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An overview of the FP7 RECONFIGURE project: industrial, scientific and technological objectives

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Abstract: This paper details the industrial challenges, goals and objectives of the European Framework 7th project termed "REconfiguration of CONtrol in Flight for Integral Global Upset REcovery" (RECONFIGURE). This project aims at investigating and developing advanced aircraft Guidance, Navigation and Control (GNC) technologies that facilitate the automated handling of off-nominal events and optimize the aircraft status and flight. These technologies will extend the operation of the current GNC functionalities that assist the pilot and optimize the aircraft performance. Thus, the aim is to provoke a change in aircraft transport towards: "Full-time, all-event availability of performance-enhancement electrical fly-by-wire". Three key enablers have been identified for moving towards this new paradigm: Flight Parameter Estimation, Fault Detection and Diagnosis, and Fault Tolerant Control.

Keywords: Aircraft, Flight Control, Fault Tolerant Control, Fault Detection and Diagnosis, Virtual Sensors.

1. INTRODUCTION

The Electrical Flight Control System (EFCS, a.k.a. Fly-By-Wire – FBW) for large civil aircraft now constitutes an industrial standard in its digital version for modern 4^{th} generation aircraft, accumulating several millions of in-service flight hours. Main advantages include sophisticated control of the aircraft, flight envelope protection functions and pilot workload alleviation [1][2], just to name a few. For upcoming and future aircraft, the next challenge could be the extension of automatic Guidance Navigation and Control (GNC) functions to make the flight task even easier with an ever reduced pilot workload while optimizing the aircraft performance. This can be translated into investigating and developing advanced aircraft GNC technologies that facilitate the automated handling of off-nominal and abnormal events. With this aim in view, a consortium has been formed to tackle this challenge within the European Framework 7th project termed "REconfiguration of CONtrol in Flight for Integral Global Upset REcovery" (RECONFIGURE). The consortium of this 3-year project (2013-2016) is composed of 9 beneficiaries from 6 European countries and is coordinated by Deimos Space S.L.U. (Figure 1). European industries, Universities and research establishments form a good balance of background in the pertinent fields. This paper is devoted to a general presentation of this project, focussing on the industrial, scientific and technological objectives.

To understand the context, relevance and motivations of the project, the current aircraft GNC state of practice should be broached. Present-day aircraft control architectures are based on hardware redundancy and fail-safe approaches. This is exemplified by Airbus EFCS concept [1][10], which provides sophisticated capabilities for detecting, controlling, protecting and optimizing aircraft GNC during flight and ground phases. The EFCS facilitates the handling of the increasingly complex engineering system that is the aircraft of today. However, the number of failure cases to consider in the aircraft design has increased compared to mechanical flight control system. Therefore, Fault Detection and Diagnosis (FDD) and Fault Tolerant Control (FTC) have become of primary interest.

Figure 1: the RECONFIGURE consortium

The industrial FDD state-of-practice by all aircraft manufacturers is to provide high levels of hardware redundancy in order to perform consistency tests, cross checks and built-in-tests of various sophistication. The current industrial FTC state-of-practice for flight control law development mainly relies on a fail-safe approach whereby, depending of the level of degradation on-board the aircraft, a nominal ("normal") control law is switched first to robust ("alternate") solutions and then, if necessary, to a "direct" law [2]. Note that despite its name, the latter law ensures a minimal level of stability augmentation, independently of the type of abnormal event. The current approach fits well in the certification process and eases the design and analysis of the system. Each control law is designed off-line for different levels of robustness and each includes a set of specific GNC functions which assist the pilot all along the flight. Some of these functions are switched off as the control law is switched from "normal" to "direct" and, even though this state-of-practice is safe, it is also known to decrease the easiness of the piloting task. In addition, as these functions are de-activated, the use of automatic guidance (Auto-Pilot) or navigation systems (Flight Management) can be prevented. For upcoming and future aircraft, extending GNC functions would contribute to the development of an easier-to-handle aircraft, which will de facto result in decreased pilot workload. This is visualized by the shift seen in Figure 2 from the black dashed (current state of practice) to the black solid line (the wanted innovation), which exemplifies the desire to extend, as long as possible, the nominal and highest level of flight control law.

