Enhancing preliminary aircraft design through operational considerations: a data-driven approach

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Abstract. Nowadays, digitalisation of aircraft, of their operations and their support became a crucial component for all the market players of the aeronautical industry. This technical field occupies an increasingly significant place, due to the generation of a substantial volume and an extensive variety of operational data. This new trend suggests taking those data into account during preliminary design and certification steps, in order to include additional considerations during those phases, such as operational criteria, maintenance, added value, development times or certification delays. In that way, this paper aims at suggesting a methodology to consolidate the aircraft design and certification processes though the use of those novel “digital” resources.

1. Introduction

The objective of this paper is to propose a methodology that would allow reinforcing the aircraft design and certification processes through the use of new resources, brought by the digital breakthrough of this modern era. As an example, those design and certification processes could benefit from all the data measured along the life-cycle of the whole aircraft in order to reduce design uncertainties and conservatisms for the next generations to develop. This document aims therefore at suggesting a method that could be used to improve preliminary aircraft design and certification processes, using a data-driven approach, focused on operational data.

For that purpose, this paper will first address the context of design and certification processes nowadays, including an historical analysis of this background. It will then address the sources of uncertainties this methodology aims at addressing and the overall objectives of this procedure under development. Finally, it will detail the resources available for that purpose, as well as the methodology developed in itself.

1.1. Context

Nowadays, data is mainly used to improve the accuracy of state predictions on existing systems. Similarly to what is done in Structural Health Monitoring or Prognostic and Health Management, this data is therefore used to optimize and monitor features such as Remaining Useful Life or maintenance interval estimation. However, this data is not directly taken into account during the early design and certification phases, in order to determine the advantages that the design and certification processes could take from such a data-integrated approach.

This prospective advantage might be illustrated by studying how a variation of the 1.5 safety factor described by CS25.303 may affect aircraft preliminary design properties. As an example, Figure 1 depicts a sensitivity study that had been performed on a short and medium-haul mission profile (800 NM and 2750 NM), based on the CeRAS (CSR-01) reference aircraft. This study
had been carried using the FAST-OAD\textsuperscript{[2, 3]} aircraft design tool and illustrates the influence of the design safety factor on aircraft properties, such as the Maximum Take-Off Weight (MTOW).

More specifically, it can be observed that reducing solely the 1.5 Safety Factor by 0.1 allows lowering the final MTOW of the designed aircraft by 1.5\%. There is thus a significant interest in reducing the uncertainties that the different safety factors cover in order to be able to optimise the most important figures of merit of aircraft designs.

![Figure 1. Sensitivity of the design MTOW with respect to the CS25.303 safety factor, for the CeRAS (CSR-01) aircraft, with design mission ranges of 2750 (turquoise) and 800 NM (brown).](image)

1.2. Historical analysis

Having a deeper look at the safety factors levied in the certification, it can be observed that those safety factors have proven their effectiveness in aircraft safety for a very long time. They are also at the core foundation of the certification process, allowing to build confidence on designed aircraft or on their structures.

From the historical point of view, factors of safety have not changed per se. For example, the 1.5 safety factor prescribed in CS25.303 has not changed in the last 90 years \textsuperscript{[4]}. Moreover, the modifications of certification chapters are mainly related to their conditions of application or to clarifications of their content.

\textbf{Current (01/12/1978 ⇒ Now)}

| The suitability and durability of materials used for parts, the failure of which could adversely affect safety, must... |
| The suitability and durability of materials used in the structure must... |

\textbf{(c) Take into account the effects of environmental conditions, such as temperature and humidity, expected in service.}

\textbf{Initial (3/11/1964 ⇒ 1/2/1977)}

| The suitability and durability of materials used for parts, the failure of which could adversely affect safety, must... |
| The suitability and durability of materials used in the structure must... |

\textbf{Table 1. Main differences between the applicable amendment of CS/FAR 25.603 (Materials) and the initial version of these specifications (03/11/1964).}

As an example illustrating those variations, Table 1 shows the difference between the initial release of CS/FAR regulations and the amendment currently applicable (amendment 25, \textsuperscript{[4]}) for CS25.603. It illustrates at the same time amendments of the conditions of applications and clarifications about the conditions to take into account.
1.3. Sources of uncertainty

In regard to the mainspring of safety factors and certification requirements in general, they introduce multiple conservatism sources (e.g., see Table 3). This is due to the way certification enforces to consider certain characteristics such as material properties or load specifications. The way those features are considered aims amongst other at covering the areas of uncertainty indicated on Table 2, such as material properties scattering, manufacturing variability or inaccurate characterisation of the fluctuating operating conditions (loads, environment, ...).

