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A Method for Actuator Lock-in-place Failure Detection in Aircraft Control Surface Servo-loops

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Abstract: This paper deals with a signal-based method for robust and early detection of lock-in-place failures (a.k.a. jamming) in aircraft control surface servo-loops. Early and robust detection of such failures is an important issue since they may cause additional structural load and affect the sustainability of civil transport airplane. The proposed signal-based scheme uses a sliding-mode differentiator to provide derivatives of measurable signals in noisy environment. Jamming events are next detected by using a dedicated decision making-rule that is able to detect actuator outage (the stuck value can be near zero). The proposed monitoring scheme has been tested on Airbus test facilities located at Toulouse, France. The results confirm good level of robustness and performance, even in extreme situations. The proposed technique can be applied, with slight modifications, to any type of actuator, *e.g*. Hydraulic, Electro-Hydrostatic (EHA) or Electro-Backup-Hydrostatic (EBHA) actuators. *Copyright © 2014 IFAC*

Keywords: Fault Detection, Fault Diagnosis, Lock-in-place failure, Actuator fault, Flight control

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1. INTRODUCTION

The required technological advances which have been identified by the aeronautics sector to achieve the long term goals of greener aviation are multiples and challenging. For future civil aviation, new technological options will be needed to produce incrementally more efficient and environmentally friendlier aircraft. In this general context, early and robust diagnosis (Zolghadri *et al.*, 2013; Efimov *et al.*, 2013) of faults that have an influence on structural loads (Besch *et al.*, 1996) could contribute to the aircraft structural design optimization. Fast detection of such failures, while keeping at the same time the current robustness level, allows the designers to save weight by avoiding structure reinforcement and so improve the overall aircraft performance in terms of fuel burn, noise, range and environmental footprint (Goupil *et al.*, 2013).

The paper deals with a challenging Electrical Flight Control System (EFCS) failure case which may affect structural load: the jamming (a.k.a. lock-in-place failure) of aircraft control surfaces. A jamming is a system-failure case where the control surface is stuck at its current position, see Fig 1. The consequence of a lock-in place failure in an aircraft control surface is a dissymmetry in the aircraft configuration, which must be accommodated by using the other available control surfaces. The result is an increased drag, which leads to increased fuel consumption since the remaining safe control surfaces stay permanently deflected. Increased fuel burn means an increased carbon footprint and a possible aircraft diversion in case of a lack of fuel. For instance, if a jamming occurs during a long time aircraft operation, substantial drag and again excessive fuel consumption may be produced, and they can even call into question the fulfilment of the initial flight mission (*i.e.*, involving a landing on a diverting airport for refuelling in case of a sufficiently high deflection jamming). Therefore, a timely detection of jamming, especially of the primary control surfaces (e.g., elevator, rudder, ailerons), is of primary interest for both an economical and easy-to-handle operation of an aircraft.

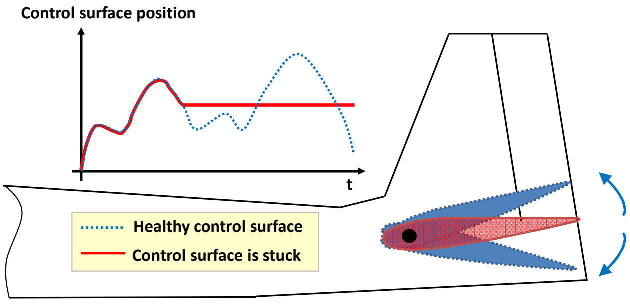

Fig. 1: Lock-in-place failure in control surface position

2. ANTECEDENTS AND CONTRIBUTION

2.1 *State-of-practice*

A typical Airbus Flight Control Computer (FCC) architecture is composed of two separate channels according to Fig. 2: a command channel (COM) and a monitoring channel (MON). The COM channel is mainly devoted to flight control law computation and the servo-control of moving surfaces. The MON channel is in charge of the permanent real-time monitoring of the COM channel and all components of the EFCS (sensors, actuators, other computers). As it can be seen in Fig. 2, each channel receives a dedicated control surface or actuator position, thanks to dedicated sensors.

