Reconfigurable flight control system

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Abstract - The article explains the possibility of applying the system of parametric methods, structural reconfiguration control and reconfiguration of the object control objectives to prevent the transition to the current flight situation into a catastrophic one and maintain the specified level of safety. The article presents a block diagram of a control system developed reconfigurable dynamic system, and describes how it works. A mathematical model of the aircraft, taking into account the influence of the particular situation.

Keywords - aircraft; faults or failures to the actuators/sensors or structural damage; reconfiguration; flight control system; loss of control in flight; survivability

I. INTRODUCTION

The complexity of solving the problem for ensuring flight safety is continuously growing due to the increased usage of aviation equipment, apart from the known effects leads to a significant increase in the probability of collision with mechanical units, and expanding the range of its functional tasks performed. Comparative analysis of the ICAO statistics showed that 35% of the loss of aircraft are associated with failures and injuries of automatic control systems. [1] Also is necessary to mark the extremely high transience of emergency, which requires immediate intervention in the situation for the necessary control actions to prevent its development or escalation to disastrous. All this leads to the increasing role of board means of automatic detection of damage and control the external contour surfaces of an aircraft in flight, the development of advanced methods and systems for automatic reconfiguration control actions, and intelligent decision support systems for the crew at accidental situations. Emergency situations are known characteristic of high transience flow to about ten seconds, which in turn requires instant intervention in the situation and develop the necessary control actions that will (to prevent the development of an emergency) to prevent the development of emergency and transition in her disastrous.

All of the above determines the purpose of scientific research which is primarily in the development of methods for diagnosing the state of the external aerodynamic contours and on the basis of automatic systems allow us to fix the time, place and degree of occurrence of damage in flight, as well as the system of methods and means of automation of processes reconfiguration to restore stability and controllability of the aircraft and thus provide a specified level of safety in terms of occurrence of specific situations in flight.

II. ANALYSIS OF PUBLICATIONS

Many methods have been proposed to solve the problem of preserving controllability and stability aircraft when unexpected situation appears during flight. As shown in Fig. 1 [2] they have fallen into two main categories: active [3,4,5] and passive [6,7]. In the passive category, the faulted control system continues to operate with the same controller; the effectiveness of the scheme depends upon the original control law's possessing a considerable degree of robustness. The passive methods are essentially robust control techniques which are suitable for certain types of structural failures. These failures can be modeled as uncertainty regions around a nominal model of system. There are many types of common failures, which cannot be adequately modeled as uncertainty. Therefore, it is important to constitute the controller, which more directly addresses the concrete situation. The active category involves either an on-line re-design of the control law after failure has occurred and has been detected, or the selection of a new pre-computed control law. In this study an active fault-tolerant control system against different degree of actuator failures is considered [8].

Perez et al. presented a fault tolerant control application using neural networks-based compensation schemes. The design consists of supervising the process possible faults using an observer that allows determining the present fault and its direction and then it will be used a classification neural network which will activate the appropriate controller according to the identified fault type. In this work the superior tank water level was controlled [9].

Wang et al. presented the design of a lateral control system for a loitering aircraft of aileron-less folding wing. The paper focused on bank-to-turn by differential movement of elevators and skid-to-turn by rudder deflection. The flight path track loop was designed based on the self-organizing fuzzy control algorithm for the aircraft to fly in a desired path. They claimed the results show that the control plans are feasible and the control system is adequately robust to meet the requirements of the course control [10].

Romulus et al. presented a new on-line parametric identification and discrete optimal command algorithm for mono or multivariable linear systems. The method performed to the automatic command of the flying objects' movement. They claimed that the simulation results obtained with good results, for identification and optimal command of an air-air rocket's movement in vertical plain regarding to target's line [11].

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Canureci et al. presented a methodology for using the results of a simulation on a laboratory installation in the level control in coupled tanks. They claimed that the research would be extended to also implement modeling algorithms and detection and localization of the possible faults types that appear in the plant [12].

Romulus et al. presented an algorithm for identification of the longitudinal and lateral movements of an aircraft. For identification a reduced order observer has been projected. With the obtained reduced order observer a stabilization compensator has been made. They claimed that the obtained results show that the algorithm may be used with good results to any system's identification [13].

