UDC 629.735.015.7.2:656.7.08(045)

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OPTIMAL CHOICE WITHIN A FAULT TOLERANT FLIGHT CONTROL SYSTEM

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Abstract. *Safety of aircraft during the flight is one of the most important problems that concerns of all aviation. Failures/faults main elements automatic control system and damages to the external contour of the aircraft by foreign objects always lead to a change the characteristics of the aircraft, direct and indirect economic costs and sometimes to injury or death of passengers and crew. Real-time active fault tolerant control system makes it possible to warn or prevent emergency situations and thus improve safety.*

Keywords: active fault tolerant control system, actuator, adverse flight conditions, aircraft, control system, failure/fault, loss-of-control, reconfiguration, sensor, stability and controllability.

1. Introduction

In the past ten years, 59 % of the fatal airliner aircraft accidents were caused by loss-of-control in flight and another 33 % by controlled flight into terrain (Ranter…2007). The accident reports published by National Transportation Safety Board (NTSB) have revealed that most in-flight loss-of-control accidents were triggered by faults including subsystem/component failures, external hazards, and human errors (NTSB…2007). With hindsight, it is easy to say that most of these accidents could have been prevented if the maintenance were performed better to avoid component failures, or if the aircraft had not entered the hazardous region, or if the flight crews had not made mistakes, but it is impossible to eliminate all the faults that may threaten flight safety.

Malfunction or jam of aircraft control surfaces like elevators, rudders, ailerons can be very dangerous since these faults not only result in the reduction of control authority, but they also impose persistent disturbances on the aircraft. The jammed control surface position can be anywhere in the operational range and is not known a priori. If the jam position is not too far away from the trim condition, the remaining control authority may be enough to be utilized to maintain a safe flight. However, if the jam occurs near an extreme position, the available control authority may not be able to offset the effect of the persistent disturbance caused by the jam.

The first fault the Flight 261 crew members encountered was a horizontal stabilizer jam at 0.4°, which was near the trim condition. This fault was not severe and the pilots were able to keep the aircraft aloft at 31,050 feet preparing for an emergency landing. But about twenty minutes later, the horizontal stabilizer was moved by an excessive force with huge noise from 0.4° to a new jam position, 2.5° airplane nose down, and the airplane began to pitch nose down, starting a dive. Things got worse after that – pilots lost control of the pitch axis, and the aircraft crashed into the ocean 11 minutes and 37 seconds later (Chang et al. 2004). Flight 232 DC–10 in Sioux City, Iowa 1989 (which suffered a tail engine failure that caused the total loss of hydraulics) (Burcham et al. 2004; Gero 2006), the Kalita Air freighter in Detroit, Michigan, October 2004 (where engine No 1 was shed but the crew managed to land safely without any casualties) and the DHL A300B4, Baghdad, November 2003 (which was hit by a missile on its left wing and lost all hydraulics, but still landed safely using only the engines) (Burcham et al. 2004), represent some examples of successful landings using clever manipulation of the remaining functional redundant control surfaces. Here it can be seen that one of the main factors that enabled safe landing after faults/failures is the clever manipulation of the redundant control surfaces to achieve the desired level of acceptable degraded performance. In the event of an emergency due to faults/failures, pilots will use all the available resources to help in a safe landing.

A reconfigurable flight control system might have prevented the loss of two Boeing 737s due to a rudder actuator hard-over and of a Boeing 767 due to inadvertent asymmetric thrust reverser deployment.

The 1989 Sioux City DC-10 incident is an example of the crew performing their own reconfiguration using asymmetric thrust from the two remaining engines to maintain limited control in the presence of total hydraulic system failure. The crash of a Boeing 747 freighter aircraft (Flight 1862) in 1992 near Amsterdam (the Netherlands), following the separation of the two right-wing engines, was potentially survivable given adequate knowledge about the remaining aerodynamic capabilities of the damaged aircraft (Smaili, Mulder 2000).

Adaptive or reconfigurable flight control strategies might have prevented the loss of two Boeing 737s due to a rudder actuator hardover and of a Boeing 767 due to inadvertent asymmetric thrust reverser deployment.

2. Analysis results of recent research and publications

In the literature, most of the motivation and research work in fault tolerant control involves solving problems encountered in safety critical systems such as aircraft. 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. AFTCS is a complex combination of three major research fields, Fault Detection and Isolation (FDI), robust control, and reconfigurable control (Halim Alwi 2006).

