An example of a multidisciplinary process applied to an Airbus design:
Optimisation of the A380 weight and ride comfort by an active flight control system

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Abstract. Multidisciplinary Design Optimisation is frequently looked at as the use of new computational tools, coupling together models of various disciplines in a single numerical environment, integrating a mathematical optimisation algorithm with tuned design characteristics so as to optimise the objective criteria.

Although this "tool" aspect is an important one, the deployment of Multidisciplinary Design also represents challenges in terms of organisation, competence, and engineering processes. The objective of this paper is to illustrate such aspects of MDO, focusing on one particular example: the optimisation of the interactions between the electronic flight control system and the structural loads and dynamic behaviour of the A380 aircraft. These processes will be presented along with the well-known V&V cycle of the system development where each part of this "V" has different objectives and induces differences in engineering activities and the relationships between disciplines. It will be shown that this MDO process not only relies on integrated multidisciplinary models and mathematical optimisation dependent on the phase and part of the FCS design, but also on engineers from the different disciplines sharing their knowledge, models, and exchanging technical information.

1 INTRODUCTION

Multidisciplinary Design Optimisation is frequently looked at as the use of new computational tools. Two main specifications are attached to these methods and these are compared to a more traditional engineering approach.

- MDO methods represent interactions between different disciplines, coupling together various models in a single numerical environment. For example, a traditional set of disciplines considered in an MDO framework is aerodynamics, loads, structure, and weight prediction.
- Aircraft design requirements and design variables are defined and modelled by the tools within this framework. A mathematical optimisation algorithm is incorporated in the tool to tune the design characteristics and optimise the objective criteria.

Although this "tool" aspect is an important one, the deployment of Multidisciplinary Design also represents challenges in terms of organisation, competence, and engineering processes. This second aspect of MDO is recognised in several papers, which highlight the potential impact of its application on the mindsets, responsibilities, and organisations of engineering teams [1],[2].

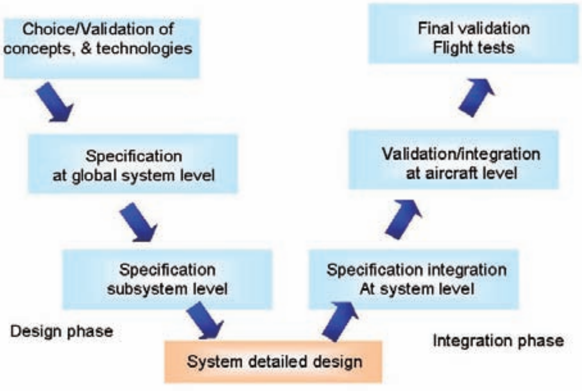
This paper will illustrate such aspects of MDO, focusing on one particular example: the optimisation of the interaction between the electronic flight control system and the structural loads and dynamic behaviour of the A380.

These interactions (effect of the flight control system on manoeuvre and gust loads, aeroelastic stability, passenger ride comfort) are well known and must be studied at least in a “checking mode” to guarantee the aircraft safety. However, since the first introduction of flight control system technology on a civil aircraft -the A320- Airbus wanted to go beyond checking. Their Enginners took advantage of this interaction for product optimisation by introducing an active control of gust loads that allowed wing structural weight savings to be made. This first introduction of active load control was then pushed further on all subsequent Airbus products: manoeuvre loads alleviation function and active structural mode response control for increased passenger comfort on the Long Range A330 and A340 (first introduction on civil aircraft) [3], optimum control techniques to perform integrated flexible aircraft control design on A340-600 [4]. The A380 inherited this extensive Airbus experience with Fly-by-Wire technology on civil transport aircraft, and pushed the flight control system optimisation for structural load alleviation much further, delivering a level of load reductions and ride quality never accomplished before. This was achieved together with meeting the challenges of aeroservoelastic stability and manoeuvrability.

This achievement was both the result of the competence and motivation of engineers contributing to this program as well as the clear and efficient processes allowing structure, loads, and system specialists to capture the key inter-disciplinary relationships and transform them into shared activities of modelling, design, and validation. This paper will describe these processes by reference to the well-known V&V cycle of the system development where each part of this “V” has different objectives and induces differences in engineering activities and the relationships between disciplines.

2 THE SYSTEM “V&V” (VALIDATION AND VERIFICATION) PLAN

The development of the system is commonly summarised in a sketch representing the activities “at aircraft level” compared to more “component specific” activities as a function of the development schedule:



This part is then followed by the actual detailed design and manufacturing of the system itself, which is normally considered at a very system-specific level. For most of the components of the flight control system, they are not developed and manufactured by Airbus directly. They are developed and manufactured by a system supplier who works on their own site.

