8th IFAC Symposium on Fault Detection,
Supervision and Safety of Technical Processes (SAFEPROCESS)
August 29-31, 2012. Mexico City, Mexico

Assessment on the ADDSAFE Benchmark Simulator of an H-infinity Fault Detection Design for Aircraft

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Abstract: In this article the verification assessment of an aircraft fault detection and diagnosis (FDD) scheme based on H-infinity is presented. The proposed scheme is designed to detect abnormal aircraft behaviour, specifically aileron faults leading to degradation of performance. The design follows a global approach based on an H_∞ FDD filter residual generator augmented with simple threshold and time-based logic for residual evaluation. The design development and verification is part of a European 7th Framework Program project entitled "Advanced Fault Diagnosis for Sustainable Flight Guidance and Control (ADDSAFE)". The verification results show that the proposed FDD scheme satisfies the demanding performance and robustness metrics established for on-board aircraft assessment by the ADDSAFE industrial partners.

Keywords: Aerospace Engineering, Flight Control, Fault Diagnosis, Validation, European Project.

1. INTRODUCTION

Current industrial practices [1] for fault detection and diagnosis (FDD) are perfectly developed and certified to ensure satisfaction of the strict commercial and civil regulations. The state-of-practice consists mainly in consistency checks between redundant signals computed in different Flight Control Computers (FCC). The consistency checks are based on threshold monitoring where the difference between both signals is used to determine whether an abnormal situation has occurred.

In order to address the "sustainable" aircraft of the future (i.e. More Affordable, Smarter, Cleaner and Quieter –as stated by the European Commission Vision 2020 objectives [2]), an European Union 7th Framework Program project named "Advanced Fault Diagnosis for Sustainable Flight Guidance and Control (ADDSAFE)" [3,4] was established in July 2009. The overall aim of ADDSAFE was to contribute to aircraft structural design and performance optimization thanks to the use of model-based Fault Detection and Diagnosis (FDD) techniques in the Flight Control System (FCS). For example, it can be demonstrated that improving the FCC FDD allows to optimize the aircraft structural design resulting in weight saving –which in turn helps improve aircraft performance and to decrease its environmental footprint.

Within the ADDSAFE benchmark [3,4,5], one of the relevant fault scenarios concerns the detection of an abnormal aircraft behaviour leading to the degradation of the aircraft performance. More precisely, the case of a control surface jamming on the roll axis is defined, i.e. an aileron stuck at a fixed deflection.

In this article a global FDD approach is proposed and assessed using the industrial verification tools from ADDSAFE. The approach is based on an H_∞ FDD filter residual generator and a simple logic for residual evaluation. The advantage of the proposed global design is that with straight forward residual evaluation (in essence, adding time-based conditions and thresholds) full detection coverage for all the ailerons can be achieved without requiring independent FDD designs for each aileron (which increases wiring and hardware complexity).

The layout of the article is as follows. Section 2 provides details on the ADDSAFE project and its objectives. Section 3 presents the project verification and validation (V&V) process and its associated tools and metrics while Section 4 describes the selected fault scenario. Section 5 presents the FDD scheme and Section 6 summarizes the verification results with the conclusions given in Section 7.

2. ADDSAFE PROJECT

A consortium of European industrial partners (Airbus and Deimos Space), research establishments (DLR, SZTAKI and IMS-CNRS) and Universities (Delft, Leicester and Hull) has been established with funding from the European Union 7th Framework Program with the goal of examining and demonstrating the potential industrialization of modern model-based fault detection and diagnosis methods for its application to commercial aircraft. The project, led by Deimos Space, is entitled "Advanced Fault Diagnosis for Sustainable Flight Guidance and Control (ADDSAFE)" and started in July 2009 with a duration of three-years [3,4].

The importance of the studies carried out within the project arises, on the one hand, due to the representativeness of the benchmark proposed by Airbus [4,5], which consists of a generic civil aircraft model and realistic fault scenarios, and on the other hand, the industrial validation of the more promising designs in the actual Airbus flight control system Verification & Validation (V&V) process.

Airbus and Deimos as industrial partners are in charge of benchmarking, verifying and validating the designs in addition to defining the benchmark (Airbus) and providing the functional engineering simulator (Deimos) based on Airbus benchmark. The rest of the teams (also including Deimos as a full R&D partner) are tasked with studying, developing and applying selected model-based FDD techniques to the benchmark. Initially, the project aimed at assessing the 2 most promising designs. However, the vast majority of the FDD designs submitted by the consortium presented very encouraging results and a very low computational load. So, it was decided to test the 5 most promising designs [4].