Patton (Patton 1997) 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. Both the FDI and reconfigurable controller need to be robust against uncertainty and disturbance (Halim Alwi 2006).

In article (Zhang, Jiang 2003) 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.). 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 airplane in the conditions of origin special situations in flight operation (Kazak 2010) is devoted. For reconfiguration of controlling influences in case of failures of drives and governing bodies two approaches (Kazak 2010) 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.

Structural – control redistribution between operational governing bodies for recovery of acceptable characteristics of controllability and stability in the conditions of unexpected situations in flight. Patton (Halim Alwi 2006; Patton 1997), classify fault tolerant control system into two major groups: Passive Fault Tolerant Control Systems (PFTCS) and Active Fault Tolerant Control Systems (AFTCS). In PFTCS the controller is designed to be robust against faults and uncertainty. Therefore when a fault occurs, the controller should be able to maintain stability of the system with an acceptable degradation in performance. PFTCS does not require FDI and does not require controller reconfiguration or adaptation.

3. Problem

Scientific research is a problem of developing the AFTCS for proceeding controllability and stability aircraft under adverse flight conditions.

4. Solve the problem

At first let us clarify the terminological distinction between a fault and a failure (Boškovic, Mehra 2002; Ducard 2009; Halim Alwi 2006; Isermann 2006):

– 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.

A reconfigured flight control system is required to perform failure detection, identification, and accommodation following a battle damage and/or failure to a critical control surface. To implement a failure accommodation strategy, a variety of control surfaces (speed brakes, wing flaps, differential dihedral canards, spoilers etc.) and thrust mechanisms (differential thrust, thrust vectoring) can be used. This means, most control surfaces will have triple redundancy. In terms of the control surface itself, there exist secondary control surfaces that can be used in an emergency or in an unconventional way to achieve the same effect as the primary control surface (Fig. 1).

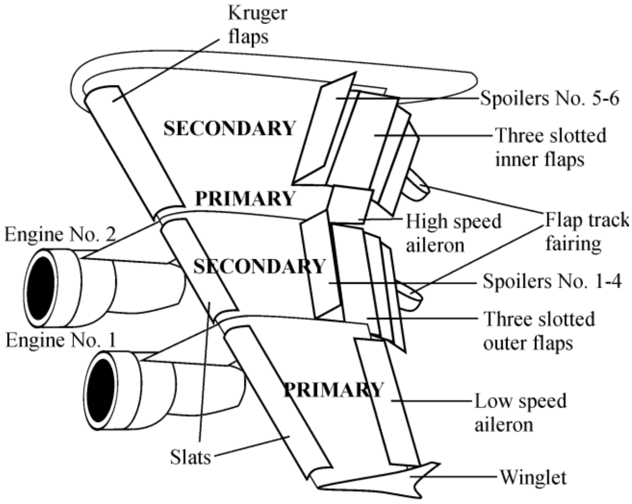

Fig. 1. Large transport aircraft: typical control surfaces

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 (Fig. 1) which is normally used to set the angle of attack, can also replace elevators for pitch movement (Halim Alwi 2006).

The proposed DS-AFTCS system is shown in Fig. 2.

It consists of the parametric and structural reconfiguration, identification current condition, reserve algorithm control surface actuator, diagnostic system.

In the conditions of considerable uncertainty arising from the sudden failures or faults elements of automatic control system, damages the external contour of the aircraft, changes in the external environment, decision of choosing the tactics and strategies of extension the flight is possible with crew or probabilistic models. However, in both cases, traditional approaches are characteristic unacceptably high decision-making time, which may lead to undesirable shift the current flight situation to emergency of flight, and in some cases even a catastrophic situation. Based on the above, scientific task is to restore the aircraft controllability and stability in the unexpected flight conditions based on the reconfiguration methods and intelligent technologies.

The failures/faults elements of automatic control system, assessment of the dangerousness of the refusals and operational decision-making by the method of further flight control are very essential tasks.

