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A non-conservative H_-/H_∞ solution for early and robust fault diagnosis in aircraft control surface servo-loops ☆

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ABSTRACT

The presented work is undertaken within the FP7-ADDSAFE (Advanced Fault Diagnosis for Sustainable Flight Guidance and Control) project, a European collaborative project that aims to propose new fault diagnosis techniques for AIRBUS aircraft that could significantly advance the aircraft performance, e.g. by optimizing the aircraft structural design (weight saving) or decreasing its environmental footprint (e.g. less fuel consumption and noise). The paper discusses the design of a model-based fault detection scheme for robust and early detection of faults in aircraft control surfaces servo-loop. The proposed strategy consists of two fault detectors: The first fault detector is based on a H_-/H_∞ residual generator that maximizes sensitivity to any kind of control surface servo-loop faults whilst simultaneously minimizes the influence of unknown inputs. The second fault detector consists of a pure H_∞ residual generator that is sensitive to a restricted set of faults and robust to unknown inputs. By such a structured strategy, it is shown that it is possible to discriminate between different fault types occurring in the control surfaces servo-loop. Monte-Carlo campaigns from a highly representative simulator provided by AIRBUS as well as experimental results obtained on AIRBUS test facilities demonstrate the fault detection performance, robustness and viability of the proposed technique.

1. Introduction

Electrical flight control system (EFCS) fault detection performance is directly related to the aircraft structural design. Early and robust fault detection implies direct structural design improvements leading to weight saving and thus improvement of the overall aircraft's performance (fuel consumption, noise, range, environmental footprint). More recently, the introduction of electro-hydraulic actuators (EHA) on the A380 (Goupil, 2011) allowed for replacing the three conventional hydraulic circuitries by two hydraulic ones plus two electric layouts, and this saves one ton mass for the aircraft. In this context, a solution for structural design optimization consists of robust and early detection of the faults that may have an influence on structural loads. This appears to be highly related to aircraft sustainability goals: improving the performances of fault diagnosis in EFCS allows the aircraft manufacturer to optimize the aircraft structural design and to achieve weight saving, see the book (Zolghadri, Henry, Cieslak, Efimov, & Goupil, 2013). Typical EFCS-failure cases causing significant structural loads are runaway, jamming and oscillation of control surfaces. This paper aims at proposing a model-based method for fault detection of jamming and runaway events occurring in a control surface.

There exist numerous model-based fault detection and isolation (FDI) candidates in the literature that can be used for fault diagnosis in aircraft, see for instance the surveys (Blanke, Kinnaert, Lunze, & Staroswiecki, 2003; Chen & Patton, 1999; Ding, 2008; Gertler, 1998; Henry, 2011; Isermann, 2005a; Zolghadri et al., 2013). To name a few successfully applied approaches, one can refer to the oscillatory failure case (OFC). For instance a simple nonlinear model prediction with an OFC dedicated decision algorithm is used in Goupil (2010). Nonlinear observer based approaches are used in Alcorta-Garcia, Zolghadri, and Goupil (2011). Berdjag, Cieslak, and Zolghadri (2012) propose a strategy jointly using a fuzzy logic approach called "soft-voting" and a filtering approach based on the so-called "harmonic filter". The problem of elevator runaways is considered in Caglayan, Rahnamai, and Allen (1988) and in Gheorghe et al. (2013) where a Kalman-based approach is proposed to solve the problem. In Alwi and Edwards (2011) and Alwi, Edwards, and Marcos (2012), sliding mode observer schemes for actuator and sensor fault reconstruction are considered. For the actuator fault reconstruction scheme, the scheme involves a virtual system. In Vanek, Seiler, Bokor, and Balas (2011), a geometric-based approach is proposed to tackle the problem of control surface

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jamming or being disconnected from the actuator. Finally, H_∞ approaches are proposed in Marcos, Ganguli, and Balas (2005) and Mattei, Paviglianiti, and Scordamaglia (2005).

Among a large number of existing solutions, this paper focuses on candidate methods which offer the possibility of reuse (or building around it) with adequate design and tuning engineering tools. The H_∞ technique (see for instance Appleby, 1990; Edelmayer, Bokor, & Keviczky, 1994; Mangoubi, 1998) and its extension, the H_-/H_∞ technique (Henry & Zolghadri, 2005a, 2005b), could provide such a framework since:

- It offers tunable design parameters through the so-called shaping filters that allow the designer to specify the fault detection performance and thus to manage the trade-offs.
- It offers a reasonable computational burden since the final fault diagnosis scheme results in a simple LTI (linear time invariant) filter. It follows that the FDI scheme can be easily embedded within the structure of AIRBUS in-service monitoring systems as a part of the flight control computer (FCC) system.
- A systematic analysis procedure with formal proofs based on the so-called *"generalized structured singular value μ_g"* (see the precursor methodological work reported in Henry & Zolghadri, 2005a, 2005b) enables to check if all FDI objectives are achieved in the face of specified structured and/or unstructured model perturbations. The procedure involves a necessary and sufficient condition that takes into account the nature and the structure of the model perturbations and this enables to get a non-conservative H_-/H_∞ solution. The degree of conservativeness of the FDI design can then be quantified through this post-design analysis, allowing the user to get a clear idea on how the design trade-offs should be re-tuned to get as close as possible to the required FDI performance levels.

