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Multi-Disciplinary Design and Analysis of Aircraft Rear Fuselage and Tail Surfaces

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Abstract

The preliminary design phase of aircraft components is crucial for the robust definition of the product. This is the time to carry-out the optimisation of the configuration but often the cost of the generating the geometric and numerical analysis models curtails the full implementation of a formal multidisciplinary design optimisation process. This paper presents an overview of a multidisciplinary analysis framework for aircraft rear fuselage and tail components. The central element of the framework is a multi-model generator which automatically creates aerodynamic and structural analysis models from a common parametric geometry model. The geometry engine has been developed specifically for this application and contains features oriented to facilitating the creation of the discretised meshes required by mid-fidelity analysis methods as well as a CAD model of the complete component.

Keywords: aircraft, MDO, aerodynamics, optimization, empennage, panel methods, finite elements method.

1 Introduction

The design process of complex systems is iterative and evolves from a conceptual phase, where semi-empirical or statistical prediction methods are used to draft a first engineering model, to a preliminary design phase using medium fidelity analysis methods to provide a first analytical view of the system responses, which makes possible an iterative concept optimisation leading to a configuration freeze. Finally, the system or component is designed in detail in a phase involving high fidelity analysis methods and physical testing and where significant changes in configuration become costly.

The aircraft design process is also performed in these three phases: conceptual, preliminary and detailed design. Given a set of top level aircraft requirements, in response to a market need, the conceptual design is generally concerned with the definition of an overall shape of the aircraft, arrangement of the propulsion system, landing gear, payload and major systems and with obtaining an initial assessment of the aircraft performance. In this phase of the design process the definition of the aircraft typically consists of general arrangement drawings showing plan and side views and some internal details. Only the most important dimensions (e.g., length overall, wing span, fuselage diameter) are defined and no attempt is made to generate external surfaces or internal structure. Performance assessment is carried out using statistical or semi-empirical methods.

In the preliminary design phase, the focus is on refining the configuration by defining external shapes, internal payload and structural arrangement and systems space allocation. The performance assessment begins to be based on numerical analysis, for which a certain level of detail is required in terms of 3D geometry, structural definition, mass properties and aircraft loads, a well as engine data and systems architecture. The preliminary design phase is critical to identify configuration challenges and opportunities and to carry out concept optimisation.

The optimisation process normally involves variation of key geometric or layout parameters in response to an overall performance assessment which should enable to identify the merit of the design and the criticality of active constraints. The rate at which the design can be “iterated” depends on the level of detail used in the concept definition and, particularly, on the complexity of the analysis models. The optimisation process is further complicated by the need to consider responses from various disciplines with different requirements on the detail of the design definition and diverse overall times of analysis (sum of model preparation, actual computational analysis time and post-processing).

The preliminary design phase is crucial as this is the time to detect major design issues associated to the configuration or the maturity of the available technology and to perform a balanced multidisciplinary concept refinement leading to a robust configuration freeze. Throughout the preliminary design phase the designer’s freedom is reduced and more downstream cost is locked in.

Once the aircraft configuration, external shapes and overall architecture is defined, the detail design phase begins. At this point the structural elements are sized, part and systems installation drawings are generated and data for manufacturing are prepared. Assuming that the preliminary design phase has produced a robust and mature design, the detail design should proceed smoothly. The high fidelity numerical analysis and physical testing should, essentially, substantiate the predictions made during the previous design phases.

After sixty years and several generations of increasingly efficient commercial jet aircraft, the classical “tube and wing” configuration is reaching a high level of maturity. This makes it difficult to obtain significant performance gains in the successive generations. Advanced technologies provide weight savings through new and lighter materials, more efficient aircraft and propulsion systems improve the overall energy efficiency and advanced design methods enable, for example, to reduce aerodynamic drag. But in order to maximise the performance it is increasingly important to use formal optimisation methods, as opposed to traditional "manual" design iterations, generally oriented to obtaining a feasible design.

Key enablers to obtaining significant performance gains from a mature concept are access to accurate analysis methods and simulations which provide a robust evaluation of the concept merit and constraints. Assuming that an overall product merit and constraint function evaluation analysis is available, covering all relevant design disciplines and which can be performed in a sufficiently reduced time, formal optimisation methods can then be applied to drive the design to its maximum potential. During the design optimisation process, some particular critical constraints may be identified as limiting factors of the performance and this knowledge may serve to initiate focused research on the particular technologies or configuration aspects requiring attention.

The asymptotic nature of performance improvement is almost a fundamental law of design -and general evolution- and the need for disruptive innovation is recognised and fostered by industry and research institutions. When competing with established technology or system concepts, the first implementations or theoretical performance evaluations of innovative solutions tend to under-perform and a certain period of development is required in order to identify their true potential. In a highly competitive business environment it is desirable to accelerate this development process by performing quick but robust performance analysis and a carrying out some design iterations. At this stage, the focus is on identifying potential show stoppers, critical technology or regulatory constraints and to assess future performance potential (figure 1).

