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Application of H-infinity fault diagnosis to ADDSAFE benchmark: the control surface jamming case

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In this article the H_∞ fault detection and diagnosis technique is applied to a representative twin-engine civil commercial aircraft. The specific failure scenario contemplated concerns the detection of an abnormal aircraft behavior 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 and the moving surface, including these two elements. The definition of the aircraft benchmark, model and fault problematic, and the development and application of the FDD technique application is part of a European Framework Programme project named Advanced Fault Diagnosis for Sustainable Flight Guidance and Control. The results, including nonlinear time domain simulations in the closed-loop functional engineering simulator, show the promising performance and robustness of the proposed solution.

I. Introduction

Current industrial practices[1] for control surface jamming detection consists mainly in consistency checks between redundant signals computed in two different Flight Control Computer (FCC) channels. These consistency checks are based on threshold monitoring where the difference between both signals is used to determine whether an abnormal situation has occurred –for example, if the difference is greater than a given threshold during a given time the detection is confirmed. This approach is perfectly valid for current aircraft and ensures the highly restrictive regulations related to commercial aircraft.

Nevertheless, for the envisioned "sustainable" aircraft of the future (i.e. More Affordable, Safer, Cleaner and Quieter –as stated by the European Commission Vision 2020 objectives[2]), the applicability of the current state of practice is becoming increasingly problematic. Highlighting the link between aircraft sustainability and fault detection, it can be demonstrated for example that improving the fault diagnosis performance in flight control systems allows to optimize the aircraft structural design resulting in weight saving –which in turn helps improve aircraft performance and to decrease its environmental footprint. Similarly, for the specific case of control surface jamming, the reaction of the aircraft to such a dissymmetry is a deflection of other control surfaces to compensate the aircraft attitude leading to an increase of drag proportional to the amplitude and to the origin of the failure. If this dissymmetry remains during a significant time it could generate fuel overconsumption and result in violation of aircraft regulations such as ETOPS (an acronym for Extended-range Twin-engine Operational Performance Standards) as well as an increase in aircraft pollution.

It is thus required to re-examine the current state of practice and possibly develop novel fault detection and diagnosis (FDD) methods that will ensure the current highest levels of aircraft safety while allowing implementation of the advanced green and efficient aircraft technologies currently being considered. Towards this goal, a consortium of European industrial partners, research establishments and Universities has been established with funding from the European Union 7th Framework Program (FP7). The aim of the project, named Advanced Fault Diagnosis for Sustainable Flight Guidance and Control (ADDSAFE[3]), is to research and develop model-based FDD methods for aircraft flight control systems faults, predominantly sensor and actuator malfunctions.

Within the ADDSAFE FDD benchmark[4], one of the relevant fault scenarios concerns the detection of an abnormal aircraft behavior leading to the degradation of the aircraft performance. This abnormal configuration is caused by an actuator and/or sensor failure within the control loop of a control surface –in exactitude, between the FCC and the moving surface, including these two elements. Consequently, the scenario considers that only one

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control surface is impacted. More precisely, the case of a control surface jamming on the roll axis is defined for ADDSAFE: an aileron stuck at a fixed deflection. Of course, this fault scenario is already addressed and solved at the highest safety standards by current (hardware-based) industrial practices. Nevertheless, as mentioned before, any improvement on the fault detection capability or any recourse to less hardware-based FDD methods will have a direct impact on the aircraft structure, performance and environment footprint and thus it is considered as a significant scenario to apply any of the model-based FDD techniques being contemplated in ADDSAFE.

H_∞-based optimization methods were developed during the 80s and attracted much attention due to their explicit consideration of robustness[5,6]. In H_∞ FDD optimization[7,8], the different fault detection and diagnosis performance indexes are optimized with respect to the generated fault residual based on two main design goals: minimization of the influence of non-fault signals (noise, disturbances, uncertainties, commands) and maximization of the effects of the faults. These goals are often contradictory since usually a trade-off is required between the residual sensitiveness to faults and its robustness to non-faults. Among other advantages, H_∞ approaches have a well-known and methodological algorithmic solution –that relies on the use of state-space linear time invariant (LTI) models— and use a standard problem formulation. Furthermore, H_∞ FDD has been applied in the last 5 years to aircraft at different levels of technology readiness, from high-fidelity simulators[9,10] to actual flight tests in research aircraft[10]. Thus, the next logical step to transfer H_∞ FDD techniques to industry is to apply them to a relevant aircraft system from within an industrially valid verification and validation (V&V) process.

This article presents preliminary results on the solution proposed by Deimos to the specific ADDSAFE fault scenario of control surface jamming. The layout of the paper is as follows. Section II presents the ADDSAFE project, while Section II summarily presents the ADDSAFE benchmark (the aircraft model and the selected fault problematic) and the functional engineering simulator (FES) that encapsulates the previous for benchmarking of the designs. Section IV covers the theoretical and methodological aspects of H_∞ FDD synthesis while also discussing practical algorithmic and implementation issues. Finally, section V and VI presents the results and conclusions.