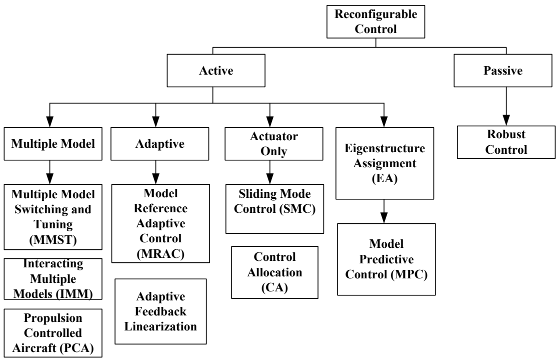

Figure 1. Classification of approaches to reconfigurable flight control

Rao et al. presented a variable structure based sliding mode controller for recovery of an aircraft from spin. The spin recovery problem was formulated as a two point boundary value problem. Using the bifurcation analysis results of the aircraft, the spin states of aircraft were identified. Once the aircraft enters into spin, the controller was activated to bring it back to a desired state which is a level flight trim solution also found from a bifurcation map of the aircraft model [14].

Thus, in the book of Kazak V.M. the factors that cause the loss of survivability of aircraft during their flight operation are reviewed. The methods and algorithms for operational evaluation and identification of aircraft and its systems state. The processes of dynamics changes in model and characteristics of the aircraft and its control circuits in abandoned situations, synthesis control, adaptive to some damage of airframe and a power plant of an aircraft [8].

III. MAIN PART

The problem is solved by reconfiguring aircraft control to provide the required level of flight safety in conditions of an accident occurrence, use parametric , structural , controlled object reconfiguration, objective aircraft control reconfiguration. Method of aircraft control in accident condition is as follows. Typical external aircraft outline damages are fixed and classified in flight on a basis of thermal fields theory. Parametric, structural reconfiguration and reconfiguration of control aims and tasks are used to provide control recovery and aircraft stability in case of accidental or catastrophic situation in flight.

Parametric reconfiguration is the change of the feedback ratios for the given characteristics of dynamic stability and controllability of controlled object.

Structural reconfiguration is a redistribution of the control to the serviceable elements for creating needed operational forces and moments to provide aircraft stability and controllability recovery during unexpected situations in flight.

Reconfiguration of the object – the object control configuration change that is provision to controls additional unusual in normal flight mode features to prevent the development of catastrophic situations or minimize its consequences.

Aim of the control reconfiguration – optimal continuation of flight among the possible alternatives choose, taking into account the criticality of damage the outer contours of the aircraft. For example, returning to the takeoff airfield Finding the airfield, and assess the feasibility of providing the emergency landing of an aircraft, or find a place of extreme landing.

The basis of reconfiguration is the fixed possibility of organization of structural and functional surplus of elements of the system, that is used as organs of control: wing flaps, interceptors, spoilers, engines etc, giving additional, not peculiar for the regular mode mission-controls of function to them, that allows to redistribute managing influences after the new algorithm of management. Introduction of configuration manager to the system of automatic control fundamentally distinguishes it from the existent systems. A configuration manager consists of two modules - module of objective, structural, self-reactance and having a special purpose reconfiguration, and also module of exposure, authentication and classification of typical refuses/of damages. In case of origin of refuse/damage the module of exposure and authentication classifies a damage and forms a command on including of the module of reconfiguration, except that, he passes in the module reconfigurations of managing actions all information about the classified refuse/of damage (id est forms the model of refuse/of damage). The module of objective, structural, self-reactance and having a special purpose reconfiguration forms new managing influences for beating back, and at impossibility of the complete beating back, maximally possible decline of consequences of refuse/of damage (Fig. 2).

