HIGH-FIDELITY BASED MDO: A CLOSER LOOK AT THE SELECTED SUB-PROCESSES OVERALL AIRCRAFT DESIGN SYNTHESIS, LOADS ANALYSIS, AND STRUCTURAL OPTIMIZATION

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Summary

MDO approaches for overall aircraft design based on high-fidelity tools and methods usually go hand in hand with complex computational processes. This is especially the case as the number of the disciplines and the complexity of the disciplinary methods and models increases. Apart from aerodynamic performance analysis of the flexible aircraft using high fidelity CFD analysis, further disciplinary sub-processes were part of three high-fidelity based MDO processes developed and applied within the DLR project VicToria. They were overall aircraft design (OAD) synthesis, loads analysis, structural optimization. In the following, the sub-processes with their simulation models, the analysis and optimizations methods, and the typical responses to be fed into the respective MDO approach are layered out. Furthermore various aspects of the complexity of the simulation models and selected results are presented.

Keywords: Multidisciplinary optimization, high-fidelity based, overall aircraft design synthesis, loads analysis, structural design, structural optimization

1. INTRODUCTION

Complex computational processes are typical for high-fidelity based multi-disciplinary optimization (MDO) approaches. Such characteristic could be observed within the DLR project VicToria, where the built-up and application of various high-fidelity based MDO approaches was one focal point.

Apart from aerodynamic optimization using high-fidelity based CFD analysis, further sub-processes were part of the MDO processes developed within VicToria. The disciplinary sub-processes comprise overall aircraft design (OAD) synthesis, loads analysis, and structural sizing respectively structural optimization. The presented paper expounds such MDO sub-processes in order to exhibit their contributions and capabilities for the respected MDO process and also their complexity when dealing with a high-fidelity based MDO approach.

The sub-process “overall aircraft design synthesis” is included to preserve global aircraft requirements during the design process. As disciplinary results affect also global aircraft parameter, an appropriate exchange and reasonable adaptations have to be taken into account. Reasonable global geometrical parameters and the position of the components like wing and tailplane have to be preserved. [1]

The sub-processes “loads analysis” covers a comprehensive loads analysis with several hundred load case where maneuver- and gust load cases are taken into account. Therein also loads analysis using loads control methods are considered.

The structural sizing and optimization is done component wise. For the set-up of the structural models component wise parametric and fully automatized approaches are used. The structural models exhibit the fidelity of preliminary design level, where the basic load carrying structural parts are modeled with finite elements (e.g. stringer reinforced skins, spars, and ribs for wings). The dimensioning is done with sizing methods following the fully stressed design concept and with gradient based structural optimization methods. With respect to the material, aluminum as well was carbon fiber reinforce plastic are taken into account.

In one case an integrated and automatized design process is used, with the basic design steps: parametric modelling, loads analysis, and structural optimization. All sub-processes have interfaces with the CPACS data format that has been developed at DLR. Such unified database facilitates the process set-up and the interfacing between the various sub-processes.

As test case basically the XRF1 from Airbus is used. The geometry the structural concept is based on the provided data of the XRF1.

2. HIGH-FIDELITY BASED MDO APPROACHES

Basically three MDO processes have been developed and applied within VicToria: the Integrated Aero-structural Wing Optimization (IAWO), the Multi-Fidelity Gradient-Based concept (MFGB), and the Many-Discipline Highly-Parallel approach (MDHP).

IAWO is an integrated process chain for aero-structural wing optimization based on high-fidelity based simulation method. The integrated structural wing box sizing in the parallel static aeroelastic CFD/CSM analysis is a principal trait of the IAWO approach. Furthermore large geometrical changes are realizable as well as the consideration of global optimization strategies. Within VicToria especially the influence of aeroelastic tailoring using carbon fiber composites and structural concepts for more flexible wings were investigated. [2]

MFGB represents a multi-fidelity gradient based process chain, which allows for several ways to employ design sensitivities for the aircraft MDO. The main disciplines comprise aerodynamics, structure and propulsion. Constraints from OAD are taken into account. One distinguishing characteristic is the implementation of efficient methods for computing disciplinary and cross-disciplinary sensitivities. [3]

MDHP is novel and cybermatrix based approach to aircraft design through multidisciplinary optimization. Therein three aspects representing a design problem are fused by an approximate Karush-Kuhn-Tucker system. For the cybermatrix, the rows of the system are arranged among disciplinary groups. Due to large computational resources thereby many human experts, means sophisticated simulation methods developed by disciplinary experts, carry out massive computational work in a parallel fashion. [4]

As the presented paper dealing with the sub-processes excluding aerodynamics is part of a session of the DLRK2020 dedicated to the DLR project VicToria, the three MDO approaches IAWO, MFGB, and MDHP with emphasis on the MDO concept and the high-fidelity aerodynamics analysis are expounded in three separate presentations [5] [6] [7].