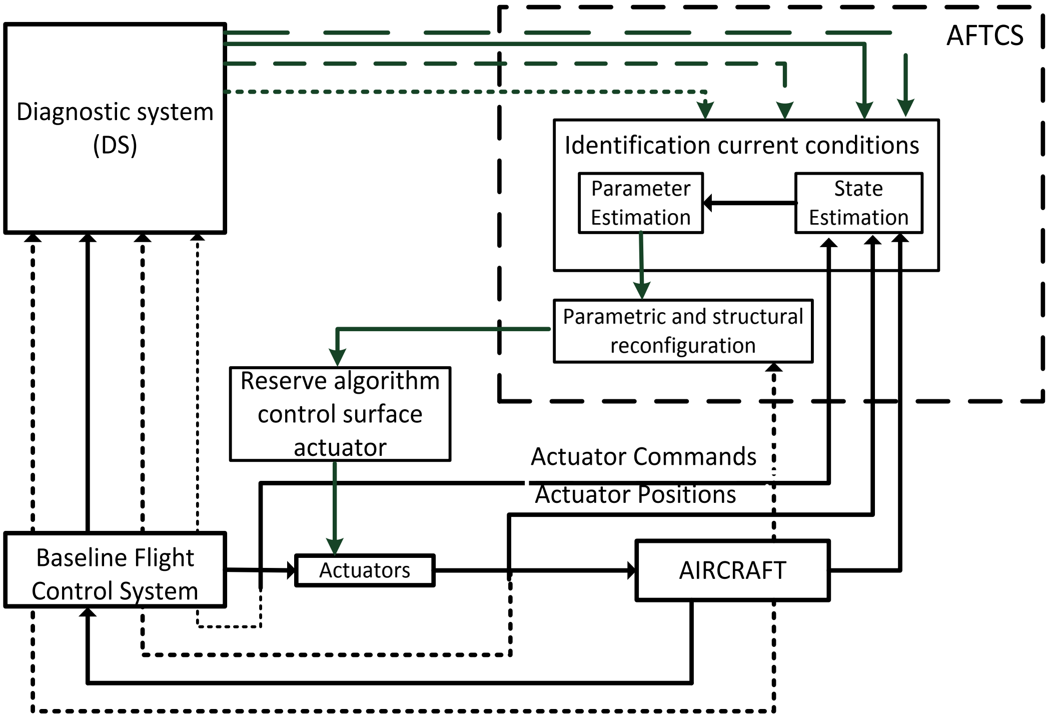

Fig. 2. Structure of the DS-AFTCS (diagnostic system-active fault tolerant control system)

There are some peculiarities of solving these tasks:

– both single and multiple failures/faults basic elements of automatic control system are consequence of the complicated combination control response;

– signals from sensors have incomplete and invalid information about downtime elements and aggregates;

– additional forces and moments appeared in terms of typical damages lift and control surfaces and causing in some cases, the loss of controllability and stability of the aircraft in flight;

– based on an assessment of the current flight situation algorithm is chosen to continue the flight, or the reorganization of the flight program and its criteria, and the appropriateness of parametric or structural reconfiguration of aircraft control.

For the stage of the initial research the possibility of preventing the transition of difficult flight situation in catastrophic, it was selected four major functional elements automatic control system: sensor, controller, actuator, control surface influencing on the three parameters: altitude H, the angle of pitch ϑ, and the angular velocity ω_z.

Depending on the specific situation in flight offered the following algorithms:

– parametric reconfiguration is to change the gains of the regulator;

– structural reconfiguration is to the redistribution of control on a serviceable actuators or control surfaces;

– reconfiguration flight program and its criteria;

– changing purpose of the flight;

– bailout.

Each typical failures/faults main elements automatic control system aircraft are assigned a number. For example, zero variant is fully serviceable aircraft. It is quite obvious that the cases when all the elements of the aircraft are serviceable, it is a full event group. The histogram of a priori failures/faults probability is shown on Fig. 3, where illustrated union of failures/faults in the group. It is allows to estimate a priori probability flight's algorithm in unexpected situation.

On a histogram the initial values of probabilities generalized ($P_0 = 0{,}5$, $P_1 = 0{,}24$, $P_2 = 0{,}2$, $P_3 = 0{,}05$, $P_4 = 0{,}01$), that corresponded probability ($P_1 + P_2 + P_3 = 0{,}49$), then continue the flight in the case failures/faults or damage by correcting control method for provide aircraft controllability and stability in flight.