3. V&V PROCESS, TOOLS AND METRICS

A key step for the successful transfer to the aeronautics practitioners of the developed FDD methods is their demonstration on standardized industrial V&V processes. The proposed validation in ADDSAFE follows a two-step process: first, an industrial software assessment tool is used for verification and secondly, validation on physical aircraft rigs is performed [3, 4].

This two-steps process allows performing a stringent V&V campaign exploring the whole flight domain, for a wide class of pilot inputs and taking into account perturbations and uncertainties (e.g. aerodynamics). It also allows using the state-of-the-art industrial validation on real test facilities for the selected FDD designs.

In this article, the focus is on the assessment stage performed by each design team prior to submission of their design for the industrial V&V. This internal assessment, as well as the first step of the industrial V&V, uses the so-called functional engineering simulators (FES) which are detailed in the next sub-section 3.1. These simulators implement quantitative metrics established to provide a numerical evaluation of the designs' performance and robustness –see subsection 3.2.

3.1 Functional Engineering Simulator

The Functional Engineering Simulator (FES), developed by Deimos Space S.L.U. for the ADDSAFE project, is a non-real-time simulator based on Simulink, Matlab and XML that includes Airbus aircraft benchmark as well as robustness and performances analysis tools for all the fault scenarios defined in the project [3,4,5]. The FES is not currently part of the Airbus industrial V-cycle [4]. However, it would be located towards the end of the development phase, between the simulation code generation and the implementation of the code in the equipment.

The FES is a term used in Space to describe a software simulator describing at a functional level the components of a system (including its operating environment). FES are used in support of the specification, design, verification and operations of space systems, and can be used across the spacecraft development life-cycle, including activities such as system design validation, software verification & validation, spacecraft unit and sub-system test activities [6, 7].

Two FES packages have been developed within ADDSAFE. One serves for simulation and verification (Sim&Ver-FES) and is released to all partners for their use during the development and application of the FDD methods. The second package is used for the industrial benchmarking and validation (Bench&Val-FES), which is performed by the industrial partners at the end of the design cycle. This later FES includes more sophisticated tools for multi-team FDD designs' benchmarking.

The Sim&Ver-FES includes a parametric campaign utility that allows each design team to assess the performance and robustness of their designs prior to their submission for the industrial V&V. The parametric campaign implies random variation within the benchmark defined ranges, of the main aircraft geometric parameters (mass and x-position of the aircraft centre of gravity Xcg), the flight parameters (altitude, calibrated-airspeed V_{CAS}) and also of the uncertainty in the measurements (Δ_{mass}, Δ_{Xcg}, $\Delta_{altitude}$, Δ_{Vcas}) and aerodynamic coefficients (Δ_{CX}, Δ_{CY}, Δ_{CZ}, Δ_{Cl}, Δ_{Cm}, Δ_{Cn}).

3.2 Quantitative and Qualitative Assessment Criteria

Quantitative and qualitative criteria are used within the ADDSAFE project to evaluate and compare the FDD designs during the industrial validation phase [4].

The quantitative component is given by metrics and a cost function which is automatically calculated by the FES for each FDD design based on parametric or Monte Carlo campaigns. The qualitative evaluation (based on Airbus FDD design and V&V teams' experience) is used to assess the designs practical implementation and relevance for industrial use. The main quantitative metrics used by the FES are:

- Detection Time Performance (DTP), defined as the ratio between the time from fault injection to its detection over the maximum allowed time for detection.
- The False Alarm (FA) rate, computed as the percentage ratio of the total number of cases yielding a false alarm n_{FA} over the total number of Monte-Carlo runs n_{MC}.
- The Missed Detection (MD) rate, computed as the percentage ratio of MD cases n_{MD} with respect to n_{MC}.

Statistics of the DTP metric, such as average, minimum, maximum and variance values are calculated but the most important, from the industrial point of view and for assessment purposes, is its maximum value –corresponding to the worst case.

A normalized cost function is computed, based on a metrics' weight performance (WP) and weight criticality (WC). The WP and WC reflect respectively satisfaction level per metric (dependent on the FDD system characteristic) and the metric criticality (independent of the FDD system, fixed by the industrial requirements). If a FDD design is strictly compliant with Airbus requirements, then it scores a WP equal to 3.