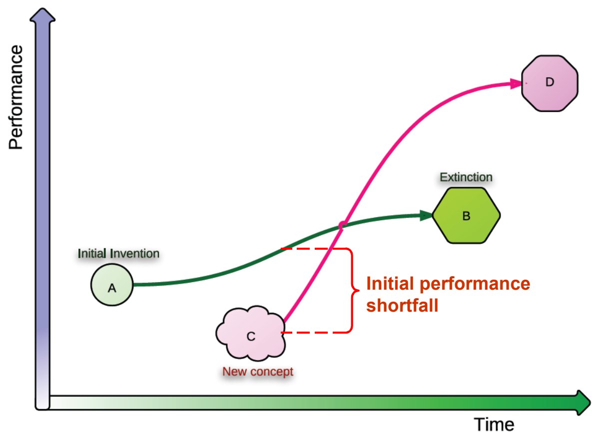

Figure 1: The "S" curves of evolutionary development and disruptive innovation, showing the initial shortfall that can be expected from new concepts or technologies before their ultimate potential is identified

On complex engineering systems, particularly since the advent of the digital computer, numerical simulation is the most convenient means of obtaining the required performance evaluation. In both product development scenarios; evolutionary improvement through optimisation and disruptive innovation supported by analysis, the use of multidisciplinary design optimisation (MDO) based on numerical simulation is one of the recognised key enablers.

The mathematical framework for MDO has been established for some years [1] and there have been periods of intense research activity and great expectations. At present, generic commercial packages exist which enable to perform MDO by driving proprietary analysis codes.

The application of multi-disciplinary optimisation in aircraft design is common practise at the early preliminary design phases [2, 3], where the analysis codes are relatively light and often rely on semi-empirical methods well adapted to conventional aircraft configurations. These semi-empirical methods are in fact very accurate within their domain of application but will be referred to hereafter as "low fidelity" methods due to their lack of generality and to the simplified representation of the product on which they operate.

As the preliminary design phase develops, the need arises to obtain higher fidelity responses (aerodynamic drag, structural weight, power consumption requirements). The margin for further design improvement may be small and thus a more refined analysis model is required in order to capture the finer points of the product or the configuration under analysis may lie outside the domain of validity of low fidelity methods. In these cases and particularly when unconventional configurations are being studied, low fidelity-based MDO cannot be applied [4].

In aircraft design, the next level of generality and fidelity in analysis methods is provided by numerical analysis (e.g., computational fluid dynamics (CFD), finite elements method (FEM)) and normally calls for a relatively accurate geometrical model of the aircraft components under study .

The mid to high fidelity analysis of a given aircraft configuration requires the generation of a 3D geometrical model, typically using a commercial CAD package. The analysis models consist of some form of discretisation of the geometry (finite element methods, aerodynamic panel methods) or the volume around it (Euler and Navier-Stokes CFD) in the form of a mesh.

Generally, the CAD model generation and the analysis meshes based on it are created by different specialists in a manual and time consuming process. CAD model generation can be automated to some extent on a restricted concept space by the use of the Knowledge Based Engineering, effectively a rule-based approach to parametric geometry modelling.

Mesh generation on generic geometries, specially for structured meshes, is significantly more difficult to automate completely. There are several examples of automatic FEM model generators in the literature [5] but their scope is either limited to a very simple representation of the structure or they can only be applied to a restricted family of geometries defined by a reduced set of parameters.

Aerodynamic analysis models are, in principle, easier to generate automatically, particularly for unstructured non-viscous codes [6]. However, the process is far from robust and tends to fail when applied to non-conventional geometries.

The fact that both geometry and analysis model generation is still largely a manual process for most mid fidelity analysis methods is one of the factors which prevents the widespread use of a formal MDO approach at the final stages of preliminary aircraft design [7]. Moreover, the various disciplines that are involved in the design process, all contributing to the overall merit of the design and all with their own constraints, use analysis methods requiring different levels of geometrical definition. Typically these methods run on different platforms and use particular formats for their input and output files with probably different names to refer to the same parameters.

The work presented in this paper has been developed with the intent of addressing some of the difficulties curtailing the use of MDO in preliminary aircraft component design, with particular application to the aft fuselage and tail surfaces of conventional commercial aircraft.

2 Overview of multidisciplinary design of aircraft components

2.1 Multidisciplinary design

The ideal merit function that should be considered when optimising any engineering product would be the return on investment. The complete evaluation of this function is generally difficult and a surrogate objective is generally sought. In the case of aircraft configuration synthesis, major contributors to the expected overall design merit are the structural weight, the aerodynamic drag and the manufacturing and operating recurring costs. A combined function of these design responses, with appropriate weighting factors, should exhibit good correlation with the final overall merit.