II. The ADDSAFE project

A consortium (see Figure 1) of European industrial partners, research establishments and Universities 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 is named Advanced Fault Diagnosis for Sustainable Flight Guidance and Control (ADDSAFE) and started in July 2009 with a planned duration of three-years.

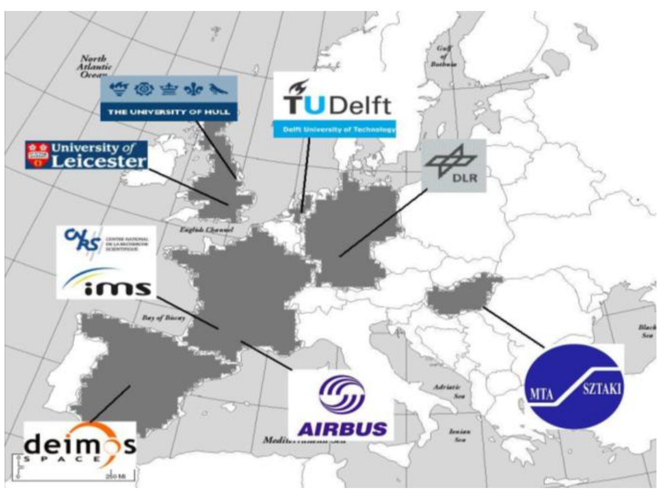

Figure 1 ADDSAFE consortium

The main challenges faced by the project are:

1. To help the research/academic community to develop the best suited FDD methods capable of handling the real-world problems faced in the aircraft guidance and control (G&C) diagnosis.

2. To ensure acceptance and widespread use of these advanced theoretical methods by the aircraft industry.

3. To contribute towards reducing the aircraft development and maintenance costs by using model-based diagnostic systems in conjunction with reliable software V&V tools.

The importance of the studies performed within the project arises due to the industrial representativeness of the benchmark, i.e. the aircraft model and fault problematic. Moreover, the final goal of the project is to validate the more promising designs in the actual Airbus' flight control system V&V cycle: covering from high-fidelity simulation models to the Iron Bird, and including real aircraft actuator rigs –which will ensure industry-wide acceptance of the results.

From a technological and scientific perspective the main objectives of the project are: (i) Identification of a set of guidelines for aircraft G&C FDD design and analysis; (ii) Improved FDD methods and understanding of their applicability to aircraft FDD; (iii) A step towards a V&V process for aircraft advanced diagnostic systems; and (iv) Demonstration of the most promising model-based FDD designs on industrial state-of-art flight simulation platform. For further information on the project and its objectives refer to[3].

Airbus and Deimos as industrial partners are in charge of benchmarking 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 (including Deimos as full research partner) are tasked with studying, developing and applying selected model-based FDD techniques to the benchmark. Each design team must provide two FDD designs, applicable to any of the fault scenarios, for benchmarking at Deimos premises. Two of these designs, selected based on the previous benchmarking, will be further matured for their validation in the actual Airbus' V&V cycle at Airbus premises at Toulouse (France).

III. The ADDSAFE Benchmark and simulation validation tools

The FDD benchmark[4] to be addressed in ADDSAFE includes the aircraft model development as well as the fault scenario definition. The benchmark is then implementation as a functional engineering simulator (FES) that will serve as the basis for the design teams' testing and the industrial benchmarking of the resulting FDD designs.

A. Airbus benchmark: aircraft nonlinear simulation model

The aircraft simulation model is highly representative of a generic twin-engine civil commercial aircraft flight physics and handling qualities, including the nonlinear rigid-body aircraft model with a full set of control surfaces, actuator models, sensor models, Flight Control Laws (FCL) and pilot inputs. It allows exploring the whole flight domain considering a wide class of pilot inputs and wind perturbations.

The aircraft benchmark model is graphically depicted by the representation of Figure 2, which showcases its five main components. The available pilot inputs are: the side stick (longitudinal and lateral inputs), the pedals, the high-lift configuration lever (slats and flaps), the airbrakes and the throttle lever. The current benchmark deals with manual control (so autopilot guidance laws are not included) but for better maneuver management, the auto-thrust control law is kept since it is useful for managing the trust and maintaining constant speed. Regarding manual laws, as the goal of the project is not to study failure reconfiguration all the unusual control laws are removed. Except for these points, all the other elements of the aircraft inboard computer are kept.

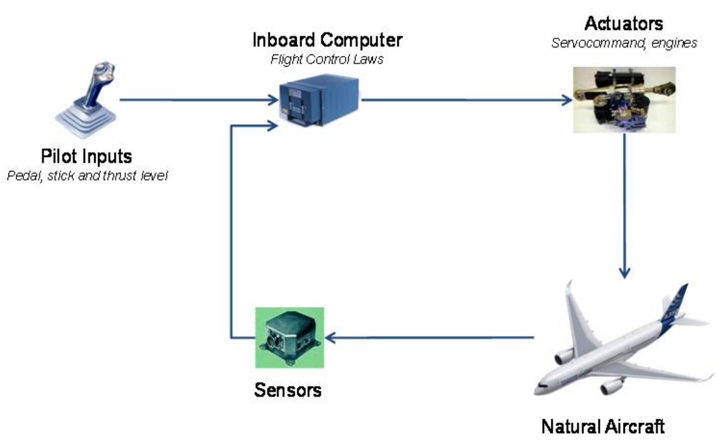

Figure 2 Closed-loop aircraft model main components[4]