To achieve this new design paradigm, three key enablers have been identified: Flight Parameter Estimation (FPE), FDD and FTC. RECONFIGURE aims at investigating and developing advanced FPE, FDD and FTC strategies either individually or in an integrated way, as well as at assessing their viability, robustness and performances in an industrial environment.
This paper is organized as follows: section 2 details the motivations and objectives of RECONFIGURE. Section 3 is devoted to the Airbus benchmark, which consists of a very high-fidelity non-linear aircraft model and a set of industrial fault scenarios. Section 4 is dedicated to the Verification and Validation (V&V) activities. In section 5, some concluding remarks and perspectives are proposed.

2. INNOVATIVE CHALLENGE, GOAL AND OBJECTIVES

The aforementioned standard FDD/FTC approaches were pragmatically pursued since aircraft manufacturers seek, above all, safety and acceptable performance (robust stability). But for the future aircraft, it has been identified the need to change the design paradigm towards a performance-oriented one, which can be termed "full-time & all-event availability of performance-optimized GNC functions". This paradigm can be translated into the desire to extend the operability of the GNC functions designed to assist the pilot in keeping the flight safe and making the flight task easier and the mission optimal. This is why the main goal of RECONFIGURE is to investigate and develop advanced FDD and FTC designs, possibly fed by FPE, with the ultimate goal to extend as long as possible the nominal GNC functionalities in order to simplify the handling of off-nominal/abnormal events and optimize the aircraft status and flight. The automatism of the GNC will help alleviate the pilots' task and optimize aircraft performance.

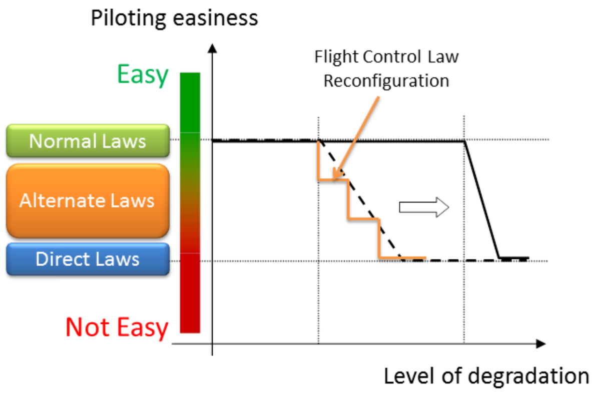

Figure 2: extending the GNC functions for an easier-to-handle aircraft.

In order to motivate the use of advanced FPE technology, note that prolonging the GNC functions may require extending the availability of some key flight parameters such as the angle of attack or the aircraft airspeed (used as a flight control law scheduling parameter). This could be achieved thanks to additional sensors, but with the main drawbacks of increasing aircraft weight, cost and hardware complexity. An interesting alternative is the use of analytical redundancy for the development of virtual sensors (VS), with the advantages of using already existing on-board information and not requiring additional sensors or any other devices. VS can be developed based upon mathematical models [3] or identification models [4]. With respect to FDD technology, even if rarely broached in the literature, it is now acknowledged that advanced FDD can contribute to the future more sustainable aircraft (demonstrate in a previous FP7 project termed ADDSAFE (2009-2012) [5]). Indeed, it can be established that enhancing FDD performance in EFCS allows to optimize the aircraft structural design (permitting weight saving), which in turn helps increase aircraft performance and improve its environmental footprint (e.g. noise, fuel consumption). Additionally to this opportunity, early and robust detection of incipient faults thanks to advanced FDD is required to extend the availability of key flight parameters. Most of the FDD methods that will be considered in RECONFIGURE arise from ADDSAFE with the noteworthy variation of focusing on abnormal events directly disturbing the EFCS. It should be noted that VS designed by FPE technology could contribute to FDD. This could also imply to investigate data fusion techniques to merge sensor measurements with soft sensors. Finally, FTC technology is obviously of primary interest to ease the aircraft control in off-nominal situations (e.g. sensor and actuator faults, changes in flight parameters). The use of active FTC strategies is strongly subject to the availability of an upstream reliable and prompt FDD system which could necessitate FPE. Therefore, the development of integrated FDD/FPE-based FTC techniques is one important goal of RECONFIGURE. Finally, it is also worth mentioning that a previous GARTEUR project [11] dedicated to FTC laid in a sense the foundations for RECONFIGURE.