4. FAULT SCENARIO

The specific failure scenario contemplated in this article concerns the detection of an abnormal aircraft behaviour leading to the degradation of the aircraft performance. This abnormal configuration is caused by an actuator or a sensor failure in the control loop of a control surface, between the Flight Control Computer (FCC) and the moving surface, including these two elements, see Figure 1. Consequently, only one control surface is impacted.

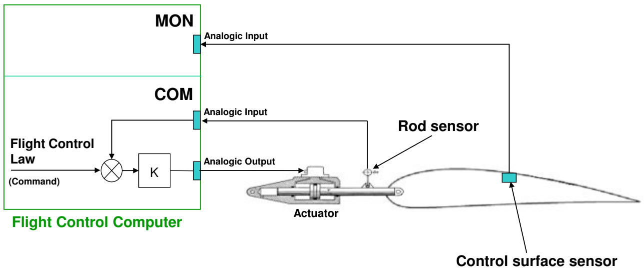

Figure 1 Actuator and sensor localization in the control loop

More precisely, the case of an aileron stuck at a fixed deflection is considered. The reaction of the aircraft to this dissymmetry is a deflection of other ailerons, or possibly other control surfaces like the rudder, leading to an increase of drag proportional to the amplitude and to the origin of the failure (Figure 2). If this non-optimized configuration remains undetected during a significant time it could result in fuel overconsumption. The failure root cause could be for instance a sensor bias: e.g. the actuator rod is servo-controlled at 0 degree but an undetected bias on the position sensor leads to an unwanted deflection of an unknown amplitude, proportional to the bias.

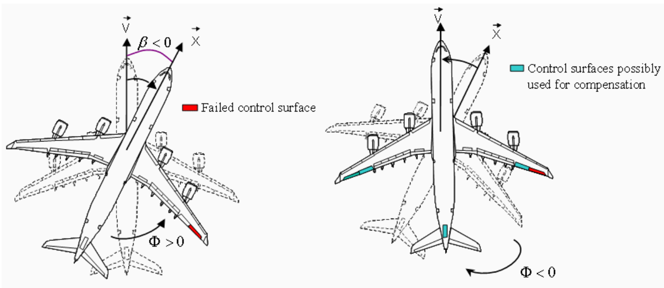

Figure 2 Effect of aileron jamming and potential control surfaces used for compensation

The simulated scenario is a jamming of the left inboard aileron at a fixed small deflection during a cruise flight phase. Three different cases are proposed:

S1.1 "Liquid" jamming, i.e. an additive bias occurs on the rod sensor (the control surface is still under control);

S1.2 "Solid" jamming, which means that the control surface is stuck at a fixed position. This is strictly speaking the real case of a control surface jamming (any upstream command has no effect as the control surface is physically jammed);

S1.3 Aileron disconnection: physical disconnection between the control surface and the actuator rod. However, the rod sensor works correctly.

The overall FDD requirement is to detect the aileron jamming in order to perform a system reconfiguration on the healthy adjacent actuator or to make the pilots aware of the situation. The proposed designs must be compliant with industrial requirements such as real-time implementation constraints. In particular for this failure case, there is no immediate consequence, thus a relatively long time (in the order of minutes as opposed to seconds) is acceptable to detect and confirm the failure.

5. FAULT DETECTION AND DIAGNOSIS SCHEME

A global FDD approach is proposed based on an H_∞ FDD filter (residual generation) for detecting left-inboard-aileron (ALI) and left-outboard-aileron (ALO) faults, augmented with simple logic (residual evaluation) for the isolation of faults between the ALI and right-inboard-aileron (ARI).

The advantage of the proposed global design is that with straight forward residual evaluation (in essence, adding logic-based conditions and thresholds) full detection coverage for all the ailerons can be achieved without requiring independent designs (which increase wiring and hardware complexity). Additionally, since the proposed design looks at the flight mechanics behaviour of the aircraft it can be easily carried over to other families of aircraft with minor tuning. On the other hand, a disadvantage of a global design is that its robustness against different manoeuvres must be ensured. But it is noted that any local design must be equally tested for these cases if it relies on any global measurement (e.g. an aircraft attitude parameter, such as roll rate, or aerodynamic force estimator).