The next phase is the right hand side of the “V”. This describes the validation activities. Such validation activities call for both simulation analyses and test analyses. Validation is performed firstly at subcomponent levels of the flight control system, which is typically the role of the “elementary test rig” (e.g. servocontrol, sensors, or computer specific tests).. This FCS validation is performed on the whole system using a simulated environment (typically the role of the “flight control test rig, or the so called “iron bird”), before the final validation, which is achieved by the flight tests.

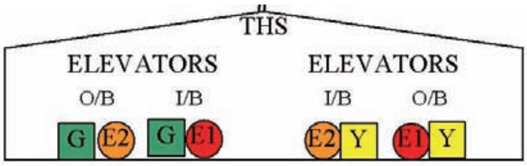
These three phases are sometimes not clearly separated, but this classification is used in the following paragraphs to show the different kind of activities that took place among system designers and loads and aeroelastic specialists to support a multidisciplinary flight control system design for the structural optimisation of the A380.

3 MULTIDISCIPLINARY SYSTEM-LOADS AND AEROELASTIC PROCESS DURING SYSTEM INITIAL DESIGN PHASE

As far as the system load and aeroelastic interactions are concerned, the first key outcome of this phase is the definition of the objectives that must be met by the flight control system and the selection of the concepts and technologies that will enable the realisation of these objectives. For this purpose, an important pre-requisite is a good load and aeroelastic culture among system designers, and vice versa, allowing the development of a shared understanding between the different specialists of all potential EFCS effects. Such competence was already available at the beginning of the A380 program thanks to experience of past aircraft programs and research and technology projects. As an illustration, many specialists of control law design were fully familiar with the famous “flutter plots” that are frequently considered outside the aeroelastic community as an awful superposition of many curves. Similarly, some load and aeroelastic engineers had good backgrounds in both modern automatic control techniques (like H2/H°° that were used to define some control laws used on the A380) and detailed features of Airbus’s FCS philosophy. This cross culture has always been favoured, in order to allow system specialists to anticipate potential aeroelastic or load increases linked to particular design features by themselves and to allow loads specialists to propose an innovative flight control system strategy and tuning resulting in load reductions. This knowledge sharingmust not muddle clearly defined responsibilities: system specialists keep the full responsibility of system specification design and validation, and load or aeroelastic specialists keep all responsibilities linked to load levels supplied for structure sizing or flutter statements.

The initial FCS structure interaction analyses done in the early stages of the FCS delivered many important design decisions on the A380 and influenced nearly all system requirements written in this phase. Some examples of these requirements are given below:

The servocontrol specification took the bandwidth and duty cycles into account to allow the introduction of structural mode control later on; the servocontrol damping mode characteristics were specified from aeroelastic analyses in failure conditions; the necessary introduction of a 5000psi hydraulic circuit was immediately recognised so as to have a reduced servocontrol stiffness - specific analyses were launched early on to manage control surface aeroelastic instability risks; the FCS sensors locations were defined based on aeroelastic control and stability objectives and structural mode shape characteristics. An unusual asymmetric FCS architecture replaced a failure case where both outer elevators were oscillating by a case where one inner elevator and one outer elevator oscillates - this is much less severe for the tailplane dynamic excitation (see the figure below which is an extract of an FCS architecture showing the inner and outer left and right elevator power supplies shared between green and yellow hydraulic circuits and 1 and 2 electrical circuits).



The early analyses of the load case hierarchy and structural weight drivers resulted in the agreement between loads and control specialists on the top level objectives/requirements for active load control and identify the control strategies to be developed during the detailed design phase of the control laws. For example, the benefit of active control of wing fatigue in turbulence was recognised. This makes the A380 the first ever civil aircraft to use active control for alleviating fatigue loads.

In summary, this initial system design stage permitted the definition of objectives, concepts and technologies, and also led to the identification of potential risks. A successful initial phase is a key milestone towards the optimisation of the flight control system for loads and aeroelastics. However, its process relies more on engineers sharing their understanding of their respective disciplines, developing a common vision and goal, and exchanging their "mono disciplinary" models and tools, rather than on new-coupled multidisciplinary models and simulation tools or mathematical optimisation algorithms.

4 MULTIDISCIPLINARY SYSTEM-LOADS AND AEROELASTIC PROCESS DURING SYSTEM DETAILED DESIGN PHASE

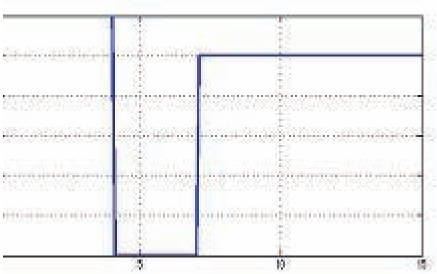
As mentioned earlier, this stage corresponds to detailed design and manufacturing activities that are performed in the system supplier company for many components of the EFCS.