Several constraints, from different design disciplines, must be taken into consideration in the aircraft design process: from purely geometrical restrictions imposed by certification regulations (e.g., maximum wing span, location of cabin doors for evacuation) and space allocation requirements (payload and cargo accommodation, maintenance envelopes) to complex handling qualities objectives expressed in terms of stability margins and controllability requirements.

The stability and control requirements are particularly relevant in the design of tail surfaces, whose function is to provide the aerodynamic force to restore the aircraft attitude in the event of perturbations during flight and to produce the control forces required by the pilot to alter the aircraft trajectory. The tail surfaces must remain functional even in the non-linear stall regime of the wing, where the horizontal tail must be able to reduce the angle of attack of the aircraft to bring it back to level flight. The maximum control power that can be exerted by the controls occurs at deflection angles where there is flow separation and therefore this is also a non-linear and complex aerodynamic condition.

Additionally, the tails operate in a flow field significantly influenced by the presence of the wing, fuselage and possibly the propulsion system. Therefore, the aerodynamic evaluation of the tails is not a trivial exercise and requires the use of either well calibrated semi-empirical models for a conventional configuration or a mid to high fidelity numerical simulation method even for mildly unconventional geometries.

The tail surfaces and the rear fuselage are significant contributors to the overall aircraft drag at high speed. Drag calculations including transonic effects, particularly for unusual geometries, require the use of high fidelity CFD on a detailed geometric model.

The weight of the aft fuselage and tail surfaces can be estimated from semi-empirical correlations for conventional configurations. Again, when unusual geometries are under study, a more general approach is required. A possible process to obtain structural weights is to carry out a structural sizing on a finite elements model of the structure, what requires access to the loads and a structural optimisation method. Clearly, to generate the FEM of the structure a detailed definition of the aircraft external geometry and internal layout is required. The manual generation of a FEM is a slow and unwieldy process. Moreover, in the initial phases of the design process the loads, which calculation require access to the aerodynamic characteristics, flight mechanics model and mass properties, are not available. A final but non-trivial point is the need to use an automatic structural sizing method, generally based on mathematical optimisation techniques.

An acceptable approach for the calculation of the sizing loads is to couple an aeroelastic model with the FEM and prescribe the flight conditions deemed to be relevant for loads. Some of these will correspond to book cases but for complex manoeuvres certain general assumptions on the flight Mach number, altitude, and aircraft attitude and control deflections are required.

Part of the final weight of a major aircraft component is not dependent on the loads and is called "non-structural" mass. This includes the weight of the systems, paint, sealant and other elements of the aircraft. The non-structural mass can be estimated based on the size of the component and particular specifications (e.g., power requirements, etc…) for systems, which remain stable during the component geometric configuration synthesis loop and can be updated between major aircraft design iterations.

The non-recurring manufacturing cost is well correlated with the size and complexity of the aircraft components. The recurring manufacturing cost is, in a first approximation, related to the weight of the structure and the unit cost of the materials.

If the overall rear fuselage and tails weight, drag and cost functions have been obtained, as well as a detailed geometric model on which the geometric constraints can be assessed and the aerodynamic responses required to perform the handling qualities constraint evaluation are available, an iterative design optimisation process can be, in principle, carried out.

From the previous discussion, which is in fact a simplified summary of the early preliminary design process of a component such as an aircraft aft fuselage and empennage, the key ingredients required to implement an analysis driven configuration synthesis become apparent, namely:

- 1: A detailed geometric model including external surfaces, internal structural layout and a means to evaluate purely geometric constraints: overall size, internal space allocation, external geometric considerations (tail-strike angles, airport compatibility, etc...).

- 2: A means to obtain the relevant aerodynamic responses contributing to an optimisation objective function (aerodynamic drag) and constraints (stability derivatives, control power and stall angles) for handling qualities.

- 3: A means to obtain the structural and non structural weight given the external geometry, relevant overall aircraft parameters (considered fixed during the configuration optimisation of the tail surfaces), material properties and systems layout and requirements.

- 4: A means to evaluate the recurrent manufacturing cost and, ideally, also operating cost of the component.

- 5: An optimisation method which, considering the value of the design objective function and constraints and which by variation of an ideally small number of key parameters (mainly geometric shape and size and internal structural layout) will improve the design iteratively until all the constraints are satisfied (feasible design approach) or until no further improvement is possible (optimality conditions satisfied).

The conceptual and preliminary design process already follows the previous scheme but very often the generation of the geometric and analysis models is an expensive and slow manual process. When the definition of the configuration reaches a certain level of detail, soon after the conceptual phase, the design evolution progresses in long design loops until a feasible or, preferably, optimum design is obtained.

The implementation of an automated (or, at least, "more automated") analysis driven design process has the following key enabling factors:

- A: Ability to automatically generate a sufficiently representative geometric model of the component, including structural and systems layout, of adequate quality to serve as the basis for the evaluation of aerodynamic and structural responses using mid to high fidelity numerical simulation methods. The geometric and structural model generation must be possible from a relatively reduced number of parameters in order to facilitate the subsequent optimisation.

