MOB – A EUROPEAN PROJECT ON MULTIDISCIPLINARY DESIGN OPTIMISATION

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Abstract

An aircraft design and optimisation system is presented which adopts different levels of analysis tools (Low- and High Fidelity) for the aerodynamic, structural, aeroelastic and flight mechanic modelling. The system, called Computational Design Engine (CDE), connects modules supplied by different partners from industry, research establishments and from universities, and is distributed over several hardware platforms. In the first part, Low- and High Fidelity modules are presented and the layout of the CDE is discussed. In the second part details and results of an application of the CDE for the optimisation of a Blended Wing Body freight aircraft are presented.

1. Introduction

The European Aerospace Sector is facing a number of critical challenges. One being the threat posed by technology drift allowing emerging nations, with low labour costs, to design and manufacture low cost conventional civil aircraft. To meet this, Europe must introduce optimised and innovative aircraft created through the use of advanced design and manufacturing methods and tools. The second challenge is the increasing use of a collection of companies, distributed across Europe, for the design, manufacture and entry-into-service of new aircraft types. This move reflects both the loss of engineering skill and the need to risk share major projects across a number of separate organisations. This implies that distributed design teams will undertake future designs with the membership of each of these teams potentially being quite small in number with respect to the engineers involved. The overall strategic target for the project MOB (**M**ultidisciplinary **O**ptimisation of a **B**lended Wing Body) is to create methods and tools to allow distributed design teams to create innovative aircraft with the potential for high market penetration.

2. MOB Objectives

In order to meet these strategic objectives the MOB project has been set up to create an effective distributed design system able to handle a complex innovative concept that provides significant improvements over existing designs. The primary purpose of the project is the development of tools and working methods to facilitate the multidisciplinary design of large scale and complex aeronautical products by distributed teams, employing different design approaches and a variety of discipline-based programs, employing either *commercial off the shelf* (COTS) products or proprietary codes. A specific software application is then used to

plug all the design and analysis tools within a complex computational framework, to facilitate the implementation of **M**ulti-Disciplinary **D**esign and **O**ptimisation (MDO) methodologies. This distributed-but-integrated, complex design system is termed the **C**omputational **D**esign **E**ngine (CDE). The CDE structure allows the specific design tools to be coupled in a multi-disciplinary manner and ensures the continuity and consistency of information flow through the design cycle. Within this cycle models with increasing level of fidelity are used in different stages of the design process.

The key objective is to create a system allowing both co-operative and innovative design to be undertaken by a distributed design team employing their own specific design tools and methods.

The secondary objective is to demonstrate a CDE by application to a problem of intrinsic interest, namely a BWB (Blended Wing Body) aircraft. Because this is a highly novel concept existing MDO tools are inadequate and its use as a driving scenario for the project will demonstrate the benefits of a more flexible CDE methodology based upon simulation of the product. Satisfaction of this second objective both validates the CDE tool set and establishes a team of European aeronautical engineers able to support the actual design of a BWB aircraft.

2.1 The Team

The MOB consortium had a genuine multi-national and multi-company composition, comprising English, Dutch, German and Swedish members, ranging from universities to research establishments and leading European aerospace industries (see the complete list of participants in the table).

Many of the MOB team were active in an earlier EU funded MDO project which focused on the design of a large civil aircraft wing linking structures, aerodynamics and manufacturing aspects within the optimisation process.

Cranfield University	UK
Technical University Delft	NL
QinetiQ (formerly Defence Evaluation and Research Agency)	UK
Stichting Nationaal Lucht-en Ruimtevaartlaboratorium	NL
Deutsches Zentrum für Luft- und Raumfahrt e.V.	D
Saab AB	SWE
European Aeronautic Defence and Space Company	D
British Aerospace Systems Ltd	UK
Council for the Central Laboratory of the Research Councils	UK
Kungliga Tekniska Högskolan (KTH)	SWE
Technische Universität Braunschweig	D
Technische Universität München	D
Universität Siegen	D
Universität Stuttgart	D
Technische Universität Berlin	D

2.2 The Blended Wing Body Basic Configuration

The starting Blended Wing Body configuration came from an initial design study undertaken by Cranfield University to meet the civil passenger transport requirement. However, it was felt that a passenger version of the BWB aircraft would have unnecessarily complicated the design process by bringing up problems like emergency evacuation, whilst the objectives of the project could be met by investigating the design of a "simpler" freight aircraft configuration.

2.3 The CDE Basic Configuration

Based on the prerequisites discussed in section 2.2 above, the project came forward with a paradigm for the overall design and optimisation process for the CDE [1] as shown in Figure 1. The green boxes represent the various disciplines (or disciplinary teams using specific discipline-based tools) involved in the aircraft design, such as aerodynamics, structure, flight mechanics etc.

The discipline boxes do not communicate directly with each other but interaction takes place via a single control "box" holding the product data model (the yellow boxes in Figure 1). It is actually here that the specific-but-consistent aircraft models are generated to feed the various discipline specific analysis tools.

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The MDO modules, shown in orange are independent of any specific discipline, though they steer and opportunely invoke them during the design and optimisation cycle.