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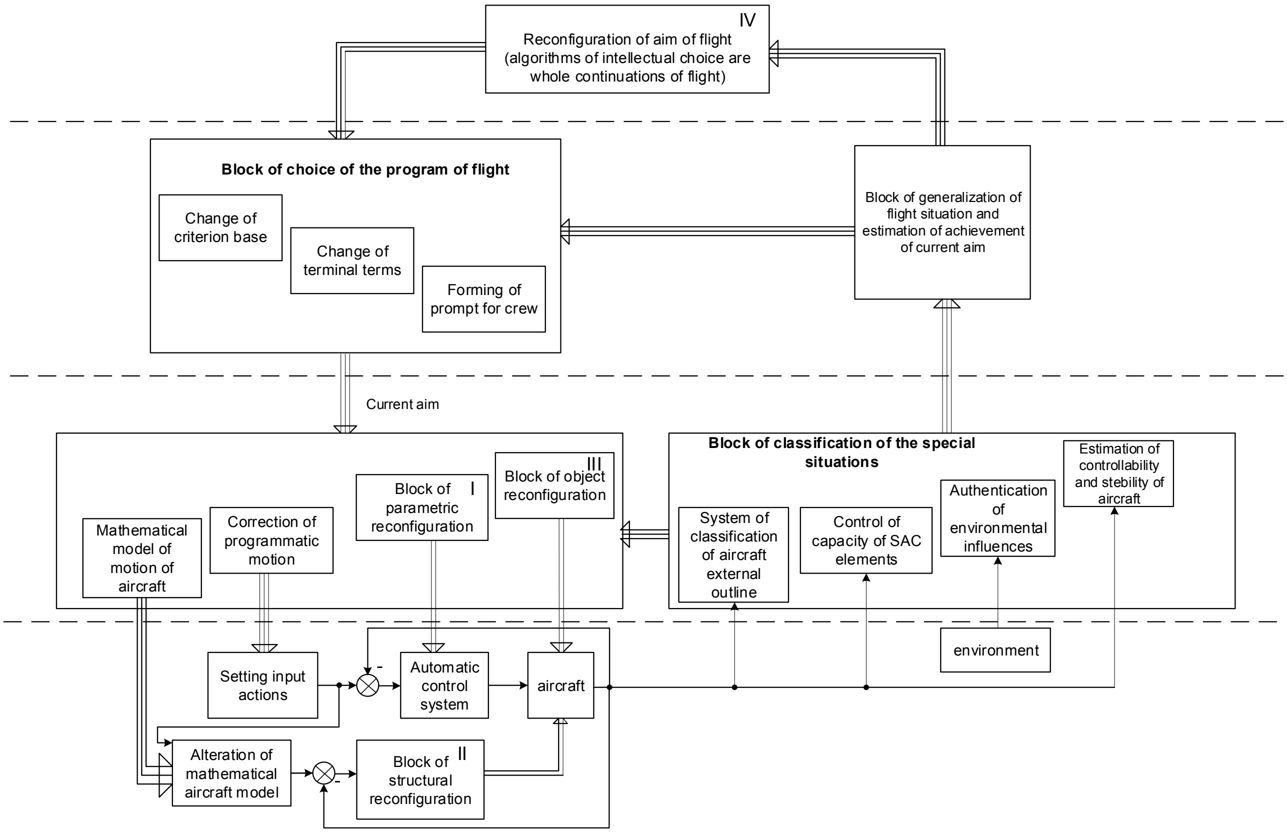

Figure 2. Flow diagram of reconfigurated control system of aircraft in the conditions of origin of exception condition on wing

In general, the mathematical model of the aircraft with the influence of destabilizing factors can be expressed by the equation:

$$\dot{x} = f(x,u,\xi) \tag{1}$$

where $x = \{x_1,...,x_n\}$ – state vector of the object; $u = \{u_1,...,u_m\}$ – control vector; $\xi = \{\xi_1,...,\xi_k\}$ – vector perturbation. Equation (1) is non-linear with variable parameters. However, as noted above, in particular solving problems controls assume a number of assumptions, largely simplifying the mathematical model of the source. In the derivation of the equations assume that the aircraft is a rigid body with constant mass. We believe the fixed air environment, ie, the vector of the earth and the air velocities coincide LA.