The actuator component is based on three elements: the actuator model itself, a control surface position saturation that could be dissymmetric and a rate limiter representing the physical limitations. The input to the actuator model is commanded actuator position (output of the FCL computation) while the output is the realized actuator position. The actuator model describes the physical behavior of the actuator rod speed in function of the hydraulic pressure delivered to the actuator and in function of the forces applied on the control surface and reacted by the actuator[4]. Although it is termed an actuator model, it should be noted that the modeling covers the control loop, between the Flight Control Computer (FCC) and the control surface, including these two elements. As ADDSAFE does not aim at studying failure reconfiguration, only one actuator is simulated per control surface (no adjacent redundant actuator).

Flight mechanics modeling is based on the so-called fundamental principle of dynamics. In the ADDSAFE aircraft model, both a quaternion system and a Euler angle formulation are used. The flight mechanics include the main forces and moments acting on the aircraft: aerodynamic effects, gravity and engine thrust.

An Integrated Sensor Model (ISM) allows simulating very accurately all sensors involved. A plethora of information is needed and integrated in the model: sensor characteristics (location, noise, filter...), calibration data, aerodynamic coefficients, flight mechanics equations, system requirements (e.g. delays), etc. This model is thus very complex and will not be detailed here due to confidentiality reasons. Both the actuator and sensor models include specific blocks for failure scenario simulations.

B. Airbus benchmark: control surface jamming fault scenario

The specific failure scenario contemplated in this article concerns the detection of an abnormal aircraft behavior 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. Consequently, only one control surface is impacted.

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 3). If this dissymmetry 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.

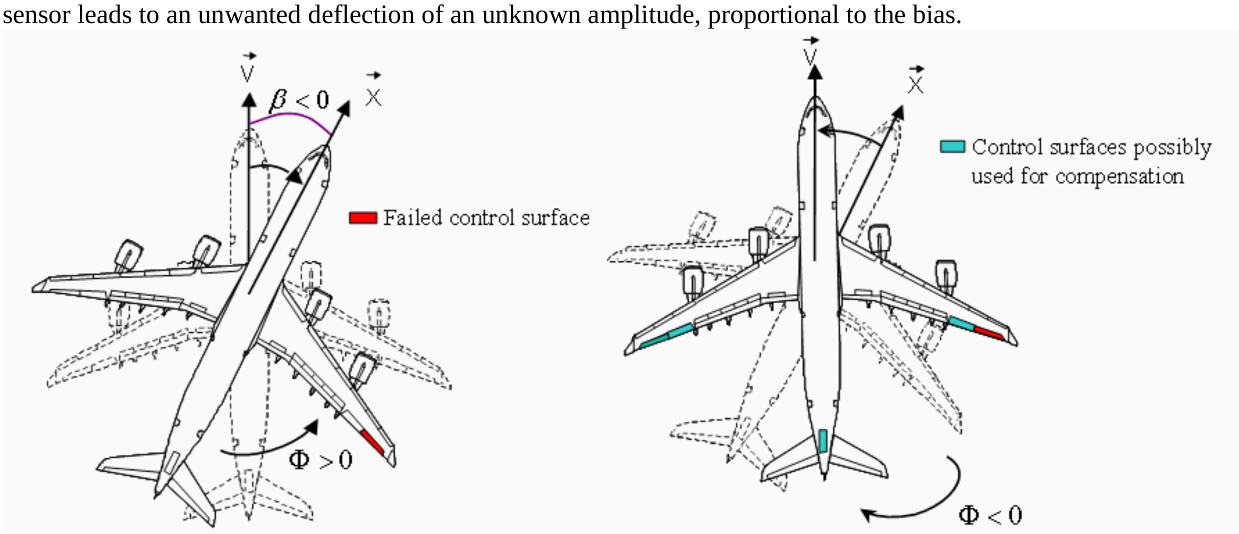

Figure 3 Effect of the aileron jamming and control surfaces possibly used to compensate[4]

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, which means that 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. The proposed designs must be compliant with industrial requirements such as real-time implementation constraints. In particular, in this failure case, there is no immediate critical consequence, a relatively long time (in the order of tens of seconds) is acceptable to detect and confirm the failure.

C. Deimos benchmarking V&V tools: functional engineering simulator (FES)

The ADDSAFE-FES is a non-real-time simulator based on Simulink/Matlab/XML that encapsulates the ADDSAFE benchmark as well as including robustness analysis tools for all the fault scenarios defined in the benchmark. The ADDSAFE-FES main objectives are:

- To provide a faithful simulation environment for the selected fault scenarios.
- To support the development and assessment of the FDD algorithms being developed within the project.
- To benchmark the FDD algorithms.

Deimos Space has developed two Functional Engineering Simulator (FES) packages. One serves as a simulation and verification FES (Sim&Ver-FES) released to all partners for their use during the development and application of the FDD methods and the other for the industrial benchmarking and validation (Bench&Val-FES) performed by the industrial partners at the end of the design cycle –which includes more sophisticated tools for multi-team FDD designs' benchmarking.