The described RECONFIGURE goals are investigated through four main scientific and technological objectives:

1- Advanced parameter estimation and fault diagnosis approaches (FPE/FDD): for this first objective, RECONFIGURE can be considered as the continuation of ADDSAFE, but with the notable difference of focusing now on abnormal event scenarios directly affecting the aircraft EFCS such as wing-ice, or in the estimation of key flight parameters (e.g. in case of loss or degraded Angle of Attack (AoA) measurement). Furthermore, RECONFIGURE timely follows ADDSAFE and thus benefits from that project lessons learnt while maximizing impact in European competitiveness for both projects.

2- Reconfigurable GNC approaches: this project will investigate techniques that offer the capability to adjust, or even adapt, to abnormal events. This will make great strides to start the development of the aforementioned performance-oriented paradigm since for each situation, the control law will be reconfigured and/or adapted to the best aircraft condition while optimizing the performance. In essence, the techniques to be developed will try to keep the current GNC mission-optimal functionalities continuously operating or, at least, for as long as possible, and, when unavoidable, smoothly switch between the “normal”, “alternate” and “direct” control laws.

3- Integration issues: the two above objectives are contemplated from an independent perspective but in fact they must interact on-board, especially if the FPE/FDD information is to be used, as it must, by the reconfigurable GNC approaches (active FTC). Thus, it is of primary interest to explore the issues related to their integration from a practical perspective (e.g. quality, accuracy, delays of the information) as well as to consider approaches that directly generate integrated designs.

4- Certification, clearance approaches: it must be recognized that there is still a definite gap in the certification of the proposed techniques (either individually or in an integrated way) that precludes taking full advantage of them (see [6] for one the few works on this topic). This gap arises mainly due to a lack of research in the practical limitations arising from the interaction of the different FPE, FDD and FTC modules. Similarly, until now, research in the EFCS clearance problem, which is a precursor of certification, has focused almost exclusively on the clearance of fixed control laws [7].

The last three objectives represent a noteworthy step beyond ADDSAFE, whose assessment of the viability and performances of the advocated model-based FDD techniques has permitted the possibility for proposing RECONFIGURE.

3. THE AIRBUS BENCHMARK

The benchmark consists mainly of: (i) a very high-fidelity non-linear aircraft model which serve as a platform for simulation of (ii) realistic fault scenarios and abnormal situations. The development of the benchmark also implies the definition of industrial constraints and requirements for real-time implementation, as well as the definition of industrial V&V process and constrains. This section focusses first on the aircraft model development and release to the consortium and then on the industrial scenarios. Industrial implementation and V&V constraints will be broached in section 4.

3.1 Aircraft model

Although the aircraft model will inherit components from the benchmarks used in previous European projects [5][7], it represents a notable increase in the technological readiness level (TRL) for the simulation model. This increase in TRL is required due to the specific need to access more deeply in the flight control system, demanding a relative strong development effort from Airbus side.

To be fully representative of the aircraft and system dynamics, it has been decided to deliver an in-flight validated non-linear model of the aircraft. It includes a model of all the closed-loop components: flight dynamics, but also actuators, sensors, flight control computers, etc. The simulation tool containing the aircraft model was developed within Airbus to design the flight control laws and protections, including the nonlinear domains for general handling qualities studies. The development simulator was then used to test and tune control laws with a pilot in the loop. This simulator is fitted with wind tunnel data and some but limited real flight data. Consequently this simulator will never replace the flight test as the ultimate validation tool, as some uncertainty is remaining. The first version of this model was developed in 1984 for the A320 based on wind tunnel data [10].