- B: Ability to automatically generate the aerodynamic and structural analysis models and run the numerical simulation to obtain the relevant responses. This generally entails the creation of discretised meshes adapted to the component's geometry and structural layout. Ideally, all the required analysis models shall be generated from the same definition of the geometry, i.e., all the information required by any of the involved disciplines must be contained in the geometric model. All the numerical models for each analysis discipline shall be consistent geometrically and should have a similar level of fidelity.

- C: An optimisation framework capable of interpreting the responses from each of the single-discipline analysis, build a complete merit function and evaluate the design constraints. The automatic optimisation process can be performed using some sort of finite-difference gradient evaluation by direct perturbation of the parameters defining the geometry or using surrogate models of the overall responses constructed previously by sampling the design space.

Various examples of applications of automatic geometry generation in aircraft design exist in the literature. The development of multidisciplinary design optimisation (MDO) in the past 20 years has been very fruitful and several optimisation frameworks are documented and even available commercially.

The greatest difficulty that must be overcome in order to implement a mid or high fidelity analysis driven design process is the development of a capability to generate automatically consistent analysis models from a common geometry definition. The problem is recognised in the MDO research community has been approached through the development of various examples of aircraft multi-model generators (MMG).

The following sections describe the development of a the building blocks for the development of an analysis driven design framework for the multidisciplinary design optimisation of aircraft rear fuselage and tail components. The suite of computer programs is referred to in what follows as MARES (multidisciplinary analysis of rear ends).

2.2 Components of a mid fidelity MDO framework

The main building blocks of a generic multidisciplinary design framework for aircraft rear fuselage and empennage components are shown in Figure 2.

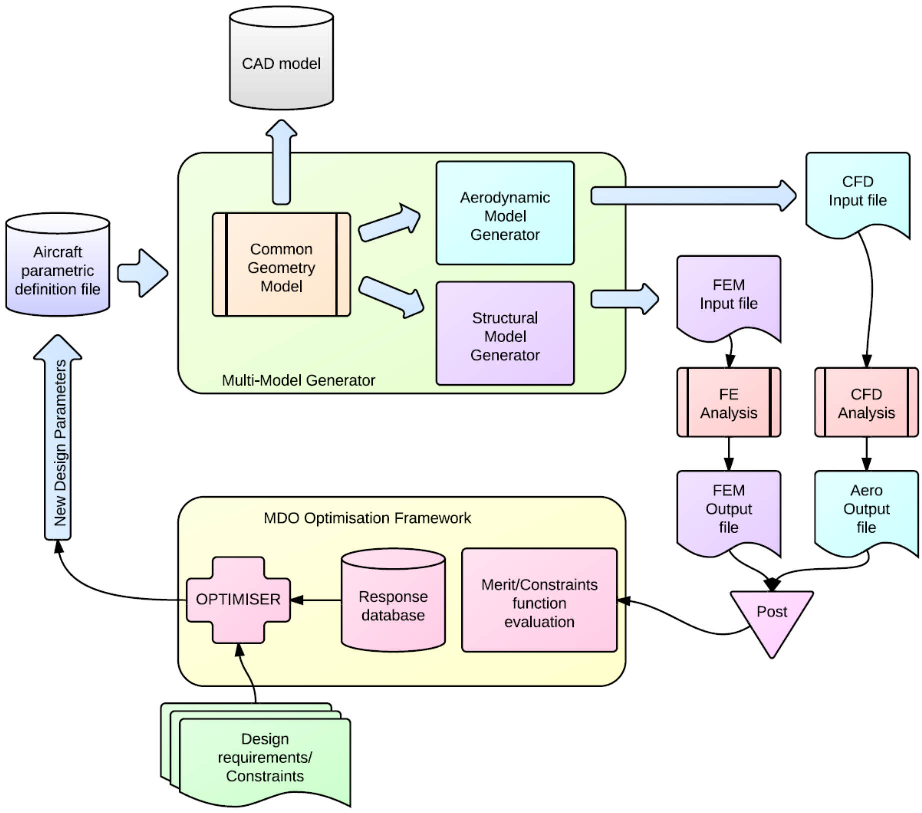

Figure 2: Multidisciplinary design process model for aircraft rear fuselage and empennage components

The two principal components are a multi-model-generator (MMG) and a multi-disciplinary design optimisation method (MDO).

2.3 Multi-model generator (MMG)

2.3.1 Common geometry model (CGM)

The multi-model generator module has at its core a parametric geometry engine developed specifically to produce external aerodynamic surfaces of high quality.