Then, taking into account the input assumptions, the dynamics of the movement of aircraft, taking into account the negative impact of destabilizing factors in the associated coordinate system describe the following equations:

$$\begin{cases} \dot{V}_x = (V_y\omega_z - V_z\omega_y) + (n_x - \sin\vartheta)g \\ \dot{V}_y = (V_z\omega_x - V_x\omega_z) + (n_y - \cos\vartheta\cos\gamma)g \\ \dot{V}_z = (V_x\omega_y - V_y\omega_x) + (n_z - \cos\vartheta\sin\gamma)g \\ \dot{\omega}_x = \dfrac{\omega_y\omega_z(I_y^2 - I_yI_z + I_{xy}^2) + \omega_x\omega_z I_{xy}(I_z - I_x - I_y) + I_{xy}M_y + I_yM_x}{I_xI_y - I_{xy}^2} \\ \dot{\omega}_y = \dfrac{\omega_x\omega_z(I_xI_z - I_x^2 - I_{xy}^2) + \omega_y\omega_z I_{xy}(I_x - I_y + I_z) + I_{xy}M_x + I_xM_y}{I_xI_y - I_{xy}^2} \\ \dot{\omega}_z = \dfrac{\omega_x\omega_y(I_x - I_y) + (\omega_x^2 - \omega_y^2)I_{xy} + M_z}{I_z} \end{cases}$$

$$\begin{cases} n_x = \dfrac{P_x - (c_x\cos\alpha - c_y\sin\alpha)qS + R_x^{\text{воз}} + R_x^{\text{о.с.}}}{G} \\ n_y = \dfrac{P_y - (c_x\sin\alpha - c_y\cos\alpha)qS + R_y^{\text{воз}} + R_y^{\text{о.с.}}}{G} \\ n_z = \dfrac{c_zqS + R_z^{\text{воз}} + R_z^{\text{о.с.}}}{G} \end{cases}$$

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where $\dot{V}_x, \dot{V}_y, \dot{V}_z$ – the projection of the linear acceleration of the aircraft on the axis of the coordinate system related; $\dot{\omega}_x, \dot{\omega}_y, \dot{\omega}_z$ – the projection of the angular acceleration of the aircraft on the axis of the coordinate system related; V_x, V_y, V_z – the projection of the linear velocity of the plane on the axis of the coordinate system related; n_x, n_y, n_z – longitudinal, transverse and normal overload; M_x, M_y, M_z – moments of the external forces on the appropriate axes; $\omega_x, \omega_y, \omega_z$ – the projection of the angular velocity of the aircraft on the axis of the coordinate system related; ϑ – pitch angle; γ – angle of roll; g – acceleration of gravity; I_x, I_y, I_z – moments of inertia of the aircraft relative to the considered axis; q – velocity head; G - The weight of the aircraft; P_x, P_y, P_z – thrust vector with respect to the considered axis; c_x, c_y, c_z – dimensionless aerodynamic coefficients of drag, lift and side force in semi-combined system of coordinates; $R_x^{\text{воз}}, R_y^{\text{воз}}, R_z^{\text{воз}}$ – components of the total force vector of the perturbations caused by the influence of the environment related to the coordinate system; $R_x^{\text{o.c.}}, R_y^{\text{o.c.}}, R_z^{\text{o.c.}}$ – Supplements to the full force vector caused by the occurrence of the particular situation in the associated coordinate system.

Moments of the external forces on the appropriate axes represent the following relationships:

$$\begin{cases} M_x = (m_x \cos\alpha + m_y \sin\alpha) qlS + M_{P_x} + M_x^{\text{воз}} + M_x^{\text{o.c.}} \\ M_y = \left(m_y \cos\alpha - m_x \sin\alpha\right) qlS + M_{P_y} + M_y^{\text{воз}} + M_y^{\text{o.c.}} \\ M_z = m_z q b_A S + M_{P_z} + M_z^{\text{воз}} + M_z^{\text{o.c.}} \end{cases}$$

where m_x, m_y, m_z – dimensionless aerodynamic coefficients roll moment, yaw moment and longitudinal moment in the associated coordinate system; b_A, l, S – mean aerodynamic chord, span and wing area of the aircraft; $M_{P_x}, M_{P_y}, M_{P_z}$ – mean aerodynamic chord, span and wing area of the aircraft; $M_x^{\text{воз}}, M_y^{\text{воз}}, M_z^{\text{воз}}$ – Supplements to the full momentum vector caused by exposure to the external environment in a coupled system of coordinates; $M_x^{\text{o.c.}}, M_y^{\text{o.c.}}, M_z^{\text{o.c.}}$ $M_x^{\text{воз}}, M_y^{\text{воз}}, M_z^{\text{воз}}$ – Supplements to the full momentum vector cause a particular situation in a coupled system of coordinates;