The methodology used to arrive to the final global design is:

Step 1: System and fault scenario analysis

1.1. Assess the nonlinear system behaviour using a single nominal simulation per no-fault and fault cases (a total of 9 simulations) and the most pertinent available measurements (states, sensors and actuators). The intention is to quickly determine which input/output/states carry the most information for the purposes of FDD design.

1.2. Assess the linear system behaviour examining the linear time invariant (LTI) variability in terms of eigenvalues for a wide range of flight conditions throughout the flight envelope. The intention is to select a flight condition for design or the need to develop more complex models, e.g. linear parameter varying (LPV).

Step 2: Residual Generation

2.1. Define the *for-design* LTI plant using the selected input/output/states and flight condition. This just entails trimming and linearizing the nonlinear system at the chosen flight condition.

2.2. Define the H_∞ FDD interconnection based on the above LTI plant and FDD objectives. The proposed set-up is very general, i.e. applicable to any aircraft family, and facilitates the following sub-step by

2.3. Define the optimization weights. This is really the main residual generation tuning stage. The first two groups of weights, sensor and actuator, are used for robustness purposes and are based on 1st/2nd order approximations of the actual models. The last two groups of weights, fault and residual, are used for performance purposes and are the real tuning knobs used by the designer. The weight tuning uses initially the same nonlinear simulation cases as in step 1 and then a tuning set consisting of 25 random simulations.

Step 3: Residual Evaluation

3.1. Analyze the residuals for the no-fault cases using the above tuning set. Since in the ADDSAFE benchmark there are 6 (longitudinal and lateral/directional) manoeuvres a total of 25*6=150 simulations are used.

3.2. Analyze the residual for the fault cases using the same tuning set but applied to each of the three types of faults (S1.1, S1.2, S1.3) and the 6 manoeuvres. In total there are 25*3*6=450 simulations.

3.3. Implement threshold and condition/time-based residual evaluation logic. The previous analyses will guide the engineer in the implementation of a, as simple as possible, logic assessed using the above 600 runs.

Step 4: Verification

4.1. Assess the FDD robustness and performance using a verification set (all the pertinent parametric cases from the Benchmark & Verification FES: 1 parametric campaign per each no-fault/fault case under the different manoeuvres).

4.2. Tune the residual evaluation logic, and if necessary re-design starting again from step 2.

The residual generation (Step 2) is based on the H-infinity approach and after Step 1 the definition of the *for-design* LTI plant (step 2.1) is guided by the selection of a cruise-flight condition in the middle of the flight envelope using all the aileron commands and the states/measurements corresponding to the lateral/directional aircraft motion. The defined synthesis interconnection (step 2.2) is given in Fig.3 and consists of 6 components: the LTI plant ("Plant"), sensor and actuator models ("sensors" and "actuators"), a distribution matrix ("K") and the two design tuning knobs ("Wfa" and "Wres").

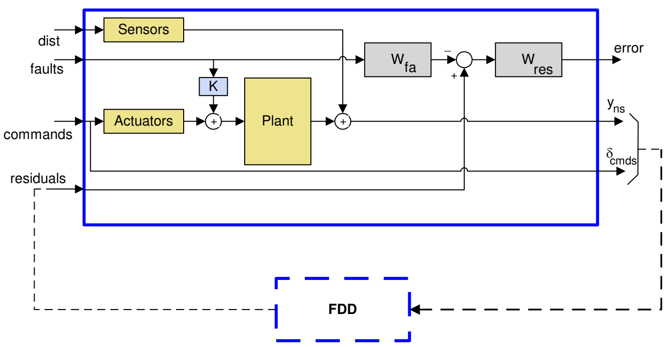

Figure 3 FDD H∞ design interconnection

The selection process of the "K", "sensor" and "actuator" models is based mainly on the information we have on the system and thus has no real difficulty. The "K" distribution matrix is just used to adequately introduce the fault signals into the proper actuator channels, while the "sensor" and "actuator" models are based on constant or 1st order simplifications of the models from Airbus.

