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THE INVARIANT ADAPTATION OF THE AIRCRAFT CONTROL SYSTEM IN EMERGENCY SITUATION DURING THE FLIGHT

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Abstract

Purpose: *The aim of this study is to develop a method for compensating the effects of failures of the aircraft automatic control system during the flight.* ***Methods:*** *This article reviews an approach based on the methods of theory of absolute nonlinear invariance.* ***Results:*** *In this paper, we present the example of a case of compensation of failure of the elevator with using the solution of the equation of the absolute invariance for pitch angle. Synthesis of automatic control device of aircraft orientation angles based on the analysis of the equations of the absolute nonlinear invariance is presented.* ***Discussion:*** *The use of the reconfiguration of the aircraft control system to ensure its survivability in flight is a perspective direction. However, the development of the concept of motion control of the aircraft with the use of the theory of absolute invariance will allow to realize an effective developed aircraft control method that will have advantages compared with the existing methods.*

Keywords*:* absolute non-linear invariance; control system; failure; reconfiguration of control system; flight safety

1. Introduction

Control motion of modern aircraft is provided in the conditions of considerable uncertainty and variety in the values of the parameters and characteristics, flight modes and environmental influences. Besides, variety of emergency situations (incident) can occur during the flight. For example, these may be equipment failures and external disturbance, whose influence must be compensated.

At the present time, ways and means to prevent accidents due to the failure of aeronautical engineering (AE) for different types of aircraft differ considerably among themselves and in some cases are not sufficiently effective. One of the modern means of fault tolerance and survivability of the aircraft is a reconfiguration that is purposeful change of linkages between elements of the system and subsystems, with an aim to maintain its performance in case of failures of individual components and sub-systems [1]. Reconfiguration of the automatic control system (ACS) in case of failure of actuators and control surfaces consists in the redistribution of control actions on the serviceable controls for the purpose of creating the necessary control forces and moments to preserve an acceptable control quality.

2. Analysis of the latest research and publications

The issue of diagnosis and fault-tolerant control of dynamic objects using the reconfiguration has been actively investigated as domestic scientists, and abroad. The system methods of survivability of aircraft in special situations in flight as a result of damage to the external contours and control surfaces set out in the sources [2, 3]. The authors of [4, 5] have considered the algorithmic methods of fault tolerance of ACS with transformation of the system structure by the addition to it devices and connections such way that control algorithm becomes modified. Methods for model-based analysis for fault diagnosis and fault-tolerant control were proposed in [6 - 8]. Note that existing methods are focused on a narrowly defined character of disturbances subject to compensation. The methods developed for linear systems have a pronounced disadvantage associated with a long process of adaptation. In the available literature it is not mentioned the possibility of compensation of simultaneous failure of AE and turbulent atmosphere effects. No answer on the question of compensation of a combination of two or more different failures in

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different contours of ACS, for example, simultaneous failure of the engine and the control surfaces or the elements of the wing mechanization.

Despite numerous scientific publications, results of numerical simulation and certain tests have been carried out on real prototypes the use of fault-tolerant control is still very limited. Therefore, now the scientific problem of development and improvement of methods for fault-tolerant aircraft flight control in a turbulent atmosphere and under influence of disturbances caused by failures of aviation equipment is relevant.

The purpose of the article is development of a method to compensating the effects of failures of the aircraft automatic control system using the theory of invariance.

3. Formulating of the automatic controller synthesis problem using the theory of invariance

Synthesis of automatic controller of aircraft orientation angles is based on the analysis of the equations of the absolute nonlinear invariance [9, 10], obtained for the equations which are describing the dynamics of change of aircraft orientation angles. The choice of this approach is due to its flexibility.

Along with the synthesis of automatic controllers the task of ACS reconfiguration for compensate the failure of control system is solved. Solution of task of the control system synthesis would allow realizing new forms of aircraft movements.

The method of obtaining of conditions of absolute nonlinear invariance was designed for significantly nonlinear systems [10]. Significantly nonlinear system is defined as a system of equations:

$$dx/dt = f(x,t). \tag{1}$$

It is the system with piecewise-continuous right-hand side which is considered in some domain Q of pseudo-Euclidean space. Such definition of significantly nonlinear system has a sufficient degree of generality and physically justified. This definition also covers a class of systems that cannot be described by analytic functions or are described using functions which do not have continuous derivatives. Therefore, it is quite justified to consider the aircraft as significantly nonlinear system. The concept of solutions of differential equations with discontinuous right-hand side is used for the systems with discontinuous right-hand sides. From the definitions it follows that in the determination of the solution $x(t)$ the values of f at the points of gap should be ignored. The value of the function on continuous areas is considered.