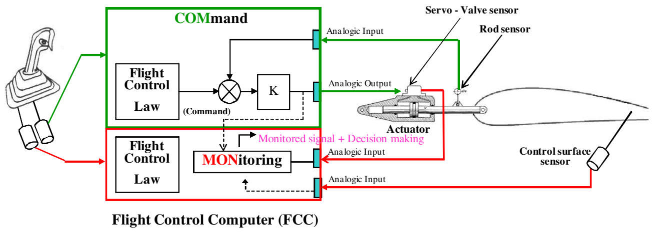

Fig. 2: Command and monitoring channels in Airbus FCC

The current industrial practice for control surface jamming detection can be divided into two steps: residual generation and residual evaluation. The residual is computed according to (Goupil, 2011; Zolghadri *et al.*, 2013)

$$r = |u - y| - |u|, \tag{1}$$

where y represents the position given by the control surface sensor (see Fig. 2) and u is the command signal (called pilot order in the following) provided by the flight control law.

The decision making-rule corresponds to a threshold-based approach given in Fig. 3. Alarms are triggered when the signal computed in (1) exceeds a given threshold during a given time window called confirmation time. By setting the pair (threshold and confirmation time), the classical tradeoff in Fault Detection and Diagnosis (FDD) must be made between the false alarm rate, missed detection rate and the detection time performance.

This technique ensures the highest level of safety imposed by the current certification process, and provides sufficient fault detection without false alarms.

2.2 *Need for improvement*

It is clear that any modification of the above existing in-service and already proven technical solutions should be motivated by a real industrial need. The main reason for improvement is related to the fact that the applicability of hardware redundancy-based fault detection is becoming increasingly problematic under growing requirements towards the future greener and easier-to-handle aircraft. From load point of view, aircraft certification is obtained when it is proven that the structure complies with the dedicated regulations. As composite materials are used more and more, this involves also reduced structural loads on the aircraft. Consequently, the improvement of the current monitoring techniques is becoming a challenging issue to decrease the minimal detectable control surface jamming position, while keeping a good level of robustness.

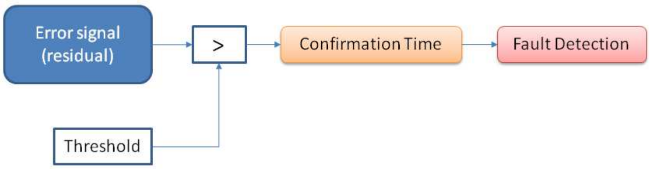

Fig. 3: Threshold-based approach for decision making

The above arguments motivate the research for innovating approaches for control surface jamming detection at lowest amplitudes and in less confirmation time. However, one should have in mind a number of important industrial constraints, among others:

- Low computational load;
- The possibility of coding using a restricted symbol library to make feasible implementation in the FCC;
- Restricted tuning complexity since the technique is to be used by non-specialist operators;
- The detection technique should be easily adaptable for other type of actuator, for example Hydraulic, Electro-Hydrostatic (EHA) and Electro-Backup-Hydrostatic (EBHA).

2.3 *Related works and contribution*

Detection of actuator jammings has been reported in several recent works. In (Varga, 2007), the design of residual generators with least dynamical orders is addressed for a Boeing 747-100/200 aircraft. A steady-state-based approach is proposed in (Yang *et al.*, 2010). This approach, developed in a linear setup, can be used to detect small actuator stuck faults including actuator outage (the stuck value is equal zero). It is a point of great importance since these small stuck faults, especially the outage ones, are often difficult to be efficiently detected. To take into account the wide operation range of an aircraft, some papers are based on the use of multiple linear models (Kim *et al.*, 2008; Heredia *et al.*, 2008; Li & Yang., 2012). In this context, a bank of parallel observers designed by eigenstructure assignment is proposed in (Wang *et al.*, 2007) to generate fault-dependant residual signals. Lock-in-place fault can also be estimated by means of the fuzzy adaptive observer given in (Zheng *et al.*, 2009; Lo *et al.*, 2009), linear parameter varying techniques (Hecker *et al.*, 2011; Vanek *et al.*, 2011; Henry *et al.*, 2012, 2014; Varga and Ossmann., 2014) or Kalman filter (Rupp *et al.*, 2005; Han *et al.*, 2009). Finally, a dedicated Kalman filter is introduced between residual generation and decision-making blocks in (Gheorghe *et al.*, 2013). Based on a nonlinear model of the actuator, the authors provide guidelines to tune the dedicated Kalman filter in a FDD purpose. Results obtained on Airbus test facility show an improvement with respect to current industrial techniques. However, for a stuck near to zero, the fault may go undetected.

