ARTICLE IN PRESS
JID: JARAP [m5G;August 4, 2016;20:36]

Annual Reviews in Control 000 (2016) 1–8

Contents lists available at ScienceDirect

Annual Reviews in Control

journal homepage: www.elsevier.com/locate/arcontrol

Full Length Article

Practical design considerations for successful industrial application of model-based fault detection techniques to aircraft systems

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ARTICLE INFO

Article history:
Received 11 December 2015
Revised 18 May 2016
Accepted 1 June 2016
Available online xxx

Keywords:
Model-based fault detection
Aircraft and flight systems
Flight tests
Abnormal control surface position

ABSTRACT

This paper discusses some key factors which may arise for successful application of model-based Fault Detection (FD) techniques to aircraft systems. The paper reports on the results and the lessons learned during flight V&V (Validation & Verification) activities, implementation in the A380 Flight Control Computer (FCC) and A380 flight tests at Airbus (Toulouse, France). The paper does not focus on new theoretical materials, but rather on a number of practical design considerations to provide viable technological solutions and mechanization schemes. The selected case studies are taken from past and on-going research actions between Airbus and the University of Bordeaux (France). One of the presented solutions has received final certification on new generation Airbus A350 aircraft and is flying (*first commercial flight: January 15, 2015*).

1. Introduction

1.1. Problem setting

Despite continuing improvements and insertion of new technologies, sustainable air transport will be a serious worldwide challenge given the anticipated increase in the traffic volumes and continuing expansion of the world's aviation network. By 2030, air traffic is expected to have doubled with a demand for several thousands of new passenger and freight aircraft. In a more crowded sky, one of the main issues for the development of future aircraft programs is to provide society with an air transport that leaves a smaller carbon footprint. In this context, new technological options are more and more needed to produce incrementally more efficient and environmentally friendlier aircraft. Robust and early detection of incipient faults that may have an influence on structural loads, has been identified as one of the contributing factors for the overall aircraft structural design optimization, and so for better performance in terms of fuel burn, noise, range and environmental footprint. The paper deals with three important failure cases related to the Electrical Flight Control System (EFCS) which are considered to be an important issue for achieving sustainability goals and for early system reconfiguration.

1.2. System description

For Airbus airplanes, the simplified functional bloc of servo-loop control of moving surfaces is depicted in Figs. 1 and 2 (Goupil, 2010, 2011). Here COM represents the command channel and MON is the monitoring channel in the Flight Control Computer (FCC). The COM channel is in charge of servo-loop computation. The MON channel ensures, mainly, the permanent real-time monitoring of the COM channel and of all the components of the flight control system (sensors, actuators, other computers, probes…).

Faults can be located in the servo-loop of the moving surfaces, between the FCC and the control surface, including these two elements. In the following, it is assumed that faults affect only one control surface.

1.3. Typical failure cases

1.3.1. Oscillatory failure case

Oscillatory failure Case (OFC) is an abnormal oscillation of a control surface due to component malfunction in control surface servo-loops. This signal, of unknown amplitude and frequency, can be propagated downstream the control loop to the control surface, and could excite the airplane structure producing structural loads (Fig. 1), see Goupil (2010). If OFCs of given amplitude cannot be detected and passivated in time, this amplitude must be considered for load computations. If the result of this computation falls outside the load envelope, then it is necessary to reinforce the

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http://dx.doi.org/10.1016/j.arcontrol.2016.07.003
1367-5788/

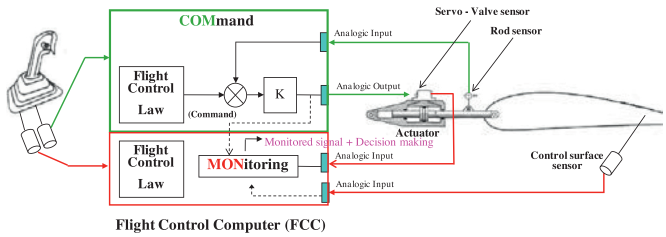

Fig. 1. Simplified block diagram of control surface servo-loop.

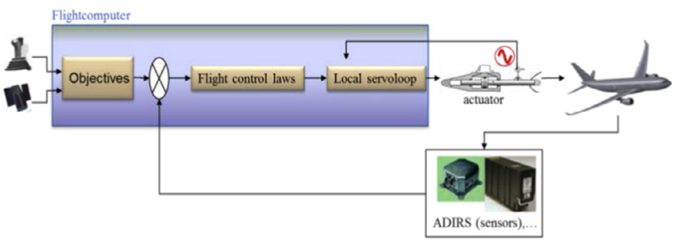

Fig. 2. Local servo-loops and global piloting loop.

structure. So, in order to avoid reinforcing the structure and consequently to save weight, low amplitude OFCs must be detectable at a very early stage. Note that because OFC is of unknown amplitude and frequency, and also because the time window allowed for its detection should be very short, classical methods (correlation-based, non-parametric methods) or dedicated nonlinear observer and adaptive identifier (Hou, 2005, 2007), or techniques reported in Bobstov, Efimov, Pyrkin, and Zolghadri (2012) on parametric estimation of harmonic signals cannot be applied.