The methodology hereafter presented offers to consider all kinds of information generated during the system life-cycle in order to be able to reduce the previous uncertainties and finally to enable a potential reduction of some safety factors.

| Areas of uncertainty          | Conservatism sources               |
|------------------------------|-----------------------------------|
| Loads                        | Material properties               |
| Materials                    | Loading specifications            |
| Analysis                     | Certification tests               |
| Environment                  | Safety factors                    |
| Manufacturing                | Structural redundancy             |
| Epistemic uncertainty (Lack of knowledge) |                                  |

**Table 2.** Design areas of uncertainties. **Table 3.** Design conservatism sources.

1.4. Objectives

Implementing such an approach requires therefore to fulfil the following objectives:

(i) Determining design and certification constraints that could be relaxed using operational data;
(ii) Including formally the operational data within the preliminary design and certification framework;
(iii) Identifying the most sensitive design and certifications parameters through sensitivity studies. This would allow highlighting the most promising design settings and certification criteria for such data-driven applications, similarly to what has been shown previously;
(iv) Suggesting evolutions of design and certification methods, according to the previous conclusions.

Regarding this paper, the objective is mainly to present how data-driven applications could be used in a design and certification context, to identify the mainspring and the tools that could be used for such an approach, and finally to suggest a methodology for implementing this data-driven approach.

2. Resources

Implementing a data-driven methodology will require to merge different information, generated by various sources and tools, for the purpose of optimizing the system identification. In this respect, the means and resources selected for that purpose are:

(i) **Certification** related data and requirements in general, which can be obtained using formal certification analysis. For that purpose, Figure 2 depicts a reduced example of the certification analysis that has been carried out on the Vertical Tail Plane (VTP).
(ii) **Physical models**, allowing to determine the internal behaviour of a system, depending on external conditions, measurements or stimuli. For the ongoing implementation, this is for example achieved using static and dynamic structural models of the VTP.
CS-25 (Subpart B)

CS 25.1 43 (a) (c) (d) Controllability and Manoeuvrability

(a) (See AMC 25.1 43(a) and (b)) The aeroplane must be safely controllable and manoeuvrable during:

1. Take-off
2. Climb
3. Level flight
4. Descent
5. Approach and go-around
6. Approach and landing

(d) The maximum control forces permitted during the testing required by sub-paragraphs (a) through (c) of this paragraph for short term application for yaw control is equal to: 667 N (150 lbf) for short term application and 89 N (20 lbf) for long term application.

Figure 2. Reduced requirements model for the Vertical Tail Plane, based on CS-25.

(iii) Pre-existing data-driven applications can also be used for that purpose. Based on activities carried at the MIT, we can rely on the Digital Thread concept. As illustrated on Figure 3, this “thread” allows updating estimates and predictions of stochastic data in order to reduce their uncertainty level, thanks to a fusion of:

- Properties measured during the whole life-cycle of previous generations of a given system or design;
- Data acquired prior to design, such as offline experimental results, measured on coupon tests;
- Data measured during aircraft operations, such as handled loads or system usage.

Figure 3. Digital Thread concept.

Figure 4. Data-driven design environment.

It could therefore be used to reduce uncertainty margins of stochastic parameters that influence the most design properties of interest. This would for example enable lowering safety factors while guaranteeing a constant safety level or failure rate.

Another applicable data-driven tool is the digital twin concept which can be used to characterise accurately the evolution of the system state and properties, depending on observations of the systems, its environment and its use over time.

(iv) Integrated data-driven design environment (Figure 4). Similarly to what is currently done for Structure Health Monitoring, this would allow integrating information from different horizons such as loading conditions, structural and material properties and to
combine them with an accurate usage monitoring of the system of interest in order to perform real-time estimates of the evolution of the system’s state.

3. Methodology

Based on the different tools identified previously, a methodology has been developed, in order to implement data-driven design and certification applications. This methodology is depicted on Figure [5] and focuses on a given System of Interest (the Vertical Tail Plane, for the implementation in progress). It is then extended with a functional analysis (see its truncated version on Figure [6]), allowing to define the main functions of the system, the characteristics influenced by those functions and the data sources that would allow to characterise them accurately.

![Figure 5. General methodology for data-driven overall aircraft design processes applied to a given System of Interest (SoI).](image)

The system knowledge is then enriched using data originated from the different horizons introduced previously. As depicted on Figure [5] those data sources are gathered under the following three main categories:

- **Physical models**, as it is amongst other done using structural models;
- **Certification requirements**, derived from formal analysis of applicable certification requirements and modelled using tree-like techniques (Figure [2]);
- **Data sources** measured on-line, on existing designs. Those data are currently made of strain information, which is presently simulated using FEM models.

Then, the Digital Thread approach will be implemented. As shown on Figures [7] and [3] the Digital Thread (Dt) is based on information measured during the whole life-cycle of the system of interest, as well as information measured prior to the system design, such as coupon test results.

Those measurements (zt) are intended to be provided by on-line sensor measurements in the future. However, they are currently simulated from the theoretical inputs applied to the system (yt), through FEM simulation results from mechanical software or aerodynamic computations. As an example, the actual loads applied to the system, its material properties and the information about the manufacturing process are currently used to estimate the structural deformations of the VTP. In the reality, it would not be possible to measure directly the real inputs of the system (e.g. the actual loads or material properties). This is why this methodology aims at
Figure 6. Truncated functional analysis of the Vertical Tail Plane.

Figure 7. Detailed flow diagram of the Digital Thread.

considering system measurements which depends directly on those inputs and would therefore allow recovering indirectly information about the system inputs and state.