The paper presents a signal-based strategy for early and robust detection of control surface jammings of any magnitude, even near zero. Robustness and performance of the proposed approach are assessed using a high fidelity Airbus benchmark, real flight data and the System Integration Bench (SIB)[1]. As it will be seen, the proposed solution could be a good and technologically viable candidate for detection of a lock-in-place failure in control surface servo-loops.

The remainder of the paper is organised as follows. Section 3 is devoted to the proposed signal-based scheme and Section 4 presents the validation of the proposed solution on Airbus test facilities.

3. PROPOSED SIGNAL-BASED STRATEGY

The proposed monitoring strategy is based on two successive steps. The first step consists mainly in estimating on-line derivatives of the pilot order *u* and the control surface position *y*. In the second step, the signals derived from the first stage are evaluated using a dedicated decision making-rule to diagnose researched jamming events.

3.1 Signal-based differentiation and filtering

The block diagram of the overall strategy is depicted in Fig. 4. Two signals are provided to the dedicated decision making-rule. According to Fig. 4, these signals are filtered by a filter F_1 and a Sliding Mode Differentiator (SMD). The role of each filtering block will be explained in the following. The main filtering block is the SMD block. SMD corresponds, in its basic form, to the first-order sliding mode differentiator of (Levant, 2003). This can be also replaced by the non-homogeneous differentiation algorithm reported in (Efimov and Fridman, 2011). For the sake of simplicity, only the basic differentiation algorithm is considered in the following. SMD is used to provide robust derivative estimates with a low computational load. The main advantages of this differentiator are its robustness against measurement noise, finite-time convergence and the fact that the accuracy of the derivative estimates can be evaluated. It is given by

$$SMD:\begin{cases}\dot{z}_0 = -\alpha_0\sqrt{|z_0-\zeta|}\times sign(z_0-\zeta)+z_1 & (2)\\ \dot{z}_1 = -\alpha_1 sign(z_0-\zeta) & (3)\end{cases}$$

where $z_0 \in R$, $z_1 \in R$ are the state variables of the differentiator. α_0 and α_1 are the tuning parameters. ζ is the input signal of SMD that can be defined according to

$$\zeta(t) = \zeta_0(t) + v(t) \tag{4}$$

with ζ_0 is the noise-free signal that is corrupted by a bounded noise $v: R \to [-\lambda_0, \lambda_0]$, $0 < \lambda_0 < +\infty$. By using the first-order differentiator (2)-(3), the variable z_1 is an estimate of the desired noise-free signal derivate $\dot{\zeta}_0$ with an accuracy that can be computed by using the following developments.

According to (4), the system (2)-(3) is discontinuous and affected by the disturbance v. Introducing variables $e_0 = z_0 - \zeta_0$, $e_1 = z_1 - \dot{\zeta}_0$, the system (2)-(3) can be rewritten as follows:

$$\dot{e}_0 = -\alpha_0\sqrt{|e_0|}sign[e_0] + e_1 + \delta_0 \tag{5a}$$

$$\dot{e}_1 = -\gamma\, sign[e_0] + \delta_1 , \tag{5b}$$

where $\delta_0 = \alpha_0(\sqrt{|e_0|}sign[e_0] - \sqrt{|e_0 - v|}sign(e_0 - v))$ and $\delta_1 = \alpha_1\big(sign(e_0) - sign(e_0 - v)\big)$ are the disturbances generated by the presence of noise v. $\gamma = \alpha_1 + \ddot{\zeta}_0\, sign[e_0]$ is a strictly positive piecewise continuous function if the parameter α_0 and α_1 are selected according to (Levant, 2003), *i.e.*

