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Improving safety requirements of the launch complex by developing modified launch vehicle control algorithms at the initial flight part

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Abstract
The paper is devoted to develop a launch vehicle (LV) motion control algorithms for solution of the two special control problems at the initial flight part: controlled engines plumes displacement and LV emergency displacement in case of engine failure. The implementation of the displacement process in both tasks provides the execution of specified preset programs. For the formation controllers of the LV angular motion control system this paper proposes a modified version of analytical design of controllers (AKOR) problem solution. Efficiency of the developed control algorithms is verified by the simulation results of modeling the algorithms as a part the detailed perturbed LV motion model.

1. Introduction

Reducing the cost of launching payload using launch vehicles is one of the key tasks of modern astronautics. Among the known ways to solve this problem, such as multiple use of the first stage of the LV, launching the LV from the ocean surface, etc., an important measure is to increase the safety requirements for the launch facilities (LF). As such requirements, this paper considers measures aimed at reducing the thermodynamic and mechanical effects of the LV on the structures of the launch complex.

During the LV flight at the initial flight part (in the altitude ranges from zero to 300 m), the jet engine plumes have a negative thermal impact on the structures of the LF (flame duct, umbilical tower etc.) [1]. Also in the case of one of the jet engines failure, there is a possibility of LV collision with the umbilical tower located near the launch pad resulting in the destruction of the LF [2]. Besides, in case of an emergency shutdown of the jet engine, to improve the safety of astronauts and the LF, the LV must be displaced from the launch pad along a certain trajectory to the pre-selected area.

There are at least two opportunities to improve the launch complex safety requirements:

1) to use passive methods of the LF structures protecting, such as the heat-resistant, high-strength materials in the designs of the LF and other auxiliary means [3];

2) to use special control algorithms for the controlled jet engines plumes displacement and/or LV emergency displacement in case of the jet engine failure [2, 4].

In modern conditions, featured considerable competition in the global launch services market aiming to reduce the costs of payload insertion into space, including by reducing the cost of maintaining and repairing the facilities of the launch complex. And so, the advantage of the second method over the first is obvious.

The implementation of the controlled LV motion at the initial flight part consists of two tasks: LV optimal trajectory design [5, 6] and the LV motion control along the designed trajectory [1, 2]. In this paper, the first task is considered as solved.

The implementation of nominal control programs is the second task of the LV motion control, which must be performed by the LV control system. This problem is the subject of consideration in this paper. Depending on the type of emergency situation on board the LV, it is possible to reconfigure the structure and parameters of the controllers. To implement such a reconfiguration, it is necessary to develop a set of control algorithms and use the algorithms from this set in flight for a specific situation – the jet engines plumes displacement, engine failure, etc.

The disadvantage of the existing control algorithms are the heuristic approach to their formation. For this reason, the applied algorithms do not have sufficient robustness, since they do not take into account external disturbances and the LV current actual parameters.

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The aim of this paper is to study possibilities to implement improved safety requirements to the launch complex by developing of a modified LV control algorithms at the initial flight part that implement preset programs in the specific situations including

1) controlled displacement of the jet engines plumes to prepared heat-insulated sector on the launching plane;
2) controlled LV emergency displacement in a direction from the LF in the case of an emergency shutdown of the jet.

To find the structure and coefficients of the controller, a modified version of the AKOR problem solution is used. The basis of the AKOR problem is the Letov-Kalman's theory [7, 8]. A feature of the solution considered in the paper is the more general formulation, assuming the presence in the output vector of the control vector and the right side of the state equation contains the vector of deterministic inputs.

The result of the AKOR problem with a controlled output solution is the algorithm for optimal control of a linear nonstationary system with a quadratic criterion.

The subject of study is the control system of the hypothetical LV (see Figure 1). The LV consists of one central core and four side cores. Each of them has one engine with the same technical characteristics.