3. DISCIPLINES WITHOUT AERODYNAMICS

Aside from CFD analysis and optimization applied for aerodynamic design further sub-processes are part of the mentioned MDO approaches. They belong to overall aircraft design synthesis, loads analysis, and structural sizing respectively optimization. The paper lays out the mentioned MDO sub-processes in order show to their contribution and capabilities for the selected MDO process, but also their complexity when dealing with a high-fidelity based MDO approach.

3.1 Overall Aircraft Design

The overall aircraft design synthesis sub-process is mandatory to ensure an aircraft configuration that fulfills the global requirements. In order to take into account for the disciplinary methods affecting also global aircraft design parameters (e.g. wing position at the fuselage, structural weight, aerodynamic characteristics) an appropriate exchange of disciplinary results is preserved. A striking argument regarding the necessity to incorporate OAD methods within the MDO process can be seen in the aircraft's consistent mass breakdown in FIGURE 1 for the maximum take-off weight and in FIGURE 2 for the operating weight empty. DLR's interpretation of the XRF1 mass breakdown is the results of the new conceptual aircraft design tool openAD [8].

Due to the estimated aerodynamic characteristics, like lift and drag, as well as the engine performance, the gross mass and the related center of gravity positions are heavily impacting the overall aircraft performance as shown in FIGURE 3 for the flight trajectory and in FIGURE 4 for the payload range characteristic.

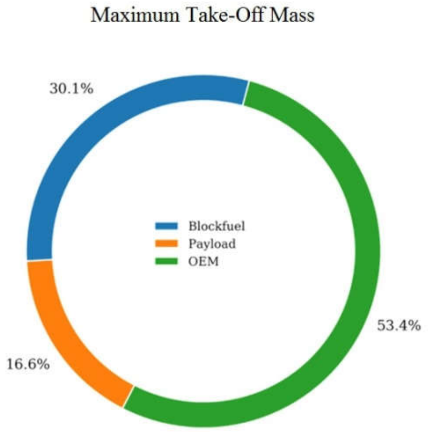

FIGURE 1 XRF1-DLR mass breakdown for the maximum take-off mass from openAD

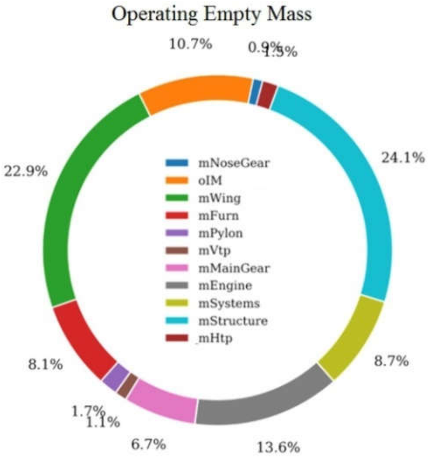

FIGURE 2 XRF1-DLR mass breakdown for the operating empty mass from openAD

If updated information is available from high-fidelity calculation for aerodynamics and structure, openAD acts as a synthesizer for a consistent overall design and ensures that the top level aircraft requirements are fulfilled. An in-house mission analysis tool is used for trajectory visualization and overall mission calculation. Step climbs are taken in to account at the cross over point where the fuel performance is better at the next 2000ft step altitude. The actual fuel performance at a given point in time t is calculated from the actual mass properties at that point, the actual flow situation from the trimmed high-fidelity polar and the actual condition of the engine needed to ensure the force equilibrium.

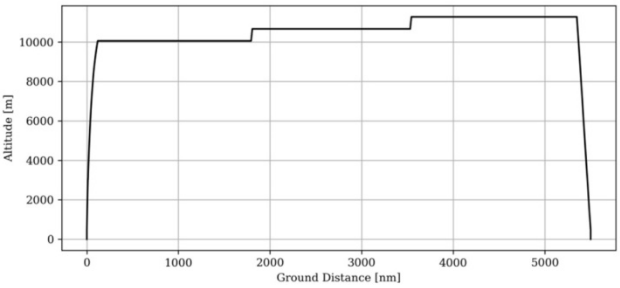

FIGURE 3 Flight trajectory of the design mission from DLR's mid-fi standard overall aircraft design workflow

In **FIGURE 3** the design mission of the aircraft is visualized with its two step climbs for optimum block performance. In order to retrieve a full payload-range capability associated to the aircraft design as shown in **FIGURE 4**, several missions need to be calculated in accordance to the respective characteristic of the mission.

