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METHOD OF THE AIRCRAFT CONTROL RECONFIGURATION WHEN UNEXPECTED SITUATION APPEARS DURING FLIGHT

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Abstract. *Comparative analysis of the ICAO statistics showed that 35% of the aircraft losses associated with failures and damages of automatic control systems, mainly with failures of drives and external damage of tours and controllers. Classification of approaches to reconfigurable flight control systems is shown. The aim of this work is to develop method of reconfiguration to save the stability and controllability of the aircraft during the collisions with mechanical, biological and electrical elements.*

Keywords: aircraft; flight control system; loss-of-control; reconfiguration; stability and controllability; unexpected situation.

1. Introduction

Reliable operation of complicated objects such as nuclear power and power transmission, gas-transport companies and chemical industry, space and aviation technology requires advanced automatic control properties of the restoration of their handling in an emergency or catastrophic situation due to reconfiguration:

- control actions;
- structure;
- configuration facility control or target problems;
- thereby maintaining a safe operation.

The complexity of the problem of flight safety is continuously growing due to the increased usage of aircraft, in addition to known effects leads to a significant increase in the probability of collision with mechanical, biological and electrical units, as well as expanding the range of functions performed her tasks.

Comparative analysis of the ICAO statistics showed that 35% of the aircraft losses associated with failures and injuries automatic control systems, mainly with failures of drives and external damage of tours and controllers.

Also, it should be noted unusually high transience of emergency, which in turn requires immediate intervention in the situation to take the necessary control action to prevent its development or escalation of catastrophic.

This causes the increasing role of board automatically detect the external contour damage and control surfaces of an aircraft in flight, the development of advanced methods and systems for automatic reconfiguration control actions, and intelligent decision support systems crew in an emergency situation.

The **aim** of this work is to develop method of reconfiguration to save the stability and controllability of the aircraft during the collisions with mechanical, biological and electrical elements.

According to the statistics, collisions with birds as the cause of the emergency flight situations are on the third place after equipment failures and human factors [14].

Annual damage caused by the collisions with birds only in the U.S. is 400 million U.S. dollars and 1.2 billion U.S. dollars to commercial aircraft in the world [2, 4, 10].

To evaluate scale of the problem posed by birds and to maintain current level of safety we make a comparative analysis of statistical data [1].

During the period from 1990 till 2011 only it the United States was recorded 122,495 cases of aircraft collisions with birds.

Since 1988, more than 219 people in the world were killed in clashes aircraft with birds [4].

For civil aircraft most vulnerable parts (Fig. 1) [12]:

- engines are 48.9 % of collisions;
 - wings are 21.1 % of collisions;
 - fuselage is 9.0 % of collisions;
 - cabin windows are 6.7 % of collisions;
 - landing gears are 6.7 % of collisions;
 - random radar stations are 4.9 % of collisions
- tail is 2.7 % of collisions.

In the article [8], risk of aircraft collision with birds was calculated, depending on the altitude:

- up to 100 m risk is 45.8 %;
- 101-400 m risk is 28 %;
- 401-1000 m risk is 12.7 %;
- 1001-2000 m risk is 7.5 %;
- 2001-5000 m risk is 5.2 %;
- over 5000 m risk is 0.8 %.

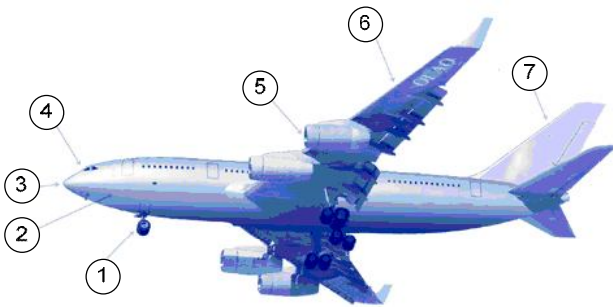


Fig.1. Places of hits (collisions) and damages between the different parts of civil aircraft:

- 1 – landing gear;
- 2 – fuselage;
- 3 – random radar station;
- 4 – cabin windows;
- 5 – engines;
- 6 – wing;
- 7 – tail

The comparative analysis of statistics of the aircrafts external outline damages about which information is given in the documents of the ICAO and also in various publications [7, 13] showed that all the typical damages can be classified according to the following criteria:

- the cause of the damage;
- the time;
- place;
- degree;
- character;
- the number of simultaneous damages.