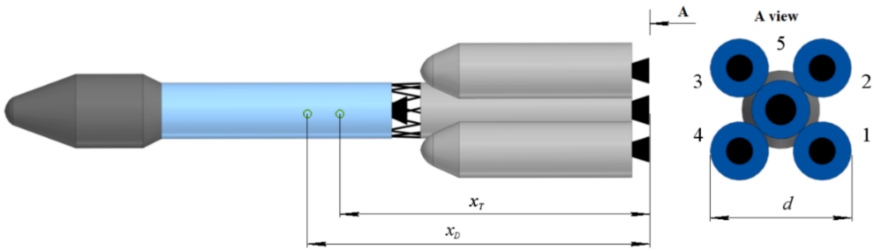

Figure 1: Configuration of the LV

2. Statement of the AKOR problem with controlled output

Let's consider linear time-variant dynamic system

$$\frac{dx}{dt} = A(t)x(t) + B(t)u(t) + \tilde{F}(t) \quad \textbf{(1)}$$

$$y(t) = C(t)x(t) + D(t)u(t), \quad \textbf{(2)}$$

$$e(t) = y(t) - z(t) \quad \textbf{(3)}$$

with arbitrary initial conditions $x(t_0) = x_0$. In this system $[x]_n$ is n-dimensional state vector, $[u]_k$ is k-dimensional control vector, $[y]_m$ is m-dimensional output vector, $[e]_m$ is m-dimensional vector of tracking error, $[z]_m$ is m-dimensional vector of required outputs, $[\tilde{F}]_n$ is n-dimensional vector of deterministic inputs.

The control quality criterion is

$$J(e,u) = \frac{1}{2}e_1^T(t_1)Fe_1(t_1) + \frac{1}{2}\int_{t_0}^{t_1}\left(e^T(t)Q(t)e(t) + u^T(t)R(t)u(t)\right)dt \quad \textbf{(4)}$$

where $[F]_{m\times m}, [Q]_{m\times m}, [R]_{k\times k}$ are weight matrices, $u(t)$ is not constrained, t_1 is preset final time, $e_1(t_1) = C(t_1)x(t_1) - z(t_1)$ is vector of tracking error in final time t_1.

It is known [9, 10], that the solution of the problem if $D(t) = 0$ and $\tilde{F}(t) = 0$ gives to the optimal control $u^*(t)$ in the form

$$u(t) = R^{-1}(t)B^T(t)[g(t) - K(t)x(t)], \quad \textbf{(5)}$$

where $[K]_{n\times n}$ is n-dimensional quadratic symmetric positive definite matrix, that obey matrix differential Riccatti

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equation, $\left[g\right]_n$ is *n*-dimensional column vector that is solution of linear vector differential equation.

However, such a statement of the AKOR problem for the system (1)-(2) with assumptions $D(t)=0$ and $\tilde{F}(t)=0$ is not general. For example, when solving this problem of the displacement of the LV's engines plumes, the output vector $y(t)$ explicitly depends not only on the state vector $x(t)$, but also on the control $u(t)$, since the control is the deflection angle of the engine nozzle, on which the position of the jets track on the launching plane depends. And in case of engine failure, the right side of the state equation (1) contains the vector of inputs $\tilde{F}(t)$ caused by the additional force and moment due to the loss of total thrust.

Thus, in a more general statement of the AKOR problem, considered in the paper, is necessary to find the optimal control $u^*(t)$ time-variant system (1)-(2) with non-zero deterministic input vector $\tilde{F}(t)$ in the right part of the state equation and additive component $D(t)u(t)$ in the equation of output, minimizing the criterion (4). The AKOR problem in this statement we will call as the AKOR problem with controlled output.

3. Solution of the AKOR problem with controlled output

The AKOR problem with controlled output can be solved using the Pontryagin's maximum principle [1, 2] or the Bellman's dynamic programming method [11, 12].

The optimal control $u*$ as a function of the state vector is written as follows

$$u^* = (R + D^T QD)^{-1}[B^T g + D^T Qz - (B^T K + D^T QC)x], \tag{6}$$

where

$$\frac{dK}{dt} = -L^T K - KL + KMK - G, \tag{7}$$

$$\frac{dg}{dt} = (KM - L^T)g + (KN - H)z + K\tilde{F}. \tag{8}$$

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

$K(t_1) = C^T(t_1)FC(t_1)$,

$g(t_1) = C^T(t_1)Fz(t_1)$.

