Impact of Fuel Systems on Aircraft Design Using a MDO Process

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Summary

Within the traditional aircraft design process, major airframe characteristics are effectively fixed by the time serious consideration is given to the integration of aircraft systems. As a result, the integration of systems may be significantly more complex and may lead to greater performance penalties than would be the case if these integration requirements were better addressed during early design. A Multi-disciplinary Design Optimisation (MDO) approach can be used, alongside conceptual design methods, to assess the impact of such decisions. Within this paper, the modelling of fuel systems has been incorporated into QinetiQ's MDO process by implementing a method of calculating fuel available following an uncontained engine rotor failure (UERF) event, which dictates fuel tank boundary placement, and a generic approach for including individual fuel systems packaging constraints. Results of a parametric variation study are presented, providing promising insights into the potential benefits of the new modelling approach. In particular, variables defining the leading-edge sweep and semi-span have been identified as being key to satisfying constraints on the fuel available after an UERF event. The work presented has been carried out as part of the Integrated Wing collaborative programme, which was part funded by the UK Department for Business, Enterprise & Regulatory Reform (DBERR).

1 Introduction

The aerospace design process is facing increasing challenges to address the design of future aircraft. In particular, stringent environmental targets for civil aircraft, such as the ACARE 2020 Vision [1] for a 50% reduction in CO_2 and an 80% reduction in NO_x, mean that novel aircraft configurations must be considered, such as blended wing body concepts, employing novel technologies, such as flow control and extensive use of composites. The addition of these novel factors into the existing conceptual design process means alternative approaches for supporting early design are required, to improve confidence in performance predictions and design decisions which can identify the best combination of aircraft configuration, technologies and systems.

Typically, during the early stages of aircraft design, relatively low fidelity concept studies, supported by limited higher fidelity preliminary design activities, are carried out to assess potential solutions. Within this stage of design the objective is to down-select a final aircraft concept which is predicted to best meet the overall aircraft programme requirements. However, in recent years, new design capabilities, based upon the application of a Multi-disciplinary Design Optimisation (MDO) approach, have emerged offering:

- the potential to assess a wider range of design freedoms simultaneously;
- improved modelling fidelity within a relatively rapid automated process;
- the incorporation of more detailed design constraints to give better integrated solutions.

The work described here specifically focuses on the use of MDO for enabling better integration of technologies and systems within the early phases of aircraft design. In particular it addresses the impact on the selection of an aircraft concept as a result of improved modelling of the fuel systems during design.

2 Integrated Wing Programme

The Integrated Wing Aerospace Technology Validation Programme [2] (IWATVP) brought together industry and researchers within a UK national project funded jointly by the UK Department for Business, Enterprise & Regulatory Reform (DBERR) and the participating industrial partners. The structure of the IWATVP covered all of the primary technologies relevant to civil aircraft wing design, as shown in Figure 1. The overall aim of the project was to validate technologies which can lead to a step change in performance towards the ACARE 2020 vision for future aircraft.

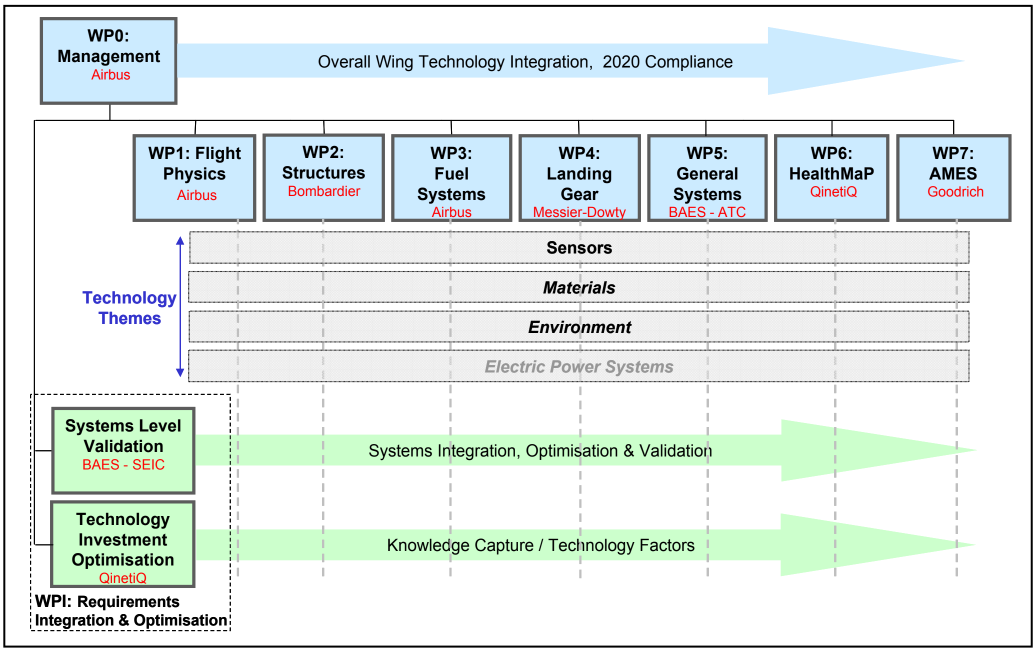

Figure 1 The Integrated Wing Programme Structure

As part of the IWATVP, QinetiQ led the work package focused on requirements integration and optimisation (WPI) with a key objective being to research and demonstrate the potential for alternative analysis and design approaches to support decision making in the early stages of design. Within WPI, QinetiQ has assessed the potential of two approaches for supporting design decisions:

- a broad exploration of the design space addressing the selection of technologies and systems (reference [3]);
- a detailed investigation of the impact of technology and system choices for specific aircraft concept types, using a physics-based MDO approach (presented within this paper).