This layout indicates that the operational system requires a communication system (represented in Figure 1 by the red connectors) able to link disciplines, data and functional activities across a network to draw together a distributed tool set into a single operating system. The tool set needs to be hung on the communications network in such a way that any user, anywhere in design team, can call any tool into play. Essentially, MOB is developing an e-design system that appears to any user as a single integrated system with a variety of tools, brought by individual team members distributed across several countries and companies, according to the design requirements.
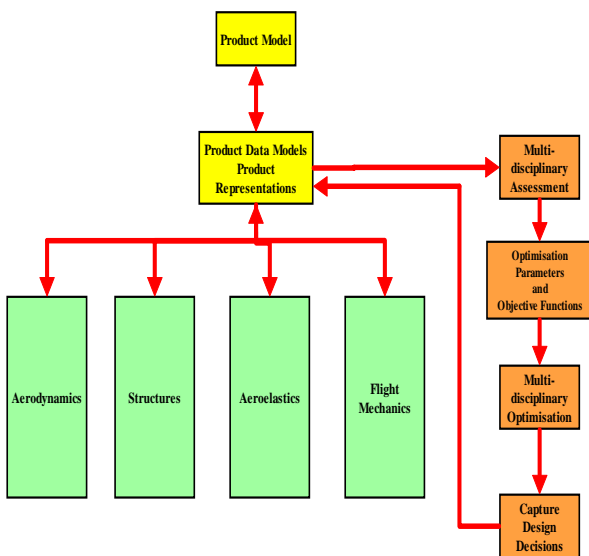

Figure 1. Basic CDE Layout

In order to make the design system comprehensive the discipline modules must be able to accommodate both low- and high-level fidelity models so that the design process can begin with a fast assessment of the initial configuration and then proceed with high quality (but more expensive) computational simulation tools. This system therefore requires:

- Automatic model generation
- Multiple geometry
- Cross-discipline connection
- Multi-level optimisation loops
- Multi-level discipline models.

The CDE building process started with the selection of a proper network communications system to provide the backbone for all the design, analysis and optimisation tools. SPINEware was chosen because of its capability to combine tools and software, supporting the construction of working environments on top of heterogeneous computer networks [2]. The next step was to select models and tools that were to be hung on the system. The underlying concept of the CDE is that it can operate at all levels in the design cycle and at all stages in the knowledge and data assembly process. As indicated above this implies an ability to include low- and high-fidelity discipline models and bring these into play at appropriate points in the design cycle. This requirement suggested a way of developing the CDE, in which various discipline-based teams could start with supporting the CDE first with low-fidelity models. When these had been successfully incorporated and tested in the CDE environment, the teams began to introduce more computationally complex and expensive high-fidelity models.

3. The Product Data and Geometry Models

In order to make the system function as a design environment a product model data and a multi-model generator (MMG) are required to manage the process and feed appropriate geometry data into the discipline tools. Ideally the product data model, the multi-model generator and the multi-model data are all separate entities or functions. For the prototype CDE a single knowledge-based engineering application was developed able to contain the whole BWB aircraft knowledge and extract specific sub-models to feed the analysis tools integrated in the CDE. The consistency of the specific models used, for example by the aerodynamic and the structure analysis tools, was in this way always

guaranteed. ICAD was the KBE (Knowledge Based Engineering) platform selected and employed for the CDE multi-model generator. The BWB aircraft, as defined in this specific ICAD application, consists in an extensively parameterized model, which allows the designer to vary the aircraft top-level configuration parameters (e.g. wing span, type of airfoils, sweep, twist and dihedral angles etc.) and facilitate the assessment of the new design solution either with high- or low-level fidelity models, according to the specific set-up of the CDE.

The BWB aircraft, is represented in the ICAD application as a complex hierarchical structure (the *product tree*), with the capability to store and represent data relations, and provide data and sub-models tailored to the specific format demanded by the various disciplinary analysis tools embedded in the CDE. The knowledge-based capabilities of ICAD are mainly exploited in this latter task, where part of the specific engineering knowledge required to pre-process and set-up the specific analysis models is embedded in the MMG rule base. E.g. the structural models delivered to the FEM analysis tools, consist in sets of ready to be meshed surface elements, which do not require any re-work by the FEM analyst.
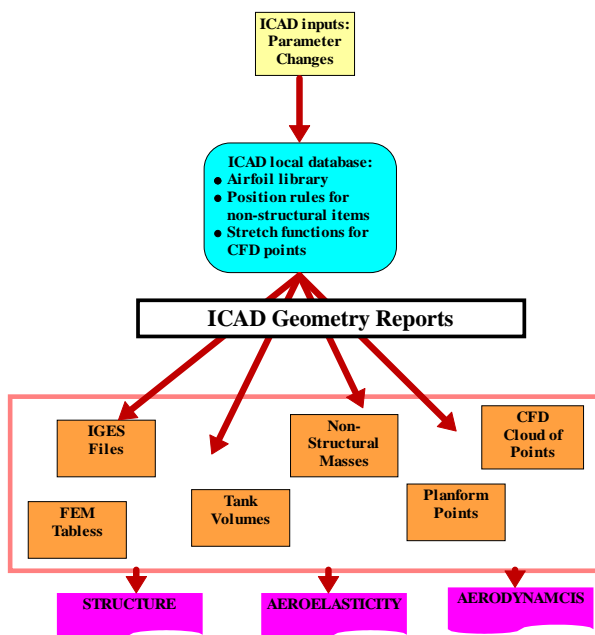