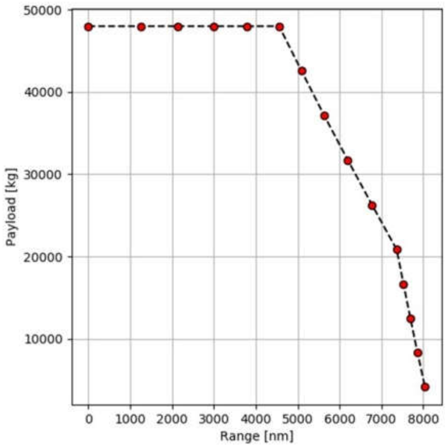

FIGURE 4 Payload range characteristic from DLR's mid-fi standard overall aircraft design workflow

Six missions (red dots) are shown with maximum payload and respective take-off-mass. Five missions were used to display the substitution line of the payload-range-characteristics with maximum take-off mass. Four more missions are shown with the maximum fuel capacity used and respective take off masses. The slope of the substitution line indicates the overall efficiency of the aircraft for a given payload range capability that is required at one single reference combination of payload and range. All missions that are not the so called "design mission" can be perceived as off-design characteristics of the aircraft. Any assessment of the aircraft can then be performed either on a certain off-design-condition that reflects a mean mission of the aircraft in operation or on weighted distribution of missions that are required from the market demand

3.2 Integrated Loads Analysis and Structural Optimization Sub-Process

For the MFGB and the MDHP approaches, apart from the aerodynamic analysis and optimization, an integrated and highly parameterized sub-process has been applied, called cpacs-MONA. [9] The fully automatized process, as depicted in FIGURE 5 is DLR's so-called aeroelastic design process using CPACS data format for the input and output. Also a structural finite element model of the complete aircraft, the GFEM/Dynamic, is output of cpacs-MONA. This model is furthermore used for the CFD/CSM-coupling and the more complex loads analysis step. The process starts with conceptual design based loads analysis as well as a set-up of a first mass model and stiffness distribution. After the parametric set-up of the simulation models for the loads analysis and the optimization models for the gradient-based structural optimization (MDHP) [7] [4] or sensitivity analysis (MFGB) [6] [3], the loads analysis using MSC Nastran takes place. Prior to the structural optimization or the sensitivity analysis the design loads are selected automatically. Therein also externally calculated loads (e.g. from VarLoads for the MDHP approach, see section 3.3) could be included. The final step is the structural optimization or as chosen for the MFGB concept the sensitivity analysis. In order to reduce the amount of sensitivities to be treated for the MFGB optimization a filtering concept was developed. In case structural optimization is chosen, the loads analysis could be repeated using the updated structural properties. Such looping until convergence leads to a consistence between the structural model and the aeroelastic loads.

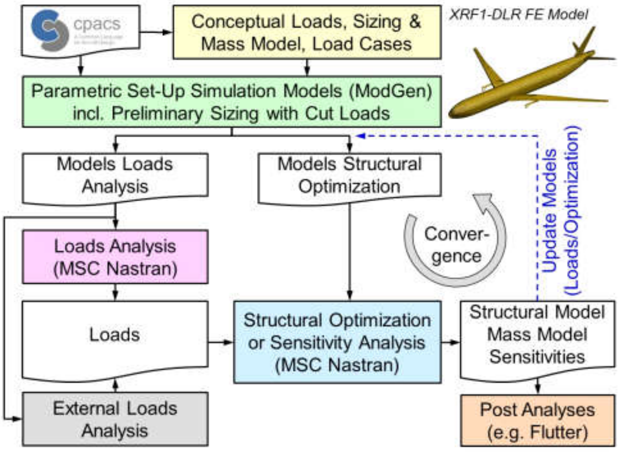

FIGURE 5 Integrated aeroelastic design process cpacs-MONA

The structural modelling for the loads analysis and the gradient based structural optimization is founded on a common parameterization concept for the outer geometry and the housing basic load carrying structure for the complete aircraft [10]. The impact of the extensive loads analysis, covering maneuver and gust loads, on the structural design, can be seen in the correlation of design fields to corresponding dimensioning load cases. FIGURE 6 displays the impact of the landing loads on the area where the landing gear is attached to the wingbox structure, while push-down maneuvers affect evidently the wing tip region compared to the other load types.