Forces and moments generated by the power plant, calculated taking into account the linkages and alignment of each engine:

$$\begin{cases} P_x = -\sum_{i=1}^{n} P_i \cos\varphi_i \cos\psi_i \\ P_y = \sum_{i=1}^{n} P_i \sin\varphi_i \cos\psi_i \\ P_z = \sum_{i=1}^{n} P_i \sin\psi_i \end{cases}$$

$$\begin{cases} M_{P_x} = \sum_{i=1}^{4} P_i (\cos\varphi_i \sin\psi_i x_i - \sin\varphi_i \cos\psi_i z_i) \\ M_{P_y} = \sum_{i=1}^{4} P_i \left(\cos\psi_i \cos\varphi_i y_i + \sin\psi_i \cos\varphi_i x_i\right) \\ M_{P_z} = \sum_{i=1}^{4} P_i \left(\cos\psi_i \cos\varphi_i z_i + \cos\psi_i \cos\varphi_i x_i\right) \end{cases}$$

where P_x, P_y, P_z - Engine thrust force components on the appropriate axes; P_i – Rod i-th engine; φ_i, ψ_i – angles of the i-th engine respectively in the vertical and horizontal planes; x_i, y_i, z_i – oordinates of the respective motors on axes. Dimensionless aerodynamic coefficients are generally expressed as a function of changes in the form of aircraft, kinematic motion parameters and criteria of similarity in flight mode:

$$c_{x,y,z}\left(m_{x,y,z}\right) = \left(\delta_{зак} / \delta_{пр}, \varphi_{ст}, \delta_{р.н.}, \delta_{р.в.}, \delta_э, \alpha, \beta, \dot{\alpha}, \dot{\beta}, \omega_x \ldots\right.$$

where $\delta_{зак} / \delta_{пр}$ – configuration of the aircraft, determined by the position of the wing mechanization (flaps, slats); $\varphi_{\text{ст}}, \delta_{\text{р.н.}}, \delta_{\text{р.в.}}, \delta_{\text{э}}$ – deviation of the control surfaces (stabilizer, rudder, elevator, ailerons); $\zeta_1, \ldots, \zeta_n$ – coefficients considering changing the shape of the aircraft (including the elastic structure;) α, β – the angles of attack and slip rates and their changes; $\omega_x, \omega_y, \omega_z$ – angular velocity;

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M - Mach number; *Re* - Reynolds number; V, H – speed and altitude; $\bar{x}_T$ – coordinate of the center of gravity in a fraction of the mean aerodynamic chord.

Despite the fact that a complete mathematical model accurately describes the spatial movement of aircraft, for the synthesis and analysis of reconfigurable SAC are important linearized model of the longitudinal and lateral movement into account the negative impact of external influences and internal processes.

To study the development of special situations in flight, and the synthesis of automated systems reconfiguration management in work were derived transfer functions relating the deviation controls the parameters describing the motion of the airplane in conditions of occurrence of the types of damage its external contour (2).

$$\tilde{W}_V^P(p) = a_x^{\delta_p^{o.c.}} \frac{A_{11}(p)}{Q(p)};$$
$$\tilde{W}_\vartheta^P(p) = a_x^{\delta_p^{o.c.}} \frac{A_{12}(p)}{Q(p)};$$
$$\tilde{W}_V^{\delta_{PB}}(p) = -a_{m_z}^{\delta_{PB}^{o.c.}} \frac{A_{31}(p)}{Q(p)}; \qquad (2)$$
$$\tilde{W}_\vartheta^{\delta_{PB}}(p) = -a_{m_z}^{\delta_{PB}^{o.c.}} \frac{A_{32}(p)}{Q(p)};$$

where:

$$Q(p) = \begin{vmatrix} (p + a_x^V + a_x^{V^{o.c.}}) & a_x^\vartheta + a_x^{\vartheta^{o.c.}} & \\ a_y^V + a_y^{V^{o.c.}} & (p + a_x^\vartheta + a_x^{\vartheta^{o.c.}}) & \\ a_{m_z}^V + a_{m_z}^{V^{o.c.}} & a_{m_z}^\vartheta + a_{m_z}^{\vartheta^{o.c.}} & (p + a_{m}^{\alpha} \\ -(a_y^V + a_y^{V^{o.c.}}) & -(a_y^\vartheta + a_y^{\vartheta^{o.c.}}) & \end{vmatrix}$$

$$= p^4 + q_3 p^3 + q_2 p^2 + q_1 p + q_0$$

– matrix longitudinal control channel;

A_{ij} – cofactor of the element i-th row j-th column of the determinant $Q(p)$.