Figure 2. ICAD Geometry Generator

In Figure 2, the structure and the operation mode of the MMG are represented: the whole parametric definition of the BWB is contained in the MMG rule-base. The designer can modify the value of the various parameters via an editable input file and ask for specific models and data as output. The ICAD application is then executed (also in batch mode) and generates a series of reports (IGES files, ASCII tables etc) to be fed to the various CDE analysis tools.
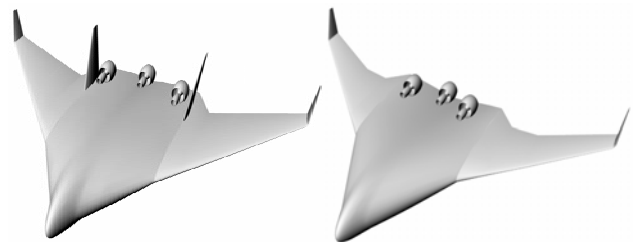

Figure 3. Configurations generated by the ICAD MMG

3.1 The Aerodynamic Models

Low-fidelity aerodynamic models were surveyed and appropriate tools identified and further developed for the project. A mean surface panel method code, WINGBODY, and an actual surface panel method code, PANAIR, were chosen. The codes have been adapted to suit the solution requirements for blended wing body geometries. Both employ inviscid linear flow (incompressible or linear compressible) governed by potential flow equations. This implies that they are not suitable for studying the transonic cruise load cases. However they are very useful as an efficient tool for other load cases for the CDE, e.g. for the approach load case at Mach=0.2.

For the transonic cases two Reynolds-averaged Navier-Stokes codes, namely the MERLIN code of Cranfield and NLR's ENFLOW code were employed as high-fidelity aerodynamic models. Both use structured multi-block grids and automated grid generation.

The output from these CFD tools is used both to provide data on lift, drag etc. and as a data source for other tools, for example, providing aerodynamic data which can be transformed within CDE system into air loads

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for the structural model as shown in Figure 4. Reference [4] gives a full description of the aerodynamics modules and its role in developing the BWB design.

Both in case of low and high fidelity analysis, the geometry was provided by ICAD in the specific format required by either the panel or CFD codes developed by the different MOB parties.
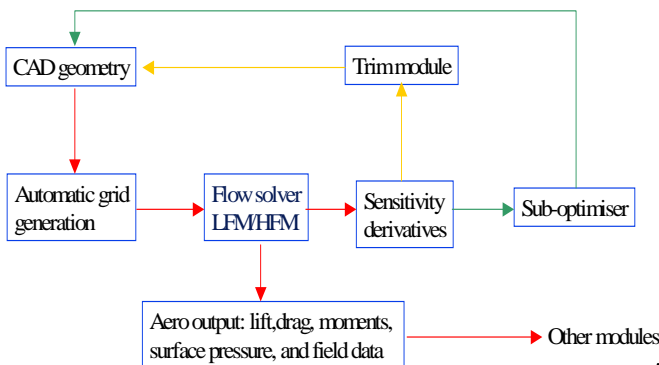

Figure 4. Linkage between Components of the Aerodynamics Module

3.2 The Structural Models

The structures module picks up output from the ICAD geometry and data model which is converted into either a low-fidelity model based on simple beam assumptions, used in the initial development of the prototype CDE, or a high-fidelity Finite Element model. The loads on the structure were obtained from the aerodynamic module in either low- and high-fidelity form for the air load component or as a loading list from ICAD for the non-structural masses.

For the high-fidelity model this module has to perform three major tasks or activities. The first, is to create a NASTRAN finite element model with an appropriate mesh density and element layout. This is accomplished through the use of a "smart" PATRAN session file, which is able to read the geometry and associated information produced by ICAD. This advanced use of session files provides PATRAN with the flexibility to adapt the structural FEM-model to all the geometry perturbation and topological variation occurring when changes are made in ICAD, in one of the

overall design parameters described above. The second task is to apply both the aerodynamic and non-structural mass loads to the finite element model. This requires selecting appropriate data from a CFD run, communicated via SPINE, which has then to be converted into finite element nodal loads through the use of a new program, PALMS, generated by BAE during the course of the project. The final activity is that for each structural model thus created a minimum weight optimisation program must be run so that, at the lowest level in the CDE hierarchy, minimum weight designs are created. An outline of this sub-system within the CDE framework is shown in Figure 5. Further details of the structural model and its linkage to ICAD within the CDE are given in reference [3].
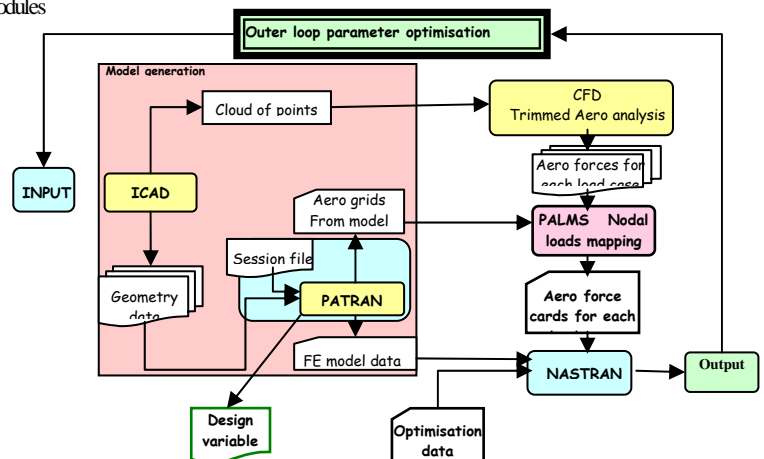

