AERO-STRUCTURAL OPTIMIZATION OF A MALE CONFIGURATION IN THE AGILE MDO FRAMEWORK

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Abstract

Aircraft, and in particular military aircraft, are complex systems and the demand for high-performance flying platforms is constantly growing both for civil and military purposes. The development of aircraft is inherently multidisciplinary and the exploitation of the interaction between the disciplines driving the design opens the door for new (unconventional) aircraft designs, and consequently, for novel aircraft having increased performance. An important feature of modern aircraft development processes and procedures is to enable the engineers accessing complex design spaces also in the conceptual design phase in which key configuration decisions are made and frozen for later development phases. Pushing more MDO and numerical analysis capabilities into the early design phase will support the decision-making process through reliable physical information. It is worth mentioning that these design spaces are very large and can hardly be grasped and explored by humans without a structured approach and massive support of numerical analysis methods. Therefore, from the start of the aircraft development, process computer simulations play a major role in the prediction of the physical properties and behavior of the aircraft. Recent advances in computational performance and simulation capabilities provide sophisticated physics based models, which can deliver disciplinary analysis in a time effective manner, even for unconventional configurations. However, a major challenge arises in aircraft design as the properties from different disciplines (aerodynamics, structures, stability and control, etc.) are in constant interaction with each other. This challenge is even larger when specialized competences are provided by several multidisciplinary teams distributed among different organizations. It is therefore important not only to connect the simulation models between organizations, but also the corresponding experts to combine all competences and accelerate the design process to the best possible solution.

1 Introduction

Multidisciplinary collaboration is at the core of AGILE [1], an EU-funded Horizon 2020 project, started in 2015 and finishing in 2018. AGILE is developing the next generation of aircraft Multidisciplinary Design and Optimization processes, which target significant reductions in aircraft development costs and time to market, leading to cost-effective and greener aircraft solutions. AGILE has set ambitious performance targets to achieve by the end of the project in 2018: a reduction of 20% in time to converge the optimization of an aircraft and a 40% reduction in time needed to setup and solve the multidisciplinary optimization in a team of heterogeneous specialists, targeting novel configurations. This will lead to improved aircraft designs and a 40% performance gain, compared to aircraft in service today, is expected for large passenger unconventional aircraft configurations. To meet the challenges of the AGILE project a team of 19 industry, research and academia partners from Europe, Canada and Russia are collaborating together. The compo-

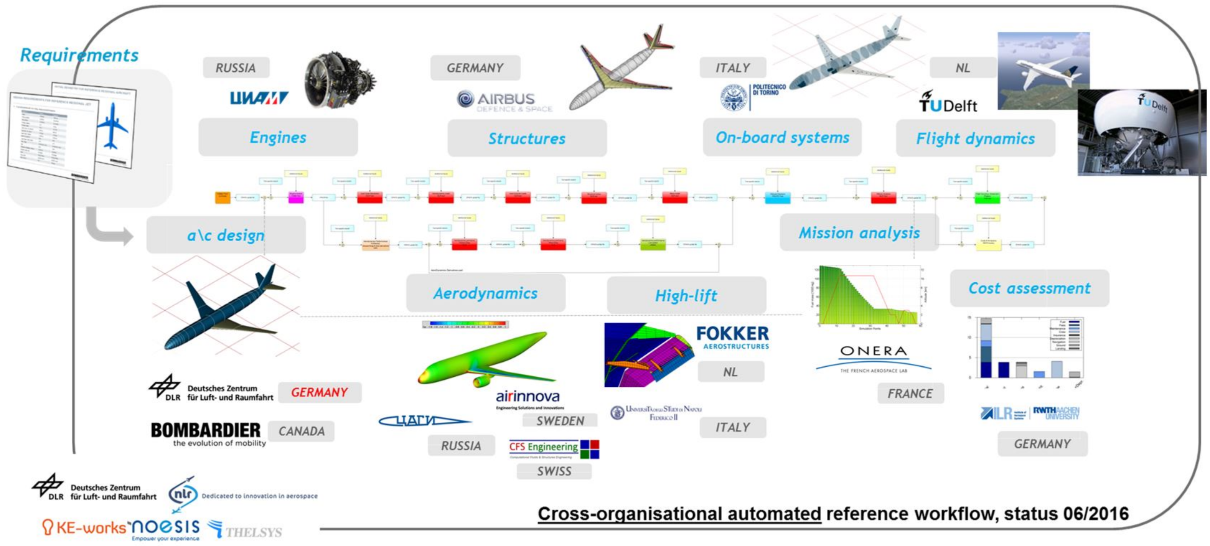

Fig. 1 : AGILE Collaborative MDO framework: individual competences are distributed multi-site, and hosted at different partners networks