1.3.2. Runaway

A runaway is an unwanted, or uncontrolled, control surface deflection that can go until the moving surface stops if it remains undetected. A runaway can have various dynamic profiles and is mainly due to an electronic component failure, mechanical breakage or FCC malfunctions. Low speed runaway results in an undesired pitch maneuver that may significantly degrade the aircraft controllability and that may increase the pilot workload. High speed runaways generally do not impact the aircraft trajectory but lead to additional loads that must be taken into account in the aircraft structural design objectives. The detection of the runaway must be accomplished before the control surface position exceeds a few degrees from its trimmed value. A detected runaway will first result in servo-control deactivation and then in system reconfiguration which means that there is a hand over between redundant actuators and between the FCC.

1.3.3. Jamming

A jamming, or lock-in-place failure, is a generic system-failure case which generates a stuck control surface at its current position. The jamming of an aircraft control surface creates an asymmetry in the aircraft configuration, which must be compensated by appropriate deflections of other control surfaces. A well-known negative effect of jamming is the resulting increased drag, which leads to increased fuel consumption since the remaining safe control surfaces stay permanently deflected. Increased fuel burn means an increased environmental footprint and a possible aircraft diversion in case of lack of fuel. For example, during a coordinated turn, if an elevator is jammed, the reaction of the aircraft is weaker and for compensation, more deflection will be demanded on the remaining elevators as well as on the Trimmable Horizontal Stabilizer. Due to the coupling with the roll axis, an additional asymmetrical deflection of the aileron will be required. In the case of landing with strong crosswind, a stuck rudder could prevent to correctly control the aircraft and to compensate the induced sideslip. Another example is when jamming occurs during a long time aircraft operation. In this case, a surface jamming may produce substantial drag and again excessive fuel consumption and can even obstruct the fulfilment of the flight mission (i.e., the need for landing on a diverting airport for refuelling). The paper focuses on the elevator runaway and jamming. The elevator setting controls the pitch angle, an important function especially during take-off and landing.

1.4. Current industrial practices for fault monitoring

The avionics of current-day aircraft is termed as modular integrated full glass cockpit. The systems are coupled with multi-function displays and communication units, multi-mode interactive instruments for control, guidance and navigation, fault management systems and health monitoring diagnostic capabilities. The state-of-practice to detect unexpected events and to obtain full flight envelope protection at all times is to provide high levels of hardware redundancy in order to ensure a sufficiently available control action. Fault monitoring is mainly performed by cross checks, consistency checks, voting mechanisms, and Built-In Test techniques (which include hardware sensors and software error correcting codes) of varying sophistication. Flight conditions-based thresholds, once validated with all the known delays and uncertainties in the signal propagation, are used for rapid recognition of out-of-tolerance conditions. Today, these standard techniques are implemented in all modern airplane systems, are the standard industrial practice, and fit into current industrial certification processes.

The basic method for OFC detection on board the A380 aircraft is reported in Goupil (2010). The residual is generated by comparing the real position y of the control surface with an estimated position produced by the nonlinear model in open-loop. The residual is decomposed in several spectral sub-bands. The OFC detection is performed, in each sub-band, by counting oscillations on the filtered residual. This consists in counting successive and alternate crossings of a given threshold. The failure amplitude that is detectable depends on the model quality. OFC can be detected by counting around zero alternate and successive crossings of the threshold for liquid failures and by counting around the opposite of the estimated position for solid failures. See Goupil (2010) for more details. This procedure is currently in service on all A380 airplanes. For the runaway case, the residual generation is done by comparing the signal delivered by the servo-valve sensor, which represents an image of the current command sent by the COM channel to the actuator, to a kind of theoretical current computed in the MON channel from the actual control surface deflection (generally sensed directly on the control surface by a dedicated sensor) and from the command computed with dedicated redundant sensors in the MON channel. The error signal is computed as follows:

$$\varepsilon = i_{COM} - i_{MON} = i_{COM} - K(u_{MON} - y_{MON})$$

where K is the servo-control gain, u_{MON} is the command computed in the MON channel and y_{MON} is the control surface position acquired in the MON channel (Fig. 1), i_{COM} is the command current directly sensed on the servo-valve.

The monitoring signal for jamming fault detection ε, at each sampling time k, is defined according to Zolghadri, Henry, Cieslak, Efimov, and Goupil (2014):

$$\varepsilon = |u - y| - |u|$$

where y represents the surface position given by the control surface sensor, and u is the command signal provided by the flight control law. Decision making corresponds to a threshold-based approach. Alarms are triggered when the signal resulting from the

Please cite this article as: A. Zolghadri et al., Practical design considerations for successful industrial application of model-based fault detection techniques to aircraft systems, Annual Reviews in Control (2016), http://dx.doi.org/10.1016/j.arcontrol.2016.07.003