The ADDSAFE-FES Database (FESDB) constitutes the tool's data model. This database consists of a collection of XML files called data files. The information they contain is organized according to a certain structure based on a set of tables. Each table is a set of records and each record may contain a number of fields of three types: parameters, uncertainties and links. The format of the XML data files of the FESDB is formally defined by a specific XML schema, which gives a precise description of their structure. The schema defines a number of element types specifying their contents and attributes. With this schema and the tabular structure of the XML files the ADDSAFE Benchmark can be completely described in a harmonized and version-controlled manner. Thus, the completed Sim&Ver-FES released to the consortium is a highly structured software, including easy-to-use Simulink interfaces and a clean directory configuration, see Figure 4.

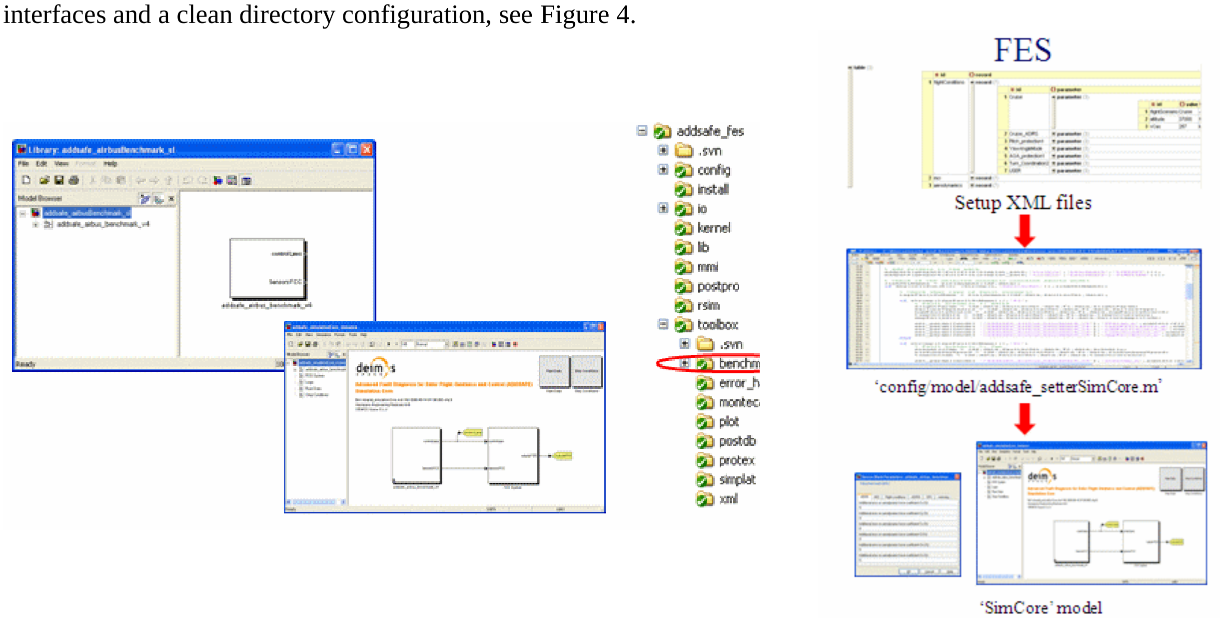

Figure 4 ADDSAFE: Sim&Ver-FES software package

In terms of output visualization and analysis, e.g. for parametric simulations, raw data plots show the output of all the simulation repetitions, as well as the nominal simulation. Once a simulation has been run, the raw simulation outputs can be post-processed to obtain new variables for the analysis of the system. Figure of merits (FOM), which are scalar quantities used to characterize the performance of a FDD system, are implemented to provide a quantitative benchmarking of the designs based on an Airbus' defined FDD performance and robustness matrix.

IV. Global Fault Detection and Diagnosis Design

The essence of model-based open-loop fault detection and isolation (FDI), or fault detection and diagnosis (FDD), problem is depicted in Figure 5 and can be formalized as:

FDI/FDD problem: Given a model of the nominal system G_u and knowledge (measured or estimated) of the inputs u and outputs y of the system, determine a filter $F=[F_U\ F_Y]^T$ that provides a fault estimate $res=\hat{f}$ with information on the faults f entering the system (through G_f).

This fault estimate $res=\hat{f}$ can provide an indication of the fault's presence – fault detection – or provide as well an indication of the fault location/source – fault isolation[7]. Fault detection requires only a single (scalar) while fault isolation requires a set (vector) of fault estimates in order to be able to distinguish between faults.

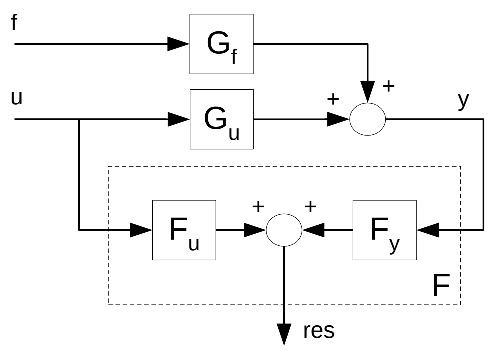

Figure 5 Basic model-based FDD design architecture

Most model-based FDI approaches are designed for the open-loop system (i.e. not including the controller). However, it is also possible to perform FDI on closed-loop system. There are some significant differences between the properties of the two approaches[11], with open-loop FDI being favored essentially due to its ability to use more information on the system (i.e. although it sounds counter logical, the presence of the controller hides information by absorbing the fault effects due to its natural robustness characteristics) and its ability to retrofit the designed FDI filter on an existing controlled system.