3 MDO Process

When performing a MDO assessment of a complete aircraft it is important that a realistic level of modelling detail is used. Whilst variables perturbing individual parts of the aircraft (*e.g.* wing) can be optimised it is important to evaluate their influence on the whole aircraft configuration. For such a study, the following factors should therefore be modelled to a sufficient level of detail:

- 3D configuration geometry (external aerodynamics and internal structural);
- packaging and integration of systems;
- stability, control and mission analysis.

Having established a core MDO capability, it is then possible to make further enhancements to the process by including additional modules or constraints. This then allows for the possibility of assessing the impact novel technologies or system choices have on the whole aircraft concept.

3.1 QinetiQ Multi-Disciplinary Concept Assessment and Design Capability

To meet these requirements, both for military and civil aircraft, QinetiQ has built a Multi-Disciplinary Concept Assessment and Design (MDCAD) capability over many years [4][5][6][7]. Development of the MDCAD capability has been driven both by the need to be applicable to novel aircraft configuration design, and to reduce the overall elapsed time for design and performance assessment. Rather than low-fidelity, semi-empirical tools, the resulting capability uses computational, physics-based performance prediction tools already in use within individual discipline groups within QinetiQ [8][9][10][11]. This ensures that the resulting capability is applicable to both novel and conventional concepts. In addition, this approach results in the output of concepts which are more compatible with later stages of design thus helping to reduce the overall design cycle.

Past applications of the MDCAD capability have typically demonstrated the importance of simultaneously optimising multiple levels of design parameters at both a configuration level (*e.g.* wing planform) and at a deeper discipline level (*e.g.* aerodynamic shaping, structural component sizing). Additionally, the optimisation process has been run for concepts with a number of constraints active, including mission constraints (*e.g.* range, low-speed performance, stability) and packaging constraints (*e.g.* fuel volume). Within IWATVP WPI, the QinetiQ MDCAD capability has been enhanced by incorporating additional tools that model the integration of further technology and system choices.

3.2 The MDCAD Framework

The MDCAD capability comprises of a bespoke framework utilising Python-based [12] scripting which automates the process across a network of machines with differing operating systems. Additionally, the automated generation of full external aircraft surfaces, structural layouts, local surface features (*e.g.* blending), deployable devices and internal packaging and systems is achieved by using a rules-based, parametric CAD model generator, based upon CATIA V5 from Dassault Systèmes [13]. Computational physics analysis tools (*e.g.* Computational Fluid Dynamics (CFD) and Finite Element Analysis (FEA)) and optimisation tools are interfaced with this central CAD model within the software framework, to enable rapid analysis and optimisation at the MDO level. In order to simplify the automation of the process, the exchange of information between the disciplines is standardised.

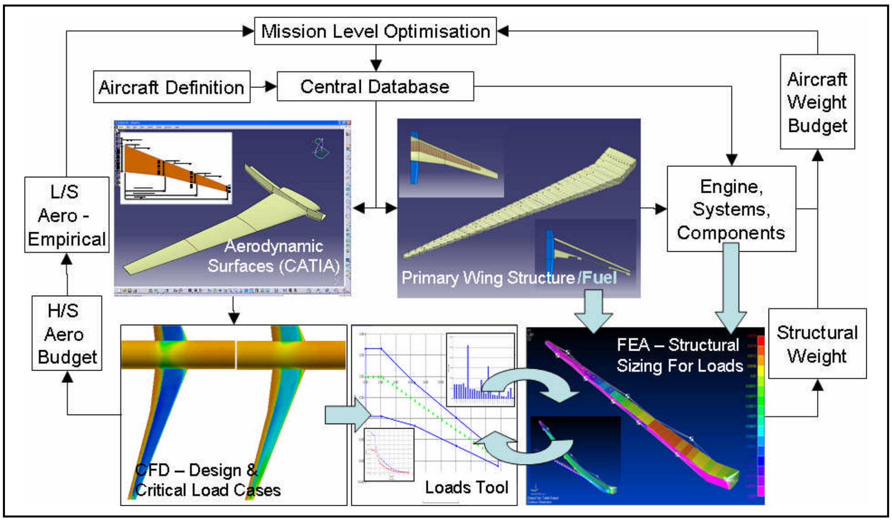

Figure 2 The Baseline MDO Framework

The baseline MDO framework used within IWATVP WPI is shown schematically in Figure 2 for a generic civil aircraft case. The aircraft concept is defined in terms of typical configuration parameters, such as wing planform variables, and the fuselage length, diameter, *etc*. Additionally, more detailed parameters are also specified which define the external aerodynamic surfaces (*e.g.* camber, thickness and twist) and also the primary structural components (*e.g.* spar and rib locations and sizing). Each of the configuration and detailed parameters is available for overall concept optimisation. These parameters are used to drive the CATIA V5 rules-based CAD geometry generator, which creates both the external CAD surfaces and the internal structural geometry.

