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DESIGN OF FAULT TOLERANT CONTROL SYSTEM FOR AIRCRAFT WHEN ACTUATORS FAULTS AND STRUCTURAL DAMAGE OCCUR

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Abstract. In this article control, parametric, structural and object reconfiguration was given. Fault tolerant control system for recovering controllability of the aircraft when an unexpected problem (such as faults or failures to the actuators/sensors or structural damage) occurs during a flight is proposed.

Keywords: fault tolerant control system; aircraft; faults or failures to the actuators/sensors or structural damage; reconfiguration; flight control system; loss of control in flight; stability and controllability.

Introduction

In recent years, drastic increases in the available on-board computational power have allowed the flight control community to consider the application of on-line parameter estimation techniques. In particular, the real-time extension of the parameters identification process has immediate and potentially very important applications for control of time varying aircraft systems, such as an aircrafts subjected to substantial changes in the dynamic and aerodynamic characteristics [1].

The safety of aircraft passengers has been and will continue to be an important issue in the commercial aviation industry. Figures 1 represents some recent civil aviation safety statistics [2]. It shows that «loss of control in flight» is one of the most important occurrence and involves the most fatalities. Loss of control during flight is one of the motivating factors for reconfiguration of controlling influences: the idea is to restore controllability and stability of the airplane in the event of faults, failures or airframe damages. In [3] two examples of successful and unsuccessful implementation are given by the pilot of reconfiguration. In the first case the left section of the elevator of the Delta L1011 airplane appeared is clamped in situation 19° in case of take-off. The pilot prevents failure by reconfiguration. The second case is connected to DC-10 airplane failure on May 25 1979 in Chicago, called loss of section of the flap of the airplane. The subsequent simulation of a situation showed that the pilot could avoid failure by means of reconfiguration.

The problem of achieving some level of performance and stability in the case when these unexpected scenarios occur, especially for safety critical systems (e.g. aircrafts, satellites, chemical and nuclear power plants) requires a different control strategy rather than just having a robust or adaptive controller (which only guarantees stability and performance for perturbations in the nominal conditions of the main systems). An example of a system which requires such a control strategy is the problem of increasing the survivability of an aircraft when an unexpected problem (such as faults or failures to the actuators/sensors or structural damage) occurs during a flight.

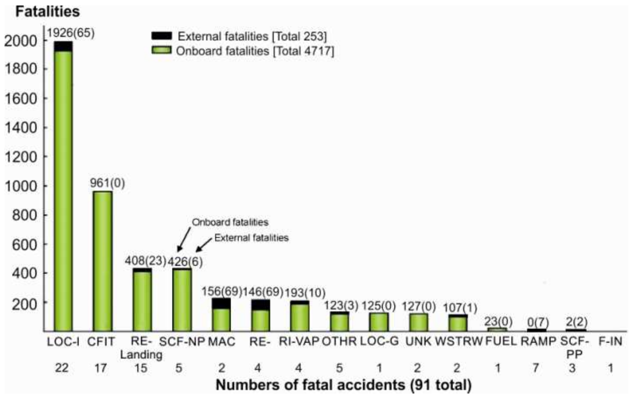

Fig. 1. Aircraft accidents statistics for worldwide commercial jet fleet, 1999-2008 (statistic data from [2]): LOC-I – loss of control- in flight; CFIT – controlled flight into or Toward Terrain; RE-Landing – Runway Excursion-Landing; SCF-NP – System/Components Failure or Non-Powerplant; MAC – Midair/Near Midair Collision; RE-Takeoff – Runway Excursion Takeoff; RI-VAP – Runway Incursion -Vehicle, Aircraft, Person; OTHR – Other; LOC-G – loss of control-ground; UNK – Unknown or Undetermined; WSTRW – Windshear or Thunderstorm; FUEL – fuel related; RAMP – Ground Handling; SCF-PP – System/Components Failure or Powerplant; F-NI – Fire/Smoke (Non-Impact)

When a fault occurs in a system, the main problem to be addressed is to diagnose what fault has occurred, and then decide how to deal with it. The problem of detecting a fault, finding the source/location and then taking appropriate action is the basis of fault tolerant control. The problem of detecting a fault, finding the source/location and then taking appropriate action is the basis of reconfigured flight control system.

Main part

At first let us clarify the terminological distinction between a fault and a failure [4; 5]:

– fault is an undesired change in a system parameter that degrades performance: a fault may not represent a component failure;

– failure is a catastrophic or complete breakdown of a component or function (to be contrasted with a fault which may be a tolerable malfunction).

For a control surface, there are two major types of failures. As shown in fig. 2, *a*, the control surface may become ineffective and float at the zero moment position. The control surface can also be locked at any arbitrary intermediate position (fig. 2, *b*) or reach and stay at the saturation position as shown in fig. 2, *c*. Mechanical failures may also happen. This is the case when the mechanical link between the control surface and its corresponding actuator or servo breaks [5; 6].