Figure 5. Layout of the Structural High-Fidelity model

3.3 The Aeroelastic and Flight Mechanics Models

Within the modular structure of the CDE a limited number of tools were selected for the aeroelastic module in order to limit interface developments. An ICAD-NASTRAN link discussed in section 3.2 is used to employ NASTRAN finite element models for structural analysis. Aeroelastic analysis is either performed by means of the NASTRAN aero module (considered Low Fidelity) or by means of the flexible ZAERO flutter program (considered High Fidelity). The High Fidelity module has the capability to perform also

transonic flutter analysis by introducing steady CFD results and unsteady airloads from DLR's Transonic Doublet Lattice Method (TDLM) code. A typical example of a transonic flutter analysis of the Blended Wing Body is shown in Figure 6.
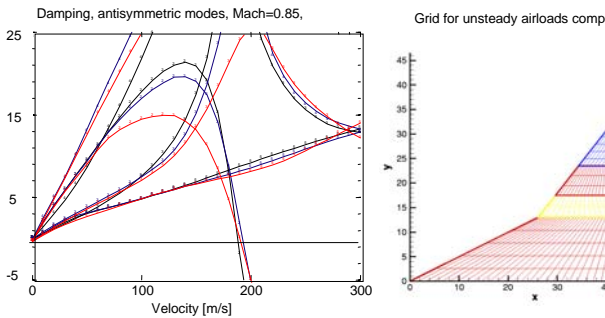

Figure 6. The figure shows the influence of transonic unsteady aerodynamics from TDLM code on BWB flutter damping (blue/black: subsonic airloads, red: TDLM).

Trim calculations are performed by extending the scope of the ZAERO software aeroservoelasticity. This combination is linked to the rest of the CDE via SPINE providing a complete and adequate aeroelastic analysis capability which can be directly accessed by any consortium member. In addition a trim module for the rigid aircraft, developed by SAAB, including a capability to optimise the trim strategy, was integrated into this module. A link to the EADS structural optimisation system LAGRANGE (as an alternative to NASTRAN optimisation) was established, as well as the interface to import unsteady aerodynamic data in the compact form of Aerodynamic Influence Coefficients (AIC) or transonic (TAIC) from specific unsteady CFD codes i.e. TDLM.

This capability allows the creation of designs lying within required limits with respect to the flutter boundary and control effectiveness. It also allows a design to be assessed from a trim and controllability viewpoint.

The layout for the flutter component of the CDE is illustrated in Figure 7. As with the other modules in the CDE this figure illustrates the complexity of the individual modules included in the CDE. Details of this activity are given in reference [5].
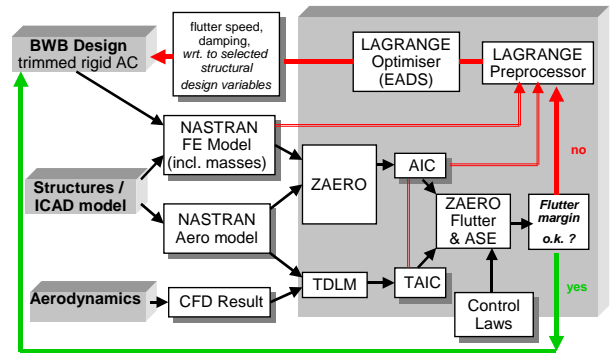

Figure 7. Layout of the Flutter Component

4. The Operational Prototype and selected Examples

A prototype CDE was created using the combination of tools described above in order to test the concept against an actual design requirement. The "designer" using the CDE was the team at NLR in Holland and disciplines selected by this team included structures, aerodynamics and flight mechanics. The design task, chosen by the design team, was the maximisation of the Brequet range for constant "Maximum Take Off Weight" (MTOW). The Brequet range objective function depends on the aerodynamic lift/drag ratio and structural weight. As constraints, the aircraft controllability margin was used together with limits on the structural stress levels. Design variables are wing-twist, sweep and airfoil thickness. The set-up for this design exercise was based on a response surface optimisation approach, which implies that for selected combinations of design variable values the aircraft is being analysed and points generated in design space. Based on these design points an approximate "response surface" was constructed, which can be used to find the optimum design. The CDE architecture to perform the design exercise is presented in Fig.8.
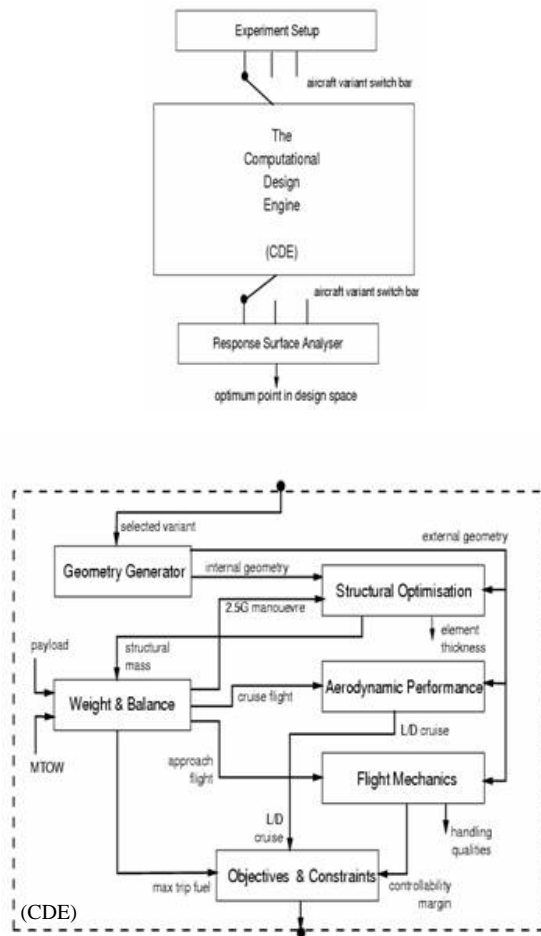
Figure 8. The Prototype CDE Layout