The provided benchmark is represented by the yellow box in Figure 3. Because of Airbus’s development framework and proprietariness restrictions, this model is provided to the consortium as a black box with restricted input/output information. Thanks to the black box format the consortium benefits from using: (i) a precise non-linear model of the aircraft flight mechanics adjusted from wind tunnel data and limited flight test data; (ii) actuator model developed with the support of Airbus suppliers and Airbus testing facilities teams; (iii) realistic sensor models’ behavior. This is based on the functional description delivered by Airbus suppliers but adapted in a Matlab/Simulink interface to only consider the required features for flight control design. Transient features as sensors power-on as well as internal monitoring of the sensors are removed. A particular focus may be done in the engine model. Because of the complex task and specific knowledge required for engine modelling, from Airbus point of view, the engine model is a black box delivered by the engine supplier and integrated to the whole aircraft simulation platform. Finally several other models complete the simulator architecture such as a ground effect model for landing and taxing simulation purposes, a wind model to simulate representative disturbances based on the average wind and turbulence defined by the user and many others (hydraulic and electrical systems, fuel system, atmospheric model, etc.). Overall the simulation tool is composed of 38 different models.

However, in order to enable the different partners to test their own FDD / FTC designs, Airbus has extracted a part of the flight control computer in a Simulink model. This includes the baseline controller with interfaces to plug each partners’ designs. The entire control law design is presented in a

Matlab/Simulink environment. The benchmark architecture is completed by a Matlab-based interface that handles: characteristics of the scenario; data flow from aircraft model (sensors outputs) to the control laws; commands computed by the control law to the aircraft model (actuators inputs) and; the synchronization of the incoming/outgoing signals.

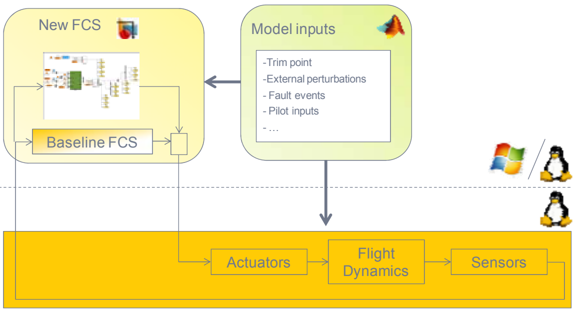

Figure 3 : Airbus benchmark architecture

The benchmark provided to partners is complemented with a simplified version of the aircraft model (Figure 4). This simplified version allows the project partners to preliminary tune their FDD and FTC algorithms. The structure of the simplified benchmark is composed of a linear model of the aircraft, the linear part of the baseline controller and simplified actuator and sensor models. The relationship between the fully representative model and the simplified one is schematized in Figure 4. The linear model of the aircraft is a linearized version of the flight dynamics at a given flight point. However, the user has the option to define the flight point where the model should be linearized. Hence, the partners can choose as many design points as needed to tune their FDD/FTC algorithms. With regards to the linear part of the baseline controller, this is essentially the same law as the fully representative model but without the compensations handling the time-varying behaviour of the aircraft. The simplified actuator model is a second order transfer function with rate and amplitude limitations, while the sensor model is simplified to a filter and a time-delay. Finally, it has to be remarked that all the features of the simplified models are open to the partners, who can modify them if needed for FDD/FTC concerns.

3.2 Industrial scenarios

Three faulty or abnormal scenarios are under consideration, covering a comprehensive spectrum of events: sensor faults, robustness to uncertain aerodynamic effects, and actuator faults.