$$\alpha_0 = 1.5L^{1/2},\ \alpha_1 = 1.1L \tag{6}$$

with $|\ddot{\zeta}_0| \le L$. Since $|v| \le \lambda_0$, it follows that $|\delta_0| \le \alpha_0\sqrt{2\lambda_0}$, $\delta_1 = 0$ for $|e_0| \ge \lambda_0$, $|\delta_1| \le 2\alpha_1$ and $\delta_1 e_0 \ge 0$ for all $t \in R$. Hence, the accuracy of derivatives in noisy environment is given by the following theorem.

Theorem 1. (Levant, 2003) *Let* ζ_0 *be continuously differentiable,* $|\ddot{\zeta}_0(t)| \le L$ *and* $|v(t)| \le \lambda_0$ *for all* $t \ge 0$*. Then, there exist* $0 \le T < +\infty$ *and some constants* $c_0 > 0$, $c_1 > 0$ *(dependent on* α_0 *and* α_1 *only) such that for all* $t \ge T$ *:*

$$|z_0 - \zeta_0| \le c_0\lambda_0^{0.5},\ |z_1 - \dot{\zeta}_0| \le c_1\lambda_0^{0.25}. \qquad \blacksquare$$

The result of Theorem 1 states that the estimate z_1 of the derivative $\dot{\zeta}_0$ is corrupted by an error bounded by $\lambda_0^{0.25}$ due to noisy environment.

Remark 1: Based on the available physical knowledge of the actuator type (hydraulic, EHA or EBHA), the signal ζ (the input of sliding-mode differentiator) can be processed through appropriates filters with an appropriate cutting frequency in order to improve the accuracy of signal derivatives. It is desirable to choose linear-phase filters so as to introduce no deformation on signals which will be processed by the differentiator.

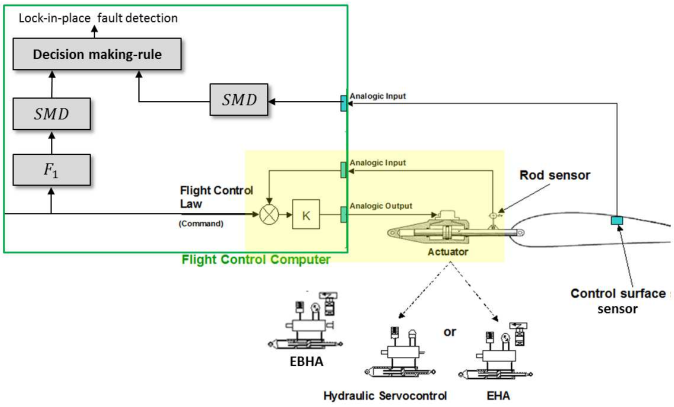

Fig. 4: Proposed FDD scheme in aircraft control surface

The filter F_1 is introduced to model the dynamics of the servo-controlled loop, between the pilot order *u* and the control surface position signal *y*, taking into account the delay of this closed loop. Its stationary gain is equal to 1 and its parameters are tuned to model the dynamic response of the servo-loop. Here, F_1 is a second-order discretized filter defined according to

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[1] Airbus bench is located at Toulouse, France.

$$F_1(z) = \frac{K_1 T + (z-1)K_2}{K_1 T + (z-1)(z-1+K_2)} z^{-d} \qquad (7)$$

where K_1 and K_2 are the tuning parameters, T is the sample time, and d is the delay between the pilot input and the controlled surface position. The delay can be estimated, using a real input-output dataset and a correlation analysis (Ljung, 2007). The parameters K_1 and K_2 can be optimized using a model-matching-based process (Gheorghe *et al.*, 2013). The process consists in optimizing the filter parameters in such a way that the difference between the output of the filter and the measured surface position is minimized, that is

$$(\hat{K}_1, \hat{K}_2) = \arg\min_{K_1, K_2} \left\| y\big|_{K_a, \Delta P, F_{aero}} - y_{F_1}(K_1, K_2) \right\|_l$$

where y_{F_1} is the output signal of filter F_1. K_1 and K_2 are the tuning parameters of a second-order filter for F_1 and y is the measured surface position in different operating situations involving variations of actuator parameters. For an electro-hydraulic actuator, for example, these parameters are damping coefficient K_a, hydraulic pressure ΔP and aerodynamic forces F_{aero}.