2. Analysis of publications

In the literature, most of the motivation and research work in reconfiguration control involves solving problems encountered in safety critical systems such as aircrafts, satellites, chemical and nuclear powerplants.

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. 2 [6] they have fallen into two main categories: active [5, 15, 16] and passive [9, 17].

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 [3].

To design Active Fault Tolerant Control Systems (AFTCS), one of the important issues to consider is whether to recover controllability of aircraft under adverse flight conditions.

The active fault-tolerant control systems consist of two basic subsystems [11]: Fault Detection and Isolation (FDI) or system identification and control reconfiguration or restructure.

Patton also discussed the relationship between these fields of research.

For a typical AFTCS scheme, when a fault/failure occurs either in an actuator or sensor, the FDI scheme will detect and locate the source of the fault.

The reconfigurable controller will try to adapt to the fault, therefore providing controllability and stability

In article [16] is given a good bibliographical review of reconfigurable fault tolerant control systems.

The paper also proposes a classification of reconfiguration methods which is based on a few categories (the mathematical tools used, the design approach used, the way of achieving reconfiguration, reconfiguration mechanisms, control structures etc.).

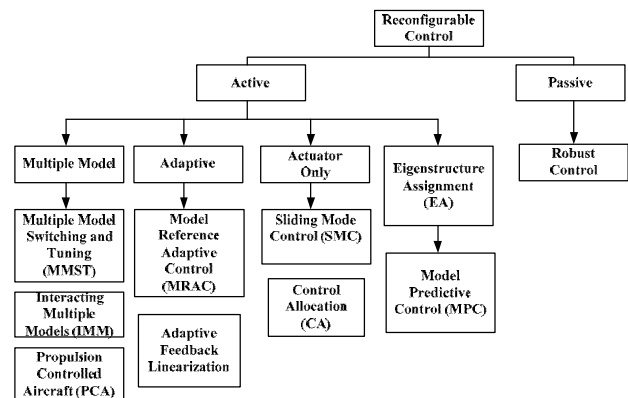


Fig.2. Classification of approaches to reconfigurable flight control

It also provides a bibliographical classification based on the design approaches and the different applications, discussing open problems and current research topics in AFTCS.

Development of methods and models of reconfiguration of controlling influences aboard the aircraft in the conditions of origin special situations in flight operation [7] is devoted.

For reconfiguration of controlling influences in case of failures of drives and governing bodies two approaches [7] are used: parametric and structural.

Parametric change of feedback factors of the executive mechanisms taking into account a technical status of the airplane, for improving of efficiency of their functioning.

The proposed methods in [15, 16] based on the estimation of effectiveness factor of the faulty actuator.

The actuators are 100% effective (in executing the control commands), if during normal operation, the actuators operate exactly as directed by the controller.

When faults occur in actuators, such as partial loss of a control surface, or pressure reduction in hydraulic lines, in the case of an aircraft, partial blockage of a control valve in process control, or voltage reduction/amplifier saturations in electrical servo systems, the actuators would not be able to fulfill the control commands completely.

In such cases, it is said that the effectiveness of the actuators has been reduced [16].

In the above papers to quantify faults entering control systems through actuators, a parameter known as the reduction of the control effectiveness factor is used [15], which represents the loss of the one-to-one relationship between the control command and the true actuator actions.

In these studies, the control effectiveness factor is employed as the actuator fault parameter and estimated via Kalman filter [3].

But the control effectiveness factor of faulty actuator is assumed as the same for all elements of corresponding control distribution vector (or appropriate column of control distribution matrix).

