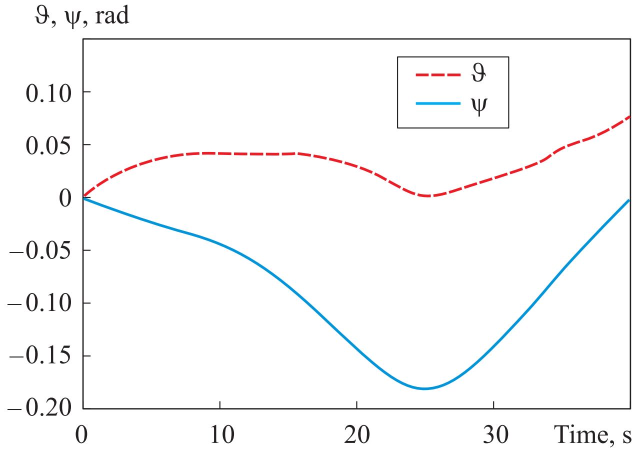

Fig. 8. Executed LV pitch (ϑ) and yaw (ψ) angles

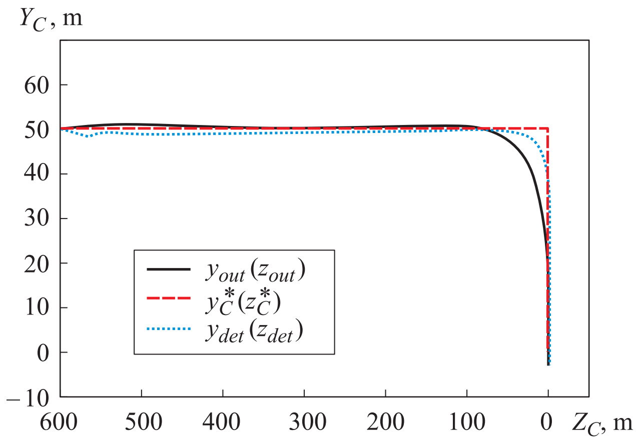

Fig. 9. Projections of the LV trajectories on the horizontal plane, calculated with the simplified $(y_{out}(z_{out}))$ and detailed spatial $(y_{det}(z_{det}))$ models, as well the program trajectory of the LV characteristic point $(y_C^*(z_C^*))$

Conclusion. Thus, a method for constructing an algorithm for controlling the motion of a LV at the initial part of the flight when one of the jet engines fails, in order to move the LV along a predetermined program displacement trajectory to a given site in the horizontal direction has been developed. By solving a modified problem of analytical design of regulators, a structural and parametric synthesis of control laws for the pitch and yaw channels of the LV has been carried out.

The efficiency of the solution obtained is confirmed by numerical simulation results: the deviations of the projection of the LV characteristic point onto the horizontal plane from the required displacement trajectory are in the permissible limits. The demanded pitch and yaw angles are small.

The performances of the developed control algorithms is also confirmed by the results of modeling the detailed spatial model of motion of the vehicle with use optimal control laws with gains obtained with the simplified model. The simulation results give similar values of the output variables.

The task of constructing optimal regulators of the control system in case of the LV's jet engine failure should be continued by considering more detailed models of the LV motion, taking into account aerodynamic forces and moments, the center of mass position shift by the time, considering additional disturbances, such as horizontal wind in the atmosphere [15, 16].

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