To facilitate the tuning and the comprehension of the "Wfa" and "Wres" weights, a generic first-order transfer function model is used, see Eq. 4, where the low-frequency gain is given by $K_{LF}=K$, the high-frequency gain by $K_{HF}=Ka/b$ and the bandwidth by $\omega_B= K_{LF}/b= K_{HF}/a$.

$$W = K\frac{as+1}{bs+1} = K_{LF}\frac{K_{HF}/\omega_B\, s+1}{K_{LF}/\omega_B\, s+1} \qquad \text{Eq. 1}$$

To start their design process it is noted that since the faults considered (disconnection, solid jamming and liquid jamming) act for all the ailerons in the same manner, the "Wfa" for the ALI and the ALO can be initially considered to be the same and if necessary tuned afterwards. Similarly, "Wres" for each of the two channels can be considered the same since we desire similar performance in the detection. Thus, we only have to modify two transfer functions by using the parameters K_{LF}, K_{HF} and ω_B for each of them following some general rules:

– The speed of detection and the fault frequency range of action can be modified using ω_B respectively in "Wres" and "Wfa".

– The low-frequency gain K_{LF} of "Wres" and "Wfa" can be used to satisfy the gamma level < 1 (which indicates satisfaction of objectives) and to tune the residuals magnitude response to faults.

The tuning is guided by analyzing the transfer functions of the FDD but principally by the time response of the FDD when subjected to the nonlinear simulations set used in the nonlinear assessment (step2.3). After a few trials and errors, the final weights are obtained.

Once the residual generator has been designed it is analyzed to assess its robustness and performance characteristics (Step2.3). As it is always the case in a practical implementation, some type of residual evaluation logic is necessary (Step 3). In this case, the evaluation of the residual indicated a simple logic base rule supported by static thresholds and time-based rules was sufficient.

The final scheme, composed of the H-infinity filter (residual generation) and the threshold/time-based logic (residual evaluation) components, was implemented following Airbus special Simulink library [4] and evaluated (Step 4).

6. FDD SCHEME ASSESSMENT

The assessment performed by the design team uses the Simulation & Verification FES option "PARAM", which allows setting up automated fault and no-fault scenarios sweeping through the benchmark parameters ranges. Note that the "PARAM" option sweeps through a specific combination of the parameters yielding 324 different simulations per scenario, of which only 158 are valid (i.e. within the acceptable flight envelope and aircraft limitations). A total of 3792 random simulations are used formed by:

- 158 different flight conditions (mass, XCG, VCAS, altitude, Δ_{mass}, Δ_{Xcg}, Δ_{Vcas}, $\Delta_{altitude}$, Δ_{aero}) spread throughout the flight envelope
- 6 different flight manoeuvres for the no-fault cases: cruise, pitch-protection1, nose-up, AoA-protection1, yaw-angle-mode and turn-coordination2.
- 18 manoeuvres/fault cases formed by combining:
  - 3 manoeuvres (cruise, yaw-angle-mode and turn-coordination).
  - 3 types of faults (S1.1, S1.2, S1.3) in the left-inboard (ALI) and right-inboard (ARI) ailerons

Table 1 presents the resulting statistics (false alarm rate FA, missed detection rate MD, and min/mean/max DTP). The DTP values are normalized with respect to the maximum allowed detection time in order to respect proprietary concerns. Observe that no false alarms appear and that no missed detection occur (these are the two most critical metrics, with the former the utmost one). Looking at the detection times it is noted that the maximum values, which are the most critical [4], are all well within the limit (i.e. DTP_{max}<<1) and that for most of the cases (i.e. looking at the mean statistics) the FDD scheme performs even much better.

Indeed, this design obtained excellent industrial verification marks [4] and was selected as one of the 5 designs to be carried over to Airbus industrial validation cycle.

Table 1 DEIMOS preliminary FDD design: assessment results

Info			Rates (%)		Normalized DTP		
Set		# runs	FA	MD	Min	Mean	Max
TOTAL		3792	0	0	0.016	0.084	0.388
ALI	S1.1	316	0	0	0.220	0.226	0.377
	S1.2	316	0	0	0.061	0.211	0.264
	S1.3	316	0	0	0.016	0.029	0.213
ARI	S1.1	316	0	0	0.119	0.230	0.388
	S1.2	316	0	0	0.174	0.212	0.272
	S1.3	316	0	0	0.024	0.045	0.215
No fault		1896	0	--	--	--	--

In the following plots, the residual and system/controller responses are given for a representative set of PARAM simulations (the figures contain the full 158 valid runs).

Figure 4 and Figure 5 show respectively the FDD residual signals (from the H_∞ filter) and the system and controller responses for the PARAM set corresponding to a left-inboard-aileron disconnection during cruise flight. Again, all axes are normalized to respect proprietary concerns except those of the residuals which are not related to the fault size.