sition of the Consortium reflects the heterogeneous structure that is characteristic for today's aircraft design teams. During the first year of the project (Design Campaign 1, DC-1), a reference distributed MDO system has been formulated to resolve the design of a single conventional configuration. In the second year (Design Campaign 2, DC-2), several optimization techniques have been investigated, also applying high fidelity (HiFi) techniques in MDO. During the last third year of the project, currently ongoing, all the developed methodologies and the AGILE MDO framework [2][3][4] are deployed to setup and solve multiple aircraft design and optimization problems for novel configurations, the *Design Campaign 3*. This study consists of six different concepts in six sub-tasks. This paper is focused on the AGILE task 4.5 which is the concept definition and shape optimization of a MALE UAV configuration. Figure 1 indicates the domains of the specialists' competences integrated into the process setup during the second year, indicating the location where such simulation competences are hosted, and the specific partners providing such a competence within their IT networks.

2 Requirements definition

The baseline of this design study is the *OptiMALE* aircraft from the German research project AeroStruct [20]. All missing Top Level Aircraft Requirements (TLAR) of this concept the were defined by Airbus Defence and Space and iterated with the partners from Leonardo. They are listed in table 1.

Two reference missions were defined for the *OptiMALE* A/C: One transfer- and one surveillance mission. The latter is presented in detail in figure 2 and table 2, because it was chosen as optimization reference mission.

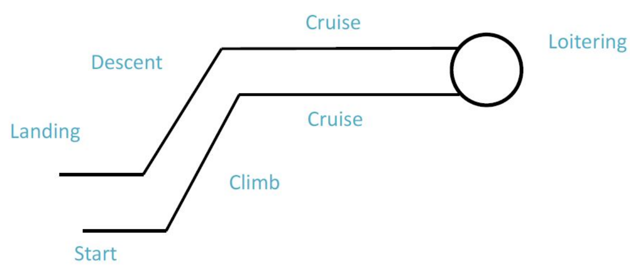

Fig. 2 : Surveillance mission profile

Requirements:	
Cruise above civil transport	> 15 km
Range	> 12 000 km
Runways length	2500 m
Cruise speed	$150\,\mathrm{m\,s^{-1}}$
Dive speed	$180\,\mathrm{m\,s^{-1}}$
Landing speed	$55\,\mathrm{m\,s^{-1}}$
Payload weight	800 kg
Payload volume	$4\,\mathrm{m^3}$
Payload power consumption	10 kW
Two external fuel tanks	
Electric powered hydraulic system	
SatCom Communication system	
SEP	$160\,\mathrm{m\,min^{-1}}$ @ 6 km
SEP	$50\,\mathrm{m\,min^{-1}}$ @ 15 km
SEP	$0\,\mathrm{m\,min^{-1}}$ @ 18 km
Roll rate	$60\,^{\circ}\,\mathrm{s^{-1}}$
Sink rate	$4\,\mathrm{m\,s^{-1}}$
Climb rate	$160\,\mathrm{m\,min^{-1}}$

Table 1: Top Level Aircraft Requirements

Start	
Climb	> FL 500
Cruise flight	> 1000 km @ FL 550
Loitering with 1.05 g at FL 200 ÷ FL 450	> 20 h
Cruise flight	> 1000 km @ FL 550
Descent	

Table 2: Surveillance Mission

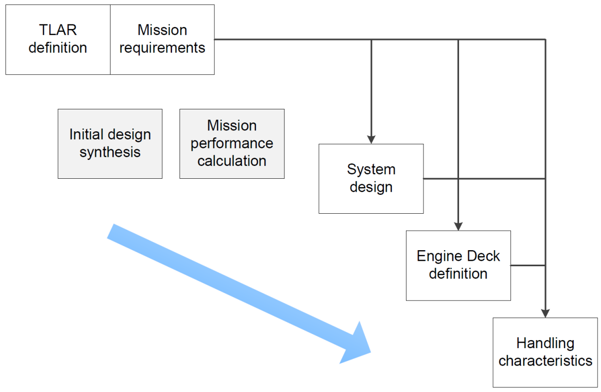

Fig. 3 : Task 4.5 - preliminary design work-flow

3 Preliminary design work-flow

Following concept phase, the next steps were the definition of the system architecture by Politecnico Torino, the design of the engine deck by CIAM, the analysis of the handling characteristics by TU Delft and the mission performance analysis by the DLR. The complete initial work-flow is shown in fig. 3.