The matrices of equations (7) and (8) are

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

$N = B(R + D^T QD)^{-1} D^T Q,\ G = C^T QC - C^T QD(R + D^T QD)^{-1} D^T QC,$

$H = C^T Q - C^T QD(R + D^T QD)^{-1} D^T Q.$

Optimal automatic-control system structure formed using the solution (6) is presented on the Figure 2.

4. Technique for solving control problems of the LV at the initial flight part using the AKOR method

The solution of the AKOR problem with controlled output consists of the following steps:

1) Form the LV motion equations at the considered flight part.

2) Linearize the LV motion equations.

3) Form the output equation.

4) Set the desired output.

5) Form the control criterion by selection of the weight matrices elements taking into account the composition of the output vector and the vector of desired output.

6) Design the controller in an analytical form using the solution of the AKOR problem with controlled output.

7) Set the initial weight coefficients, as well as the boundary conditions for the matrix $K(t_1)$ and the vector $g(t_1)$ for calculating the controller coefficients.

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8) Calculate the controller coefficients by integrating the matrix differential Riccati equations (7) and (8) in the inverse time.

9) Simulate a closed-loop control system with the substitution of the controller coefficients at each time step.

10) If necessary, to improve the control quality and the accuracy of tracking specified control programs, return to step 7 and refine the weight coefficients.

11) Analyze the efficiency of the controller developed using the linearized model by modelling a detailed non-linear model of the LV motion taking into account the random horizontal wind using simulation modelling.

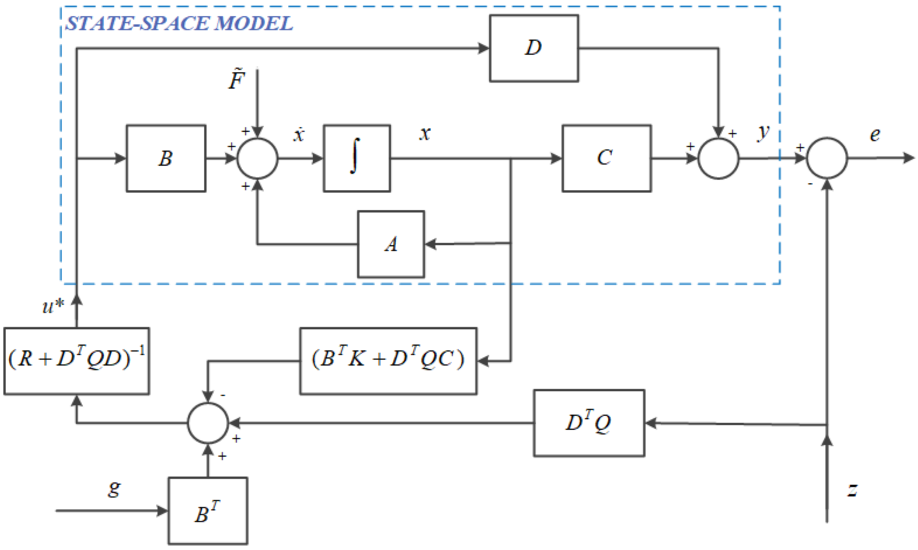

Figure 2: Optimal automatic-control system structure

5. Implementation of the technique for two particular LV control problems at the initial flight part

In this section, we present the implementation of the considered technique for solving the above problems: controlled displacement of the jet engines plumes and controlled LV emergency displacement in the case of an emergency shutdown of the jet engine.

5.1 LV motion equations at the initial flight part

The situations were considered where displacement of the engines plumes and the LV emergency displacement occur in the pitch plane facing away from the umbilical tower (see Figure 2). The nozzles of all jet engines are deflected synchronously. In the case LV emergency displacement, for concreteness, it was assumed that there was a complete failure of the first jet engine ($i=1$) in the second of the flight $t_0=2$ s.