In solving the problem of automatic controller synthesis the functional equation of absolute nonlinear invariance for compensated dynamic systems can be written in the form [10]:

$$p = f(x,y,u), \tag{2}$$

where $f(x, y, u)$ – right-hand side of the differential equation describing the dynamics of the controlled parameter; x – controlled parameter; y – vector of variables describing the condition of the system, and disturbances acting on it; u – vector of variables that are considered as control.

The purpose of the automatic control is the conversion of the system from state with value of the controlled parameter x_0 to state in which the controlled parameter has a target value x^*. If at any period of time the value of p^* which provides aforesaid conversion is known then at each time t relatively the variables u the equation:

$$p^* = f(x,y,u) \tag{3}$$

must be solved.

The obtained solution u^* of the equation (3) is the value of control at the time t. If the control has a discrete character, at the step of generation of control actions at the time t_i the element p_i^* of sequence $\{p_i^*\}$ that ensures the achievement of control goal in a finite number of steps must be generated. Relatively variables u a solution of the equation:

$$p_i^* = f(x_i, y_i, u) \tag{4}$$

must be provided.

The solution of equation (4) is the control action on the i-th control step. In a simple case, the sequence elements could be defined as:

$$p_i^* = \frac{1}{\Delta t_i}\left(x^* - x_i\right). \tag{5}$$

From the above it follows that the failure of the airplane control surfaces may be compensated by the reconfiguration of the control system. This may be reflected by changes in the composition of the vector u. The vector u can be written as $u = (u_1, u_2)$, where u_1 – variables that cannot be controlled because of failure; u_2 – the remained part of the vector u. Then instead of the equation (4) at step of development of the control action relative to variables u_2 the equation:

$$p_i^* = f(x_i, y_i, u_{1i}, u_2) \tag{6}$$

must be solved.

The solution u_{2i}^{*} of equation (6) is a control action on the *i*-th control step which ensures the achievement of control goal in a finite number of steps using the invariance theory and compensates a failure of control group u_1.

Implementation of reconfiguration is possible for aircraft which have energy redundancy such as redundant control surfaces. For the successful reconfiguration in case of failure it must be at least eight independent control surfaces [4]. To describe the reconfiguration of the ACS for parry the impact of the consequences of failure of control surfaces consider a model of a hypothetical aircraft with advanced wing mechanization which has the following controls:

- Rudder (u_r – the angle of deflection of the rudder);
- Elevator (u_e – deflection angle of the elevator);
- Left and right ailerons (u_a^{l1} and u_a^{r1} – deflection angles of the left and right ailerons);
- Left and right flaps (u_f^{l1} and u_f^{r1} – deflection angles of the left and right flaps);
- Left and right slats, each slat is divided into four sections which can be controlled separately (u_{slat}^{l1}, u_{slat}^{l2}, u_{slat}^{l3}, u_{slat}^{l4}, u_{slat}^{r1}, u_{slat}^{r2}, u_{slat}^{r3}, u_{slat}^{r4} – deflection angles corresponding sections of the left and right slats);
- Left and right slots of Clark-Y airfoil, each slot is divided into two sections that can be controlled separately (u_s^{l1}, u_s^{l2}, u_s^{r1}, u_s^{r2} – width of the corresponding sections of the left and right slots).

4. The method of solving the problem of compensation of the consequences of failures in the control system using the theory of invariance. Compensation of elevator failure

For solve the problem it is necessary to write the equation of the pitch angle controller [11] and the equation of the absolute nonlinear invariance for it. The change of the pitch angle ϑ depends on the values of the projections of the angular velocity ω_y and ω_z. It is possible to control the change in the value ϑ of operating w_y and w_z. With low value of roll angle γ only ω_z has significant effect on the pitch angle ϑ. The equation of the absolute nonlinear invariance for pitch angle has the form:

$$p^{*} = \omega_y \sin\gamma + \omega_z \cos\gamma, \qquad (7)$$

p^{*} is defined from the formula (5):

$$p^{*} = \frac{1}{\Delta t_1}\left(\vartheta^{*} - \vartheta\right), \qquad (8)$$

where ϑ^{*} – desired value, and ϑ – the current value of the pitch angle.

If ω_z selected as main parameter which can control the value of the pitch angle ϑ the control ω_z^{*} is the solution of equation (7):

$$\omega_z^{*} = \frac{1}{\Delta t_1 \cos\gamma}\left(\vartheta^{*} - \vartheta\right) - \omega_y \operatorname{tg}\gamma, \qquad (9)$$

where Δt_1 – time through which the pitch angle ϑ should take the value ϑ^{*} at constant speed ω_z^{*}.