In order to launch the design system an initial configuration is required and is indicated in Figure 8 as the "experimental set-up" which sets the initial ICAD parameterised design. The optimisation system then makes sequential changes in the three design variables which are fed through ICAD to create a sequence of structural and aerodynamic models in the manner described above. A complete description of the prototypes CDE can be found in the paper at reference [6]. (CDE)

4.1 The Optimisation Strategy

The optimisation strategy is based on a multi-level approach with a multi-disciplinary aircraft design task as global level and a structural design task on the local level. The global level comprises only those design parameters which impact all disciplines, typically a limited set of

(e.g. planform) parameters. On a local structural level several hundred groups of FEM-element thicknesses are used as design variables.

For the global design task a Response Surface strategy is preferred over gradient based optimisation schemes. The reasons for this are threefold. First, most analysis modules do not have the required sensitivity analysis for efficient gradient based optimisation. Secondly, this provides an opportunity to relax the timing of the various tasks over the multiple sites, partners and disciplines. This opens ways to efficient parallel processing. Finally, the number of global design variables required is small, making scanning the design area affordable. A response surface represents the shape of the objective and constraint functions in the design space and thereby provides excellent means to visualize the trade-offs between the various disciplines.

Inside the structural level the situation is different. Sensitivity information is available. Moreover the number of design variables is such that gradient based optimisation is more effective.

A response surface methodology requires evaluation of properties of aircraft variants at *a priori* selected points in the design space. This information is provided by the Computational Design Engine.

4.2 Weight and Balance

The *Weight and Balance* module is responsible for keeping a record of all items contributing to the weight of the aircraft. The flight mechanics and aerodynamics disciplines require additional knowledge in terms of centre of gravity location and moments of inertia.

Items are classified according to:

- *Non-structural Items* consisting of items not belonging to the primary aircraft structure (e.g. systems). Saab provided a methodology based on conceptual design methods to estimate the weight of the various components (for most items this is simply a fraction of the aircraft MTOW). The ICAD MMG defined the precise location (and eventually weight

scaling) of these components, with respect to the main structural elements, and representing them as a distribution of concentrated point masses. The total non-structural mass for the BWB reference configuration is W_{nst} = 65158 kg. Figure 9 illustrates the location of the various non-structural items relative to the external shape of the configuration.
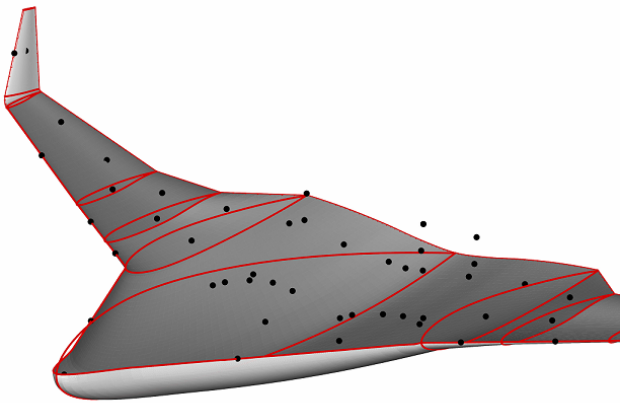

Figure 9. The non-structural items are represented as point masses connected to the aircraft structure.

- *Structural Items* are the main load bearing components such as: ribs, beams, stiffeners, skin panels, etc. This information is obtained from the Structural Optimisation Module. The total structural mass for the BWB reference configuration is W_{st} = 57243 kg. Operational Empty Weight (OEW) is W_{OEW} = 122401 kg.
- *Payload* comprises LD3 containers (freighter configuration). For the BWB configuration, a fixed 113 tons of payload is carried in 174 LD3 containers distributed over a double deck cargo hold. The distribution of the containers over the cargo hold is provided by Cranfield University, see Figure 10.
- *Fuel* stored in two body trim tanks and in the main wing tanks. A fuel scheduler controls the filling and draining of tanks to ensure control over the aircraft centre of gravity. The distribution of fuel is different for each individual loadcase driving the various disciplines, Figure 11

shows an example. Available trip fuel weight (TFW) is computed as the difference between MTOW and the sum of non-structural weight, structural weight, and payload weight. For the BWB configuration, MTOW is fixed at W_{MTOW} = 371280 kg, hence trip fuel weight for the reference configuration is W_{TFW} = 135878 kg.
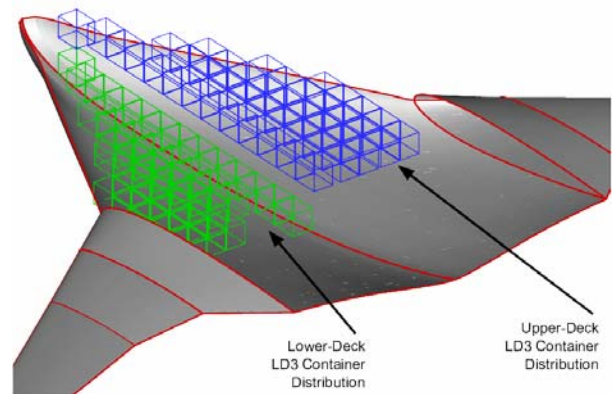