The LV motion in the longitudinal plane (displacement maneuver plane) in the starting frame is described by the following differential equations

$$
\begin{aligned}
&\dot{x}_C = V_{xC},\\
&\dot{y}_C = V_{yC},\\
&\dot{V}_{xC} = (P_\Sigma \cos\vartheta - mg + X_a \cos\vartheta)/m,\\
&\dot{V}_{yC} = (P_\Sigma \sin(\vartheta+\delta_\vartheta) - (X_a - Y_a)\sin\vartheta - Y_a\cos\vartheta)/m,\\
&\dot{\omega}_z = (-P_\Sigma(x_T - x_B)\sin(\vartheta-\delta_\vartheta) + (X_a - Y_a)y_T\sin\vartheta - Y_a(x_D - x_T)\cos\vartheta + (P_i - \tilde{P}_i)\tilde{l})/I_z,\\
&\dot{\vartheta} = \omega_z,
\end{aligned}
\tag{9}
$$

where x_T is coordinate center of mass, $x_C = h$ is flight altitude, $y_C = l$ is distance from starting point to LV, ω_z is angular rate of LV relative to lateral axis, ϑ is pitch angle, I_z is moment of inertia relative to lateral axis, $X_a = C_x qS$ is aerodynamic longitudinal force, $Y_a = C_y^\alpha \alpha qS$ is aerodynamic normal force, m is mass; L is characteristic length,

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S is characteristic (frontal) area; $q = \rho(h)V^2/2$ is air pressure, x_D is distance from nozzle edge plane of jet engine to LV pressure center; V_{xC}, V_{yC} are projections of the airspeed V, P_Σ is total thrust of all working order engines, P_i is nominal engine thrust, $\tilde{P}_i$ is thrust emergency jet engine (in normal flight $\tilde{P}_i = P_i$), $\tilde{l}$ is arm of thrust emergency jet engine.

It should be noted that the LV mass and coordinates of the vehicle center of mass are changing over time, i.e., (9) is time-variant equations.

5.2 Simplifying and linearization of LV motion equations

At the initial flight part, deviations of the LV motion parameters from nominal values in the LV vertical motion are small. Therefore, while developing control algorithms of the closed-loop control system for the solving problems of the jet engines plumes displacement and LV emergency displacement, LV motion model can be described using the linearized equations with time variant coefficients.

The system (9) can be rewritten in the linearized form, with using previously described simplifications by the reducing the order to the 4th and analytical calculation of the equations for the for vertical speed and altitude. Then system (9) takes the following form

$$\begin{aligned}
&\dot{V}_y = \left(P_\Sigma m(\vartheta + \delta_\vartheta) - (C_x - C_y^\alpha)\rho V^2 S\vartheta - C_y^\alpha \rho VSV_y\right)/2m,\\
&\dot{\omega}_z = ((C_{x0} - C_y^\alpha)\rho V^2 S y_T \vartheta - P_\Sigma I_z (x_T - x_B)(\vartheta - \delta_\vartheta) - C_y^\alpha \rho VS(x_D - x_T)V_y + I_z(P_1 - \tilde{P}_1)\tilde{l})/2I_z,\\
&\dot{y} = V_y,\\
&\dot{\vartheta} = \omega_z.
\end{aligned} \tag{10}$$

Let's write down a system (10) in the vector-matrix form in the Cauchy normal form (1), in which the following elements

$x = \left[V_{yC} \;\vdots\; \omega_z \;\vdots\; y_C \;\vdots\; \vartheta\right]^T_{4\times1}$, $u = \left[\delta_\vartheta\right]_{1\times1}$,

$$A = \begin{bmatrix}
-C_y^\alpha \rho VS/2m & 0 & 0 & [2P_\Sigma - (C_{x0} - C_y^\alpha)\rho V^2 S]/2m\\
C_y^\alpha \rho VS(x_D - x_T)/2I_z & 0 & 0 & [(C_{x0} - C_y^\alpha)\rho V^2 S y_T - 2P_\Sigma(x_T - x_B)]/2I_z\\
1 & 0 & 0 & 0\\
0 & 1 & 0 & 0
\end{bmatrix}_{4\times4},$$

$B = \left[P_\Sigma/m \;\vdots\; -P_\Sigma(x_T - x_B)/I_z \;\vdots\; 0 \;\vdots\; 0\right]^T_{4\times1}$, $\tilde{F} = \left[0 \;\vdots\; (P_1 - \tilde{P}_1)\tilde{l}/I_z \;\vdots\; 0 \;\vdots\; 0\right]^T_{4\times1}$ is the input vector of deterministic disturbance due to the first engine failure (during normal flight: $\tilde{P}_i = P_i$ and then $\tilde{F} = [0]_{4\times1}$).