3.1 Engine deck definition

The engine deck design was performed by the Central Institute of Aviation Motors located in Moscow. The required input for the engine definition was provided in CPACS format by Airbus DS. Mainly the mission parameters and requirements had to be converted to the proper format. One major constraint to the engine design was the fixed pylon size. This allowed only a very small bypass ratio. The design decision to use two smaller engines instead of one big engine for redundancy reasons increases also the thrust specific fuel consumption (TSFC). Following fig. 4 an increase in by pass ratio could significantly reduce the TSFC.

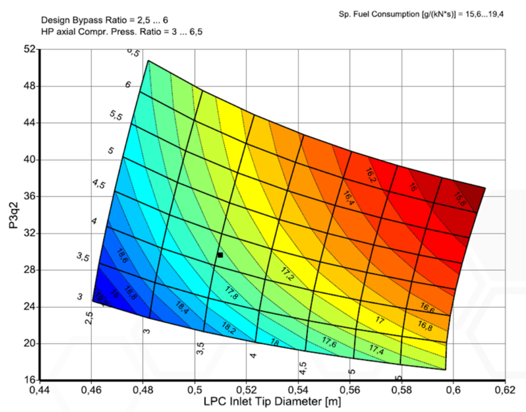

Fig. 4 : Engine cycle optimization

A very important input for the engine design is the system power consumption. Several iterations were necessary to converge between the consumers and the power supply.

3.2 System design

The system design was performed by the Department of Mechanical and Aerospace of Politecnico di Torino. It was decided to use a more electric system architecture for the *OptiMALE* aircraft. This is realized with an overall electric actuation concept except the flaps and the landing gear, which are hydraulic powered. The hydraulic pump is electrically powered and will be switched on for start and landing. For the anti-icing system it was decided to use an electro impulse solution. This concept provided the best trade-off between weight and power consumption for this aircraft configuration. Further information on this topic can be found in [17] and [18].

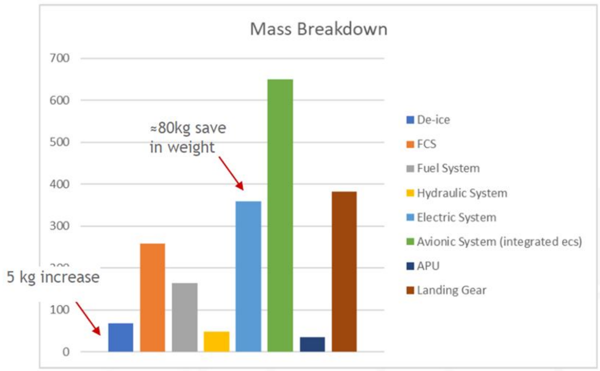

Fig. 5 : On-board system weight estimation

3.3 Handling qualities evaluation

The handling quality evaluation of the *OptiMALE* concept was performed by the Flight Performance and Propulsion department at TU Delft. The main required input were mass and inertia data, provided by Airbus DS, and aerodynamic data provided by AIRINNOVA.
Figure 6 shows a visual excerpt of the results and the main design recommendations are listed below. Further information concerning the tools and methodology used by TUD can be gained here[19].

- To assess required elevator deflection at the approach condition with wing flaps in the landing configuration with a high fidelity aerodynamic analysis
- Dutch roll: frequency relatively low and in some cases unstable. Recommendation to add a yaw damper to the flight control system
- To assess low speed high weight condition with panel method and to account for deformed wing shape
- At low speed and high weight, the roll mode time constant is too large and time to achieve a bank angle of 45 degrees is large
- Increased span (b), this improves the roll mode and at the same increases the moment arm of the ailerons.
- Increase of the aileron size (span) will improve the time to bank criterion.