3.3 The MDCAD Design Process

From a combination of the wing planform parameters and the variables that define the profiles of the thickness and camber of the wing, a 3D representation of the wing can be created. From this, using rules that define the location of the spars, rib and stringer spacing, in addition to high-lift and control devices, a CAD representation of the primary wingbox structure can be generated. This CAD representation is also used to calculate the capacity of the fuel within the wingbox region and is then translated into a FEA compatible model for use with MSC NASTRAN [14]. Figure 3 shows the resultant structural geometries for two different planform variations. For these cases, the rules defining the spar location, rib spacing and number of stringers have remained constant.

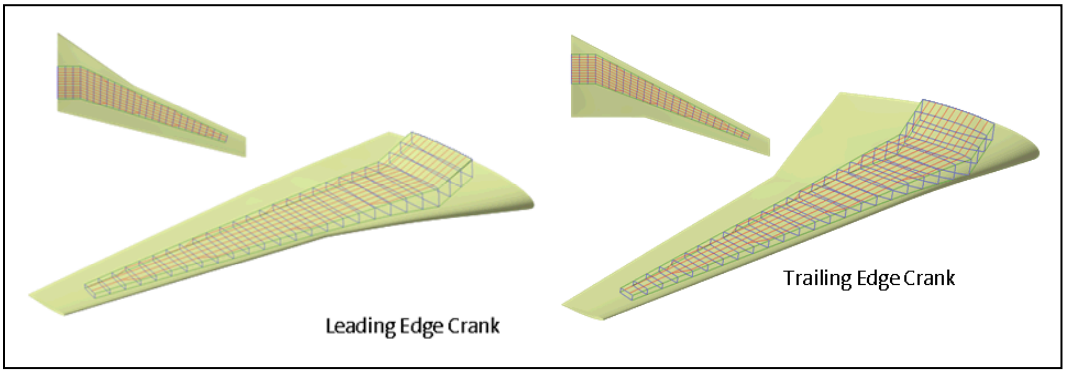

Figure 3 The structural layout for two different planforms

The external CAD surfaces are analysed using CFD to generate aerodynamic performance information together with aerodynamic loading information. During the structural analysis of the wing, the aerodynamic loads are applied, together with loads associated with the fuselage mass components, high-lift systems and fuel carriage (see Figure 4). The primary structural components (spars, ribs, skins, stringers) are analysed and their thicknesses optimised using FEA to generate structural weight information.

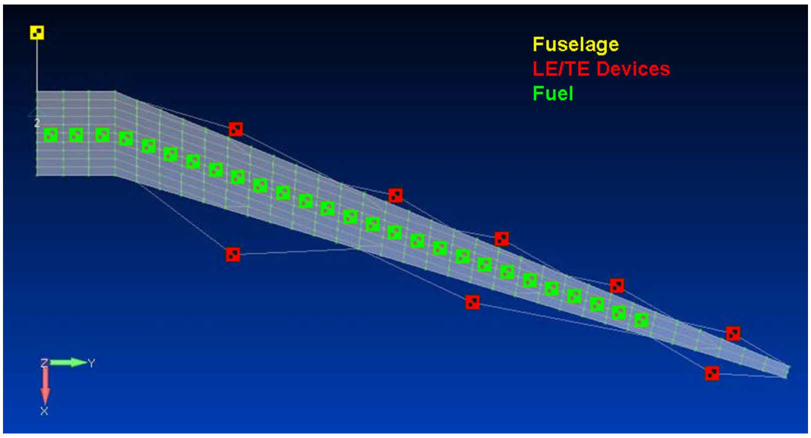

Figure 4 FEA model showing the fuselage, high-lift devices and fuel masses

3.4 Problem Formulation

The aerodynamic performance predictions from CFD and the weight predictions from FEA, together with details of the chosen engine and associated specific fuel consumption are fed back into the overall optimisation problem formulation. A mission analysis module is used to calculate the performance of the aircraft from which various optimisation objective functions, such as total fuel burn or maximum range, can be derived. Typically, numerous constraints are also included within the process; *e.g.* operational requirements for fuselage cabin size, payload, cruise Mach number, *etc*.

4 Aircraft Fuel Systems

The integration of fuel systems within an aircraft imposes many complex constraints upon the overall design. At the early stages of design an initial layout of the fuel systems must be incorporated which satisfies a number of constraints that influence aircraft performance, refuelling times and safety. In particular these factors have an impact on the shape of the wing, the wing structural layout and sizing and the position of the centre-of-gravity of the aircraft for calculation of the Basic Operating Sequence (BOS). It is therefore desirable to model these constraints at a higher level of fidelity within the MDCAD capability in order to better represent the drivers for aircraft concept design.