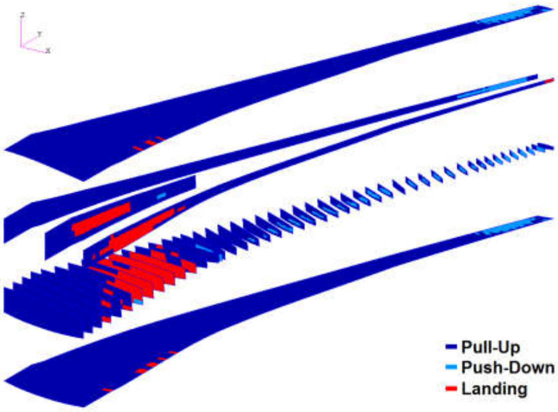

FIGURE 6 Structural wing box showing areas where specific load types dominate the structural optimization

Furthermore the comprehensive loads analysis allows for an even more sophisticated investigation regarding the design loads at arbitrary stations of the load reference axis of the aircraft configuration. In FIGURE 7 it is shown that for a particular wing station the pull-up and the push-down maneuvers lead to the maximum respectively minimum loads, while the gust and the yaw cases have to be also taken into account as design loads as far as they are part of the loads envelope.

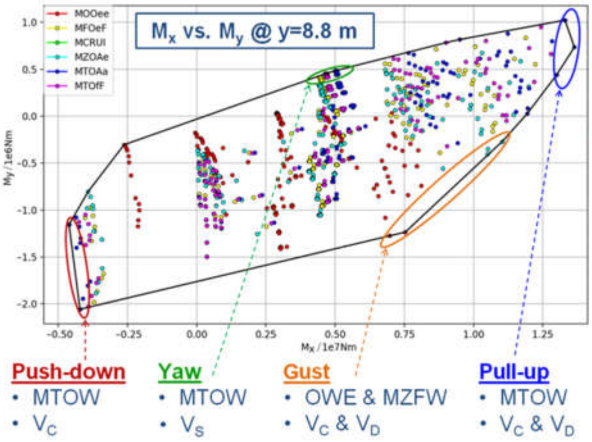

FIGURE 7 Loads for a selected wing station of the XRF1-DLR and the loads envelope

Cpacs-MONA is also capable of using data from the high-fidelity based CFD analysis part of the MDO approaches to correct the aerodynamic of the VLM/DLM panels of the GFEM/Dynamic within the comprehensive loads analysis step. Therefor the possibility of MSC Nastran to correct the lift curve slope of the panels using the so-called WKK-correction [11] is used. The CFD-data from seven different Mach numbers (0.3 to 0.83) with a small increment in angle of attack are used to calculate the correction factors for the VLM/DLM panels.

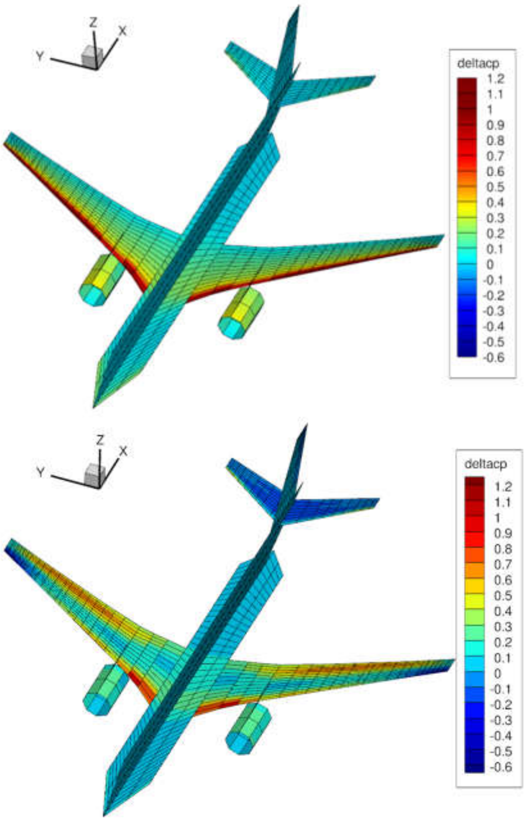

FIGURE 8 Aerodynamic mesh of the GFEM/Dynamic showing the delta pressure distribution without corrections (a) and with corrections (b)

Besides of the optional aerodynamic correction also a geometrical correction to take the camber and twist distribution of the wings into account is an inherent part of cpacs-MONA. In FIGURE 8 the delta pressure distribution (Δcp) of the aerodynamic VLM/DLM-mesh for the GFEM/Dynamic is shown. At the top part the Δcp distribution is shown for the pure VLM/DLM without any correction and at the bottom with aerodynamic and geometrical corrections.

3.3 Loads Analysis with Controls

The loads analysis used for the MDHP approach comprises the classical open loop maneuver and gust load cases, but allows also for the inclusion of an active flight control system. While the flight control system design is mainly driven by flying quality considerations, the influence of automatic flight control functions on structural loads can be substantial.