For both approaches, the requirements on the FDI filter are the same:

- To reliably and accurately detect and isolate faults.
- To be insensitive to exogenous disturbances, noise and system uncertainty.

These objectives lead to the natural requirement that the residual generator be robust, which is the main motivation for the use of H_∞ optimization FDI approaches since one of their distinguishing features is that they can explicitly include system uncertainty[5,6,7,8]. As such, they provide for a direct way to trade-off the level of robustness against the level of performance for the FDI filter. This is especially important in filtering problems, since it has a direct impact on the false alarm versus missed fault rates –which are critical for the practical applicability of an FDI filter and its industrial deployment.

A. General methodology for H_∞ FDD synthesis

The problem of designing a robust (H_∞-based) fault detection and diagnosis filter is generally divided in two main stages: robust residual generation and robust residual evaluation. We will focus on the first task, how to design a robust residual generator using H_∞ optimization techniques.

Within the task of residual generation, and from the H_∞ perspective, the methodology used for the design of an optimal FDI filter is as follows:

1. *Define the for-design linear time invariant (LTI) model*. This implies obtaining the LTI descriptions of the nonlinear system at appropriate operating points and conditions.

2. *Set the H_∞ FDD interconnection*. The H_∞ interconnection represents the posing of the mathematical FDD optimization problem. It specifies the input and output channels and establishes the design rationale. The idea behind the H_∞ interconnection is for the designer to define the transfer functions that the optimizer will try to minimize in synthesizing the FDD filter to achieve the desired fault performance and robustness trade-off.

3. *Define the optimization problem weights*. – The H_∞ interconnection contains the so-called weights, which are used to map the performance and robustness design specifications into the mathematical framework. The weights are (typically) first or second order transfer functions that the designer uses to shape the problem. The general ideas behind weight design are:

- Noise weights. They are used to attenuate the noise/disturbance effects on the fault estimation. Typically high-pass weights to indicate the high-frequency noise associated with measurement units.
- Error/performance weights. These weights, together with ideal models, represent the main performance tuning knobs. The estimation error weights parallel the performance weights in the standard control set-up. The idea is to minimize the error at low frequencies and relax the constraints at higher frequencies. Hence low-pass weights are selected for the actuator and sensor errors.
- Ideal fault weights. First and second order low-pass weights that contribute to shape the bandwidth and performance of the filter. These weights are the knobs used by the filter designer to shape the response of the residuals and define the type of problem. Since a condition of the FDD filter is to provide fault isolation, the reference fault weight is typically a diagonal matrix which emphasizes the de-coupling of the faults on the residuals.

4. *Establish the performance metric*. The performance metric for H_∞ (filter) synthesis is based on the induced L_2-norm, e.g. the H_∞ norm between the selected input-to-output transfer functions.

5. *Solve the optimization problem*. The LTI H_∞ optimization approach finds the FDI filter design F by exactly characterizing, and thus guaranteeing, the induced L_2-norm performance of the weighted transfer functions established in the H_∞ interconnection. It does so by using a quadratic Lyapunov function and solvability conditions from the well-known Bounded Real Lemma[6].

B. DEIMOS H_∞ FDD synthesis for ADDSAFE control surface jamming fault case

Following the design methodology above, the first step in the design process is to analyze the system and decide on the approach and LTI model to use. A local approach, i.e. based on the actuator model, was initially explored but due to the designer's experience and the perceived wider capabilities of a global approach, i.e. looking at the problem from an aircraft perspective, the latter was selected. This resulted in the selection of the lateral/directional dynamics of the aircraft as the basis of the LTI for-design plant. The states are sideslip (β), roll (p) and yaw (r) rates and roll angle (ϕ). The outputs are the states plus lateral acceleration (n_y) while the inputs are the flight control law commands for: rudder (δ_{rud}), left inboard aileron (δ_{ail}), right inboard aileron (δ_{air}), left outboard aileron (δ_{aol}) and right outboard aileron (δ_{aor}).

The standing objective, based on the fault case specification, is to *robustly detect* any of the three possible types of faults: liquid, solid and disconnection. Nevertheless, efforts are made to also obtain estimation performance –albeit for the preliminary results shown in this article, the focus is strictly in how fast we can detect any of the faults without suffering false alarms or missing faults.

The FDD interconnection is based on a fault model-matching approach that allows to transform the otherwise resulting min-max problem into a minimization problem, i.e. $min \mid res - f \mid$. The interconnection includes simple models of the actuators as well as noise, error and performance weights. All the weights (the specific weights are not given due to proprietary and patenting reasons) are either constant or first-order to minimize the number of states – recall that H_∞ synthesis will result in a filter with the same number of states as those in the interconnection[5,6,7,8].