It is possible to control ω_z by changing the value of torque M_z which depends on the coefficient m_z [11]. The pitch angle control of the aircraft is performed using the elevator. The value of m_z changes by varying the angle of deflection of the elevator u_e. The coefficient m_z is considered as a function of u_e: $m_z = m_z\ (u_e)$. The equation of the absolute nonlinear invariance for ω_z has the form:

$$p^{*} = I_9\omega_x^2 + I_{10}\omega_y^2 + I_{11}\omega_x\omega_y + I_{12}m_z\left(u_e\right)\vartheta S B_a. \qquad (10)$$

p^{*} is defined from the formula:

$$p^{*} = \frac{1}{\Delta t_2}\left(\omega_z^{*} - \omega_z\right), \qquad (11)$$

where ω_z – the current value of the angular velocity; B_a – the length of the mean aerodynamic chord; S – wing area; Δt_2 – time through which the projection of the angular velocity ω_z should take the value of ω_z^{*} at constant acceleration $d\omega_z/dt$; I with subscripts – solution of the equations of aircraft motion relative to the derivatives $d\omega_x/dt$, $d\omega_y/dt$, $d\omega_z/dt$ taken from [11].

Consider the case of "jamming" of the elevator at some position. In this case the elevator position cannot be changed by using control commands. Thus if the angle of deviation of the elevator at time *t* was u_e^{0} and at the time *t* elevator failure has occurred then the angle of deviation of the elevator at subsequent times will remain u_e^{0} control command will not have an action on the elevator position.

The method of compensation has to ensure the continuation of effective control of pitch angle despite the failure of the elevator.

In normal modes during cruising flight, climb and descent to control the position of the aircraft in space the elevator, rudder and ailerons are involved. Based on proposed model of the aircraft in case of failure of the elevator it is possible to use flaps, slats and slots to compensate the failure of the elevator.

The coefficient of aerodynamic moment m_z depends on the position of the elevator, flaps, slats and slots. Therefore m_z can be considered as a function of variables u_e, u_f, u_{slat}, u_s:

$$m_z = m_z\left(u_e, u_f, u_{slat}, u_s\right). \quad (12)$$

Here the values of u_e, u_f, u_{slat}, u_s are summary deflection angles of corresponding control surfaces:

$$u_f = u_f^r + u_f^l;$$

$$u_{slat} = u_{slat}^{r1} + u_{slat}^{r2} + u_{slat}^{r3} + u_{slat}^{r4} + u_{slat}^{l1} + u_{slat}^{l2} + \\ + u_{slat}^{l3} + u_{slat}^{l4};$$

$$u_s = u_s^{r1} + u_s^{r2} + u_s^{l1} + u_s^{l2}.$$

In accordance with the pitch angle control law at step of regulating at time t the equation of absolute nonlinear invariance for pitch angle is solved with relative to the variable u_e. The solution u_v^* of the equation provides the equality:

$$m_z\left(u_e^*, u_f, u_{slat}, u_s\right) = c_i, \quad (13)$$

where c_i – the value of the left-hand side of equation (10) at the time t_i.

If at time t_j, $j<i$ there was a failure of the elevator, the u_e^0 will be the actual position of the elevator at the time t_i. To compensate the failure it is necessary to ensure equality:

$$m_z\left(u_e^0, u_f, u_{slat}, u_s\right) = c_i. \quad (14)$$

Such equality can be achieved by solving the equation (10), in the right part of which is a function of the form (12), relatively the variables u_f, u_{slat}, u_s if $u_e = u_e^0$. To find solutions u_f^*, u_{slat}^*, u_s^* of such equation it is possible to use the solution u^* of equation (10) obtained in time t_i as a result of work of pitch angle controller.

Implementation of equality (13) will mean that:

$$m_z^{u_e}u_e^* + m_z^{u_f}u_f + m_z^{u_{slat}}u_{slat} + m_z^{u_s}u_s = c. \quad (15)$$

In the event of failure:

$$m_z^{u_e}u_e^0 + m_z^{u_f}u_f + m_z^{u_{slat}}u_{slat} + m_z^{u_s}u_s = \\ = c - m_z^{u_e}\left(u_e^* - u_e^0\right). \quad (16)$$

Control actions u_f^*, u_{slat}^*, u_s^* must satisfy the equality:

$$m_z^{u_e}u_e^0 + m_z^{u_f}u_f^* + m_z^{u_{slat}}u_{slat}^* + m_z^{u_s}u_s^* = c. \quad (17)$$

Seeking control can be represented as:

$$u_f^* = u_f + \Delta u_f, u_{slat}^* = u_{slat} + \Delta u_{slat}, \\ u_s^* = u_s + \Delta u_s, \quad (18)$$

where Δu_f, Δu_{slat}, Δu_s – the values of the total change in the deflection angles of serviceable control surfaces.