The complete aircraft parametric definition in MARES is contained in a single input file. A parser module interprets the geometric parameters, many of which are non-dimensional or compound (for example, the trapezoidal planform definition based on the values of surface, taper and aspect ratio and sweep angle) and creates the two-dimensional models of the fuselage and lifting surfaces. The three-dimensional surface models are constructed by modulation of topological tubes by the 2D guiding curves and smooth interpolation of fuselage master cross-sections or aerofoils in the case of lifting surfaces.

Various miscellaneous aircraft components required to perform, for example, space allocation analysis are also generated from their parametric definition contained in the aircraft file. MARES performs the rendering of the geometry and includes the facility to evaluate surface quality with various methods (e.g., Gaussian curvature, isogonic contours, zebra stripping). The internal modules of the common geometry model and some examples of instantiated geometry are shown in Figure 3.

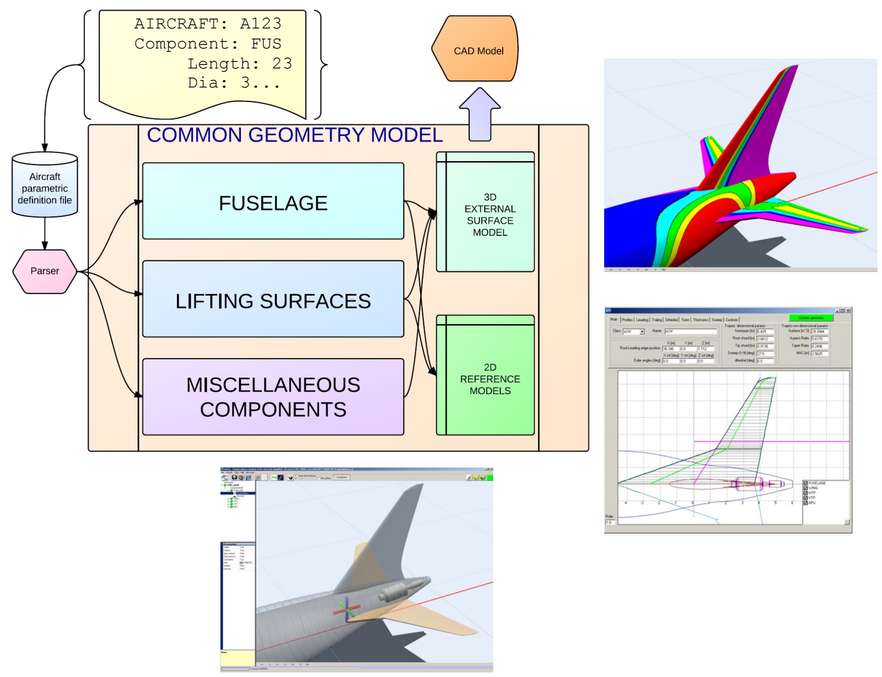

Figure 3: Components of the common geometry model generator and examples of 2D and 3D geometric models

2.3.2 Aerodynamic model generator (AMG)

Once the aircraft geometry is available, the analysis models can be generated. In MARES the topology of the surfaces is particularly simple as all the components for which aerodynamic analysis is required are modelled with a single bi-parametric patch. This facilitates the subsequent generation of a structured quadrilateral mesh on the aircraft surface for a potential panel aerodynamic analysis method (VSAERO).

The structured mesh generation is performed on a two dimensional mapping of the components and their intersections (Figure 4). A Laplacian smoothing process improves the mesh quality before mapping the panels back into 3D space. Finally, the wake filaments are automatically generated and the VSAERO input file is written. MARES can launch the aerodynamic analysis code and retrieve the results automatically for interactive design. When performing the full multidisciplinary analysis loop, the MDO module drives the MMG and AMG, launches the aerodynamic analysis and retrieves the results in order to build a response surface of the aerodynamic quantities of interest.