5.3 System output equations

The control system output equations are

1) in the displacement of the engines plumes problem - the coordinate of the jet trace in the projections on the horizontal plane:

$$y_p = y_C + h\vartheta + h_B \delta_\vartheta\,, \tag{11}$$

where $h_B = h - x_T + x_B$ is altitude of a center of the engine chamber swing, x_B is distance from nozzle edge plane to the center of the engine chamber swing;

2) in the LV emergency displacement problem – the coordinate of the LV characteristic tail point in the projections on the horizontal plane:

$$y_t = y_C - x_T \vartheta\,. \tag{12}$$

This point was chosen in order to verify the requirement that the LV will not collide with the umbilical tower. Form the output vector equation of the form (2)

$y = \left[V_{yC} \;\vdots\; \omega_z \;\vdots\; y_{31} \;\vdots\; \vartheta\right]^T_{4\times1}$; $z = \left[0 \;\vdots\; 0 \;\vdots\; z_{31} \;\vdots\; 0\right]$; $D = \left[0 \;\vdots\; 0 \;\vdots\; d_{31} \;\vdots\; 0\right]^T_{4\times1}$;

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$$C = \begin{bmatrix} 1 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 \\ 0 & 0 & 1 & c_{34} \\ 0 & 0 & 0 & 1 \end{bmatrix}_{4\times 4}.$$

The differences between the two models of controlled displacements are depicted in the Table 1.

Table 1: Components of the state equations and output equations for solving two LV control problems at the initial flight part

The displacement of the engines plumes problem	The LV emergency displacement problem
$y_{31} = y_p$	$y_{31} = y_t$
$c_{34} = h$	$c_{34} = x_T$
$d_{31} = h_B$	$d_{31} = 0$
$z_{31} = z_p^*$	$z_{31} = z_t^*$
$\tilde{P}_1 = P_1$	$\tilde{P}_1 \neq P_1$

Thus, in the displacement of the engines plumes problem, the inputs vector in the state equation is zero, and the outputs vector depends on the control. in the LV emergency displacement problem, the inputs vector is non-zero due to the additional force and moment due to shutdown of the emergency engine and the outputs vector does not depend on the control.

5.4 Descriptions of displacement programs

While starting the LV one of the high-rise LF nearest the launch point is the umbilical tower (see Figure 3) [13]. Depending on the type and size of the umbilical tower, restrictions are imposed on the program of the jet engines plumes displacement. In a point of fact, after the lift-off the LV should move vertically to avoid hitting the cable-filling tower, then softly move in the direction of displacement OL on preset distance from starting point not setting jet engine plumes close to the tower. The speed of displacement jet engines plumes is subject to a priori choice. For a faster displacement, large angles of jet engines nozzles deflection may be required, and too slow displacement will be ineffective in terms of the thermal effect of the LV plumes on the LF. An example of the preset displacement plumes program shows on the Figure 6.

In case of the LV's jet engine failure at the initial flight part, special attention should be paid to both the safety of astronauts (in case manned LV starts) and the safety of the launch complex. These requirements impose restrictions on the direction of displacement OL and the LV emergency displacement program from the LF. It should be formed for every specific launch complex and cosmodrome, taking into account the location of the LF and landing area of the capsule with astronauts (see Figure 3). An example of the preset displacement emergency program of the LV shows on the Figure 7 [14].

5.5 Control criterion

Efficiency of control is evaluated by quadratic terminal integral criterion. The terminal part of criterion is used to provide preset final angular state of the LV at the end of displacement phase – vertical orientation and zero rate of LV. This requirement is caused by the fact that after completing the displacement phase, the LV must continue its motion according to the regular pitch program. The integral part is some kind of a "penalty" for deviation of current output parameter $y(t)$ from its preset program value $y^*(t)$. The weight matrices $[F]_{4\times4}, [Q]_{4\times4}, [R]_{1\times1}$ of the control criterion (4) with nonzero elements: $f_{11}, f_{22}, f_{33}, f_{44}, q_{33}, r$ are considered.

