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A Data-Driven Approach to Detect Faults in the Airbus Flight Control System

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Abstract: This paper presents a data-driven strategy for the detection of failures impacting the flight control system. Early and robust detection of Oscillatory Failure Case (OFC) allows the aircraft structural design to be optimized, which in turn helps improve the aircraft environmental footprint thanks to weight saving. Compared to existing model-based techniques already used on in-service Airbus aircraft, this paper studies a novel signal processing approach based on distance and correlation. It is shown that a mixed similarity index between Euclidean distance and logarithmic invariant divergence gives promising detection results. This paper details the proposed approach by insisting on practical constraints due to implementation in embedded real-time systems such as the flight control computer. Preliminary results obtained from a Verification & Validation (V&V) on-going campaign are presented.

Keywords: Aircraft, Flight Control, Fault Detection and Diagnosis, Oscillatory Fault Case

1. INTRODUCTION

The Electrical Flight Control System (EFCS, a.k.a. Fly-By-Wire – FBW) for large civil aircraft has established an industrial standard for modern 4th generation aircraft. Its main advantages include sophisticated control of the aircraft, flight envelope protection functions, pilot workload alleviation and weight saving [1]. For future aircraft, one of the challenges identified by the aeronautic sector is to achieve the long term goals of greener aviation [2]. In particular, even if it is not obvious at first sight, early and robust detection of EFCS faults that may have an influence on structural loads contribute to the overall optimization of aircraft structural design and thus contribute to weight saving. This is in line with the said sustainability objectives as e.g. less weight means less fuel consumption. So, the ability to detect these faults on time and at the required level is of primary interest when designing EFCS. This can be translated into investigating and developing appropriate Fault Detection and Isolation (FDI) techniques (called monitoring) to guarantee compliance with the environmentally-friendlier objectives. The main EFCS-failure cases of interest are: (i) Runaway (a.k.a. hard-over): an unwanted deflection of the control surface that can go until its stops if not detected; (ii) Jamming (a.k.a. lock-in-place): the control surface is stuck at its current position and it is no longer possible to control it correctly; (iii) Oscillatory Failure Case (OFC): a spurious sinusoidal signal propagates through the control loop and leads to an unwanted oscillation of the control surface. This is the fault case of interest addressed in this paper.

The industrial FDI state-of-practice used by all aircraft manufacturers to detect EFCS faults is to provide high levels of hardware redundancy in order to perform consistency tests, cross checks and built-in-tests of various sophistication [1]. This current approach fits well in the certification process and eases the design and analysis of the system. But to achieve more stringent objectives, i.e., to detect earlier smaller fault amplitudes, which in turn helps improve the aircraft environmental footprint, it is required to move from these present-day approaches to more advanced techniques. Model-based strategies have been significantly investigated in the past decade [3][4]. To the best of the authors' knowledge, signal processing strategies have been rarely investigated [5]. This paper proposes to consider data-driven approaches to detect OFC in EFCS, based on signal processing methods using signal distances and correlations.

This paper is organized as follows: Section 2 gives more details on OFC root cause and FDI requirements. Section 3 is devoted to model-based approaches dedicated to OFC detection. It also provides the main reasons to move toward signal processing techniques. Section 4 is dedicated to the proposed data-driven approaches. Section 5 deals with V&V activities performed to assess the robustness and performances of the proposed technique. Some concluding remarks and perspectives are finally reported in Section 6.

2. OFC CONTEXT AND FDI REQUIREMENTS

A typical Airbus Flight Control Computer (FCC) architecture is depicted in Figure 1. It consists of a dual channel scheme where the so-called "COM" (command) channel is dedicated mainly to the flight control law computation and to the control surface servo-loop. The so-called "MON" channel (monitoring) is primarily dedicated to the monitoring of all EFCS components. An OFC is an unwanted oscillating signal propagating within the control loop. It mostly comes from an electrical component in fault mode or is due to the breaking of a mechanical element. These fault sources are located between the FCC and the control surface, including these two elements. OFC signals are considered as sinusoidal signals with frequency uniformly distributed over a low frequency range (generally lower than 15 Hz). Their amplitudes are uniformly distributed. Beyond the upper frequency, OFCs have no

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significant effects because of the actuator low-pass behaviour. For structure-related system objectives, it is necessary to detect OFC beyond a given amplitude X in a given number of periods Y, for any OFC frequency. The detection time is expressed in period numbers, which means that, depending on the unknown failure frequency, the time really allowed for detection is not the same. Two kinds of OFCs have to be considered, namely "liquid" and "solid" failures. The liquid failure adds to the normal signal (inside the control loop) while the solid failure substitutes the normal signal (Figure 2). The OFC detection methodology must take into account the specificities of these two different cases.