3.2.1 Sensor faults

Information extracted from the sensors can be used as a control or as a scheduling parameter. If used as a control parameter, the associated GNC function is basically affected when the measurements are partially erroneous or not available anymore. In the case of its use as a scheduling parameter, the EFCS is usually designed to be robustly stable to errors in the measurement. For example, the speed parameter is very challenging due to the strong aerodynamic discrepancies between the high-speed (cruise) and the low-speed (landing approach) regimes. These discrepancies can have a strong effect on the pre-computed flight control law, inducing also a degradation of the associated GNC functions, under some specific circumstances. Two sub-scenarios are considered, involving two key flight parameters: AoA and Computed AirSpeed (CAS).

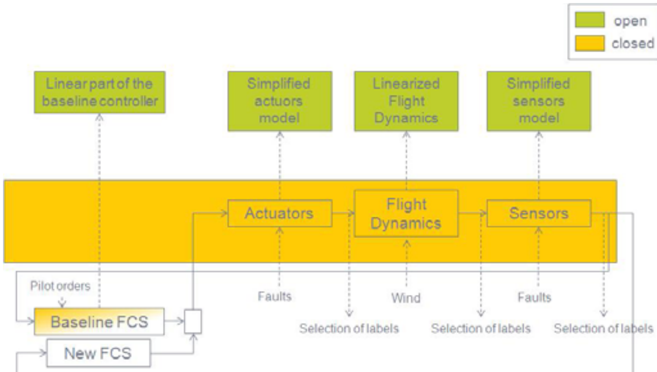

Figure 4 : Structure of the simplified benchmark

The first scenario is devoted to control reconfiguration in case of a detected total loss of CAS and AoA information, whatever the root cause and the way to detect it. CAS and AoA loss can be simultaneous or slightly delayed and it will be assumed that they are not recovered later on during the flight. It means that different kinds of sensor degradation are not considered here, only the consequence is of interest. Although this is a more FTC-oriented scenario, it is recognized that upstream FPE strategies could be also useful and complement the developments in here. Two strategies could be possible, as depicted in Figure 5 below: either keep the basic controller structure and only change its gains or switch to a new (advanced) controller, this option must also implement the switching strategy. FTC requirements include maintaining the longitudinal normal law as part of the inner-loop, so as to be able to easily manually fly the aircraft. The outer-loop objective is to maintain altitude hold and level change capability, while keeping aircraft away from angle of attack and speed limits.

The second scenario is dedicated to CAS and AoA sensor fault detection and parameter estimation. Large civil aircraft are generally equipped with 3 dedicated sensors for each of these measurements. Erroneous behaviours of 2 to 3 sources of CAS or AoA are considered, with the possibility of accounting for both abnormal behaviours leading up to 8 possible scenarios (with only two faulty measurements a total of up to 6 faulty possibilities). Additive or substitutive faults are envisaged (Figure 6): oscillation, jamming, bias, runaway, NRZ (Non-Return to Zero) and noise. For each sensor, the faults are always of the same type and different kinds of faults are not possible simultaneously (e.g. oscillation on one AoA sensor and bias on the second AoA sensor). The main FDD requirement is to provide a valid and accurate, voted value (so-called “consolidated”) for the flight control law computation and to isolate the faulty probes. The maximum acceptable error on the consolidated value is provided to the partners according to industrial requirements, as well as probability of false alarm (no degradation of the operational reliability) and of missed detection. FTC requirements are the same as for the first scenario.

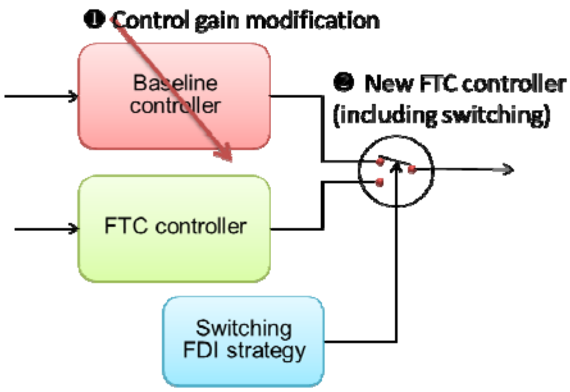

Figure 5: control reconfiguration in case of a detected total loss of CAS and AoA.