Control criterion (3) taking into account the composition of the weight matrices, takes the following form

$$J = \frac{1}{2}\left(f_{11}V_y^2(t_1) + f_{22}\omega_z^2(t_1) + f_{33}(y_{31}(t) - z_{31}(t))^2 + f_{44}\vartheta^2(t_1)\right) + \frac{1}{2}\int_0^{t_1}\left(q_{33}(y_{31}(t) - z_{31}(t))^2 + r\delta_\vartheta^2(t)\right)\, dt. \quad \textbf{(13)}$$

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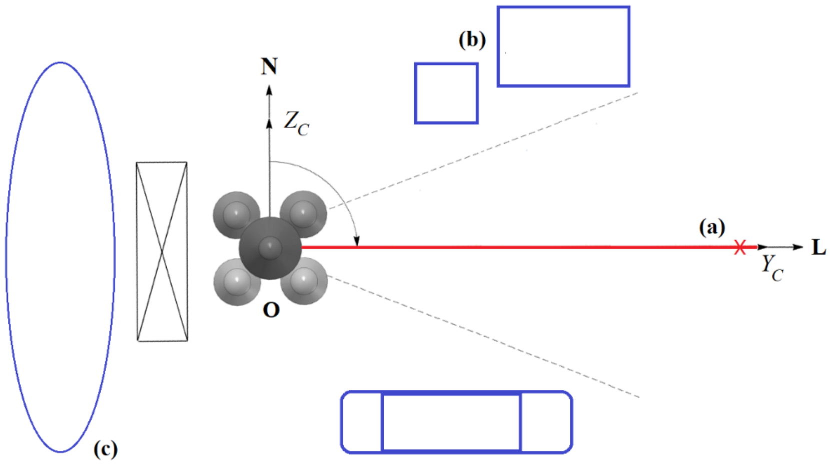

Figure 3: Example of direction of the displacements (a), location of the LF (b) and landing area of the capsule with astronauts (c)

5.6 Controller design

To the found optimal control (6) there correspond the following controller coefficients

$$\begin{aligned} &\begin{bmatrix} K_V & K_\omega & K_y & K_\vartheta \end{bmatrix}^T_{4\times 1} = -(R + D^T(t)QD(t))^{-1}(B^T K(t) + D^T(t)QC(t)), \\ &K^*_\delta(t) = (R + D^T(t)QD(t))^{-1}(B^T g(t) + D^T(t)Qz(t)). \end{aligned} \tag{14}$$

The structure of the controller in analytical form with regard to (14) is as follows

$$\delta^*_\vartheta(t) = K_V(t)V_y(t) + K_\omega(t)\omega_z(t) + K_y(t)y(t) + K_\vartheta(t)\vartheta(t) + K^*_\delta(t)\,. \tag{15}$$

5.7 Weights coefficients of the control criterion

The optimal values of the weight coefficients $f_{11},\ f_{22},\ f_{33},\ f_{44},\ q_{33},\ r$ weight matrices $F,\ Q,\ R$ of the control criterion (13) were determined by the brute force method, taking into account three main factors: the position of the moving LV and the LF should be at a certain distance, loss of energy should be minimal, boundary conditions must be met with a desired accuracy. The optimal values of the weight coefficients in considered numerical example are presented in the Table 2.