In practice, it can be met certain surface faults, for instance partial loss of a control surface (break off part of control surface), which causes to the different control effectiveness factors of the actuator.

Scientific research is a problem of developing the method of the aircraft control reconfiguration when unexpected situation appears during flight for proceeding its controllability and stability.

3. Solve the problem

At first let me clarify terminological distinction between reconfiguration control, parametric reconfiguration, structural reconfiguration, object and target reconfiguration.

Reconfiguration control – the redistribution of control actions to restore handling and stability of the aircraft in emergency situations.

Parametric reconfiguration – the redistribution of control parameters to restore handling and stability of the aircraft in emergency situations.

Structural reconfiguration – restructuring of the control system to restore handling and stability of the aircraft in emergency situations.

Object reconfiguration – the restructuring of aircraft mechanical components to restore handling and stability in emergency situations.

Target reconfiguration – changing goals and tasks control the aircraft in emergency situations.

Typical structure of reconfigurable Automatic Control System (ACS) is shown in Fig. 3.

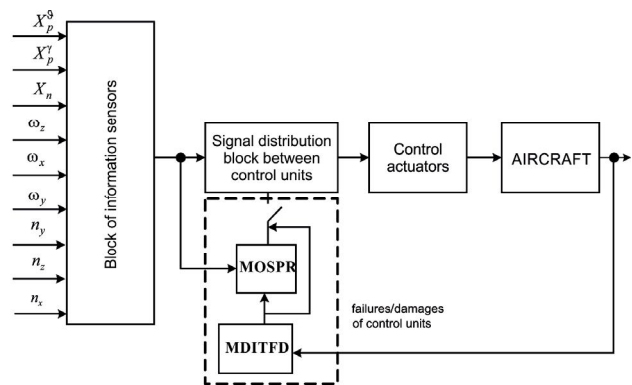


Fig. 3. Block diagram of a reconfigurable ACS:

$X_P^{\delta}, X_P^{\gamma}$ – move the control knob on the pitch and heel, respectively;

X_{II} – to move the pedals;

$\omega_z, \omega_x, \omega_y$ – the angular speed of pitch, heel and yaw respectively;

n_y – normal overload;

n_z – lateral loads;

n_x – longitudinal overload

The dashed line block is selected reconfiguration, which is part of control system reconfiguration.

Introduction to the ACS unit reconfiguration is fundamentally different from the existing control system.

Reconfiguration unit consists of two modules – Module Object, Structural and Parametric Reconfiguration (MOSPR) as well as the Module Detection and Identification of the Type of Failure/Damage (MDITFD).

The proposed system works as follows.

In case of failure/damage detection and identification module classifies damage generates a command for reconfiguring the switch module, moreover, it sends a control law reconfiguration module all the classified information about failure/damage (i.e., pattern forming typical failure/damage).

The MOSPR creates new control action, parrying the effects of types of failure/damage.

Obviously, it will be determined by disposable that is used by staff and additional controls, as well as the time of an emergency arose.

Under the influence of external and internal factors of destabilization the aerodynamic state of a moving object changes, and the characteristics of its stability and handling.

To save the set (desired) motion parameters and the desired characteristics of stability and control in terms of the destabilization factors it is necessary to solve the fundamental problem of insensitivity closed reaction system in the space state.

We assume that the linearized stationary model of controlled aircraft flight in unperturbed state described by the following nominal model in state space:

$$\begin{aligned} \dot{x}(t) &= A_0 x(t) + B_0 U(t), x(0) = x_0; \\ y(t) &= C_0 x(t), \end{aligned} \quad (1)$$

where $x(t) \in R^n - n -$ measured state vector;

$U(t) \in R^r - r -$ measured vector of control inputs;

$y(t) \in R^m, m < n - m -$ measured vector of measurements (outputs);

A – transitional matrix of state with size $n \times n$;

B – transitional matrix of control with size $n \times r$;

C – matrix of observations with size $m \times n$.