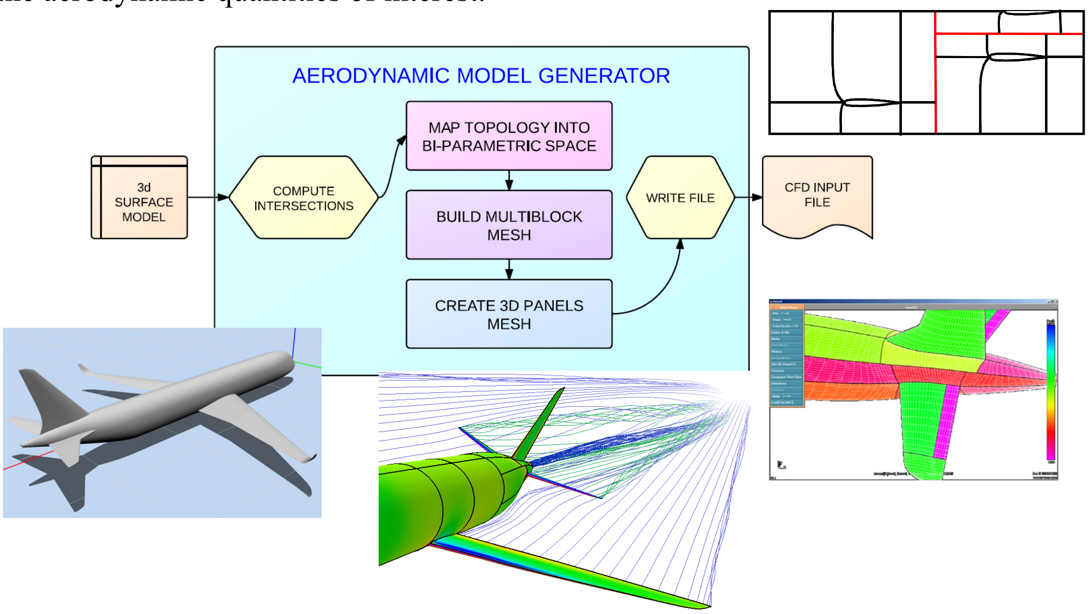

Figure 4: Modules of the aerodynamic model generator and examples of the mesh for the panels method and VSAERO results

2.3.3 Structural model generator (SMG)

To generate the structural model, the external surfaces as well as an internal structural arrangement definition file are required. The structural arrangement of the lifting surfaces is defined mostly in non-dimensional form as a function of local chordwise (x/c) and spanwise (eta) stations. This allows to generate the structural model automatically when the planform is perturbed during the design iteration process. In an analogous manner, the fuselage structural definition is referred to the non-dimensional length and height of the fuselage, with some particular parameters expressed in dimensional form.

The previously described approach to model the structure provides great flexibility to the multidisciplinary design process as the actual structural geometry definition is decoupled from the aircraft geometry and is recalculated and adapted to the external shapes and planform when these are modified.

The geometric entities corresponding to the structure are represented internally as discretised lines and surfaces in the common geometry module. In order to perform the structural analysis a finite element model is required and this is created automatically in MARES directly from the discretisation of the geometric entities. The FEM is exported to an input file ready for analysis with unit load cases.

The structural model can be exported into a CAD model by automatically generating the geometric entities corresponding to the external surfaces and the structural elements in a process where MARES drives the CATIA commercial CAD package via its application programming interface (API). The process is fully automatic and the final result is a complete CAD model including the product tree structure. A particular benefit of this approach is that, unlike in the case of the normal parametric CAD models, there is no difficulty in handling quantified sets of objects as this operation is performed by MARES.

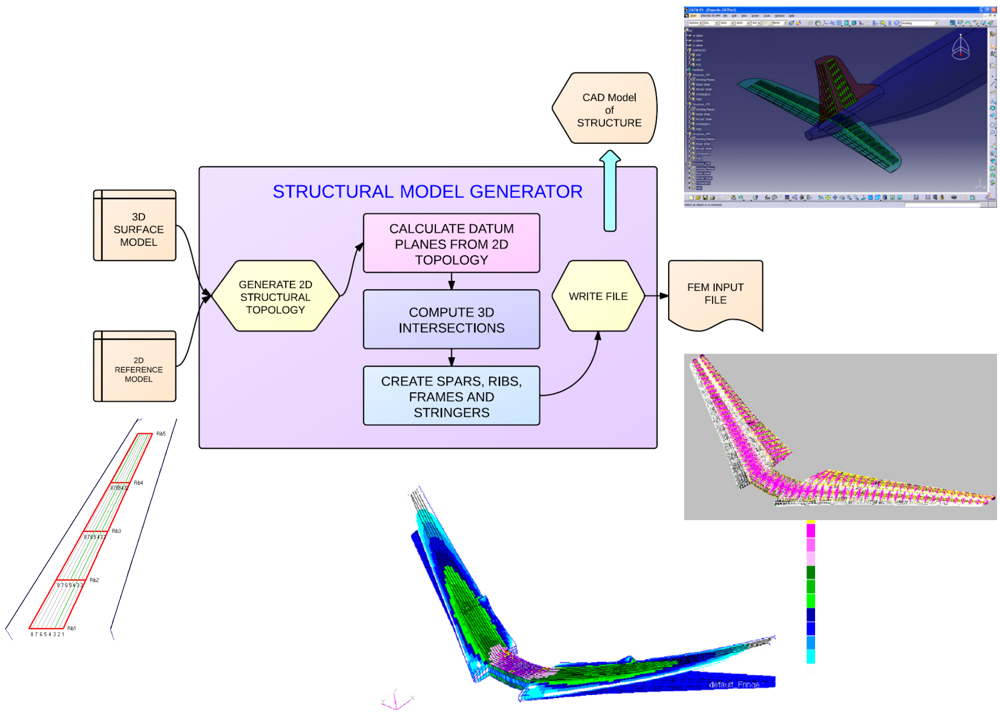

Figure 5: Modules of the structural model generator and examples of a finite elements model of a horizontal stabiliser and the FEM results

Therefore, all the external surfaces and internal structural geometry are generated and managed by the common geometry model (CGM) and structural generator model (SGM) in MARES and the CAD package (CATIA V5) is used purely as a generic geometric object instantiation library.