After application of the H_∞ synthesis algorithm[12], the FDI filter obtained has a total of 16 states, 10 inputs and 1 output (the residual signal measuring the estimate of the fault). The FDD filter has a gamma value of 0.1 (measuring its satisfaction of the optimization problem and indicating that we have ample space to improve the estimation properties.) A threshold is used on the residual signal to declare detection, the magnitude of which is based on the response of the filter to a set (at different flight conditions) for un-faulty and faulty cases.

V. Results

In this section the evaluation of the H_∞ FDD design is presented. The evaluation is performed in two differentiated steps. First, open-loop time domain simulation with LTI plants at (many) different flight conditions connected to the nonlinear actuator models from the ADDSAFE benchmark (including the fault scenario implementations) are performed. This step is used to evaluate in a pseudo-linear fashion the performance of the filter and its robustness to the changing dynamics of the aircraft across the flight envelope. Then, the ADDSAFE-FES, which includes the nonlinear aircraft as described in Section III.A, is used at the flight condition specified in the ADDSAFE fault scenario (this flight condition is different to the one used in the design of the filter). The three fault sub-cases are tested in both steps and all results show the good detection performance indicated in the tabular table below but only the case for the solid fault is graphically reported to allow ease of comparison between the linear and nonlinear simulations.

A. Open loop time domain simulations

The designed filter is first evaluated in open-loop using a set of LTI plants[†] provided by Airbus and the lateral/directional actuator models from the ADDSAFE benchmark. The latter model described in Section III.B includes all the nonlinearities such as noise, rate and magnitude saturations and aerodynamic forces on the surfaces.

These LTI plants are provided to allow design and preliminary assessment of the designs but it is noted that the filters' final benchmarking will be in the ADDSAFE-FES which results in a slightly different LTI plants after trimming and linearization. Indeed, the provided LTI plants only contain the flight mechanics information of the aircraft, i.e. they do not include any sensor or actuator dynamics.

One of the LTI plants is used in the design of the filter –after appropriate manipulation of the full motion state-space to transform it into a normalized lateral/directional LTI plant. Then, the 509 plants are used to assess the filter's performance and robustness for the following cases: (i) no fault, (ii) liquid, (iii) solid and (iv) disconnection.

There is no a single false detection on the no-fault case indicating good disturbance rejection (of noise mostly since at this simulation stage the command inputs are zero as it will be seen in Figure 6). Table 1 shows the detection time statistics (mean, minimum, maximum and standard deviation) for the three fault sub-cases and the 509 plants. It is seen that for all the cases the mean detection time is less than 1 second and the maximum time for the solid case is only of 1.43 seconds. These results are very promising in the face of the specified time-to-detect requirement (>>10seconds).

Table 1 Pseudo-linear assessment, 509 flight conditions: time-to-detect (seconds) statistics

Fault Case	Mean	Minimum	Maximum	Standard deviation
Liquid	0.4904	0.3800	0.7200	0.0616
Solid	0.8996	0.7100	1.4300	0.1228
Disconnection	0.3263	0.2700	0.4300	0.0309

Figure 6 and Figure 7 show respectively the inputs to the FDI (the 5 lateral/directional states plus the 5 lateral/directional controller commands) and its outputs (the fault estimated residual). The fault sub-case shown is for the solid fault. Notice that since the simulation is open-loop, the command signals are zero but that the states show some oscillatory behavior (see left of Figure 6). This oscillation and drifts are the result of the fault, which is applied at 2 seconds –see Figure 7. Notice that since the gamma value of the filter was 0.1 we were expecting not to have good estimation of the fault but that despite this, apart from the desired fast detection, the FDI filter is capable

[†] There are 509 LTI plants, the odd number is the result of removing some points due to valid flight envelop restrictions from a regular grid based on Mach, Vcas, altitude, mass and center of gravity position.

of 'tracking' the fault trend albeit with a large steady-state offset. As mentioned before, further tuning of the weights should allow achieving a desired compromise between fastness of detection and quality of estimation.