Expected, that B_0 and C_0 have full rank. In the considered class of aircraft equipped with reconfigurable control system with permanent structure control law is used as a feedback of outputs with the fixed gain

$$U(t) = KC_0 x(t), \quad (2)$$

where $K = \{K_1, \dots, K_m\}$ – feedback matrix of outputs.

From the formulas (1) i (2) follows, that nominal closed model of aircraft has the form:

$$\dot{x}(t) = (A_0 + B_0 KC_0) x(t). \quad (3)$$

The dynamic response of the closed-loop system (3) at any given time $0 \leq t < t_k$ can be determined by the expression

$$x(t) = \exp\{(A_0 + B_0 KC_0)t\} x(0). \quad (4)$$

From a structural view the descriptions are valid if the pair (A, B) are controllable and the pair (C, A) are observable.

Suppose that in real flight in external, including mechanical, influences and internal damages matrices of nominal system model (3) A_0, B_0 and C_0 undergo through variations of some or all of its elements.

Let the perturbation of A_0, B_0, C_0 are $\Delta A, \Delta B, \Delta C$.

Taking into account entered designations matrices of perturbed system model will be as follow:

$$\begin{aligned} A &= A_0 + \Delta A; \\ B &= B_0 + \Delta B; \\ C &= C_0 + \Delta C. \end{aligned}$$

The structure of external and internal degraded influences depends on the particular emergency situation, but in general it can be described as:

$$\begin{aligned} \Delta A &= \begin{bmatrix} S_{11}^1 \dots S_{1n}^1 \\ \vdots \\ S_{n1}^1 \dots S_{nn}^1 \end{bmatrix} \Delta_1 + \dots + \begin{bmatrix} S_{11}^v \dots S_{1n}^v \\ \vdots \\ S_{n1}^v \dots S_{nn}^v \end{bmatrix} \Delta_v; \\ \Delta B &= \begin{bmatrix} U_{11}^1 \dots U_{1r}^1 \\ \vdots \\ U_{n1}^1 \dots U_{nr}^1 \end{bmatrix} \Delta_1 + \dots + \begin{bmatrix} U_{11}^v \dots U_{1r}^v \\ \vdots \\ U_{n1}^v \dots U_{nr}^v \end{bmatrix} \Delta_v; \\ \Delta C &= \begin{bmatrix} y_{11}^1 \dots y_{1n}^1 \\ \vdots \\ y_{m1}^1 \dots y_{mn}^1 \end{bmatrix} \Delta_1 + \dots + \begin{bmatrix} y_{11}^v \dots y_{1n}^v \\ \vdots \\ y_{m1}^v \dots y_{mn}^v \end{bmatrix} \Delta_v, \end{aligned} \quad (5)$$

where $S_{ij}^\lambda, U_{ij}^\lambda, y_{ij}^\lambda \in R -$ known i, j, λ ;

$\Delta_1, \dots, \Delta_v -$ unknown and may have different, including catastrophic, meaning.

From the analysis of the expression (5) follows that necessary and sufficient condition of complete insensitivity reaction of closed system “Aircraft – reconfigured ACS” ($x(t) \in R^n$) to degraded actions of external and internal perturbations, i.e. variation $\Delta A, \Delta B, \Delta C$ model in state space is formula:

$$\begin{aligned} A_0 + \Delta A + (B_0 + \Delta B)K(C_0 + \Delta C) - A_0 - B_0 KC_0 = \\ = \Delta A + \Delta B K C_0 + B_0 K \Delta C + \Delta B K \Delta C = 0. \end{aligned} \quad (6)$$

The expression (6) shows that to achieve complete insensitivity of the reaction condition (4) is difficult because in practice it is impossible to provide a complete insensitivity of all left modes of reaction condition.

However, by selecting of the appropriate matrix of reconfiguration K we can assign to multitude different set of self-values $\lambda_i, i = 1, \dots, n$, of closed-loop system.