The usual design responses required from the structure are its weight and, possibly, the aeroelastic behaviour, in terms of flutter speed and, in the case of tail surfaces, the effect of flexibility on the stability and control derivatives.

In order to obtain these structural responses, the structural elements need to be sized, for which the loads acting on the structure are required, as well as a structural sizing or optimisation method.

One of the main objectives of the multidisciplinary design process implemented in MARES is the synthesis of the configuration of the tails, in terms of geometry and planform. The aerodynamic loads depend on the geometry and the inertial loads on the mass distribution and, therefore, the loads for the structural sizing must be calculated at every design iteration. This is by no means a trivial exercise and the approach followed in MARES is to couple an aeroelastic model to the structure and impose the flight conditions (Mach number, dynamic pressure, angle of attack and control deflections and accelerations) corresponding to the manoeuvres deemed critical for loads (figure 6).

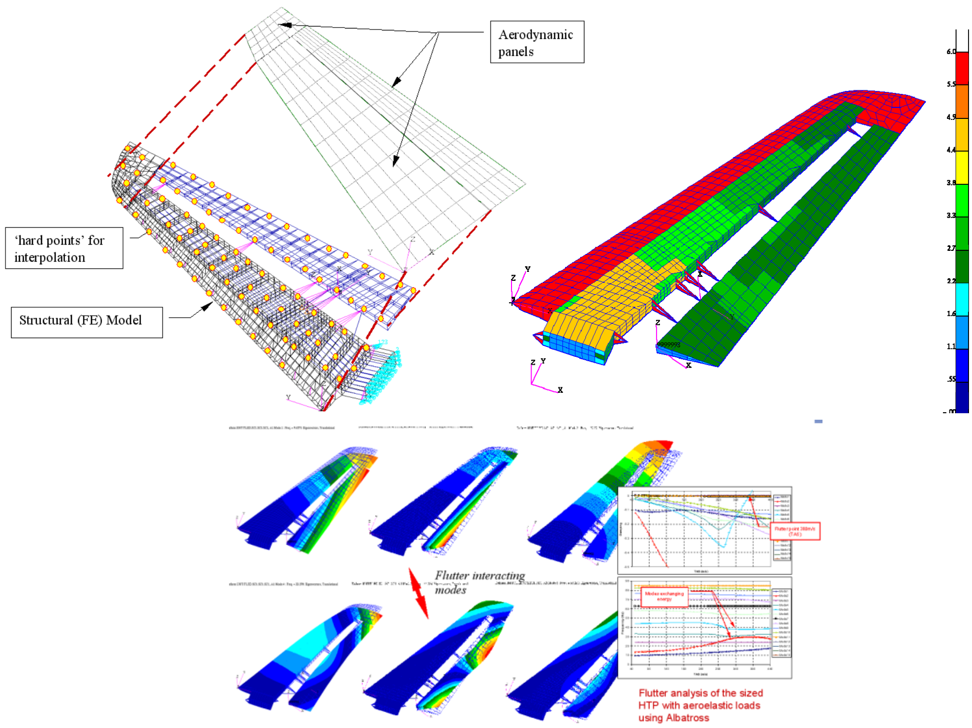

Figure 6: Coupling of an aeroelastic model with the structural FEM (top left), thickness map of the structure after sizing (top right), normal modes and flutter analysis of the sized tailplane (bottom)

The internal loads arise as a consequence of the external aerodynamic loads mapped onto the structure and the inertial forces due to the prescribed accelerations.

The structural sizing is carried out with an optimisation module and, at each sizing iteration, the aeroelastic deformation and the internal mass distribution is updated, therefore, the final results are consistent in terms of loads, mass and stiffness.

The final structural mass and flexible stability and control derivatives are processed as structural responses contributing to the overall multidisciplinary design loop.

2.4 Multidisciplinary design optimisation (MDO) module

The MDO component can be a commercial program which function is to launch the analysis codes, retrieve the results and drive the optimisation by varying the design parameters. The optimisation process seeks to maximise a design objective subject to a set of constraints and this required information must be expressed in mathematical terms and provided to the optimiser module.

From an implementation point of view, the MDO module must manage the transfer of input and output files between the MMG module and the analysis codes and launch the various computer programs (including the MMG) involved in the design loop.

A desirable characteristic of an MDO program is that design variables and responses are easily mapped to and from the input and output files.