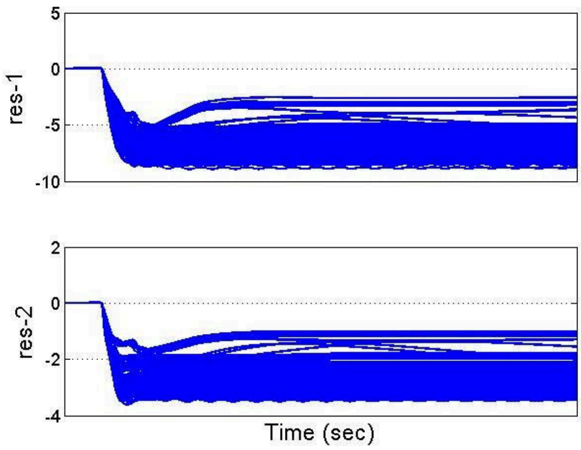

Figure 4 Residuals responses: Cruise, ALI, S1.3

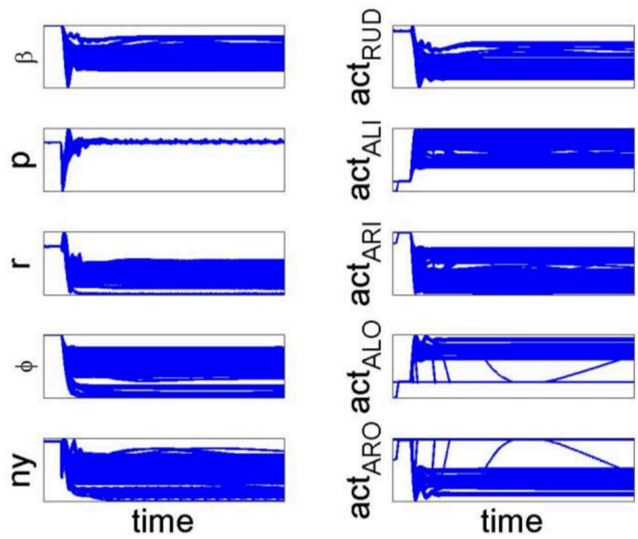

Figure 5 System and control responses: Cruise, ALI, S1.3

Similarly, each pair of figures from Figure 6 to Figure 9 show the residual, system and controller responses for respectively a turn-coordinated manoeuvre undergoing a solid jamming fault in the left-inboard-aileron and a yaw-angle manoeuvre undergoing a liquid jamming fault in the right-inboard-aileron.