The numerical values of the transfer functions:

$$\tilde{W}_V^P = \frac{3.757s^3 + 6.691s^2 + 4.224s + 1}{1.638s^4 + 2.458s^3 + 4.019s^2 + 1.92s + 1};$$

$$\tilde{W}_\vartheta^P = \frac{1.7005s^3 - 4.341s^2 + 4.078s + 1}{1.697s^4 + 2.5601s^3 + 3.345s^2 + 1.56s + 1};$$

$$\tilde{W}_V^{\delta_{PB}} = \frac{2.005s^3 + 1.111s^2 + 0.224s + 1}{1.897s^4 + 2.347s^3 + 3.006s^2 + 2.22s + 1};$$

$$\tilde{W}_\vartheta^{\delta_{PB}} = \frac{1.112s^3 + 3.213s^2 + 5.159s + 1}{0.895s^4 + 1.568s^3 + 3.0457s^2 + 4.001s + 1};$$

The zeros and poles lie to the left of the imaginary axis, indicating that the stability of the resulting system (Fig. 3-6).

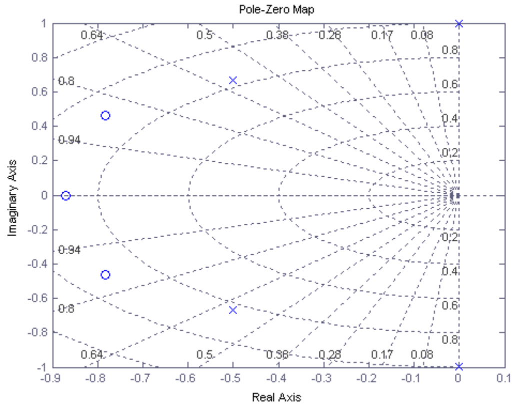

Fig. 3. Diagram placing poles and zeros of the transfer function $\tilde{W}_V^P$

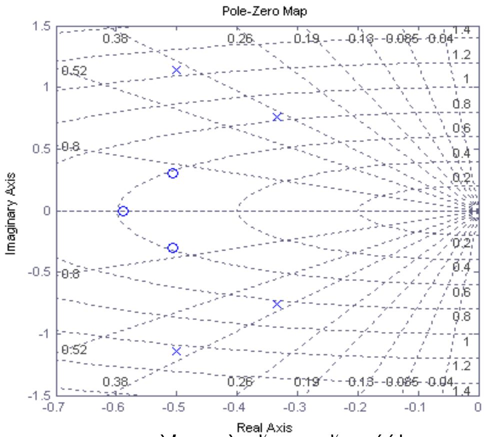

Fig. 4. Diagram placing poles and zeros of the transfer function $\tilde{W}_\vartheta^P$

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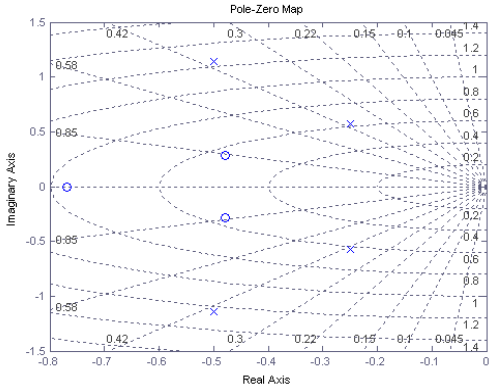

Fig. 5. Diagram placing poles and zeros of the transfer function $\tilde{W}_V^{\delta_{PB}}$