3.2.2 Robustness to uncertain aerodynamic effects: icing conditions

Icing conditions can significantly alter the shape of the wings and thus aircraft control and protections can be challenging. The consequence of progressive ice accretion is a deep modification of the pitching moment and lift coefficients, as well as a degradation of the closed-loop response at high AoA. There is no FDD requirement in this scenario. FTC requirements include an efficient AoA protection compliant with typical performance constraints. The design should be robust to different ice accretion forms and to any other un-commanded control surface motion (e.g. airbrakes runaway). FPE strategies could also be applicable here in support to the FTC activation (e.g. estimating aerodynamic coefficients changes). Finally, it should be noted that de-ice devices exist, but their effect will not be taken into account in this work.

3.2.3 Actuator faults

Current industrial FDD algorithms dedicated to actuator faults provide sufficient performance to optimize structural constraints. Under some specific circumstances, even if very improbable, successive redundant actuator faults can lead to the loss of the associated control surface. This induces degradation of the control law performance (e.g. time response, damping, precision …) leading to loss of associated GNC functions with a possible switch to a more "direct" law and an increase in the pilot workload. Assuming perfect detection of actuator loss, it is then of interest to work on control law modification to provide: (i) control performance and extended flight envelop protection; (ii) optimal guidance and trajectory planning. This third scenario will allow simulating representative detected actuator loss situations in a high-fidelity environment. In more details, a control surface is considered as fully lost after an abnormal event (e.g. faulty electronic component or mechanical breakage). The situation is known and the fault has been detected by an FDD strategy. There is no FDD requirement. The FTC objective is to help maintain efficient manual control while keeping nominal AoA protection. Due to the reduction in the number of control surfaces, the optimum aircraft response performance cannot be guaranteed for the full range of pilot inputs, thus the aircraft response should be maintained as long as the remaining actuators are not saturated (i.e. for small pilot inputs).

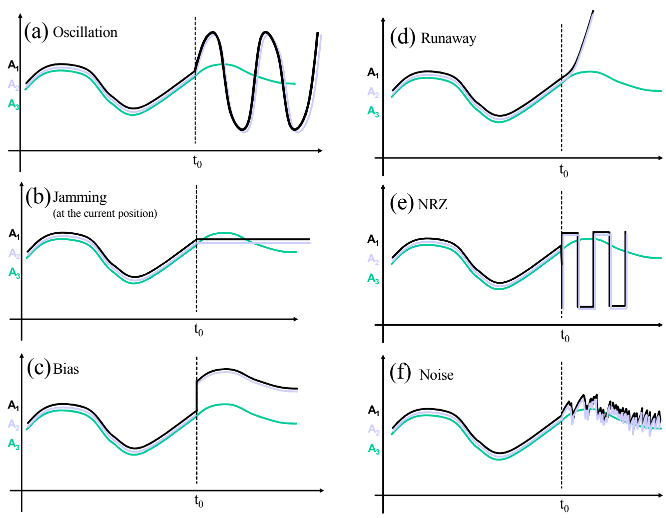

Figure 6: sensor fault catalogue.

Additionally, detection and compensation of stall load is proposed in this category of scenario although it cannot really be considered as an actuator fault situation. Stall load configuration occurs in flight when too strong aerodynamic forces apply on the control surface preventing them from achieving the commanded position. The control surface seems to be temporarily jammed (locked-in-place) at its current position. The goal is to detect and confirm that the control surface is stuck, to discriminate with a faulty event, and to estimate the control surface deflection and the duration of the stall load phase. The detection logic should trigger only beyond a given difference D, as depicted in Figure 7, between the command and the achieved control surface position. The proposed designs must be compliant with requirements on the detection time and probabilities of false alarm and missed detection.