3.2 Evaluation rule

The evaluation rule is depicted in Fig. 5. The inputs are the derivatives of pre-filtered pilot order $\dot{u}$ and control surface position $\dot{y}$. Differentiated signal $\dot{u}$ is filtered through a Finite Impulse Response (FIR) filter of appropriate order, depending on the type of the actuator. The process of confirmation time (see section 2.2) will thus start when:

- C1: the average of $\dot{u}$ is greater than a threshold σ_2;
- C2: the value of $\dot{y}$ is lower than a threshold σ_1.

A RS flip-flop is next introduced to realize a hysteresis phenomenon in such a way that an alarm is triggered if the requirements C2 is valid during all of the confirmation time in order to be robust against the "stall load" effect (healthy jamming). Thresholds σ_1, σ_2 and the confirmation time are empirically determined to achieve a good robustness (no false alarm) of the FDD scheme on the available data sets.

4. VALIDATION ON AIRBUS TEST FACILITIES

The approach proposed in the previous section has been intensively tested and validated according to the V-cycle (Goupil & Marcos, 2012). The case of a hydraulic elevator stuck has been primary investigated to assess the potential of the proposed solution. Firstly, simulations are performed using a representative Airbus benchmark[2]. Secondly, robustness is assessed using real datasets recorded during two flight tests. The in-flight recorded data come from an Airbus A380 elevator with very fast dynamics. The proposed approach is next coded in a specific graphic language to make possible its implementation in the FCC. The industrial evaluation is next done using the SIB offering the possibility to do hardware-in-the-loop simulations with a flight actuator test bench of A380 airplane as the one presented in Fig. 6. The test bench is built around a real control surface actuator with simulated command inputs, aerodynamic forces and hydraulic pressures. This bench offers also the possibility to validate the designed system in degraded configurations, as in the case of low hydraulic pressure and high loads on the control surface.

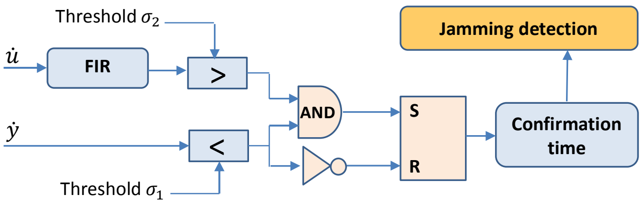

Fig. 5: Dedicated decision making rule

4.1 AIRBUS benchmark results

The benchmark is developed within Matlab/Simulink environment. It includes aerodynamic, engine, atmospheric, actuator and gravity models with a conventional autopilot. The case of an elevator stuck at the null position (0 degree) is considered when the aircraft nose points upward. Fig. 7 shows the simulation results for a jamming occurred at *t*=5 [s]. According to the results summarized in the colored parts of Table 1 (Goupil *et al.*, 2013), the proposed scheme presents an improvement since elevator lock-in-place at 0 degree is detected. It can be however noticed that this fault remains undetected until there is a maneuver. From practical point of view, this situation is acceptable since a control surface stuck at the good position does not add additional structural load on aircraft structure.

4.2 Real data sets

The robustness of the proposed scheme is assessed by using two in-flight recorded datasets (around 10 hours of flight). By an appropriate tuning of the thresholds σ_1, σ_2 and the confirmation time in an empiric manner, the detection system achieves a perfect robustness (no false alarm).