Examples of failures that cause structural damage are wing battle damage [5; 7], detachment of control surfaces, for example the rudder (flight 961, A310, Varadero, Cuba, 2005) [8] or engines (flight 1862, B–747, Amsterdam, 1992) [9], or detachments of some body parts of the aircraft e.g. the vertical fin/stabilizer (Flight 123, B–747, Japan, 1985) [10] and (flight 587, A300, New York, 2001) [10], wing (DHL A300B4, A300, Baghdad, 2003) [10], fuselage skin or cargo doors (flight 981, DC–10, Paris, 1974) [10].

As reconfiguration we will understand the control redistribution on controls for the purpose of creation of necessary control forces and moments for restoration of airplane controllability and stability in the conditions of extrasatiation during flight. Development of methods and models of reconfiguration of controlling influences aboard the plane in the conditions of origin special situations in flight operation [11] is devoted. For reconfiguration of controlling influences in case of failures of drives and governing bodies two approaches [11] are used: parametric and structural.

In large passenger transport aircraft for example, the spoilers which are typically deployed to reduce speed, can also be used differentially to create roll which normally is achieved by using ailerons; also engines can be used differentially to create yaw, which is typically achieved by using the rudder; and finally the horizontal stabilizer which is normally used to set the angle of attack, can also replace elevators for pitch movement [5].

Traditional approaches to flight control reconfiguration can entail four major and separate problems [12]:

– failure detection;

– failure isolation and characterization;

– system identification of the degraded system;

– flight control reconfiguration to accommodate the degraded sensor/actuator/airframe configuration.

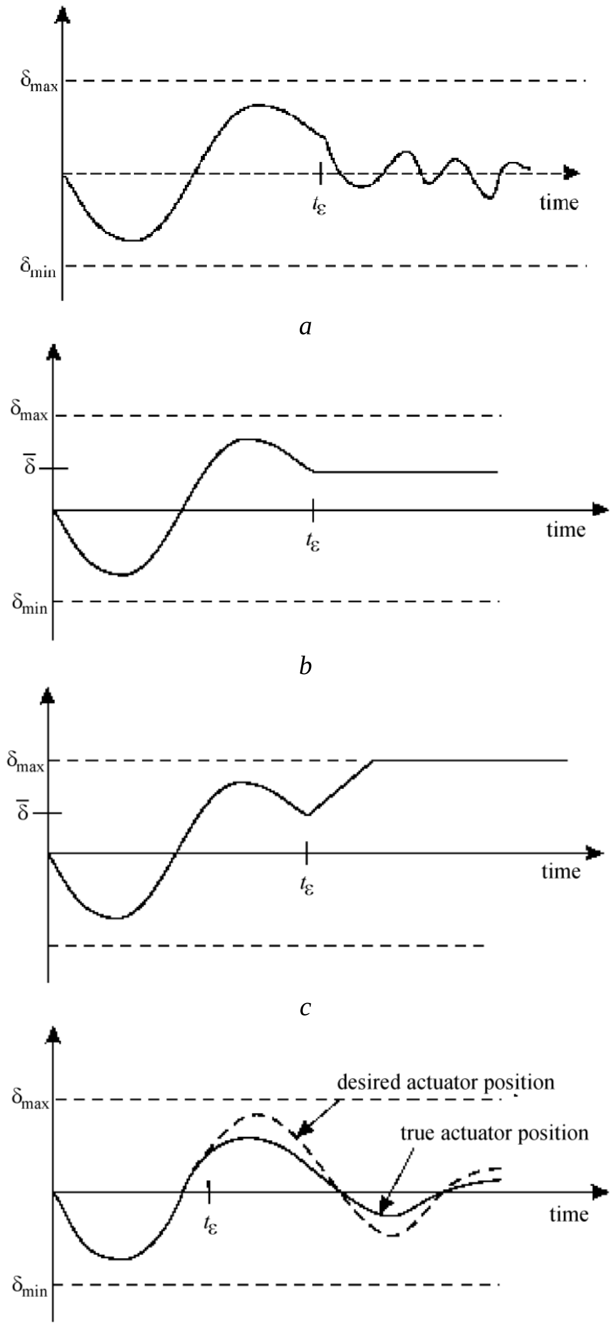

Fig. 2. Several types of actuator failures:
a – floating around trim; *b* – locked-in-place; *c* – hard-over; *d* – loss of effectiveness (actuator fault occurring after t_ε)

On fig. 3 the simplified structure chart of fault tolerant control system is provided.