The control laws are an exception firstly because its detailed design is performed internally by control specialists and secondly because the multidisciplinary optimisation cannot be managed only by specifications.A classic process to handle the control law design interaction with loads and aeroelastics was: once an updated tuning performed by the systems group. Its definition was provided to the loads or aeroelastic team to analyse its effects on the structure. In case issues were encountered, the adaptations to resolve them were defined in conjunction with system engineers an example of which would be adding a filtering if an aeroservoelastic instability occurred.

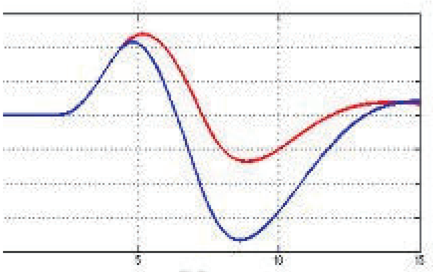
Airbus moved away from this "trial and error" control synthesis since the stretched versions of the long range A340 (A340-500 and A340-600), as it was considered that this methodology would take a long lead time to converge and would not guarantee the best control performance for these large flexible aircraft These aircraft are characterised by a small separation between rigid-body and structural dynamic frequency domains.

The design process used in Airbus is based on multidisciplinary control optimisation algorithms where all objectives from various disciplines are introduced as design criteria from the beginning. Key enablers of such processes are: engineers having sufficient competence in various disciplines (automatic control, handling qualities and loads and aeroelastics); the formulation of structure objectives as a mathematical criterion in the control laws design environment (eg comfort, aeroelastic stability and loads) and; introduction of loads and aeroelastic models into the control law design models. It is worth noting that for the development of the A340-600 where such a highly integrated control design process was used, the loads and aeroelastic specialists provided the control designers with aeroelastic models at a set of agreed flight and mass conditions, and these models where run in a specific control law synthesis environment. On the A380, the process integration was pushed further, and control law designers had the direct access of tools that generate the aeroelastic models. They also used some of the tools aircraft behaviour analyses routines.

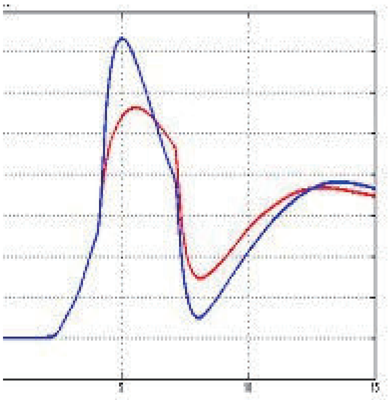
This optimisation process proved to be very efficient for the aeroelastic stability aspects and was beneficial in terms of the aircraft response in gust and turbulence (for both loads and passenger comfort). However, the optimisation of the flight control system for manoeuvre loads could not follow the same mathematical approach for two reasons. Firstly, manoeuvre load analyses require non linear models that are more difficult to manipulate during optimisation runs. Secondly and more importantly, manoeuvre alleviation very often raises questions about the level of manoeuvrability necessary for the aircraft. In some cases decisions cannot be made without pilot-in-the-loop analyses, for example, simulator tests and flight tests. However, a high level of alleviation of the manoeuvre loads has been reached on the A380 wing, fuselage, vertical tailplane, and horizontal tailplane, but this alleviation system was designed thanks to engineers' physical understanding of loads and handling quality drivers, rather than an automatic mathematical optimisation. Among the various strategies used in the pitch and lateral normal laws for this optimisation, one can mention gain scheduling, non linear filtering of control pre-command, and optimum usage of the kinematics. As an illustration, the figures below show loads during a lateral one engine out simulation with two standard control laws, the improved one (the red curves) providing a significant VTP loads reduction thanks to non-linear filtering.



Pedal input



sideslip



VTP bending

In addition to optimum normal law design, specific manoeuvre load alleviation functions were introduced, with appropriate compensations and activation/deactivation logics to ensure unchanged handling quality characteristics. Finally, some envelope EFCS protection functions (load factor, stall, and high speed protections) were used to reduce limit loads. It is worth noting that the specific Airbus philosophies on flight domain protections (which the pilot cannot override) dramatically reduce the probability of excursion of the limit loads in extreme manoeuvre situations.

And this high level of manoeuvre alleviation on the A380 has been reached together with outstanding handling qualities, acknowledged by all pilots who have flown the A380.