Furthermore, an active flight control system can enhance the characteristics of an aircraft by employing load alleviation functions and hence reduce the design loads in maneuver and gust conditions, as well as improve the drag performance by optimizing the lift distributions of flexible aircraft in cruise conditions.

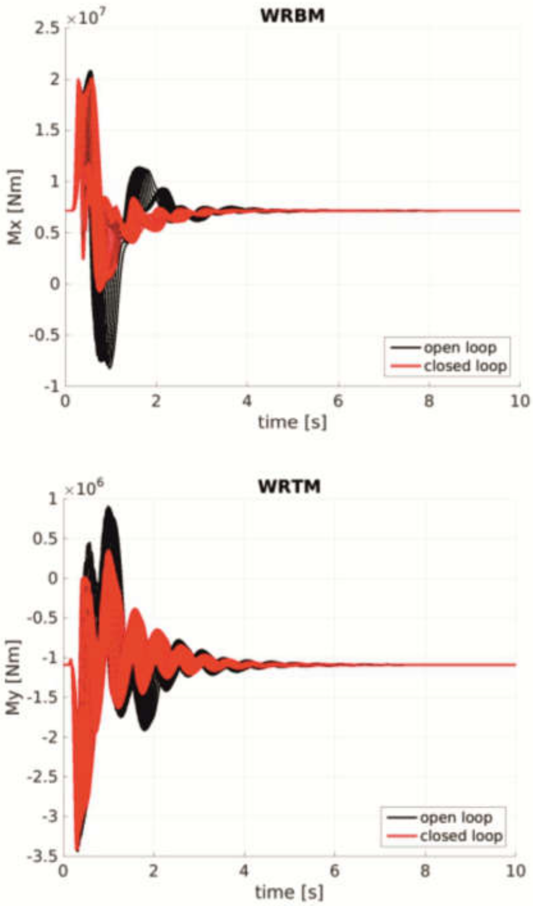

FIGURE 9 Wing root bending (a) and torsional responses (b) due to longitudinal gust excitation for open and closed loop

In the so-called Control Configured Vehicle (CCV) method, the flight control law design is an integral part of the optimization and hence flight performance boundary conditions, active load alleviation etc. have a direct influence on the optimal aircraft configuration. The method is integrated in the loads environment VarLoads. An exemplary application for the vertical tail plane is expounded in [12].

The significance of the consideration of flight control methods for loads alleviation can be seen in FIGURE 9 Therein the bending and torsion moments due to a defined gust excitation at a specific station and flight point are displayed with (closed loop) and without (open loop) load alleviation.

The structural simulation models for the loads analysis herein are the result of an assembling and condensation process using the component structural model for the wing, the horizontal respectively the vertical tail, and the fuselage as described in section 3.4.

For a fully integrated flight control system available within the VicToria MDO processes, the Nonlinear Dynamic Inversion (NDI) concept is utilized. The NDI method allows for rapid-prototyping of control algorithms based on given design specifications while automatically adapting to the current design configuration of the aircraft [13]. The major difference compared to classical methods is that actual aircraft control/ behavioral specifications are the design criteria of the control system, not control law parameters. This makes NDI ideal for application in MDO processes such as the ones employed in the VicToria project. The control law specifications can be categorized into four more or less independent design degrees of freedom (see FIGURE 10):

Control Allocation
Generalized control commands for rolling, pitching and yawing are mapped to physical control deflection commands based on automatic controllability analyses.

Inverse Model Equations
Inversion of the relation between differentiated command variables and the generalized commands leads normalized and decoupled pseudo control responses. This part thus handles any vehicle-specific dynamics.

Command Shaping
The desired aircraft behavior to command inputs is adjusted based on reference models. These inputs are then used to generate reference values for the pseudo controls in the inverse model equations and the feedback controller.

Feedback Controller
Disturbance rejection and robustness.

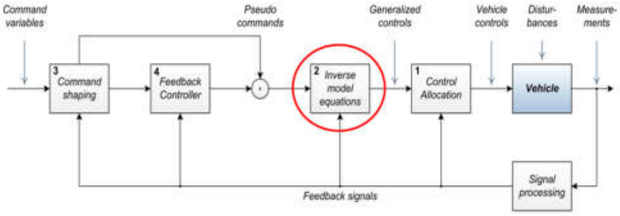

FIGURE 10 Control law aspects in INDI synthesis

Changing aircraft configurations in the VicToria optimization process affect the structural, dynamic and aerodynamic model and thus, at a bare minimum, only adaptions to the inverse model equations have to be made in the control law design.