Table 2: Weight coefficients of quadratic criterion for solving two LV control problems at the initial flight part

The displacement of the engines plumes problem	The LV emergency displacement problem
$f_{11} = 0{,}71\ (s^2/m^2),\ f_{22} = 2{,}94\ (s^2),$	$f_{11} = 0.5\ (s^2/m^2),\ f_{22} = 0.5\ (s^2),$
$f_{33} = 0{,}31\ (1/m^2),\ f_{44} = 4.92,$	$f_{33} = 7\ (1/m^2),\ f_{44} = 12,$
$q_{33} = 0{,}02\ (1/m^2),\ r = 6{,}99.$	$q_{33} = 0.5\ (1/m^2),\ r = 3.$

5.8 Simulation Results

This section includes the steps 8-11 of the technique described in Section 4. Figures 4, 6, 8 show the simulation results of solving the controlled engines plumes displacement problem. Figures 5, 7, 9 demonstrate the simulation results of solving the LV emergency displacement problem since the onset of the failure. Figures 8, 9 show results the simulation modeling. The $\pm 3\sigma_{yp}, \pm 3\sigma_{yt}$ deviations from their program values were estimated by processing of 50 realizations of the system's outputs as random processes. Horizontal wind was considered as an external disturbance of the LV motion

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model. To simulate a random horizontal wind, a second-order shaping filter with time-variant parameters was used [15].

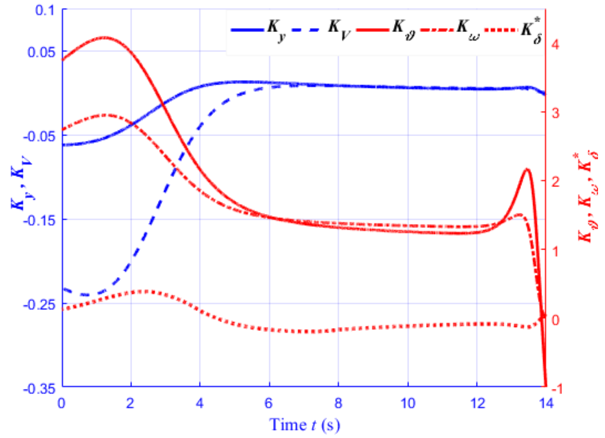

Figure 4: Controller coefficients in solving control problem of the plumes displacement

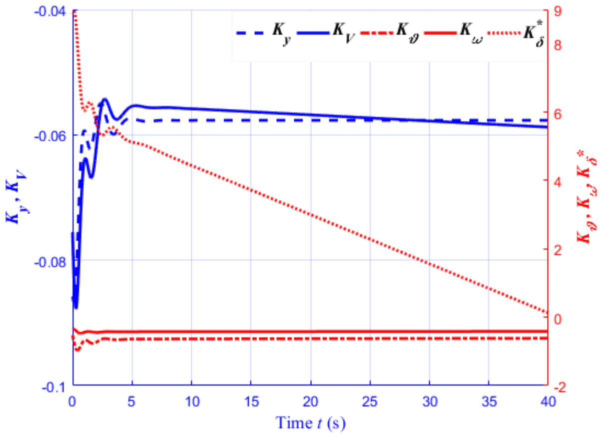

Figure 5: Controller coefficients in solving control problem of the LV emergency displacement