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

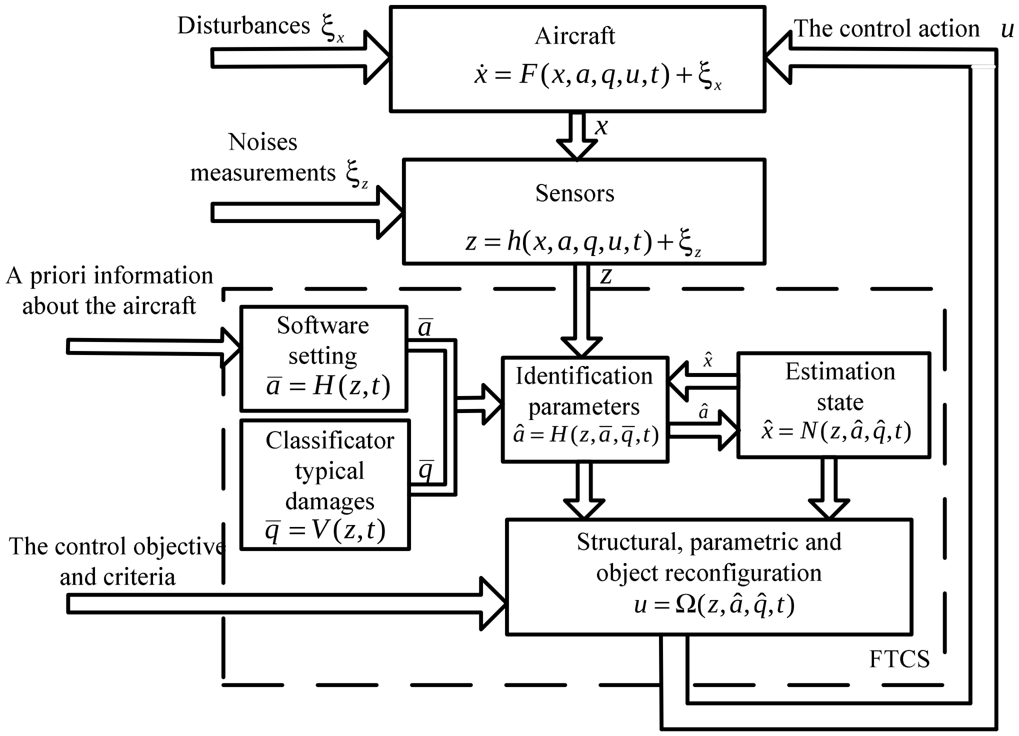

Fig. 3. Fault tolerant control system (FTCS)

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.

Let's suppose that movement of the aircraft is described by a differential equation:

$$\dot{x} = F(x,a,q,u,t) + \xi_x, \qquad (1)$$

where x – n-dimensional state vector of object defined in space X; a – r-dimensional vector of parameters accepting values from a A-set and defined by properties of the environment; q – vector of integrity of external contour of the airplane in the flight, considering influence of standard damages on aerodynamic properties of the airplane, and the m-dimensional vector of controlling influences created by reconfigured control system and belonging to the set U; t – the current time belonging to a segment $[t_0, t_f]$ on which unexpected situation in flight is defined; ξ_x - n-dimensional vector of uncontrollable perturbations (noise, measurement noises etc.); F - n-dimensional vector function of the specified arguments known, according to the assumption, on the basis of theoretical and pilot studies. Observation over movement of the airplane is carried out by means of a complex of the sensors measuring components of a status of object and control, and also integrity of its external contour in flight:

$$z = h(x,a,q,u,t) + \xi_z, \qquad (2)$$

where z - l-dimensional vector of observations in space Z; ξ_z - l-dimensional vector of the additive noises distorting indications of sensors; h - l-dimensional vector function of the specified arguments known on the basis of theoretical and pilot studies of sensors of information. Results of measurements arrive in reconfigured management system where are used for determination of response characteristics of the airplane and optimum (suboptimal) estimation of its status.

The following stage of functioning of the offered reconfigured management system is process of parametric identification of response characteristics of the airplane in the conditions of unexpected situation origin in flight which in a general view is described by the operator:

$$\hat{a} = H(z,a,q,t). \qquad (3)$$

Thus, in considered structure it is necessary that identification is carried out in some neighborhood of program value of a vector of parameters. In the course of identification the reconfigured management system considers the factors influencing dynamic properties of the airplane (unfavorable external factors and degrading internal processes).

On the basis of signals of sensors and estimates of parameters of object it is carried out optimum (or suboptimal) estimation of a status of the object, allowing substantially to increase accuracy of information on a vector:

$$\hat{x} = N(z, \hat{a}, \hat{q}, t), \quad (4)$$

where $\hat{x}$ - n-dimensional vector of an assessment of parameters of a vector x.