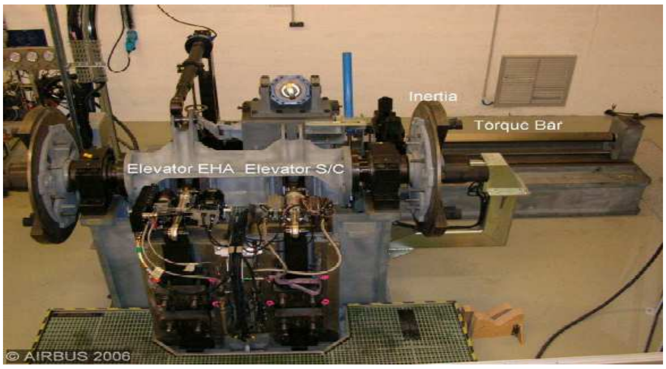

Fig. 6: Airbus actuator test bench

Performance level in terms of detection is now evaluated. The same simulation campaign performed in (Gheorghe *et*

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[2] This benchmark has been developed within the European ADDSAFE project.

al., 2013) for the jamming detection has been made. As summarized in Table 1 (normalized results for industrial reasons), small actuator stuck faults including actuator outage (the stuck value is equal zero) can be detected by the proposed approach. It is clearly an improvement. Moreover, the detection time is also smaller than the two others approaches for all considered jamming cases.

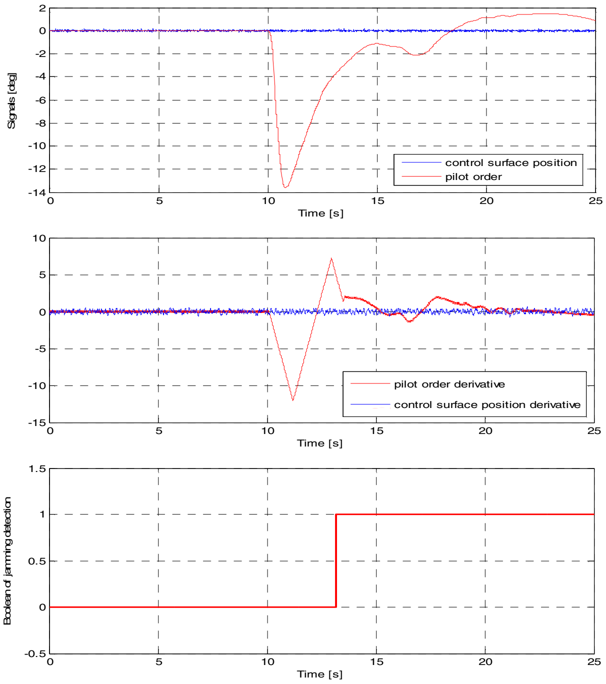

Fig. 7: Benchmark results

Table 1. Detection performance for the jamming failure case on a A380 elevator

Position of surfaces jammings	**State-of-practice**	**With a Kalman filter** (Gheorghe *et al.*, 2013)	**Proposed monitoring scheme**
Up deflection		**DTI**	**DTI**
		DTI	**DTI**
		DTI	**DTI**
		DTI	**DTI**
	ND		**DTI**
	ND		**DTI**
	ND	**ND**	
	ND	**ND**	
	ND		**DTI**
	ND		**DTI**
		DTI	**DTI**
		DTI	**DTI**
		DTI	**DTI**
Down deflection		**DTI**	**DTI**

ND: No detection, **DTI**: Detection Time Improvement compared to left column

4.3 System Integration Bench

Before making any tests on the SIB, it is necessary to implement the overall detection algorithm in the FCC by using a limited set of graphical symbols (adder, filter, integrator, look-up tables, *etc*.). This process permits to describe each part of the algorithm in dedicated "functional specification sheets". Then, an automatic generation tool produces the code to be directly implemented and the computational load of the developed scheme can be evaluated by using the execution time of each symbol. It follows that the strategy uses at most 6.5% of the computing cost allowed for the jamming case, or 0.21% of the total CPU in case of ADDSAFE project problem definition. Note that this strategy is higher of 0.18% of CPU load with regard to the Kalman solution given in (Gheorghe *et al.*, 2013) but provides a better coverage for jamming fault cases. In spite of this slight increase, the proposed scheme is thus considered as a viable solution from industrial point of view since its computational load stays lower than 2% of CPU.