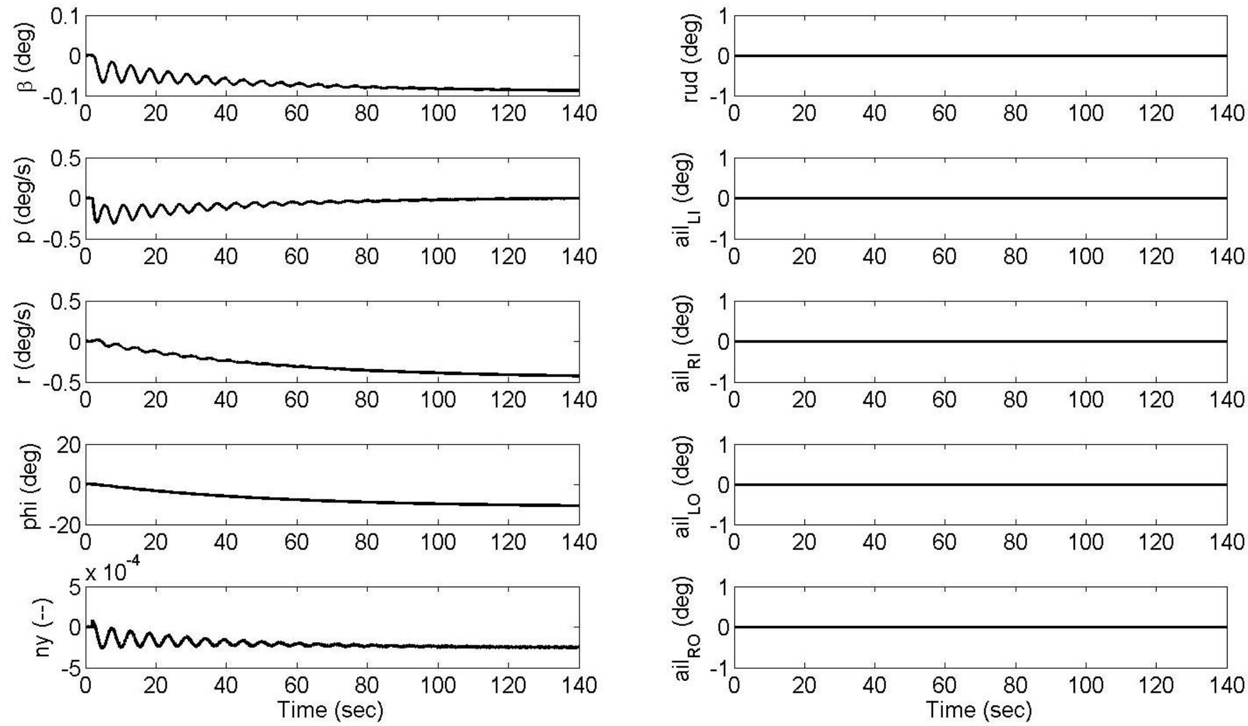

Figure 6 Linear (with full nonlinear actuator model and faults) time domain simulation: FDI inputs

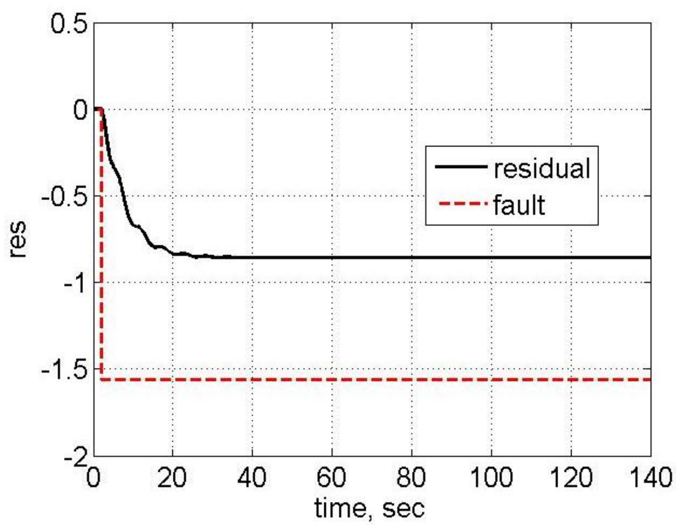

Figure 7 Linear (with full nonlinear actuator model and faults) time domain simulation: FDI residual & fault

B. Nonlinear time domain simulations

For the assessment with the ADDSAFE-FES, for this preliminary results a single flight condition is used (that defined in the fault scenario) but the three fault sub-cases are tested. In this case, this represents a true assessment in terms of the aircraft model nonlinearities, presence of controller (i.e. non-zero commands) and coupling of the dynamics due to the fault effects. The detection times are similar (see the maximum column for example) to those in Table 1: for liquid 0.6 seconds, solid 1.24 seconds and disconnection 0.42 seconds. This indicates (pending a Monte Carlo testing) that the filter's behaviour is quite robust.

Figure 8 and Figure 9 are the equivalent to the previous two but for the ADDSAFE-FES. Notice in Figure 8 that the FDI inputs include responses for the no-fault case (solid black line) and the faulty case (dashed blue line). It is easy to see that for the nominal case the aircraft is well trimmed but that even in this case the ailerons are slightly deflected (1 degree) which has a negligible effect on the residual (see solid black line in Figure 9).

For the faulty case responses (dashed blue lines), it is clear by looking at the states that the controller is more than capable of accommodation this 'small' fault but not without suffering a slight performance loss. this performance loss, see the offset roll angle, yaw rate and sideslip, is the result of the fault in the left-inboard-aileron (ail_{LI}) which the aircraft tries to compensate by deflection of the rudder and of the opposite-wing inboard aileron (ail_{RI}) –see also Figure 3. As mentioned before, if this is not corrected its effect after a long time will drastically result in additional fuel consumption and even violation of certain regulations. Looking at Figure 9 it is clear that the filter can relatively estimate the fault (although as before with a large steady-state offset).