Then the dynamic response of the closed-loop system (4) at any time $t \geq 0$ can be determined as follow:

$$x(t) = \sum_{i=1}^n [\exp\{\lambda_i t\}] v_i w_i^T x(0),$$

where $v_i = 1, \dots, n$ – linearly independent eigenvectors in (3), that satisfying the equality

$$(A_0 + B_0 K C_0) v_i = \lambda_i v_i; \quad (7)$$

w_i^T , $j = 1, \dots, n$ – eigenvectors of expression $[A_0 + B_0 K C_0]^T$, which satisfy

$$w_i^T [A_0 + B_0 K C_0] = \lambda_i w_i^T. \quad (8)$$

Right eigenvectors in expression (7) and left eigenvectors in expression (8) when normalized satisfy the condition of orthogonality, it means

$$w_j^T v_i = v_i^T w_j = \delta_{ij}, i, j = 1, \dots, n. \quad (9)$$

In expression (9) δ_{ij} – Kronecker delta function.

In practice, “catastrophic” failures are rather rare, the simultaneous failure of all components of the aircraft.

Therefore it is expedient to consider at first stage sequentially insensitivity for each own mod.

So, write the condition of complete insensitivity of the i -th left eigenmodes of closed-loop system

$$w_i^T \exp\{\lambda_i t\}, i = 1, \dots, n$$

to perturbations models $\Delta A, \Delta B, \Delta C$:

$$\begin{bmatrix} w_i^T B_0 K \end{bmatrix} \begin{bmatrix} DA & DB \\ DC & 0 \end{bmatrix}. \quad (10)$$

Enter into the condition (10) designations :

$$\begin{aligned} DB &= \begin{bmatrix} U_{11}^1 \dots & U_{1r}^1 & U_{11}^v \dots & U_{1r}^v \\ \vdots & \vdots & \vdots & \vdots \\ U_{n1}^1 \dots & U_{nr}^1 & U_{n1}^v \dots & U_{nr}^v \end{bmatrix}; \\ DA &= \begin{bmatrix} S_{11}^1 \dots & S_{1n}^1 & S_{11}^v \dots & S_{1n}^v \\ \vdots & \vdots & \vdots & \vdots \\ S_{m1}^1 \dots & S_{mn}^1 & S_{m1}^v \dots & S_{mn}^v \end{bmatrix}; \\ DC &= \begin{bmatrix} Y_{11}^1 \dots & Y_{1n}^1 & Y_{11}^v \dots & Y_{1n}^v \\ \vdots & \vdots & \vdots & \vdots \\ Y_{m1}^1 \dots & Y_{mn}^1 & Y_{m1}^v \dots & Y_{mn}^v \end{bmatrix}. \end{aligned} \quad (11)$$

Introduced in equation (11) designation comes from formula (5).

The condition of complete insensitivity of the i -th right mode of closed-loop system

$$v_i \exp\{\lambda_i t\}, i = 1, \dots, n$$

to perturbations models $\Delta A, \Delta B, \Delta C$ will be

$$[\Delta A : \Delta B : \Delta C_0] v_i = 0. \quad (12)$$

Condition (12) it is possible to apply with an equivalent expression

$$\{\Delta A^T : \Delta C^T : \Delta C_0^T\} \subseteq \{w_1, \dots, w_{i-1}, w_{i+1}, \dots, w_n\},$$

where $\{\cdot\}$ - image.

Shown conditions (10) and (12) are sufficient.

If damage or structural failure of corresponding control circuit ACS require that $\Delta B = 0$, then condition of neutralization of system parameters deviations from nominal values A_0, B_0, C_0 will be

$$\Delta A_c = \Delta A + B_0 K \Delta C = 0. \quad (13)$$

Substituting into the expression (13) reconfiguration control matrix K_1 and K_2 , we obtain the condition

$$\Delta A + \Delta C + B_0 K_2 \Delta C = 0. \quad (14)$$

Multiplying equation (14) on the left by the vector W_r and taking into account entered in the formula (11) notation, we obtain the condition of complete insensitivity of the first r left eigenmode:

$$W_r D A + G_r D C + W_r B_0 K_2 D C = 0. \quad (15)$$

In general condition (15) cannot be fulfilled only through the feedback coefficient of matrix K , then complete insensitivity we will consider consistently to each own mode. A necessary and sufficient condition of complete insensitivity of k -th left eigenmodes of closed loop system (w_k^T, λ_k) , $k = 1, \dots, r - 1$ to the perturbation model ΔA and ΔC .