The key drivers that impact the layout of the fuel system are:

- uncontained engine rotor failure;
- fuel system packaging;
- fuel management to provide wing aero-elastic bending relief and aerodynamic trim;
- protection of the fuel system against lightening strike.

4.1 Uncontained Engine Rotor Failure

Aircraft powered by turbine engines are subject to the possibility of a rotor failure, where fragments from the fan, compressor or turbine sections are ejected at high velocity from the engine. When designing the fuel systems layout, these fragments are assumed to contain enough energy and be of such a size that they cannot be contained within the engine casing. It is therefore assumed that the fragments can pass through any aircraft component encountered along the trajectories taken by the fragments, with the potential for catastrophic results. This is referred to as an uncontained engine rotor failure (UERF) event.

To minimise the impact of such a failure, aircraft safety regulating authorities, such as the European Aviation Safety Agency (EASA) and the Federal Aviation Authority (FAA), have drawn up a set of certification requirements which aircraft manufacturers must adhere to. For large aircraft, EASA certification specifications [15] state that "*Design precautions must be taken to minimise the hazards to the aeroplane in the event of an engine rotor failure*". One of the main hazards following an UERF event is the potential loss of stored fuel and as a result, this impacts on the design of the aircraft fuel tank layout. The amount of fuel lost following an UERF event can be minimised by positioning the tank boundaries such that there is always enough fuel to ensure that the aircraft can reach a diversionary airfield and land safely.

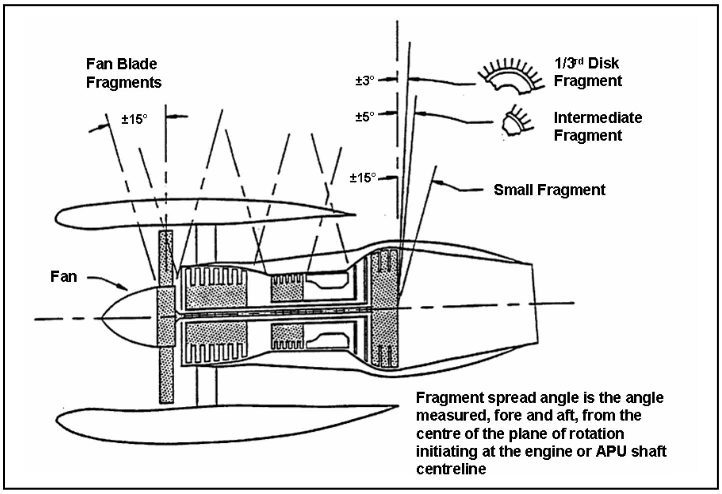

Figure 5 Fragment definitions (taken from reference [16])

The EASA regulations, within reference [16], contain a section specifically addressing the impact of an UERF event on aircraft design and define three different fragment types, shown in Figure 5, which are representative of those that might be encountered during an UERF event.

Section (9)(c) in reference [16], entitled "Alternative Engine Model", states that analysis of an UERF event can be assessed based on "*a single one-third disk fragment with a spread angle of* ± 5°". Also section 4.1 (a) of Appendix 1 of reference [16] states that "*the fragments ejected possess infinite energy making them capable of severing lines, wiring, cables and unprotected structure*". These guidelines, when mapped onto an aircraft representation will create zones that are susceptible to impact from an ejected rotor fragment. Using these zones, a fuel system designer can position fuel tank boundaries so as to minimise the loss of fuel in the event of fragments following an UERF event rupturing the wing skin within these zones. These tank boundaries will often be located at wing ribs, so the integration of UERF constraints may lead to the need to position wing ribs in order to define the extent of fuel tank boundaries.

4.2 Fuel System Packaging

It is necessary during the design of the wing to ensure that there is sufficient internal volume available, both for carriage of the required amount of fuel and also to incorporate physical components associated with the fuel system, such as pumps, valves and piping associated with distribution, refuelling and venting. Hence there will be a trade-off to be made between the aerodynamic and structural performance, versus the size and location of these components.

4.3 Fuel Management

During all flight conditions for which the wings are generating positive lift there will be a vertical, aerodynamic load acting on the wing structure, which is tending to bend the wing structure upwards. The wing structure must therefore be sized to bear this bending load, with the weight of the resulting wing structure being highly dependent upon the maximum size of this load. The weight of the fuel stored within the wing fuel tanks can be used to counteract this bending load, which will result in a lower, net load acting on the wing structure (wing bending relief), with an associated reduction in the designed wing structural weight. Modern aircraft actively manage the distribution of fuel around the various fuel tanks in order to optimise the wing bending relief over the duration of a flight.

As the fuel is used during flight, aircraft with swept wings can experience changes in the location of the centre-of-gravity during a mission, as the mass and centre-of-gravity of the fuel in the wing changes. These changes in the aircraft centre-of-gravity will impact upon the stability of the aircraft. To maintain the overall aircraft stability and trim, it is possible to use the tail and wing devices, but this could lead to potentially undesirable aerodynamic trim drag penalties. This effect can be avoided by positioning a trim fuel tank at the rear of the aircraft and using fuel management to control the centre-of-gravity of the aircraft.