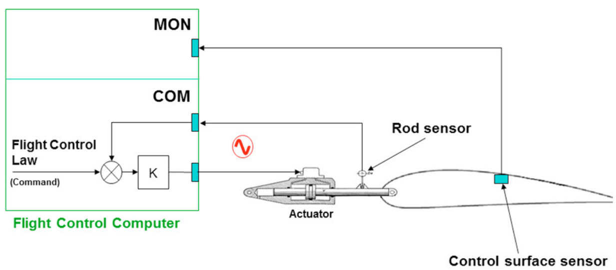

Figure 1: The Airbus COM/MON FCC architecture.

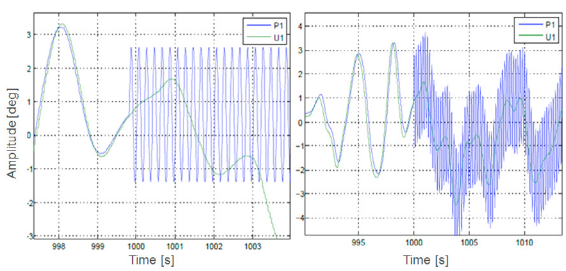

Figure 2: Solid (left) and liquid OFC (right) from t=1000s. U1 is the command signal, P1 is the control surface position.

To understand the link between OFC FDI and the aircraft weight saving, it should be noticed that an aircraft is a flexible body that has been sized to withstand a given load envelope. This is done by taking into account the effects of manoeuvers, wind gusts, turbulence and system faults during the aircraft design. If a small amplitude OFC occurs, an additional load is locally generated inside the design load envelope (green point in Figure 3). In this case, it is not required to dedicate FDI for this fault. However if an OFC with higher amplitude arises then the associated load can lie outside the design envelope (red point in Figure 3). It is then required to detect the fault quickly, before the load reaches a too high level. So, there is clearly a link between the minimum detectable amplitude and loads. More precisely, if a failure of a given amplitude cannot be detected, this amplitude must be considered for load computations. The result of this computation can lead to reinforce the structure, which de facto means increasing the aircraft weight. In order to avoid reinforcing the structure and consequently to save weight, low amplitude failure must be detected early enough.

Before the A380, Airbus aircraft are using basic signal processing techniques to detect OFCs. These solutions have been successfully validated and certified and provide a complete OFC coverage without false alarm in the EFCS.

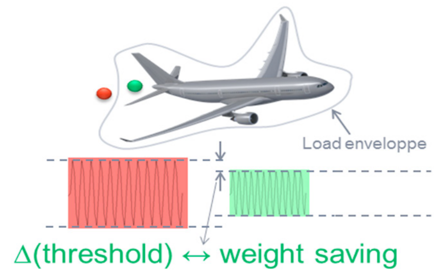

Figure 3: The red point shows a local augmentation of the structural load due to an OFC of too high amplitude.

3. MODEL-BASED APPROACHES

Primarily because of the use of new generation actuators and due to more stringent load requirements, it was not possible to equip the A380 with legacy OFC detection strategies. A basic model-based approach was developed to cover OFC detection on all primary control surfaces (ailerons, elevators and rudders) [6]. This analytical redundancy technique produces a fault indicator defined as the difference between the measured control surface position and an estimated position. A nonlinear hydraulic actuator model is used to estimate the position. In order to reduce the computational burden, some model parameters are fixed to their most probable value (e.g., hydraulic pressure, actuator damping coefficient, etc.). The decision making step consists of detecting the OFC signal within several spectral subbands by counting successive and alternate crossings of a given threshold (i.e., the fault amplitude to detect). This strategy is currently used on-board in-service A380. It provides full OFC detection coverage with very good robustness.

In order to improve this elementary model-based approach and to be compliant with more stringent load requirements (as well as a dedicated EFCS architecture), a joint parameter and state estimation technique has been developed on the A350 [7]. The online physical parameter estimation of the actuator model allows for parameter variations during aircraft flight and de facto improves the model accuracy. The estimation is done thanks to a modified version of an extended Kalman filter. A decision making-step similar to the one used in the A380 is kept. The whole strategy permits smaller fault amplitudes to be detected earlier.

These model-based techniques have been primarily investigated in particular because models were already available for other purposes (e.g. simulator development). They have proved their efficiency, viability and maturity through in-service use and have received certification on new generation Airbus A380 and A350 aircraft.

However, these approaches are still suffering from some drawbacks. Model-based residuals are always sensitive to modelling errors. A lot of techniques have been developed to compensate for these errors ([8] and references therein). But their performance often implies a complexity not compliant with real-time constraints. A strong modelling effort is also needed to get a model whose accuracy is compatible with good detection performance and reduced computational complexity. Several kinds of actuators are now used on-board a modern civil aircraft, such as the hydraulic conventional actuator or the Electro-Hydrostatic Actuator. It means that a model is needed