Before being converted into equivalent measurements, those “real inputs” are translated into statistical (“uncertain”) data, in order to take the system non-idealities into account. It is important to note that those two first steps aims at simulating the behaviour of a Digital Thread for virtual systems, for which the “real input” data are known. However, in reality, those “input-related” data would be replaced by real system measurements in the Digital Thread.

All the measurements are then fused, in order to optimize the accuracy of the system state identification, by means of all available information. Figure 7 illustrates again the Digital Thread concept, showing how all those different types of data (systems properties, measurements, resources available such as models, simulation software,...) can be merged on a “Digital Thread” using Bayesian inference[6, pp. 54–55, 75].
Simultaneously, constraint functions \( g_i \) are set. Those functions are currently defined using the Tsai-Wu criterion \[8\], in order to ensure that the designed part will not fail under the measured conditions. In addition to that, cost functions \( r_i \) are used to specify the key indicators to optimize for the selected design (currently the duration of the manufacturing process). Both cost and constraint functions are then merged in the form of a Bellman equation \( V^* (D_t) \). This equation is then used to assist the decision policy \( \pi_t \), in order to perform a global optimisation of the new generation to design, based on the information available in the Digital Thread and the decision degrees of freedom \( u_t \). For the current design, \( u_t \) is made of the local thicknesses and the ply orientations of the composite that forms the Vertical Tail Plane. This optimisation ensures therefore that the selected design will minimize the cost function while making sure that the constraint functions (“non-failure” criterion) will always be met for the selected design.

Finally, the geometry of the system is amended to produce a new generation of the system, according to the design decisions. This new geometry is then taken into account in order to evaluate the resulting manufacturing “cost” and then, re-iterate the whole process.

It is however important to note that those constraint functions are currently considering exclusively static failure criterion, without any durability or dynamic loading considerations. Indeed, the current “non-failure” criterion (Tsai-Wu) only considers static failure criterion, without any dynamic esteem or fail-safe approach. It is therefore intended to extend this constraint function with additional criterion such as fatigue, fail-safe conditions or structural constraints specified by the CS-25.

With regard to the cost function, they are defined by the MIT as exclusively proportional to the duration of the manufacturing process of the part analysed. This duration is currently computed using the ACCEM method \[9, p. 8\]. It is thus intended to extend this cost function with economic and design complexity considerations, in addition to manufacturing time aspect.

Regarding the system measurements, the only kind of sensors currently used in \[6\] are strain gauges. It is therefore intended to determine the other varieties of sensors that could extend the measurement sources in order to maximise the system representativeness and therefore the impact of the Digital Thread on the design figures of merit. In addition to that, the ongoing developments aim at extending the existing Digital Thread approach to more complex or multi-physics systems (such as the VTP), in order to involve several physical domains (instead of exclusively the mechanical domain, for the use case of \[6\]). Simultaneously, such a transition to multi-physics or more complex systems will require to widen the existing input space with additional considerations such as flight conditions or environmental impact on the system.

The resulting framework is then foreseen to be extended in order to provide validation and verification features to the design previously selected. This tool would first go to the design loop through the use of FAST-OAD, a Preliminary Aircraft Design Tool, which has been recently release in open source\[8\]. Simultaneously, it will be fed to the certification process, amongst other thanks to the certification analysis previously described.

At the end of the day, this whole framework is intended to provide decision aid tools to assist design processes in the context of data-driven applications. Those aids might be related to:

- **Key properties** of future designs;
- **Sensors** or **systems** to embed on the future design, to optimise the richness of information provided by the Digital Thread;
- **Data regulation** policy so as to provide an optimal management of the information collected through the Digital Thread.

4. Conclusion

To sum-up, the current “digital” breakthrough brought the potential of data-driven applications to light, in the context of aircraft design and certification processes. This is especially due to
the important sensitivity of the design phase to uncertain inputs, the historical framework of certification requirements and the uncertainty reduction ability provided by modern technologies such as embedded sensors or digital twins. This is why a methodology has been suggested for data-driven design applications.

This methodology is based on a functional analysis of the system per se. It is enlarged using data brought thanks to physical models and simulation results, sensor measurements and results from certification analysis (or more broadly requirement analysis). They finally aim at being fed to the design and certification processes, in order to provide uncertainty reduction or decision support features.

Based on the ongoing implementations and researches, ways forward has been identified in order to extend the features and strength of the existing “Digital Thread”. In that respect, the next steps will be related to the:

- Implementation of the Digital Thread concept and extension of it using requirement considerations;
- Extension of the Digital Thread concept developed in [6] with:
  - Constraint functions related to the requirements of CS-25, in addition to the purely economic (cost-related) functions;
  - Failure criterion improvement, in order to take dynamic and sustainability criterion into account, using for example fatigue and damage tolerance considerations, as a complement to the constraint currently considered (Tsai-Wu criterion);
  - Modelling multi-physics systems, in order to be able to extend the “Digital Thread” concepts to larger and more complex multi-physics systems.
- Integration of a formal verification tool within the framework under development, for the verification of system requirements.

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