4.4 Lightening Strike Protection

Aircraft may be exposed to lightening strikes during normal operating conditions. Reference [16] includes certification requirements to ensure that the aircraft fuel system is protected against the possibility of fuel vapour ignition. Whilst this requirement will primarily relate to the need for electrical bonding of the wing structure and components, it may also have an impact upon the positioning and packaging of fuel system components.

5 Fuel Systems Modelling

Within IWATVP WPI a number of enhancements have been made to the baseline QinetiQ MDCAD capability, in order to better represent the requirements for fuel systems integration within early aircraft concept design. To date these enhancements address:

- generation of detailed fuel volumes and locations;
- fuel management modelling;
- initial modelling of UERF constraints and their impact upon fuel tank layout;
- generic approach for including individual fuel system packaging constraints.

5.1 Generation of Detailed Fuel Volumes and Locations

Initial enhancements to the capability involved the generation of more detailed fuel volume information using the central CAD geometry modelling within the MDCAD capability. This development was primarily achieved within

CATIA V5, building upon the existing parametric CAD definition of the wing. In particular a scripted approach was developed for automatically deriving the maximum volume and centre-of-gravity of each wing fuel bay from the parametric CAD model. Figure 6 shows an example parametric wing CAD model as generated within the MDCAD capability. The wing fuel bays correspond to the volume bounded by the front and rear spars and each set of neighbouring ribs. It should be noted that this volume is an idealised maximum, since it would be reduced if the physical thickness of structural components and/or systems were modelled in more detail within the CAD definition. Additionally, in practice, as the fuel in a bay is nearly exhausted, some of the available volume will not be useable due to regions where fuel 'pools' away from a local fuel pump inlet. Engineering judgement is therefore used to make reasonable assumptions and estimates about the maximum useable fuel volume within each wing bay.

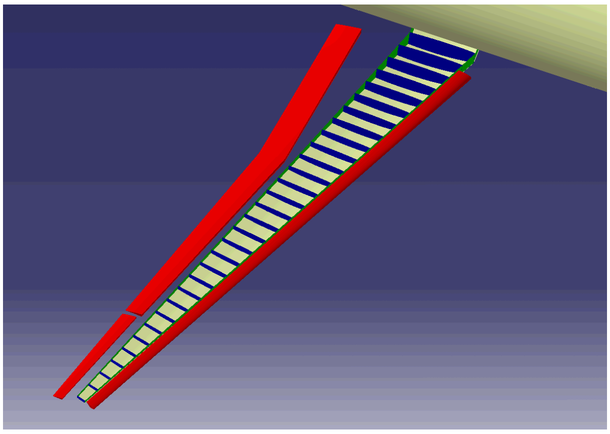

Figure 6 Parametric wing CAD model showing individual wing fuel bays

The generation of more detailed fuel volumes within the MDCAD capability provides a benefit in terms of improved accuracy for the prediction of the overall maximum available fuel capacity, which is used within the mission modelling, as well as allowing for a wider range of load cases to be modelled.

5.2 Fuel Management

The individual wing bay volumes described above can also be used in a variety of ways to improve fuel systems modelling within the MDCAD capability. For instance, multiple bays can be combined together to define an outline fuel tank arrangement. As will be seen in the following section, this choice of which wing bays to assign to which fuel tanks can be driven automatically, to satisfy UERF criteria, as part of the overall MDCAD design process.

The definition of the overall fuel tank layout, together with the definition of the volumes and centres-of-gravity of each wing bay within each fuel tank, can be used as part of a fuel management strategy model within the MDCAD capability. Currently, a simple fuel management strategy is used, corresponding to a small number of different fuel loads and associated flight load conditions. Within the FEA structural sizing process, these fuel loads are used to partly offset the corresponding aerodynamic loading.

5.3 Initial Modelling of UERF Constraints and the Impact upon Fuel Tank Layout

In order to implement initial modelling of UERF constraints within the MDCAD design process, it was first necessary to implement an automatic means for identifying regions of the aircraft geometry which would be affected by an UERF event. The combination of the engine shaft location, the shaft extent and the spread angle of ± 5°, as described earlier, allowed a fragment trajectory volume to be defined automatically for each engine, as part of the parametric CAD model within CATIA V5.

The region of the wing which could be impacted by an UERF event is dictated by the location of both the engine mounted on the local wing and by the engine mounted on the opposite wing. Examples of these fragment trajectory regions are shown in Figure 7 and Figure 8 for a port and starboard engine, both in relation to the starboard wing.