The sufficient condition of complete insensitivity of k -th right eigenmodes of closed loop system (λ_k, v_k) , $k = 1, \dots, n - k$ to the perturbation model ΔA and ΔC is

$$[\Delta A : \Delta C] v_k = 0, \quad k = 1, \dots, n. \quad (16)$$

Condition (16) is equivalent to the following expression:

$$\{\Delta A^T : \Delta C^T\} \subseteq \{w_1, \dots, w_{k-1}, w_{k+1}, \dots, w_n\}.$$

Analysis of system behavior of “Aircraft-reconfigured ACS” in abandoned situations shows that there are flight mode when it is necessary to provide the condition $\Delta B \equiv 0$.

In this case the synthesis task consists in choosing a parametric vectors $g_k \in C^m$, $k = 1, \dots, r-1$ due to which it will be quite insensitive maximum possible number of left eigenmode $w_k^T \exp\{\lambda_k t\}$ and will retain the possibility of random assignment of maximum number of eigenvalues λ_k of closed loop system.

So, diodic k -th mode of closed loop system will be absolutely insensitive if (v_k, w_k^T, λ_k) , $k = 1, \dots, r$ will be absolutely insensitive to this class of failures (variations of aircraft parameters ΔA and ΔC) and if the following conditions are satisfied:

$$g_k^T C_0 (\lambda_k E - A_0)^{-1} D A + g_k^T D C = 0$$

$$\{\Delta A^T; \Delta C^T\} \leq \{w_1, \dots, w_{k-1}, w_{k+1}, \dots, w_n\}.$$

These conditions make it possible to make a synthesis of closed loop systems "Aircraft-reconfigured ACS" with insensitive diodic modes with the help of its own variable structure.

4. Conclusions

The method of reconfiguration to preserve the stability and controllability of the aircraft related to cases its collision with mechanical, biological and an electrical element is given.

The reconfigurable automatic control system is presented.

The use of reconfigurable automatic control systems can improve the level of flight safety due to realization of new technical solutions.

Reconfiguration unit consists of two major modules: MOSPR, MDITFD.

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Д.О. Шевчук. Метод реконфігурації керування літаком в умовах виникнення особливої ситуації в польоті

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Виконано порівняльний аналіз статистичних даних ІКАО. Показано, що 35 % випадків виникнення особливих ситуацій пов'язано з відмовами та пошкодженнями систем автоматичного керування, головним чином із відмовами приводів та пошкодженнями зовнішніх обводів і керуючих органів. Наведено класифікацію існуючих походів та методів створення реконфігурованих систем керування складними об'єктами в умовах виникнення особливих ситуацій. Розроблено метод реконфігурації для збереження стійкості та керованості літака в умовах виникнення особливих ситуацій у польоті, та запобігання її розвитку або переростання в катастрофічну.

Ключові слова: втрата керованості в польоті; керованість та стійкість; літак; особлива ситуація; реконфігурація; система керування.

Д.О. Шевчук. Метод реконфігурації управління самолетом при виникненні особливих ситуацій в польоті

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Выполнен сравнительный анализ статистических данных ИКАО. Показано, что 35% случаев возникновения особых ситуаций связаны с отказами и повреждениями систем автоматического управления, главным образом с отказами приводов и повреждениями внешних обводов и управляющих органов. Приведена классификация существующих походив и методов создания реконфигурируемых систем управления сложными объектами в условиях возникновения особых ситуаций. Разработан метод реконфигурации для сохранения устойчивости и управляемости самолета при возникновении особых ситуаций в полете.

Ключевые слова: особая ситуация; потеря управляемости в полете; самолет; система управления; реконфигурация; управляемость и устойчивость.

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