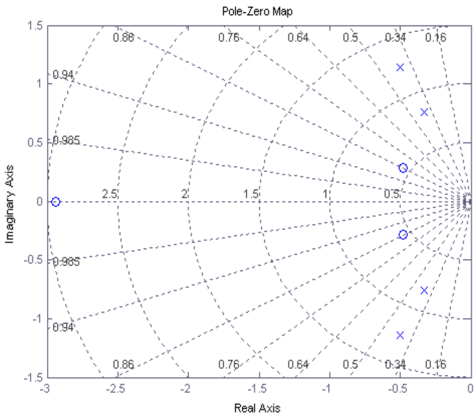

Fig. 6. Diagram placing poles and zeros of the transfer function $\tilde{W}_\vartheta^{\delta_{PB}}$

Two complex conjugate roots of the transfer function $\tilde{W}_V^{P}$ are on the boundary of stability (Figure 3). According to the disadvantage can be neglected so long as they describe the periodic motion.

IV SIMULATION RESULTS

The work for the study was drawn crash occurred with the Boeing 747. The root cause of Incidents became the engine compartment from the pylon, which resulted in significant damage to the wing leading edge. The plane has deteriorated sharply its aerodynamic and flight characteristics. Because the thrust difference arising under the influence of destabilizing moment about the normal axis of the aircraft acquired angular velocity increased slip angle. Almost simultaneously with turning left due to the difference of the buoyant forces of the left and right wing aircraft acquired left-hand roll (Fig. 7).

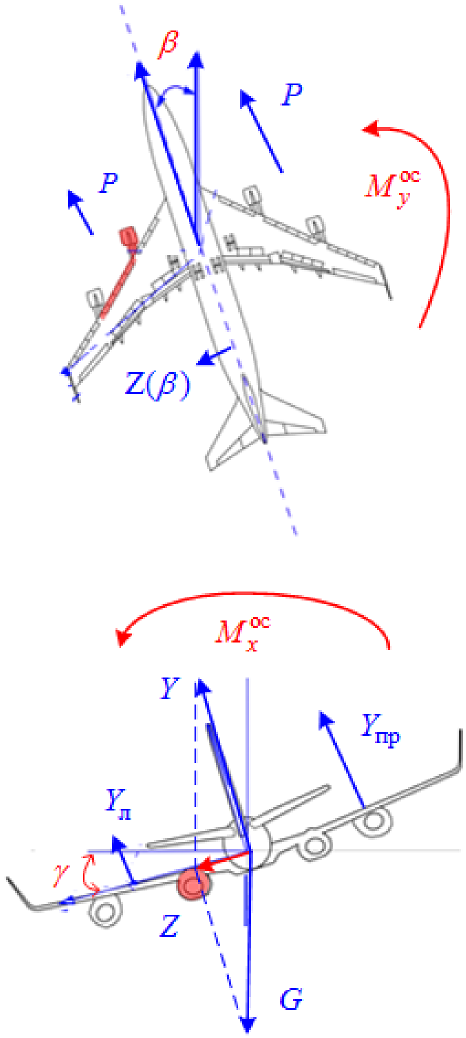

Fig. 7. Forces and moments Boeing 747

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To prevent the development of catastrophic situation and restore stability and controllability of the airplane on the need to balance the forces and moments due to rudder deflection to create a stabilizing moment and ailerons to compensate for the difference arisen lifting forces of the left and right wing (Fig. 8).