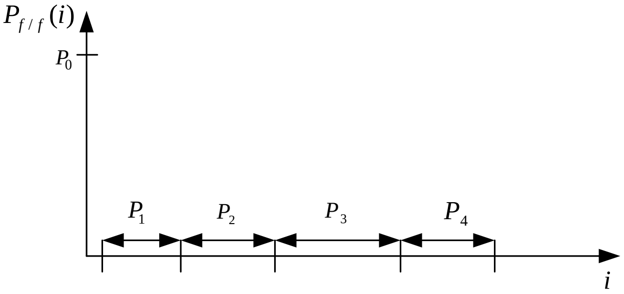

Fig. 3. Priori failures/faults probability:
P_0 – probability of fail safe performance;
P_1 – probability of parametric reconfiguration;
P_2 – probability of structural reconfiguration;
P_3 – to change flight program;
P_4 – to change of purpose of flight

As a priori probability failures/faults and damages given and posteriori information parameters such as altitude, pitch and angular velocity relative measured with Bayes' formula it is possible to count a posterior probabilities typical failures/faults or damages.

Bayes' procedure after unification failures/faults in groups allows estimating a posteriori probabilities expediency of application given algorithms depending on deviations from the norm.

For reduce the time of development necessary control actions, and avoid laborious procedure computation of continuous density functions failures/faults and damages of the continuously changing values altitude, pitch and angular velocity, proposed the field of possible values flight characteristics are divided into set of intervals.

Determined possible deviations flight characteristics (H, ϑ, ω_z) conveniently regarded as linguistic variables, each of which can take one of the following values of set (Fig. 4).

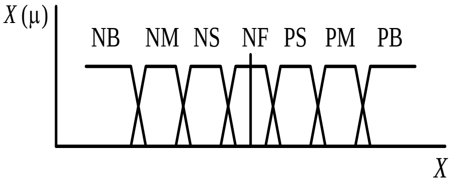

Fig. 4. The membership function of linguistic variables "ALTITUDE", "PITCH", "THE ANGULAR VELOCITY":
X – linguistic variable;
$X(\mu)$ – membership function;
NB – negative big;
NM – negative medium;
NS – negative small;
NF – normal flight;
PS – positive small;
PM – positive medium;
PB – positive big

Using a mathematical model of the aircraft and estimation of experts constitute table probabilities composed. Recalculate on the Bayes' formula produced as follows. At first performed calculation related to deviation from the norm altitude:

$$P_H = \frac{P_{f/f}(i)P(H_j/i)}{\sum_{i=0}^{n} P_{f/f}(i)P(H_j/i)},$$

where $P_{f/f}(i)$ – a priori probability of the i-th element failures/faults;

$P(H_j/i)$ – conditional probability of measured altitude H on the j-th flight characteristics, if occurred i-th failures/faults.

Then, similarly estimated deviation of ϑ and ω_z, thus as the priori probabilities used a posteriori function P obtained in the previous step. As a result, new values of the probability typical failures/faults after combining into groups for generalized alternatives further flight with the highest likelihood characterized the degree of confidence in selection of necessary control's algorithm. However, the direct calculation of the probabilities for each case is very time-consuming without ranking and combined qualitative states.

For this the obtained initial decision-making model by Bayes formula as a reference, we use the basic transformations adopted in fuzzy logic.

The qualitative assessments not only for input flight characteristics, but also for decision making described fuzzy sets. Possibility of the likelihood flight's algorithms will be considered as linguistic variables, each of which can take one of the following fuzzy sets:

$$\mathrm{A} \in \{\mathrm{NF}, \mathrm{S}, \mathrm{M}, \mathrm{B}\},$$

where A – algorithm of flight (parametric reconfiguration, structural reconfiguration, reconfiguration flight program and its criteria; changing purpose of the flight; bailout);

NF – normal conditions of flight;

S – small fuzzy set;

M – medium fuzzy set;

B – big fuzzy set.

Thus, each flight situation is characterized by three qualitative assessments of deviations form normal altitude, pitch and angular velocity, each of which takes one of the seven fuzzy sets (Fig. 4), and every typical algorithm estimated by four fuzzy sets. For example, "positive big" – deviation from the normal altitude, "positive small" – pitch deviation and "negative small" – angular velocity, corresponded "big" require reconfiguration control law, "medium" likelihood structural reconfiguration and changing flight program and its criteria, and "small" probability of bailout.