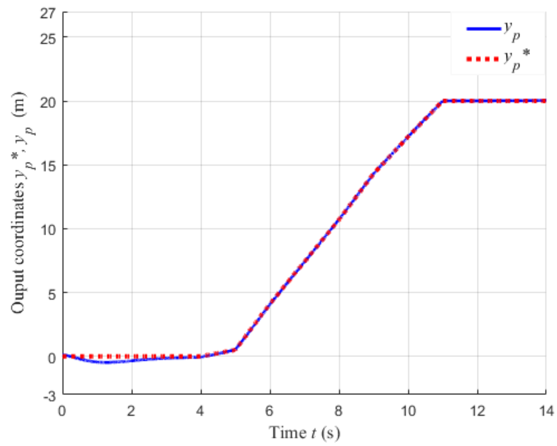

Figure 6: Preset and current positions of the plumes traces of the jet engines

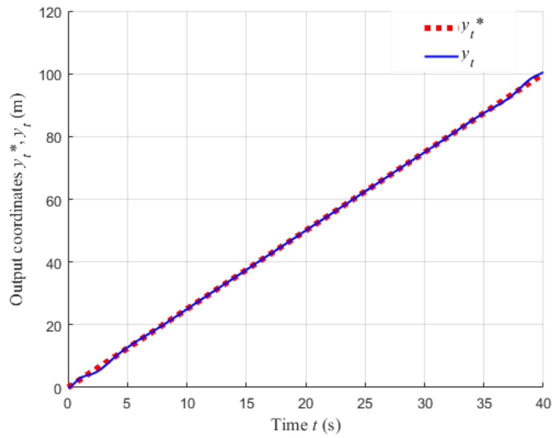

Figure 7: Preset and current coordinates of the LV characteristic tail point

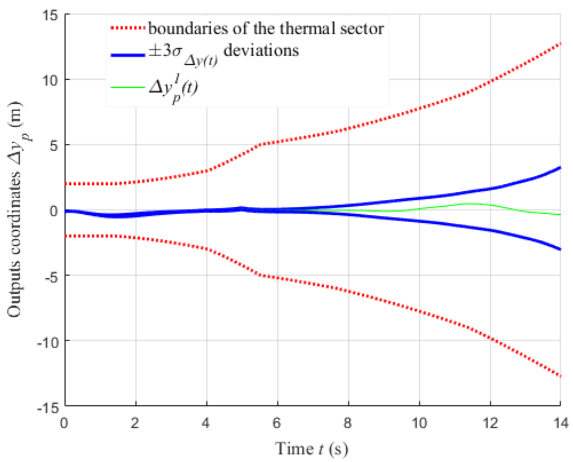

Figure 8: The boundaries of the thermal sector, the tube increments of the jet trace positions and one realization of an output random process $\Delta y_p^1(t)$

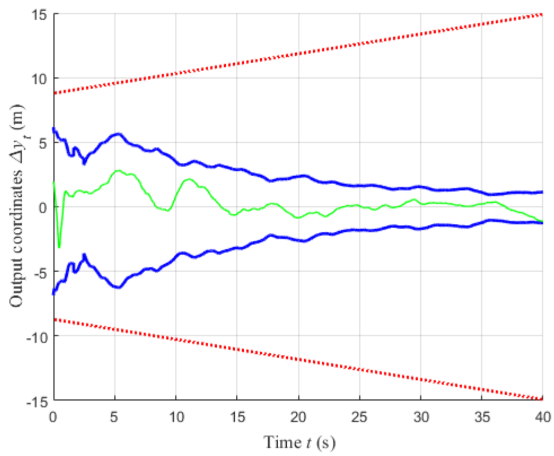

Figure 9: The boundaries of the LV emergency displacement corridor, tube increments of the LV's coordinates of the characteristic tail point and one realization of an output random process $\Delta y_t^1(t)$

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Figures 6, 7 show that the controllers (15) ensure the execution of the preset displacement programs with reasonable accuracy. Figure 8 shows $\pm 3\sigma_y$ deviations of the jets traces relative to their desired values (blue line) is within the thermal sector (red dotted lines). The diverging character of the tube is due to an increase in the LV airspeed, at which the influence of aerodynamic forces on its motion increases. Figure 9 shows, the spans of deviations of the coordinates of the LV characteristic tail point is within the permissible emergency drop corridor. The converging character of the tube is associated with the transition process of the system after an engine failure and the simultaneous need to perform a lateral maneuver of the LV for its emergency displacement under the action of external wind disturbances.

6. Conclusion and Future Work

Thus, in paper the following tasks were solved:

1) the statement of the mathematical AKOR problem with controlled output has been formulated taking into account the features of the considered LV control problem at the initial flight part and its solution in the form of optimal control of a linear time-variant system with quadratic criterion has been developed;

2) techniques have been developed for the formation of the control algorithms for the solving of controlled engines plumes displacement and LV emergency displacement according to specified preset programs using the solution the AKOR problem with a controlled output technique;

3) the performances of the developed control algorithms were verified by the results of modeling the detailed LV controlled motion model with use optimal control laws with gains obtained with the simplified model. The random horizontal wind in the atmosphere was taken into account in this detailed model.

In the future, we are going to consider a more complete set of disturbances acting on the LV motion: fuel sloshing, bending mode of the LV body, others. It is also of interesting to use the AKOR problem with controlled output technique for the developing the control algorithms at the first stage return phase.

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