4. VERIFICATION AND VALIDATION

The transition and acceptation of advanced academic methods advocated by academia (TRL levels 1 to 3) to the engineering world (TRL levels 5 and beyond) require significant industrial V&V activities. This is why one of the key objectives of RECONFIGURE is the use of standardized industrial V&V processes and tools to assess the viability, robustness and performances of the submitted designs. A three steps process will be applied through the use of: (i) a functional engineering simulator (FES) allowing a traditional Monte Carlo analysis (see [8] for more details); (ii) a worst case search tool (DLR's proprietary optimization tool MOPS [9]); (iii) an industrial Airbus simulator. A number of criteria and metrics have been defined that should be satisfied for evaluation of the industrial relevance of advanced designs. This includes quantitative criteria for which a metric can be defined and qualitative ones which rather refer to the "engineering judgment" and the Airbus experience. For FPE, quantitative metrics mainly involve the precision of the estimation with reference to the fault-free measurement which can be the output of the flight mechanics model, as well as associated statistics. FDD requirements include Detection Time Performance (an index measuring detection time normalized with respect to maximum allowed detection time) and corresponding statistics (e.g. average, minimum and maximum values), false alarm and missed detection rates. Specific high-level requirements are used for FTC, as for example: maintain longitudinal normal law (vertical load factor *Nz* control), altitude hold and level change and keeping the aircraft in a nominal (CAS, AoA) region. As an illustration, the first requirement means, among others, three kinds of conditions: (i) an homogeneous time response (lower than a given number of seconds) between the measured *Nz* and the commanded Nz_c computed in output of the flight control laws; (ii) an homogeneous Control Anticipation Parameter (CAP) value over the whole operating domain: $CAP = \frac{\dot{q}(0)}{Nz_{ss}}$ [1] where $\dot{q}(0)$ is the initial pitch acceleration and Nz_{ss} is the vertical load factor in steady state; (iii) multivariable stability margins (including nominal delays) that shall be greater or equal to: 6 dB for gain margin and 60 degrees for phase margin. Qualitative metrics mean for example: (i) the number of input parameters with or without a physical meaning (an important issue as it impacts the V&V workload); (ii) the number of input parameters to tune (an important issue for the design "genericity") and (iii) the capacity for the design team to provide a high-level functional description, including several levels of detailed description (an important issue for the industrial readability and for preparing a possible real-time implementation).

5. CONCLUSIONS

This paper is an introductory presentation of the European RECONFIGURE project, covering its main motivations and objectives. The realistic industrial Airbus benchmark (aircraft model and fault scenarios) is presented, as well as the principle of the V&V activities that will be conducted in the second part of the project (2015-2016).

The goal from RECONFIGURE has a long-term perspective of helping develop the FBW systems of tomorrow, one that will be "Full-time & All-Event Availability of Performance-Optimized FBW". The development of such a FBW will provoke a major change in the design paradigm currently followed by the aeronautical industry, where a conservative design is favoured over a performance-oriented one. But it is highlighted that RECONFIGURE does not aim to be able to provoke such a change, but rather to achieve the "small steps" necessary to initiate such a change of design mentality. With respect to a mid-term perspective, the goal of RECONFIGURE is to provide solutions that can extend the operability, or improve the design, of the GNC functions implemented in the current FBW to assist the pilot in making the flight task easier and optimize the mission.

Finally it should be noted that FPE, FDD, and FTC methods tackled by the consortium members are not described in this paper, as most of them will be presented during the RECONFIGURE invited session at Safeprocess 2015.

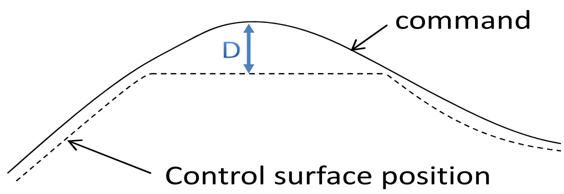

Figure 7: a typical stall load situation

[1] This criterion translates the pilots' needs of feeling a bigger acceleration in pitch when a bigger load factor is ordered.

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