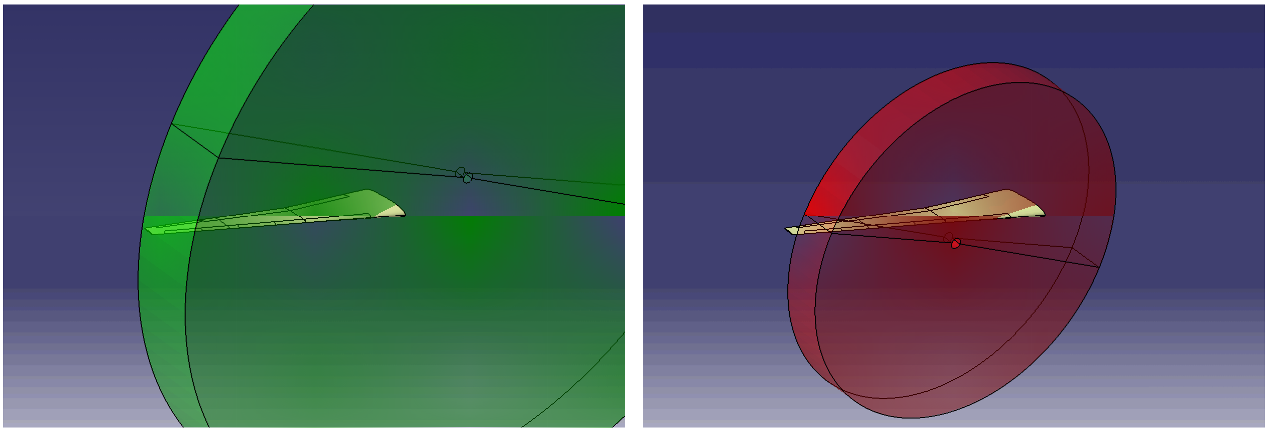

Figure 7 UERF fragment trajectory regions modelled within the MDCAD design process. Left figure shows region for port engine. Right figure shows region for starboard engine

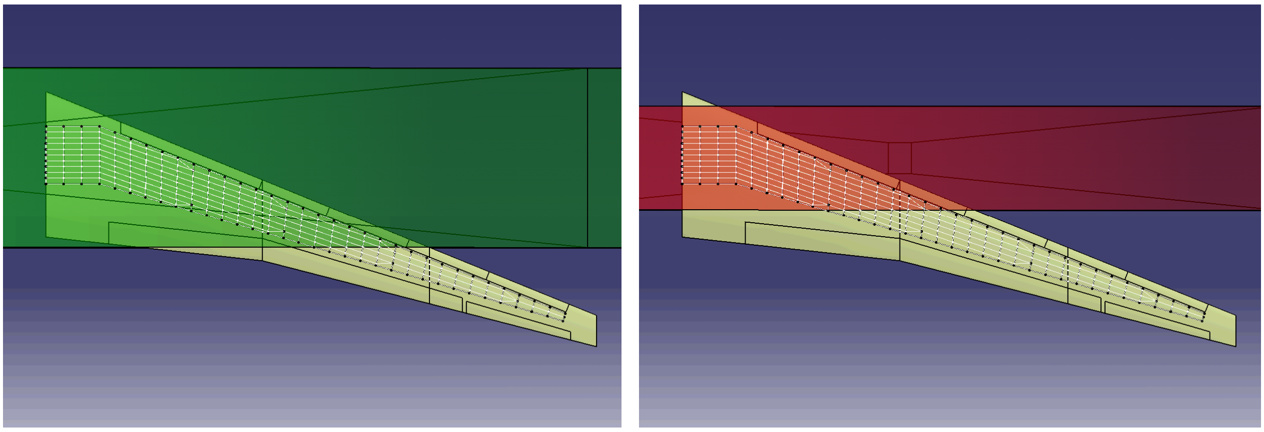

Figure 8 Planform view of UERF fragment trajectory regions modelled within the MDCAD capability. Left figure shows region for port engine. Right figure shows region for starboard engine

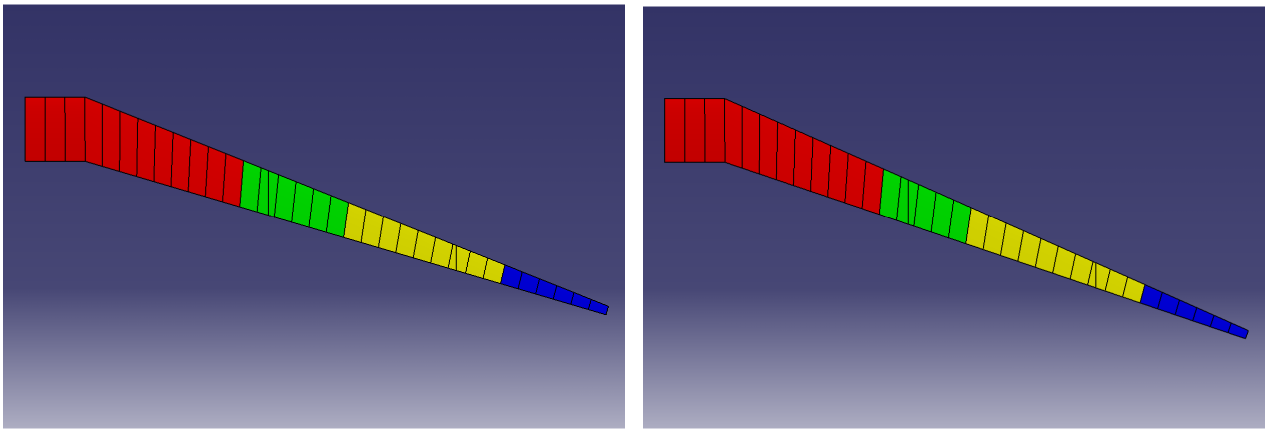

Figure 9 Wing fuel bays affected by UERF fragments. Left figure shows results for baseline wing planform. Right figure shows results for planform with wing sweep increased by 2°. Red colouring corresponds to impact of fragments from both engines, green colouring corresponds to impact from the engine on the opposite wing, yellow shows the bays that are unaffected, blue shows the bays assigned to the fuel surge tank