The robustness and detection performance of the detection system method have been validated during severe simulation campaigns. Here, some experimental results coming from the SIB are presented. The first step consists in assessing the robustness of the detection system approach by applying rich dynamics on pilot order like varying frequency sinusoidal signal (top of Fig. 8), signal generated by up and down manipulations of the sidestick (bottom of Fig. 8). The results are satisfactory since there is no false alarm for all tests.

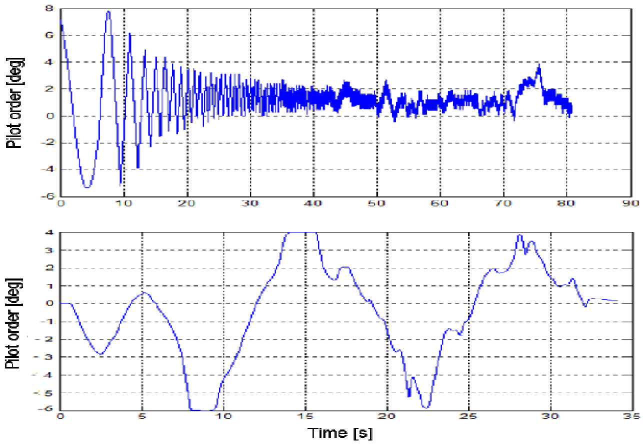

Fig. 8: Pilot order generated to assess the robustness

Detection performance is finally evaluated on the SIB. Several experiments have been performed. For example, Fig. 9 shows the experimental results when the actuator test bench is stuck at the null position (0 degree). In this case, the fault occurs at t=0 [s]. As it can be seen, the lock-in-place failure is detected at t=3.72 [s]. Note that all experiments confirm also the results given in Table 1.

5. CONCLUSION

The problem studied in this paper is that of designing a fault detection system for robust and early detection of aircraft control surface lock-in-place failures. A great effort has been made to bridge the gap between scientific methods advocated by academia and industrial needs. More precisely, the proposed technique is a signal-based one that can be applied, with slight modifications, to any type of actuators (an accurate modelling of actuator is not mandatory). The basic element is a sliding mode differentiator to provide efficient derivatives. Experimental results obtained from aircraft test bench confirm the good level of robustness and performance that can be obtained, even when the jamming occurs around zero position of the control surface. Further investigations are necessary to provide an algorithm for differentiator tuning that is able to improve the convergence time without degraded the accuracy level in a fixed sample time environment. This is the topic of our current research. Assessment of FDD scheme will be also investigated for electro-hydrostatic and electro-backup-hydrostatic actuators.

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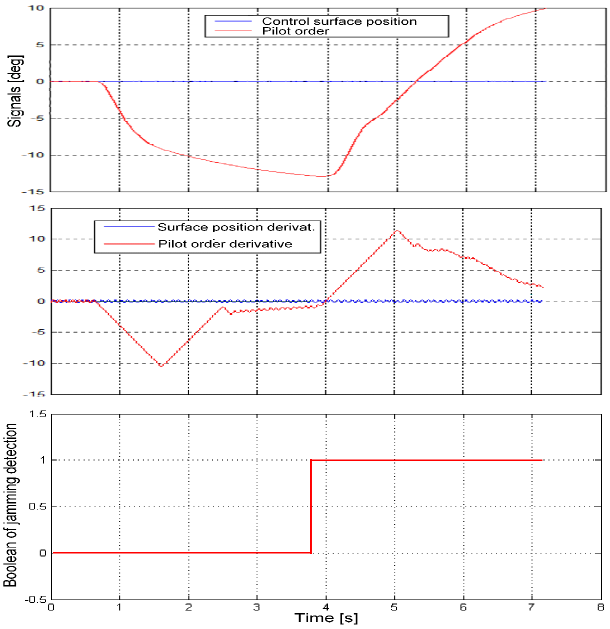

Fig. 9: Experimental results coming from the SIB