In addition to loads optimisation, the effect of the flight control system on passenger comfort in gust and manoeuvres was a key control design criterion. The A380 flight control system improves passenger comfort through several strategies./ Among others we can mention the normal law active damping of rigid body modes, structural mode control as part of Airbus's state-of-the-art since the A340-300, and precommand optimum design through 'dynamic precommand', or optimum phase management between control surfaces as described in [5].

5 MULTIDISCIPLINARY SYSTEM-LOADS AND AEROELASTIC PROCESS DURING SYSTEM VALIDATION PHASE

The final flight control systems validation before certification was done by an extensive flight test campaign, where all of the functions of the system were evaluated in nominal and failure conditions. However, as represented in the V&V process, numerous simulations and tests on ground preceded the flight tests.

The multidisciplinary work between loads and aeroelastic specialists that took place during the specification phase and the detailed design phase was of course pursued during the validation phase. The responsibility of system tests remained within the hands of the flight control system specialists. The driving idea of other actors involvement was to take benefit of simulations or tests planned for the “usual” FCS validation, and to expand them when necessary to capture expected effects (benefits or risks) of the structure – FCS interactions.

For example, servocontrol performance and stability tests were used to validate the behaviour of the structural mode control; some computer partial tests were dedicated to identify and guarantee computer delays for aeroservoelastic stability; many simulations performed on a desktop simulator for handling quality validation at the limits of the flight envelope (eg for protection function validation, or handling quality certification manoeuvres) were used for the manoeuvre load analyses.

An important innovation that enhanced the multidisciplinary EFCS validation on A380 was the wide usage of the system integration simulator for loads and aeroelastics, made possible thanks to the introduction of real time loads and aeroelastic models [6]. This test bench is named “iron bird”, or “a/c0”. Electric and hydraulic circuits, servocontrols, flight computers, and cockpits are all part of this test bench. All of these systems can be “flown” on the ground in real time, responding to pilot orders as if they were at 35000ft. The pictures below show some views on the A380 iron bird.

An automatic monitoring of loads and structural dynamic response was introduced to provid warning messages to specialists leading the simulation test whenever high loads or structural dynamic oscillations occurred. A 30seconds record of key parameters was also registered. This information is transmitted to loads and aeroelastic specialists for analyses (without stopping the simulation) as is done with a flight data recorder for technical investigation after an accident.

Thanks to this, the large numbers of tests performed for system integration are now useful for the structure – FCS interaction validation. This largely improves the vali dation of the flight control system's impact on load and aeroelastic behaviour and provides unique possibilities to validate this interaction with real hardware before the first flight.

For example, the usual flutter validation is performed in the frequency domain with linear models of the flight control system. This procedure is adequate for the safety demonstration and the system certification. However, the flexible aircraft iron bird allows an aeroservoelastic validation with the real flight computers, offering the exact system behaviour in terms of time delays and transitory phases during switches between control law modes or failure cases. These are hardly represented at all with the usual frequency domain system models.

Similarly, introduction of the loads model into the iron bird allowed performing load simulations with pilot-in-the-loop. This offers a loads check for more complex and realistic manoeuvres than the "stylised" ones defined for loads certification. In addition, the loads domain conducted a systematic clearance prior to flight-testing at the limit of the flight envelope, as these limits can be reached during some handling quality tests.

This enhanced loads validation was considered as a must because engineers always question if the alleviation seen on the particular gust or manoeuvre shapes used for producing loads for structure sizing and certification is still maintained during other scenarios. This additional effort can be considered as "the price to pay" when introducing a high level of loads alleviation through the flight control system. Integrated multidisciplinary validation processes and tools as described above are key conditions to achieve this extended validation efficiently.

6 CONCLUSIONS

This paper presents the processes developed within Airbus to improve the optimisation of the A380 loads, aeroelastics and comfort characteristics, while achieving outstanding handling qualities. This is achieved thanks to multidisciplinary optimisation of the whole electronic flight control system. It was highlighted that the process depends on the development phase to some extent, and is partially based on integrated multidisciplinary models of the aircraft and mathematical optimisation as MDO is usually understood. However, common to all phases of the process was the fact that engineers from different disciplines shared their experiences, models, and technical knowledge..

It clearly demonstrated that the loads and aeroelastic engineering community has a big role to play in aircraft design that goes much beyond their "basic" responsibilities of delivering load results for structural sizing or flutter statements. Load and aeroelastic engineers are key players in today's aircraft optimisation. As "multidisciplinary thinking" is a natural culture within this domain, there is no doubt that their contribution into the methods and the deployment of advanced MDO techniques in future aeronautics will be of the highest importance.

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