In order to identify the specific fuel bay regions which would be affected by an UERF event, a further parametric process was implemented within the central CAD modelling within the MDCAD capability. In particular, the CAD representation of the individual wing fuel bays are intersected by each of the fragment trajectory regions. Each wing fuel bay is then automatically identified as either being partially or wholly within a region (and hence affected) or fully outside (and hence not affected). In order to show this more clearly, Figure 9 shows two example wings generated within the MDCAD design process, which differ by 2° sweep. By comparing the green coloured fuel bays for the wing in Figure 9, it can be seen that increasing wing sweep by 2° results in the most outboard green wing fuel bay switching to yellow. This indicates that for the increased wing sweep case, this fuel bay is no longer affected by the UERF constraint.

Based on the example shown in Figure 9, it can be seen that sufficient information is now available to help define a sensible aircraft fuel tank layout and in particular to define the bounds of individual aircraft fuel tanks. By applying rules which dictate the allocation of wing fuel bays to individual fuel tanks, an outline fuel tank arrangement can be generated automatically as part of the MDCAD design process. This fuel tank layout can then be used as part of the fuel management modelling described earlier, to model the effects of fuel load relief for the structural design and similarly to assess the change in fuel centre-of-gravity for aircraft trim.

5.4 Generic Approach for Including Individual Fuel System Packaging Constraints

The final enhancement to the MDCAD capability provides a means for dealing with packaging constraints associated with individual fuel system components (*e.g.* pumps, valves and piping associated with distribution, refuelling and venting). To provide a generic means for dealing with these fuel system geometric constraints, individual components of the fuel system can be defined by a simple length, breadth and height packaging size, together with a location within the wing. Each component is then modelled as a simple box inside the central MDCAD parametric CAD model. Figure 10 shows a simple packaging representation for a generic fuel system component. By this means the wing geometry will be constrained to fit around each internal component during the design process.

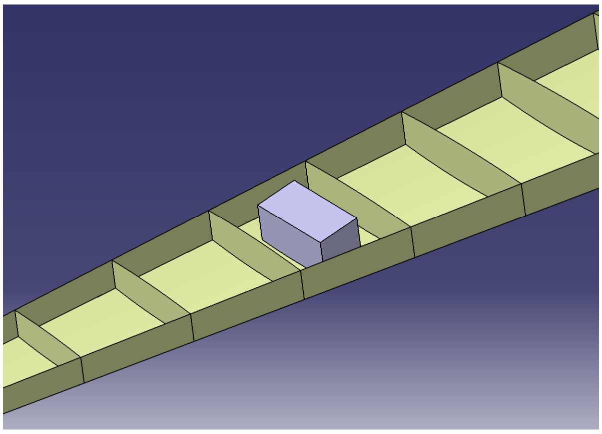

Figure 10 Generic fuel system component modelled as a packaging constraint

Specific enhancements for protection against lightening strike have not, to-date, been modelled within the MDCAD capability. However, where these requirements lead to location or local packaging considerations, it is possible to cater for these using the same generic approach for packaging constraints.

6 Results and Discussion

6.1 Parameter Variation Study

In order to initially assess the application of the new fuel systems modelling within the MDCAD design process, a design parameter variation study has been completed. Various key design parameters controlling the wing geometry, the structural layout and the fuel tank extent were assigned appropriate increments relative to a baseline aircraft definition. The MDCAD capability was run for all of the required parametric variations in order to predict the effect on the overall aircraft performance metrics and to test the robustness of the new fuel systems parametric modelling. The associated results for a selection of design parameters associated with wing planform changes (leading-edge sweep, wing root chord and wing semi-span), structural layout (rib pitch) and the ratio of the span available for fuel tanks (fuel span), are presented in Figure 11. A significant amount of data is generated for each iteration of the process, of which only a limited selection is plotted.

In Figure 11, the variable delta indicates the size of the parametric variation relative to the parameter starting value. MTOW refers to the aircraft maximum take-off weight, L/D is the aerodynamic lift/drag ratio at mid-cruise, L/W is the ratio of the aircraft aerodynamic lift to the aircraft weight at mid-cruise and trim refers to the overall aircraft aerodynamic trim at mid-cruise (measured as the difference between the location of the aircraft centre-of-pressure and centre-of-gravity). It should be noted that these parametric variations do not represent a viable design change, since only one variable is changed at a time and the aircraft is not redesigned to give a self-consistent solution for each parametric change. For example, it can be seen from Figure 11 that individual parametric variations lead to changes in the aircraft range, the lift/weight ratio and the aircraft trim. In practice, during a full design optimisation each of these performance characteristics would be modelled as constraints, such that they achieve target values as part of the design process. In particular, the range is likely to be a fixed requirement rather than an objective, the aerodynamic lift should be equal to the aircraft weight at cruise (*i.e.* L/W should have a value of unity) and the aircraft aerodynamic trim at mid-cruise should be equal to zero (ensuring that the aircraft cruise L/D ratio corresponds to a trimmed mid-cruise condition).