The results of the simulations are illustrated by Fig. 5.

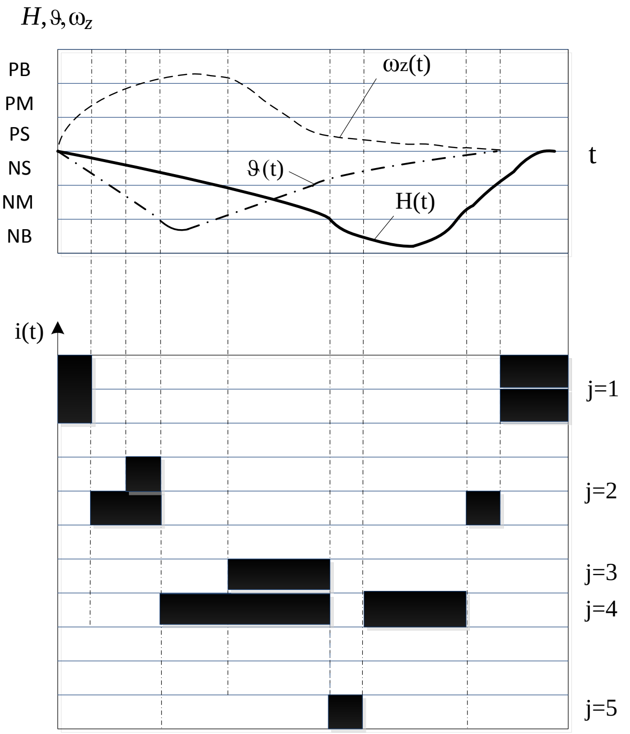

Fig. 5. Changing flight parameters and coefficients of confidence in the selection of tactical and strategic algorithm for continuation flight in abnormal situation:

PB – positive big;
PM – positive medium;
PS – positive small;
NB – negative big;
NM – negative medium;
NS – negative small

It is containing timing charts abnormalities flight characteristics H, ϑ, ω_z and the coefficients of confidence for every six algorithms (Lebedev 1999):

I – continuation of the flight;

II – parametric reconfiguration;

III – structural reconfiguration;

IV – correction trajectory;

V – changing flight's purpose;

VI – bailout.

Output coefficients resulting from the application intelligent technologies provided to reduce the risk of choosing incorrect algorithm.

As a mechanism for the implementation of the algorithm of choice strategic alternatives flight can serve multilayer recurrent neural network constructively combining both simple and complex decision-making process. In this case, the priority alternative flight is evaluated and then it sets the level of confidence in making operational decisions.

5. Conclusions

Real-time active fault tolerant control system is a main element of the strategy change the configuration of the control actions**.** It can take the initial information about the existing laws the aircraft flight control and redistribute the initial commands intact control surfaces in terms of emergency situations. In addition, important elements of reconfiguration flight control system is element of identification fault/failure.

Algorithms prevent the transition of the current situation in catastrophic are defined, and method of selecting the best alternative to continuation of flight based on intelligent technologies is considered. Thus, the proposed concept to recovering the survivability of aircraft in terms of fault/failure control surfaces or flight control system will maintain acceptable flight and technical characteristics and safe implementation flight task.

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Received 10 December 2012.

В.М. Казак[1], Д.О. Шевчук[2], С.В. Бугрик[3], Ю.Я. Смеречинський[4]. Вибір оптимального продовження польоту з використанням активної відмовостійкої системи
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Запропоновано метод вибору оптимального продовження польоту літака в умовах раптового виникнення особливої ситуації в польоті з використанням інтелектуальних технологій. Обґрунтовано алгоритми продовження польоту, що спрямовані на запобігання наслідків особливої ситуації.

Ключові слова: активна відмовостійка система, відмова, втрата керованості, керованість та стійкість, літак, несправність, несприятливі умови польоту, реконфігурація, система керування.

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Предложен метод выбора оптимального продолжения полета самолета в условиях внезапного возникновения особой ситуации в полете с использованием интеллектуальных технологий. Обоснованы алгоритмы продолжения полета, направленные на предотвращение последствий особой ситуации.

Ключевые слова: активная отказоустойчивая система, неблагоприятные условия полета, неисправность, отказ, потеря управляемости, реконфигурация, самолет, система управления, управляемость и устойчивость.

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