Incremental Nonlinear Dynamic Inversion (INDI) in principle describes the inverted model equations not in terms of absolute values, but as a linear approximation about the current aircraft state for small time increments. The advantages are that it not only copes with nonlinear control derivatives and the nonlinear Newton-Euler coupling terms, but also reduces the impact of model mismatch and uncertainties as large parts of the aerodynamic forces vanish from the derivative description of the inverse model equations.

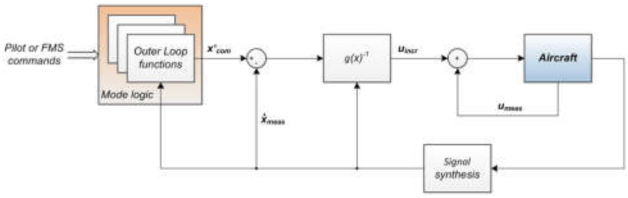

FIGURE 11 INDI control law structure

FIGURE 11 illustrates the incremental control law approach used in INDI. It can be exemplary derived from applying the classic Newton-Euler equations of motion w.r.t. angular motion, solving for the angular accelerations and employing a Taylor series expansion to obtain a first-order approximation. Making the assumption, that for small time increments the difference in angular rates is also very small, one arrives at a rather simple expression for the dynamic system [14]:

$$\mathrm{d}\delta_c = M_{\delta_c}^{-1} J(\dot{\omega} - \dot{\omega}_0)$$
$$u_{incr} = g(x)^{-1}(\dot{x}_{com} - \dot{x}_{meas})$$

The only remaining contributors are the inertia tensor J and the aerodynamic moment coefficients wrt. control surface deflections M_(δ_c), which include effectiveness w.r.t. flexible deformation of the structure.

It can be shown that, compared to NDI, these plant-linearizing control laws still remain linearizing for uncertainties regarding the rigid body derivatives and center of gravity location. Hence the robustness of INDI to changes of the aircraft configuration.

3.4 Component-wise Structural Analysis and Optimization for Isotropic Material

In order to incorporate detailed structural aspects, within the MDHP approach for the wing and the fuselage, detailed and component wise and independent structural simulation models were set-up parametrically and sized with loads from a separate loads analysis process. For the used loads analysis see section 3.3. Within the loads analysis the individual structural models were integrated and condensed into a suitable structural simulation model for the complete aircraft.

The sizing allows the mapping of design load cases to zones respectively local areas of the structure. Furthermore enhanced failure criteria, like local buckling, can be considered for the sizing.

Wing like components

For the wing as well for the horizontal and vertical tail, the parametric model generator DELiS was used [15]. Based on the central data format CPACS, DELiS automatically generates a consistent finite element mesh. The finite element model is made up of shell elements enriched with physical properties of the wing spars, ribs and skin cells and finally exported to a commercial FE solver such as ANSYS or Nastran.

For the initial sizing of the structure, a fast algorithm relying on 2D cross sections can be used. The method divides the wing structure into different cross sections at the wing rib positions and uses cut loads from the loads processes previously described as input to the sizing. The results are then transferred to DELiS and can be used as input to the FEM based sizing process. The sizing of the FEM wing structure is finally done using an in-house sizing tool where a fully stressed design method was implemented. The sizing takes into account strength and stability criteria for the wing shells.

The sizing results for the wing exhibit a thickness distribution on the different load carrying parts of the wing as seen in Figure 9. The high thickness of the wing mid spar in the center wing box is coincident with the high bending moment near to the wing root.

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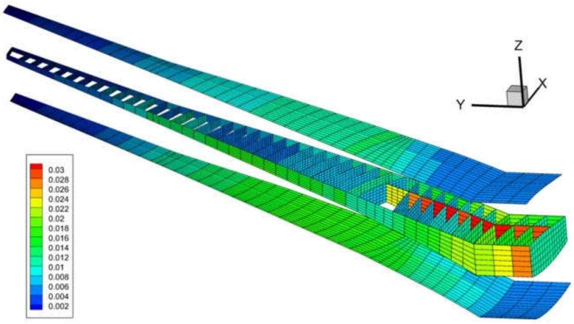

FIGURE 12 Spanwise thickness distribution of the sized wing

For a detailed structural analysis within the sizing process, different methods for integrating further modeling details like maintenance manholes can also be used. This is realized by a flexible interface to the open-source meshing tool Gmsh within DELiS which is also used for the overall mesh generation of the wing structure. Exemplary models with such detail element can be seen in FIGURE 13.

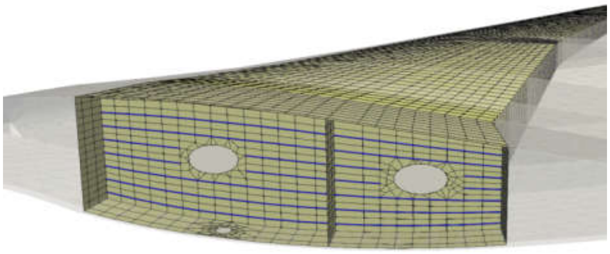

FIGURE 13 Finite element model of the wing with detailed meshing areas like around man- and hand holes.