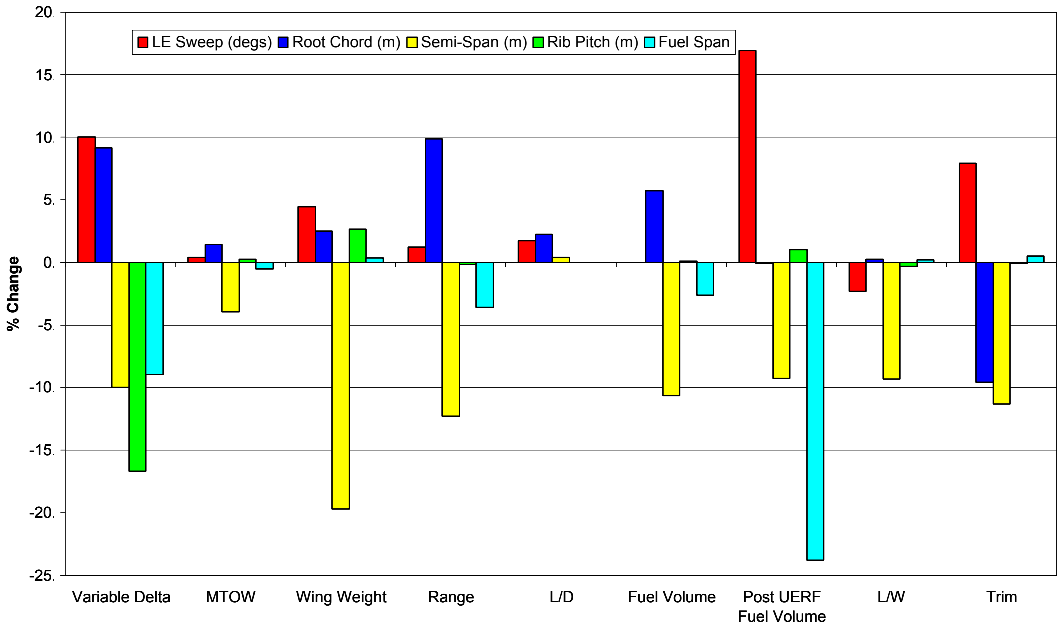

Figure 11 Design parameter variation study

In the context of the work described here, the key outputs of interest are the fuel volume (the available fuel capacity) and the post UERF fuel volume (the volume of fuel remaining in the tanks not affected by the UERF trajectory spread angles). In particular, it can be seen in Figure 11 that increasing the leading-edge sweep has little effect on the available fuel volume (wing thickness is the same as the baseline wing so internal volume is unchanged), but it has a significant effect on the volume of fuel available following an UERF event. This is in keeping with the increase in the post UERF fuel volume following a small increase in sweep described earlier, and shown in Figure 9.

The parametric study also showed that the wing semi-span could be used as an alternative variable to improve the fuel available after an UERF event. As the value of this variable increases, the fuel volume available after an UERF event would increase and it is expected that benefits to the aerodynamic performance of the wing for a wholly constrained case would be seen. However, the wing weight would also increase, as the structure would need to be additionally strengthened to cope with the higher wing bending moments, therefore demonstrating the multi-disciplinary aspect of the problem.

Despite providing an increase in the available fuel volume for the inner wing region, an increase in the variable controlling the wing root chord does not provide any additional fuel volume on the outboard wing and hence does not affect the post UERF fuel volume.

7 Conclusions

This paper has described activities completed by QinetiQ as part of the UK Integrated Wing programme where a number of developments have been made to a civil aircraft concept design process. The design process employs an MDO-based approach, which enables high-fidelity modelling and greater concept detail to be used in the early stages of design. The specific objective for the work described here has been to improve the representation of fuel systems integration requirements within the overall wing design process. In particular, the approach aims to better address the requirements for integrating fuel systems in parallel with, rather than subsequent to, the aerodynamic and structural design of the wing. This has been satisfied by implementing:

- a method of calculating fuel available following an UERF event;
- a generic approach for including individual fuel systems packing constraints.

The implementation of both methods was performed by extending the central parametric geometry modelling within the MDCAD capability and the process was demonstrated by performing a parametric variation study. For the study performed, the variables defining the leading-edge sweep and semi-span were seen as being key to satisfying constraints on the fuel available after an UERF event. Promising insights into the potential benefits of the new modelling approach have also been identified from the application of the parametric study. These include:

- the ability to automatically assess the impact of integrating additional fuel systems modelling;
- demonstrating that the drivers for fuel systems integration may potentially be quite different to the parameters that influence the total fuel volume.

This new MDO process will be applied in full optimisation mode in the near future, outside of the Integrated Wing Programme, in order to demonstrate the impact that better modelling of fuel systems requirements has on early civil aircraft wing design.

Abbreviations & Symbols

ACARE	-	Advisory Council for Aeronautics Research in Europe
CO_2	-	Carbon Dioxide
NO_x	-	Nitrogen Oxide
°	-	Degrees

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