In this paper, the proposed strategy consists of two fault detectors: The first fault detector is based on a H_-/H_∞ residual generator that maximizes sensitivity performance to any kind of control surface servo-loop faults whilst simultaneously minimizes the influence of unknown inputs. The second fault detector consists of a pure H_∞ residual generator that is sensitive to a restricted set of faults and robust to unknown inputs. By such a structured strategy, it is shown that it is possible to identify the fault category. Monte-Carlo campaigns from a highly representative simulator provided by AIRBUS as well as experimental results obtained on AIRBUS test facilities demonstrate the fault detection performance, robustness and viability of the proposed technique.

The paper is organized as follows: Section 2 is devoted to modelling issues. Section 3 addresses the design of the FDI unit. Finally, Section 4 presents the simulation and experimental results.

1.1. Notations

The notations are those used in the majority of H_∞/μ literature. $\overline{\sigma}(A)/\underline{\sigma}(A)$ denote the maximum/minimum singular values of the matrix A. $\|w\|_2$ is used to denote the L_2-norm of the signal w. $P(s)$ or simply P is assumed to be in $\mathbb{R}H_\infty$, real rational function with $\|P\|_\infty = \sup_\omega \overline{\sigma}(P(j\omega)) < \infty$ ($\|P\|_\infty$ is also the largest gain of P). For LTI systems, $\|P\|_\infty$ is accompanied by the non-zero smallest gain of P, that is the H_- gain, which is the restriction of $\inf_\omega \underline{\sigma}(P(j\omega))$ to a finite frequency domain Ω, i.e. $\|P\|_- = \inf_{\omega\in\Omega}\underline{\sigma}(P(j\omega))$. The notation $P: \left[\begin{array}{c|c} A & B \\ \hline C & D \end{array}\right]$ is used to refer to the state-space model

$$P: \begin{cases} \dot{x} = Ax + Bu \\ y = Cx + Du. \end{cases}$$

Linear fractional representations (LFRs) are extensively used in the paper. For appropriately dimensioned matrices N and $M = \begin{pmatrix} M_{11} & M_{12} \\ M_{21} & M_{22} \end{pmatrix}$, the lower LFR is defined according to $F_l(M,N) = M_{11} + M_{12}N(I - M_{22}N)^{-1}M_{21}$ and the upper LFR according to $F_u(M,N) = M_{22} + M_{21}N(I - M_{11}N)^{-1}M_{12}$, under the assumption that the involved matrix inverses exist. This assumption is discussed in the paper when it is judged necessary. Otherwise, it is assumed to be satisfied. Consider a block structure $\underline{\Delta} = \text{diag}(\underline{\Delta}_J, \underline{\Delta}_K)$ so that $\underline{\Delta}_J = \{\text{blockdiag}(\delta_1^r I_{k_1}, \ldots, \delta_{m_{rJ}}^r I_{k_{m_{rJ}}}, \delta_1^c I_{k_{m_{rJ}+1}}, \ldots, \delta_{m_{cJ}}^c I_{k_{m_{rJ}+m_{cJ}}}, \Delta_{J1}^C, \ldots, \Delta_{Jm_{CJ}}^C)\}$ and $\underline{\Delta}_K = \{\text{blockdiag}(\Delta_{K1}^C, \ldots, \Delta_{Km_{CK}}^C)\}$ with $\delta^r \in \mathbb{R}, \delta^c \in \mathbb{C}, \Delta^C \in \mathbb{C}$ and consider a complex valued matrix $M = \begin{pmatrix} M_{JJ} & M_{JK} \\ M_{KJ} & M_{KK} \end{pmatrix}$ partitioned in accordance with $\underline{\Delta}$, which defines the closed-loop equations $z = Mv$, $v = \Delta z$, $z = (z_j^T\ z_k^T)^T$, $v = (v_j^T\ v_k^T)^T$, where Δ_J and Δ_K satisfy respectively a maximum norm constraint and a minimum gain constraint. Then, the μ_g-function is a positive real-valued function of the matrix M and the specified perturbation block $\underline{\Delta}$ defined by

$$\mu_{g\underline{\Delta}}(M) \triangleq \max_{\|v\|=1}\left\{\gamma : \begin{array}{l} \|v_j\|\gamma \le \|z_j\|, \ \forall j \in J \\ \|v_k\| \ge \|z_k\|\gamma, \ \forall k \in K \end{array}\right\}$$

and is defined on a domain $\text{dom}(\mu_g)$ given by $M \in \text{dom}(\mu_g)$ iff $M_{KK}v_K = 0 \Rightarrow v_K = 0$. The interested reader can refer to Henry, Zolghadri, Monsion, and Ygorra (2002) and Henry and Zolghadri (2005a) for more details about the μ_g function.

2. Modelling the aileron servo-loop

The failure scenarios investigated in this paper correspond to abnormal aircraft behaviours caused by an actuator or sensor failure in control surface servo-loops. More precisely, we investigate the cases of control surface jamming or being disconnected from its actuator on the roll axis, i.e. an aileron is stuck at a small deflection or disconnected from its actuator. Thus, the following developments focus on the ailerons but it is assumed that the proposed solution can be extended as it is, to other control surfaces. The control surface considered in this work is the left inboard aileron of a generic AIRBUS commercial aircraft.