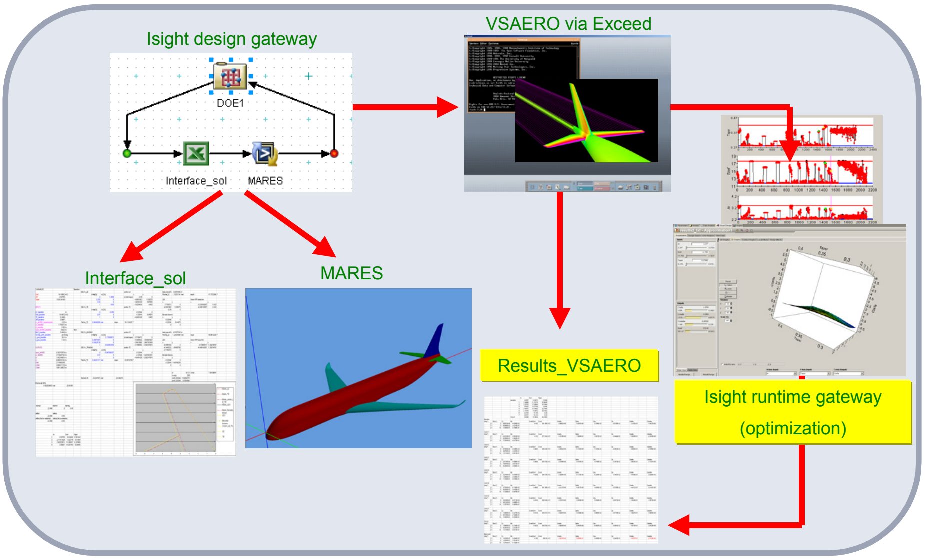

Figure 7: Dataflow for the construction of a tailplane aerodynamic derivatives response surface with MARES driven by Isight

Since most numerical optimisation problems require several function evaluations, in multidisciplinary optimisation of complex systems it is generally convenient to perform the actual mathematical optimisation using surrogate models of the response functions. There are various methods to construct a simplified surrogate model of the results of an expensive numerical analysis but generally some sort of interpolating function in several dimensions is used. A common approach is to build response surfaces through design of experiments. Figure 7 shows a simplified representation of the process required to construct the response surfaces for the aerodynamic derivatives of a tailplane using the commercial tool Isight driving the MMG and AMG of MARES and VSAERO as the aerodynamic analysis code.

2.5 Global configuration assessment

The results of a multidisciplinary synthesis of the geometric configuration of a rear fuselage and tail surfaces requires a global assessment including all the design constraints and requirements. Many design considerations are very difficult to model analytically and are therefore not included in the MDO loop. For example, accessibility and maintainability, which depend on the final shape and structural layout, are best evaluated by inspecting a detailed CAD model.

Figure 8 shows an example of a simplified maintainability assessment of a geometry generated by MARES and exported into a CAD model, including internal structure. Some of the details and elements –including the mannequins- in the CAD model have been created manually.

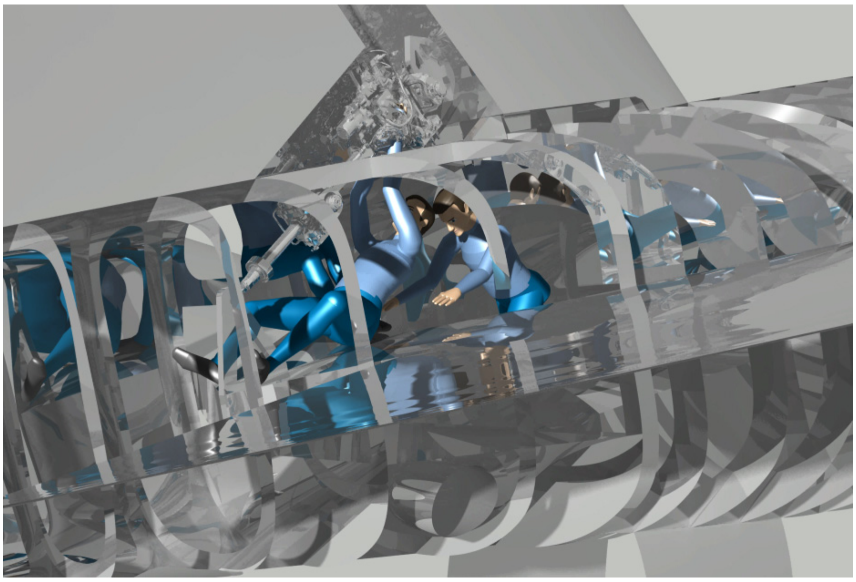

Figure 8: Example of preliminary maintainability analysis performed on a MARES generated model CAD with some manual additions.

3 Conclusions

Although mathematical multidisciplinary optimisation methods are well developed, the practical implementation of a MDO process based on mid fidelity analysis methods is curtailed by the complexity and cost of the generation of the geometric and analysis models. A multi-model generator for aircraft rear fuselage and tail surfaces has been presented where a new geometry engine has been developed with the particular objective of facilitating the subsequent generation of aerodynamic and structural analysis models. The geometry generated can be exported as a CAD model as a by-product of a common geometry generator and not as the starting point for the analysis.

Acknowledgements

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