Taking into account (16) and (17), the values of summary change of the angular deflection of flaps, slats and slots must satisfy the condition:

$$m_z^{u_f}\Delta u_f + m_z^{u_{slat}}\Delta u_{slat} + m_z^{u_s}\Delta u_s = m_z^{u_e}\left(u_e^* - u_e^0\right). \quad (19)$$

The value of $(u_e^* - u_e^0)$ can be either positive or negative. It is necessary to ensure the physical possibility of obtaining the $\Delta u_f, \Delta u_{slat}, \Delta u_s$ with different signs. Usually during cruise flight flaps, slats and slots of the aircraft are fully retracted. A feature of the implementation of the method is the need for the possibility of flaps and slats deflection on negative angles. In case of impossibility of deflection of control surfaces on negative angles due to the design features of the aircraft is possible to implement an approach when the flaps and slats are not fully retracted and deflected on insignificant angle. In turn slots have some value other than zero. These angles are sufficient to implement the required values of $\Delta u_f, \Delta u_{slat}$, Δu_s. It should be noted that flight mode, when the flaps and slats are not fully retracted, fuel consumption increases and the aircraft speed reduces, which leads to an increase of flight operations costs, but these costs can be commensurate with the achievement of the purpose of improving safety in civil aviation when it comes to saving the lives of hundreds of passengers on board of the aircraft and people on the ground.

The developed method allows realizing in practice a flexible structure of aircraft control system and its reconfiguration during the flight, what in turn allows for control of the aircraft at simultaneous failure of several control surfaces.

5. Conclusions

The use of the reconfiguration of the aircraft control system to ensure its survivability in flight is a perspective direction.

The article suggests a method for compensation of failure influences in the aircraft control system based on the theory of absolute nonlinear invariance.

The development of the concept of motion control of aircraft using of the theory of absolute nonlinear invariance will allow to realize this effective aircraft control method that will have such advantages compared with the existing methods as use of all the elements of the wing mechanization for compensation of the external disturbances on the aircraft trajectory with a maximum execution speed of the compensation process. Also suggested method will ensure proper functioning of the entire system automatic control of the aircraft in the event of failures.

The implementation of this method will make it possible to take into account the impact of reconfiguration of the aerodynamic control surfaces of the aircraft ACS on the flight speed and the power reserve of the aircraft, what will ensure a high level of flight safety under conditions of uncertainty because of the presence of failures and external disturbances.

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Інваріантна адаптація системи керування літаком при виникненні аварійної ситуації в польоті

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Мета: Метою даної статті є розробка методу для компенсації наслідків відмов системи автоматичного керування літаком під час польоту. **Методи:** В статті розглянуто підхід, заснований на методах теорії абсолютної нелінійної інваріантності. **Результати:** Наведено приклад випадку компенсації відмови руля висоти за допомогою вирішення рівняння абсолютної інваріантності для кута тангажу літака. Представлено синтез пристрою автоматичного керування кутами орієнтації літального апарату на основі аналізу рівнянь абсолютної нелінійної інваріантності. **Обговорення:** Використання реконфігурації системи керування літаком для забезпечення його живучості у польоті є перспективним напрямом. При цьому, розвиток концепції управління рухом літального апарату з використанням теорії абсолютної інваріантності дозволить реалізувати ефективний метод керування польотом, який буде мати переваги в порівнянні з існуючими методами.

Ключові слова: абсолютна нелінійна інваріантність; система керування; відмова; реконфігурація системи керування; безпека польотів.

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Инвариантная адаптация системы управления самолетом при возникновении аварийной ситуации в полете

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Цель: Целью данной статьи является разработка метода для компенсации последствий отказов системы автоматического управления самолетом во время полета. **Методы:** В статье рассмотрен подход, основанный на методах теории абсолютной нелинейной инвариантности. **Результаты:** Приведен пример случая компенсации отказа руля высоты с помощью решения уравнения абсолютной инвариантности для угла тангажа самолета. Представлен синтез устройства автоматического управления углами ориентации летательного аппарата на основе анализа уравнений абсолютной нелинейной инвариантности. **Обсуждение:** Использование реконфигурации системы управления самолетом для обеспечения его живучести в полете является перспективным направлением. При этом, развитие концепции управления движением летательного аппарата с использованием теории абсолютной инвариантности позволит реализовать эффективный метод управления полетом, который будет иметь преимущества по сравнению с существующими методами.

Ключевые слова: абсолютная нелинейная инвариантность; система управления; отказ; реконфигурация системы управления; безопасность полетов.

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