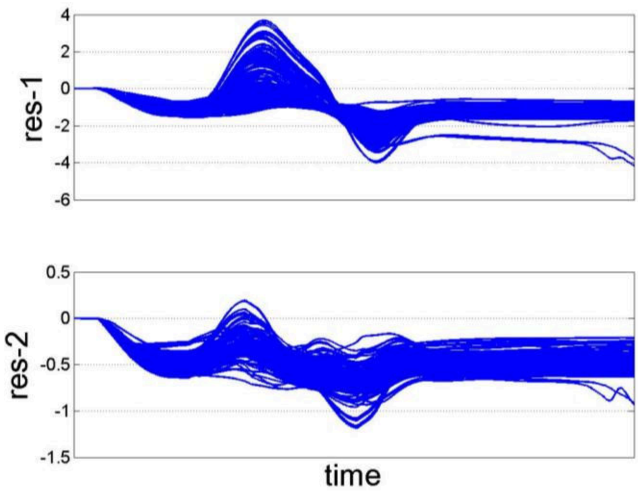

Figure 6 Residuals responses: Turn-Coord., ALI, S1.2

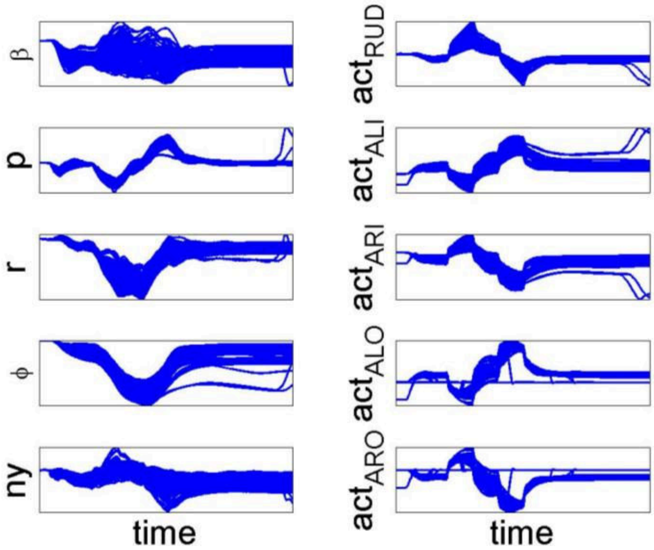

Figure 7 System and control responses: Turn-Coord., ALI, S1.2

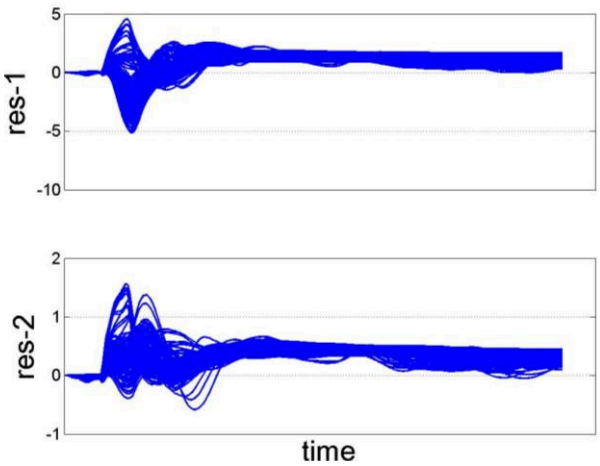

Figure 8 Residuals responses: Yaw-Angle, ARI, S1.1

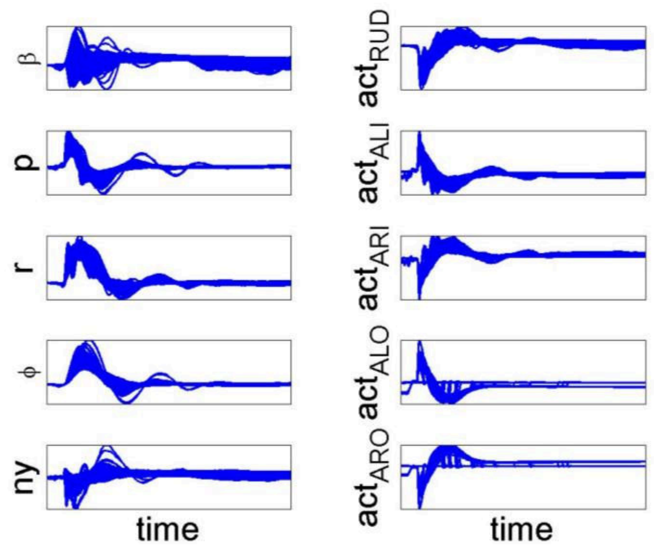

Figure 9 System and control responses: Yaw-Angle, ARI, S1.1

It can be seen in all the figures that the controller responses are quite different depending on the type of faults, compare for example the right plots in Figure 5 with those from Figure 7 or Figure 9. Similarly, looking at the left plots of the mentioned figures, it can be observed also that the manoeuvres results in a quite different dynamical response of the aircraft which indicates the challenging scenarios faced by the FDD design.

7. CONCLUSIONS

In this article the verification results of an FDD scheme has been presented. The FDD scheme is capable of detecting abnormal aircraft behaviour leading to performance loss, which is epitomized by solid/liquid jamming or disconnection faults in the left-inboard (ALI) and right-inboard (ARI) ailerons.

The approach used is global, meaning that it uses aircraft measurements and controller commands as opposed to specific inputs/output measurements of a subsystem component. This has the advantage of facilitating its application to other aircraft. The scheme is composed of a residual generator based on H_∞ optimization and a logic-based residual evaluation

The resulting global FDD design is shown to be capable of satisfying the established false alarm, missed detection and time-to-detect requirements set forth in the ADDSAFE project, not only for the default manoeuvre scenario (cruise and left-inboard-aileron) but also for the more challenging scenarios composed of lateral/directional manoeuvres under the defined aileron faults.

ACKNOWLEDGMENTS

This work was performed in the framework of the European ADDSAFE Project: Grant agreement №: FP7-233815.

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