Total procedure of reconfigured management system is optimization of controlling impacts on airplane executive bodies on a basis, set the purposes of control and criteria of optimization for preventing of development of unexpected situation in flight. The operator describing formation of a vector of optimum controls, looks like:

$$u = \Omega(z, \hat{a}, \hat{q}, t). \quad (5)$$

The optimality criterions created beforehand, define a measure, leaning on which control algorithm selects an optimum way of achievement by object of the given status. The structure of the operator depends on a method of the job of the purpose of the control, minimized criteria and a choice of a method of the optimization, to unexpected situation had time development in flight, and also an aerodynamic status of external contour of the airplane.

Conclusion

In this article control, parametric, structural and object reconfiguration was given. The main elements of the fault tolerant control system are block of structural, parametric and object reconfiguration, block of identification and isolation, block of classification typical damages. Block of structural, parametric and object reconfiguration takes the initial information about the existing laws the aircraft flight control and redistribute the initial commands intact control surfaces in terms of emergency situations. Thus, the proposed concept to recovering controllability of the aircraft when actuators fault and structural damage occur.

References

1. *Alwi H., Edwards C., Stroosma O., Mulder J. A.* On the Implementation of a Fault Tolerant Sliding Mode Scheme with Control Allocation on the SIMONA Research Flight Simulator, accepted in AIAA journal of Guidance Control and Dynamics.

2. *Christine M. Belcastro, Steven R. Jacobson* Future integrated systems concept for preventing aircraft loss-of-control accidents. American Institute of Aeronautics and Astronautics.

3. *Napolitano M. R., Swaim R. L.* 1989. A new technique for aircraft flight control reconfiguration. Proc. AIAA Guidance, Navigation and Control Conf., Pt. 1. P. 1–9.

4. *Boškovic J. D., Mehra R. K.* 2002. Fault Diagnosis and Fault Tolerance for Mechatronic Systems: Recent Advances, chapter Failure Detection, Identification and Reconfiguration in Flight Control. Springer-Verlag.

5. *Halim Alwi B.Eng.* Fault tolerant sliding mode control schemes with aerospace applications. Leicester Control and Instrumentation Research Group Department of Engineering University of Leicester.

6. *Boskovic J. D., Mehra R. K.* 2001. A Hybrid Fault-Tolerant Scheme for Flight Control Applications. In Proceedings of the AIAA Guidance, Navigation, and Control Conference and Exhibit, Montreal, Canada, August AIAA P. 2001–4400.

7. *Boškovic J. D., Mehra R. K.* 1998. A multiple model-based reconfigurable flight control system design. In Proceedings of the 37th IEEE Conference on Decision and Control. P. 4503–8.

8. The transportation safety board of Canada issues safety recommendations to improve rudder inspections on Airbus aircraft. Communiqués TSB # A04/2006 A05F0047, Transportation Safety Board of Canada, 2006.

9. *Smaili M. H., Mulder J. A.* 2000. Flight data reconstruction and simulation of the 1992 Amsterdam Bijlmermeer airplane accident. In AIAA Modeling and Simulation Technologies Conference.

10. *Burcham F. W., Fullertron C. G., Maine T. A.* Manual manipulation of engine throttles for emergency flight control. Technical Report NASA/TM-2004-212045, NASA, 2004.

11. *Kazak V.M.* 2010. System recovery methods survivability aircraft in special situations in flight. Monograph. Kyiv, Published by the National Aviation University “NAU-printing”. 284 p. (in Ukrainian).

12. *Calise A. J., Lee S. and Sharma M.* Direct Adaptive Reconfigurable Control of a Tailless Fighter Aircraft Georgia Institute of Technology School of Aerospace Engineering Atlanta.

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Д. О. Шевчук. Розробка відмовостійкої системи керування літаком в умовах відмов керуючих поверхонь чи структурних пошкоджень

Запропоновано функціональну та структурну схеми відмовостійкої системи керування для відновлення керованості та стійкості літака, в умовах відмов керуючих поверхонь чи структурних пошкоджень під час виконання польоту.

Ключові слова: відмовостійка система; літак; відмова; структурні пошкодження; реконфігурація керування; втрата керованості у польоті; система керування літаком; керованість та стійкість.

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Напрям наукової діяльності: методи відновлення керованості літака в умовах виникнення особливих ситуацій у польоті.
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Д. О. Шевчук. Разработка отказоустойчивой системы управления самолетом в условиях отказов управляющих поверхностей или структурных повреждений

Предложена функциональная и структурная схемы отказоустойчивой системы управления для восстановления управляемости и устойчивости самолета, в условиях отказов управляющих поверхностей или структурных повреждений при выполнении полета.

Ключевые слова: отказоустойчивая система; самолет; отказ; структурные повреждения; реконфигурация управления; потеря управляемости в полете; система управления самолетом; управляемость и устойчивость.

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