Figure 10. The payload, 174 LD3 containers, is distributed over two decks in the cargo hold.
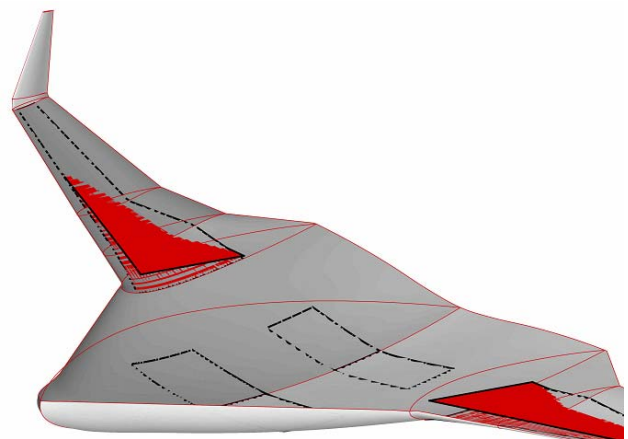

Figure 11. Tank filling is under control of a fuel scheduler which distributes the fuel over the main wing tanks and two body trim tanks. The figure shows the situation at mid-cruise with full payload on-board in which case the body trim tanks are not used.

The Weight and Balance module is assigned the task of assembling the individual mass components into critical loadcases. For each loadcase, a full set of information comprising mass, centre of gravity, moments of inertia, flight condition etc. is generated and

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written to the CDE database. This data presents the driving scenario for the subsequent analysis disciplines for assessment of aerodynamic cruise performance, structural weight, and aircraft controllability.

4.3 Aerodynamics and Trim

The overall optimisation objective, Brequet Range, calls for an evaluation of the configuration lift over drag (L/D) performance during transonic cruise flight condition at Mach=0.85, 35000 feet altitude in standard atmosphere conditions, maximum payload on board, half the trip fuel available in the wing tanks, and empty body trim tanks. Tailless aircraft longitudinal trim, by means of deflecting the partial-span trailing edge devices, does have a serious impact on the aerodynamic efficiency in cruise and needs to be accounted for in the analysis.
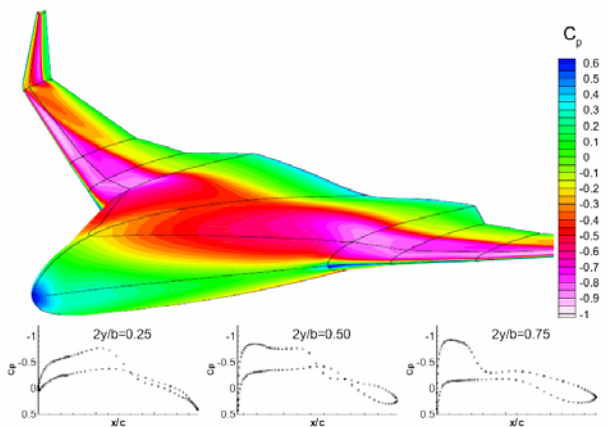

Figure 12. Example of the resulting surface pressure distribution for the BWB reference aircraft. The lift over drag ratio is *L/D* = 16.82.

L/D performance is computed by the Navier-Stokes code ENFLOW where the CFD flow solver is coupled with static Aeroelastic deformation and trim. During the flow solver iterations the angle-of attack and trailing edge control surface deflections are updated to arrive at the prescribed lift (equals the aircraft mass at mid cruise) and pitching moment (centre of aerodynamic force coinciding with centre of mass). This trimming loop is essential as the deflections of the trailing edge control devices

alter the spanloading and hence the wing bending moments.

4.4 Structures

The Structural optimisation module is responsible for sizing the primary structural elements of the configuration such that it can withstand all loads that may occur during the lifetime of the aircraft. The driving scenario is currently limited to a single load case: i.e. a +2.5G pull-up manoeuvre at sea-level altitude and Mach=0.50. The aircraft payload/fuel loading is configured such that the (wing) structure experiences maximum bending moments with minimal inertial relief: i.e. max-payload on board, full body trim tanks, and empty wing tanks.

A minimum weight structural optimisation is carried out with stress and aeroelastic (flutter) constraints. Methods with different levels of fidelity (multi-model) are implemented in the CDE

- Low-fidelity structures: Bending beam theory
- High-fidelity structures: FEM modelling
- Low Level aeroelastics: NASTRAN
- High Fidelity aeroelastics: ZAERO

The high fidelity structural module is based on the finite element method implemented in NASTRAN. The optimisation objective function is minimum weight. The optimisation constraints are element thickness T > 2mm, von Mises stress level $|\sigma| < 250$ N/mm^2 and damping g > 0.03 at the dive speed $V_D = 300$ m/s at sea-level altitude. Element thickness, grouped in so called design areas, are used as design variables.