Fuselage

The fuselage modelling and sizing within the VicToria project is performed using the PANDORA framework [16]. This tool has been developed as a consequence of some experience made during a predecessor project DIGITAL-X when individual tools for model generation and structural sizing were used. These tools were mainly based on the proprietary ANSYS FE solver and the integrated scripting language APDL (ANSYS parametric design language) [17] with limitations in flexibility and performance.

Therefore, all functionalities of the predecessor tools were integrated into the new PANDORA framework which is entirely programmed in Python. This allows the integration of specific libraries for data handling, quick data processing, visualization and various interfaces and in addition guarantees a very flexible porting to a wide range of computing systems from PCs up to compute clusters. PANDORA combines packages for CPACS based model generation, structural sizing as well as visualization of model data and results in a GUI (Graphical User Interface).

The flexibility of the tool could be extended by storing the FE model data independently from any solver format and to convert this model data base to a specific solver format on demand. Routines for coupling to ANSYS, NASTRAN and B2000++ are already available and can be extended with limited effort.

For the solver B2000++ the DLR has access to the source code, which can be transferred to various hardware platforms. In combination with PANDORA a modelling, analysis and sizing process can be performed without any proprietary license.

Besides the flexibility the performance could also be notably increased. The time to generate a full aircraft FE model in so-called GFEM quality could be reduced from more than an hour to less than three minutes and a reference sizing process of a XRF1 fuselage considering 17 load cases could be performed with only 13% of the initial computing time on an equivalent PC hardware.

The parametric fuselage model set up in PANDORA package cpacs_gfem [16] includes a detailed representation of the local fuselage reinforcements to transfer the loads from the wings and empennage into the fuselage primary structure. Structural components in the center fuselage area such as load introduction frames, reinforced pressure bulkheads, the keel beam as well as the main landing gear bay are modelled individually using shell and partly beam elements for structural reinforcements.

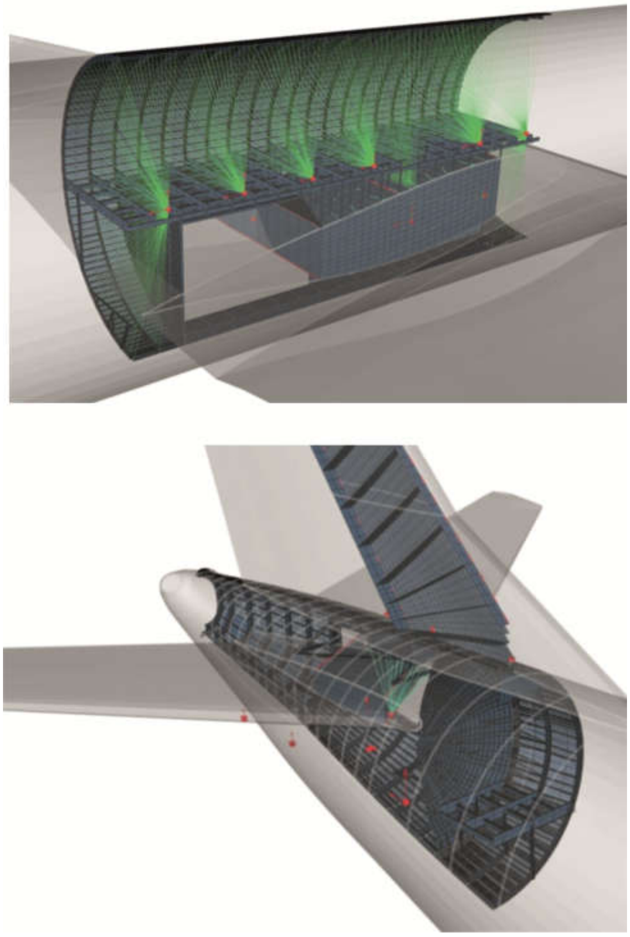

FIGURE 14 Representation of load introduction areas of the fuselage

In similar detail the load introduction of the horizontal and vertical tailplane are modelled. Exemplary structural meshes are presented in FIGURE 14.

The structural analyses using selected load cases and a subsequent sizing process in the package fe_sizer leads to required shell thickness. The sizing takes into account strength and stability criteria for the fuselage shell and sizing is done in an iterative way with the option to integrate various structural solvers such as ANSYS, NASTRAN or B2000++.