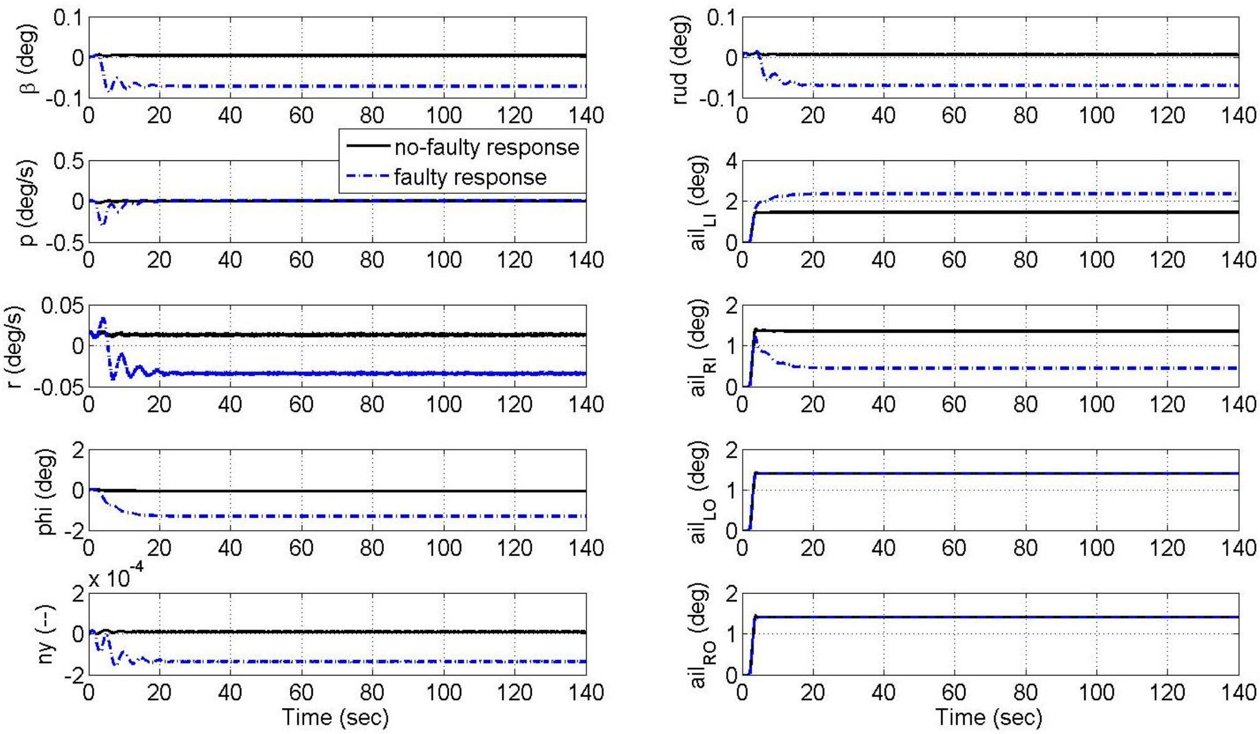

Figure 8 Nonlinear time domain simulation (ADDSAFE-FES): FDI inputs

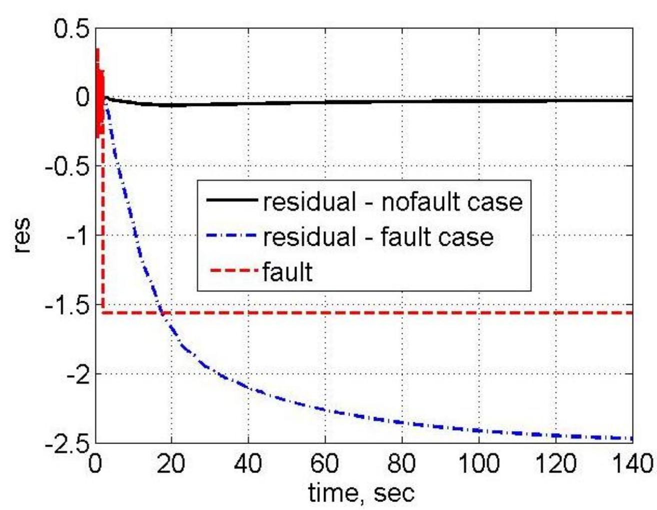

Figure 9 Nonlinear time domain simulation (ADDSAFE-FES): FDI residual & fault

VI. Conclusion

In this article a global H_∞ fault detection and diagnosis approach has been applied to the ADDSAFE benchmark for the fault scenario of a control surface jamming. This scenario concerns the detection of an abnormal aircraft behavior leading to the degradation of the aircraft performance as the result of an aileron jamming. Such jamming considers three potential causes: liquid (additive bias in the rod sensor), solid (control surface stuck at a fixed position) and disconnection (lost of physical connection between control surface and actuator rod).

As opposed to perceived disadvantages of a global approach for this scenario (versus a local one), the results show that the designed FDD filter can very quickly detect the simulated faults amply achieving the defined detection time performance (i.e. detection in less than 1 second while times of >>10seconds were allowed). Although quite complete, open-loop and closed-loop time domain simulation for the three fault sub-cases and a variety of flight conditions, the design is preliminary and the next steps are to consolidate it for improved estimation, to fully evaluate it in a Monte Carlo setting and to strive to implement the design in a computationally efficient manner taking into account the practical coding and processing requirements set forth by Airbus.

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