Estimating the structural weight of a real life aircraft cannot be entirely based on the weight from FEM calculations. The FE model does not include details about, for example: flap or aileron supports, engine attachments, spoilers etc. (Many of them are just included as con-centrated non structural masses). In traditional preliminary design statistical methods are used to estimate these mass contributions. Based on several studies that address this problem [7] a compensation factor of 1.5 is used within the

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CDE. This factor is set on the FEM-based structural mass calculation in order to get a total structural mass.

The final outputs from the structural optimisation module are: structural weight, centre of gravity, and moments of inertia. These are computed from the optimised element thicknesses and supplied to the CDE database. The resulting structural mass for the Blended Wing Body reference aircraft based on bending beam theory is: W_{st} = 57243 kg, $x_{cg\ st}$ = 31.21 m and the results based on FEM analysis is: W_{st} = 66521 kg, $x_{cg\ st}$ = 34.00 m.

The flutter constraint can also be computed by a low-fidelity as well as by a high-fidelity module. The HF-Module adopting steady CFD together with TDLM is outlined in chapter 3.3.

4.5 Flight Mechanics

The flight mechanics module is responsible for the assessment of the longitudinal (in)stability and controllability of the BWB aircraft for all weight and centre of gravity (x_{cg}) combinations (JAR/FAR/FAA certification requirement). As the most critical condition occurs at low dynamic pressure, a low-speed approach flight scenario drives the flight mechanics assessment. This evaluation comprises open-loop as well as closed-loop analysis.

The Weight and Balance discipline provides the mass distribution of the various aircraft components. This information is used to build up an aircraft weight and balance envelope. Figure 13 shows the situation for the two extreme cases of zero-payload (blue) and full-payload (green). For the full-payload case, the wing tanks are used exclusively. For the zero-payload case weights up to OEW + TFW are considered. In that case, the forward body trim tank (50 tons capacity) is used first, after which fuel carries over to the main wing tanks. Figure 13 shows how the aircraft actual centre of gravity is assessed versus the aircraft tolerable centre of gravity boundaries dictated by the flight mechanics constraints (discussed below).

Computing the tolerable centre of gravity range calls for information on the aerodynamic forces and moments for departures from equilibrium flight at low-subsonic speeds. This information is provided using panel methods by NLR (PDAERO) or Cranfield University (WINGBODY). The results are expressed as linear expansions of the non-dimensional lift (C_L) and pitching moment coefficient (C_m).

With the available aerodynamic data, the flight mechanics module computes the neutral point (x_{np}) and the tolerable forward as well as rearward centre-of-gravity (x_{cg}) boundaries according to five longitudinal assessment criteria. The first criteria applies to the take-off ground run for which a rotation speed V_r = 140 knots is taken as representative for a heavy weight transport aircraft. The remaining criteria apply to an approach flight phase at 140 knots. Adopting the required 30 percent speed safety margin on approach implies that the aircraft must be operated safely down to V_{min} = 110 knots airspeed. It is assumed that a full-authority flight control system (FCS) will not permit airspeeds below 110 knots, such that the certification requirement of demonstrating controllable handling up to the actual stall speed need not be demonstrated in the usual way. The assessment is described in detail in [6].
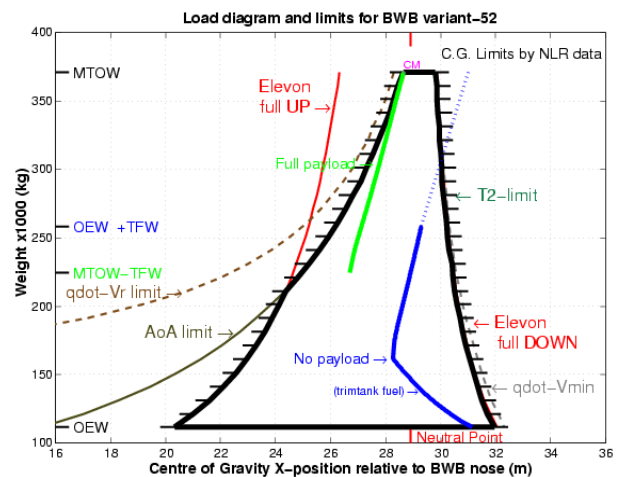

Figure 13. Aircraft weight versus centre-of-gravity envelope. The flight mechanics discipline assesses the *actual* versus the *tolerable* envelope. The result is the *Controllability Margin* (CM), which is one of the driving constraints of the optimisation on the global level.

Figure 13 illustrates the overall constraint, the Controllability Margin (CM). The controllability margin quantifies the most critical

distance between the tolerable and the actual W- x_{cg} envelopes. A positive CM value indicates that favourable conditions prevail for sufficient longitudinal controllability. A negative value indicates that at least one of the constraints is violated.

4.6 Application to Blended Wing Body Optimisation and Design Variables

The CDE was demonstrated using the Blended Wing Body concept as the driving scenario. The design task is to restore controllability while maximising the Brequet range. At the global level, 5 design variables were selected for optimisation, i.e. wing-twist θ_1, wing-thickness θ_2, wing-sweep θ_3, fuselage-length θ_4, fuselage-camber θ_5. At the local level, a high fidelity structures model was employed for weight optimisation.

The individual effects of the selected design variables were surveyed during a first optimisation run. For this purpose polynomial expansions were used to build up the response surfaces.