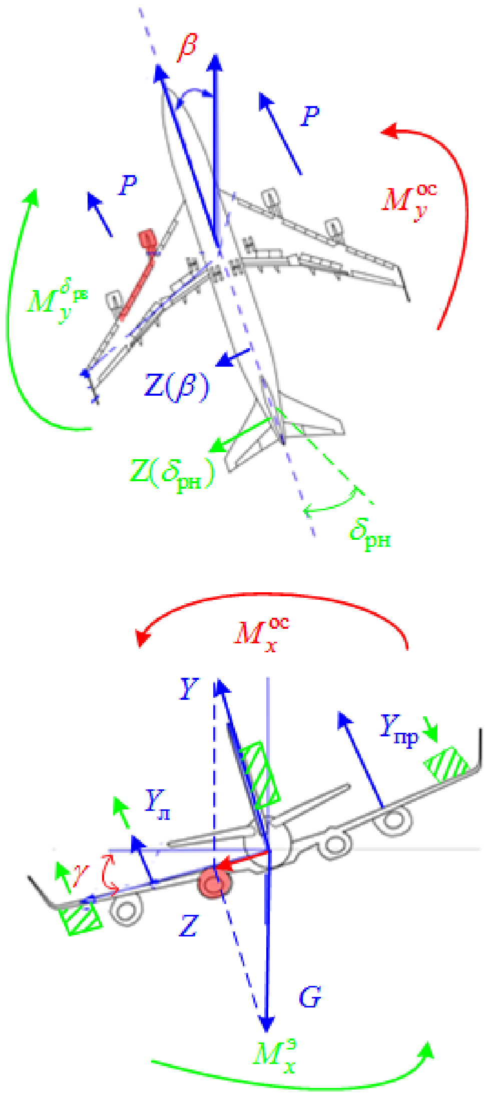

Fig. 8. The stabilizing forces and moments Boeing 747

To continue the horizontal straight flight without sliding necessary to provide dynamic handling and stability.

Mathematical modeling of the particular situation was conducted using an improved complex environment Matlab (Fig. 9) [15].

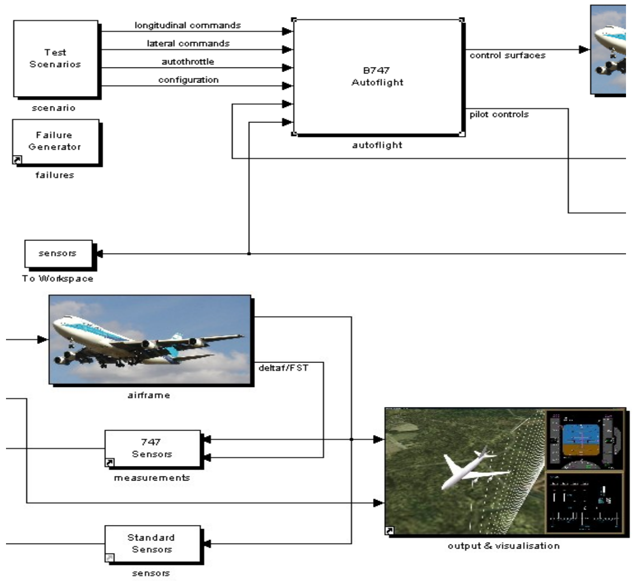

Fig. 9. The generalized structure of software, which includes the following blocks: autoflight - block automatic flight control systems, airframe - the Boeing 747 model, scenario - Action Plan (unit reconfiguration), sensosrs sensors; failure generator - generator of typical failures [15].

The results of mathematical modeling of a special illustrated in Fig. 10.

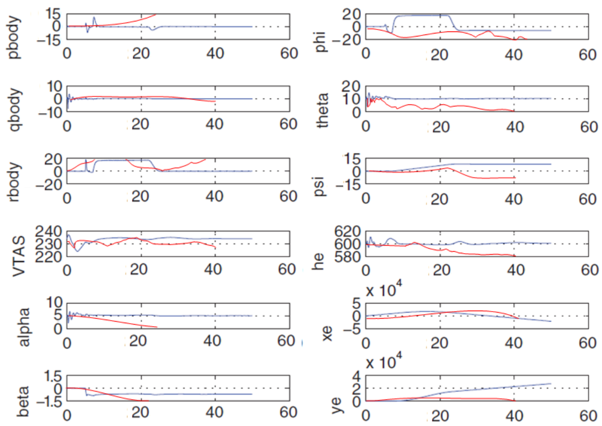

Fig. 10. The results of mathematical modeling of an emergency, where: Crane line without reconfiguration, the blue line using reconfiguration upravlyaniya plane.

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CONCLUSION

The time interval over which the reconfiguration system has wrong information about the faults / failures need not be known. If the reconfiguration system eventually generates an accurate estimate of the failure parameters, the proposed approach will result in provided increased controllability and stability of airplane under adverse flight conditions. The paper obtained the transfer functions of the longitudinal motion of the aircraft taking into account the special situation of additives that will synthesize and analyze highly automated system reconfiguration control aircraft. Analysis of the results of mathematical modeling allows us to prevent the possibility of an emergency in flight due to reconfiguration of aircraft control.

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