In FIGURE 15 an exemplary distribution of the required shell thickness of each skin bay between adjacent stringers and frames based on a few representative maneuver load cases is shown. As expected, the needed shell thickness is increased towards the center fuselage area and in the region of the window belt, where the distance or the stringers is larger and therefore the stability criterion forces the process to increase the shell thickness.

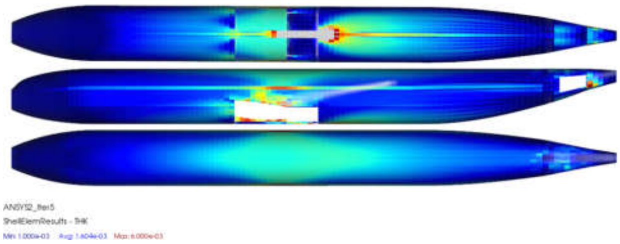

FIGURE 15 Estimated shell thickness based on an exemplary set of load cases

3.5 Wing Structural Analysis and Optimization for Carbon Fiber Reinforced Plastic Material

Carbon fiber reinforced plastic material for the wing and a specific concept for the structural optimization, are used in the IAWO approach. Therein a parametrization concept with lamination parameters as design variables has been elaborated. [18] Static strength criteria, such as buckling and damage tolerance, are incorporated as well as selected manufacturing criteria. A semi-analytical approach has been set-up and the stringer stiffeners are modelled as extra layer with analytical corresponding properties in the connected FEM model. Thus an easy variation of stringer geometry and their properties is possible without rebuilding the FEM model. Feeding back the correlated ABD stiffness allows a correct stress and deformation analysis. The usage of lamination parameter allows to cover the whole design space of composite materials in an gradient based process, where the feasibility of the lamination parameter combinations has to be ensured by extra linear constraints [19].

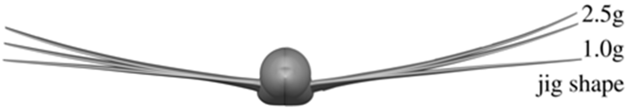

FIGURE 16 More elastic wing (right) compared to a conventional (left)

For the determination of the corresponding derivatives, the b2000++ solver is used in combination with high-performance computing in a massive parallel approach.
The consideration of different stringer types and the detailed representation of the corresponding stiffness allows a more elastic structural wing design, which alleviates loads and increase the overall performance as seen in FIGURE 16, where double T-Stringer and a stringer dominated concept allows more wing deflection in combination with CFD based load calculation and iterative convergence of loads and stiffness based on structural criteria.

FIGURE 17 shows the distribution of critical failure criteria for the reference XRF1-DLR. The consideration of local criteria is important as seen as well, where the local buckling criterion is critical for large areas of the upper cover and all the ribs.

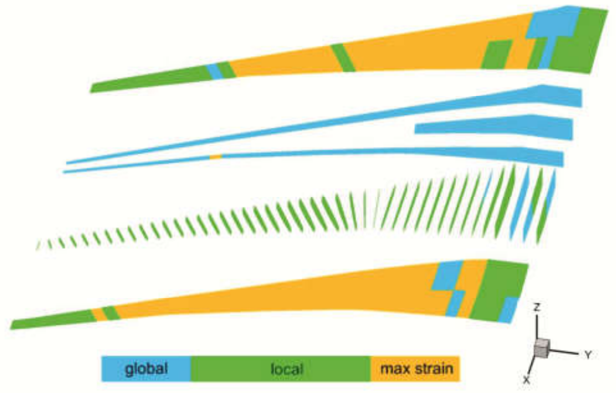

FIGURE 17 Critical design criteria

SUMMARY AND OUTLOOK

The presented paper gives an overview about the sub-processes excluding aerodynamics that have been part of the three high-fidelity based MDO approaches that have been developed within the DLR project VicToria.

The results of the sub-process overall aircraft design, loads analysis, and structural sizing respectively structural optimization are reasonably plausible, which is not self-evident for the use of such methods in MDO tasks.

Especially the structural modelling concepts exhibits a comparable high level of fidelity. All relevant structural parts are modelled with finite elements (e.g. stringer reinforced skins, spar, ribs for wings). Compared to single and fixed industrial structural models on the same level of fidelity the used parametric modelling approach allows for modifications of the simulation models that are to be expected within MDO tasks (e.g. variation of the wing planform).

The development of the sub-process is not completed. In the follow-up DLR project oLAF (Optimally Load-adaptive Aircraft, 2020-2023) for example selected sup-processes are used in the three MDO processes. Furthermore the application and further development of the sub-process loads analysis and the integrated design process stand-alone and in a loosely coupled design process is a main emphasis. Therein especially the development and application of aggressive load reduction methods are about to be pursued.

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