Aircraft variants were generated through design parameter offsets from their nominal values with a value of 3° for wing-twist and wing-sweep, 3 m for the fuselage chord length, 10 percent relative wing thickness increase (z/c: = 1.10 * z/c), and a one percent fuselage profiles aft-camber perturbation (z/c: = z/c – 0.01 * sin $(2\pi/x/c)^2$)). All perturbations are applied with negative and with positive sign. This gives rise to 10 aircraft variants which were analysed by the CDE using a cluster of 4 Silicon Graphics workstations running up to 3 aircraft variants overnight.

The first step undertakes a set of single parameter optimisations that explores the influence of each of the five design variables when considered separately. In design space this can be visualized as a 1D optimisation process. Results from these individual optimisation studies provide useful preliminary information to the designer. E.g. it provides a feel for the relative effects of the individual parameters on the objective and constraint values and allows fine-tuning the step size of the design offset parameters. Although almost all individual parameters are found to effect controllability, no single parameter was found that could restore the aircraft controllability margin (CM) to positive values. The design study continued with a second optimisation run in which the effects of pair-wise combinations of design variables are introduced into the optimisation process, for example optimising using wing-twist and fuselage length (θ_1 and θ_4). This can be visualized as optimising the design in a 2D subspace.

This gives rise to 40 additional aircraft variants (indicated as aircraft variants numbers 12 through 51) which were analysed by the CDE again using a cluster of Silicon Graphics workstations running over a weekend.

From the resulting pair-wise combinations of design parameters, the designer can start to build up knowledge on which design variable combinations are most effective in achieving the design targets. For example, from all 10 2D design subspace combinations available the combination of fuselage-camber versus wing-sweep and fuselage-camber versus fuselage-length are both equally effective in driving the design closer towards the feasible design space.

Note that the Brequet range equation allows a separate assessment of the impact of structural weight changes and aerodynamic L/D efficiency changes in cruise.

The conclusion from this second level optimisation study is that controllability can be improved by shortening the fuselage and increasing the aft-camber of the fuselage profiles. However, the impact on the overall design objective (Brequet range) is negative.

The data from the second level optimisation process allows the design to move to the equivalent of a 3D design subspace involving triple combinations of design variables. It should be noted that the response surfaces thus constructed, no longer involve a full factorial approach.

From a visual inspection of the response surfaces, the wing-twist, fuselage-camber, and fuselage-length combination seems most promising. Design entry was processed by the

CDE to get one additional point supporting the 3D response surface near the expected optimum in the design space. Figure 14 and Figure 15 present the results.
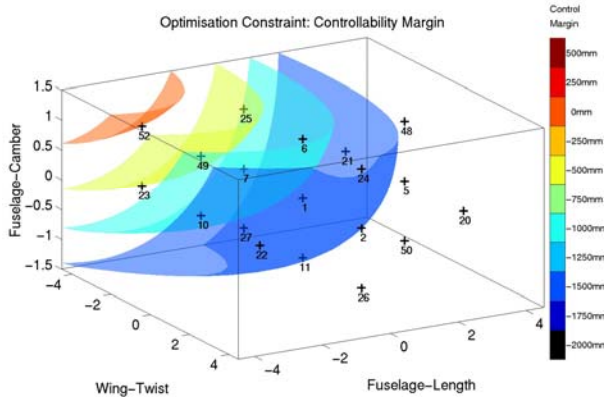

Figure 14. Controllability Margin in the 3D wing-twist, fuselage-length, fuselage-camber design space.
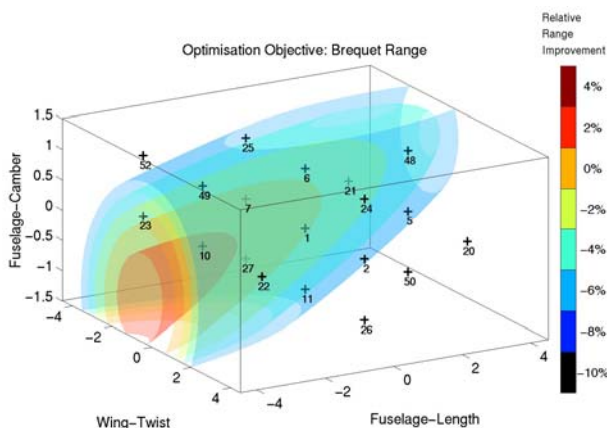

Figure 15. Relative Brequet range improvement in the 3D wing-twist, fuselage-length, fuselage-camber design space.

Optimal Design of Experiments techniques can be employed in the exploration of higher order combinations of design variables equivalent to 4D and 5D design subspaces where the full-factorial approach does become prohibitively expensive. This has not yet been undertaken but is a topic for future research.

5. Conclusions and Outlook to the Future

A Computational Design Engine, or CDE, for multidisciplinary design and optimisation specially tailored to the needs of a multi-level, multi-model, multi-site environment has been designed and implemented.

The project has demonstrated that a complex set of tools distributed over a network can be drawn together to form a single design system and a CDE, in which the tools and fidelity levels can be changed, provides a very effective design environment. The system was demonstrated with an application to the Blended Wing Body configuration. For this tailless aircraft concept it is not surprising that the flight mechanics constraint dominates the design problem. It was shown that the CDE is applicable in the early stages of aircraft design process to find the ball park area of a feasible designs after which a more performance driven optimisation can be performed.

A future MDO within a more advanced CDE will require an ability to include other factors in the total design process e.g. structural design concepts, manufacturing costs, maintainability.

Acknowledgement

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