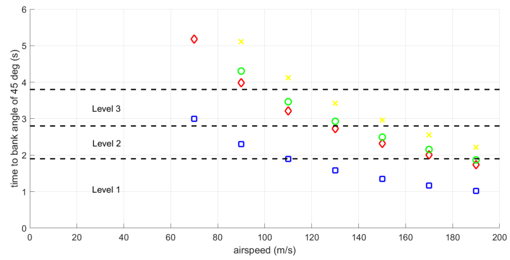

Fig. 6 : Roll control effectiveness time to achieve a bank angle of 45 deg

4 Aero-elastic shape optimization

The preliminary design of the *OptiMALE*, resulting from the performed work was the foundation for the second main task within this work package, which is presented in this chapter.
The workflow of the aeroelastic shape optimization shown in fig. 7 consists mainly of three nested loops: The aeroelastic analysis loop, the sizing optimization loop and the shape optimization loop.
The aeroelastic loop, shown in fig. 8 is at the heart of this process. The analysis is initialized with an undeformed aerodynamic model and an unloaded structural model. The aerodynamic

pressures are converted to forces and are applied on the structural model. The structural displacements from these loads are applied on the aerodynamic model in return. The process returns a converged aeroelastic load-case after a number of iterations. These resulting forces are used in the next step, a structural sizing optimization. Here the optimal thicknesses for a minimal structural weight are computed, while maintaining structural strength and stability constraints. Of course, the stiffness of the structure is changed during this sizing step, so the aeroelastic loop has to be repeated.
After the structural weight is converged, the endurance of the actual configuration needs to be evaluated with an aeroelastic calculation in cruise condition. In the shape optimization loop as the most outer loop, the geometry of the wing is updated and the analysis models are morphed thereafter.

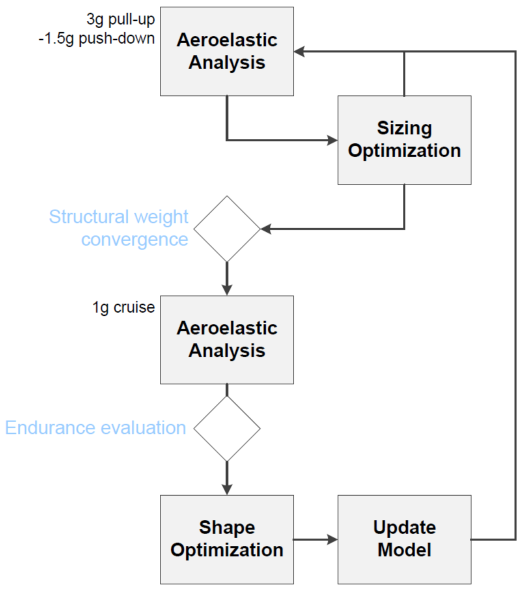

Fig. 7 : Optimization workflow schema

4.1 Analysis and Tool-chain preparation

The implementation of the central aero-elastic loop was performed by four of the partners involved in the AGILE task 4.5. The aerodynamic competence is provided by both, by AIRINNOVA and CFSE. The structural expertise is offered by Airbus DS, and the FSI is done by DLR-LY. Furthermore, DLR is hosting the structural tools of Airbus DS due to industrial network security issues.
The reference design configuration layout of the *OptiMALE* is a CPACS [11] file, enriched during the preliminary design phase of this sub task. This database was used to produce the aerodynamic and structural analysis model used in this aeroelastic shape optimization workflow.

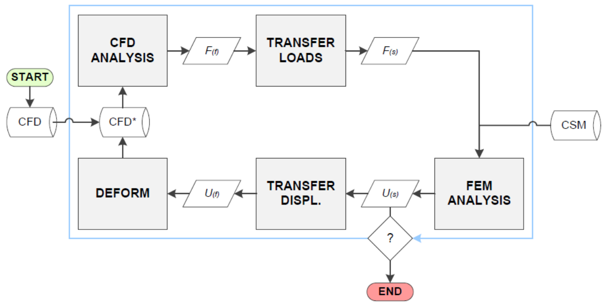

Fig. 8 : Aeroelastic loop

4.1.1 *Aerodynamic model generation*

In the FSI loop, the aerodynamic calculations were performed in Lausanne by CFSE. In a first time, an unstructured mesh of 2.3 M tetrahedron cells has been created by converting the original *OptiMALE* CPACS file to a SUMO file[4]. This operation is fully automated and allows to rapidly generate a surface mesh of the skin of the aircraft, using the open-source software SUMO[5]. As next step a volume mesh is generated by using the software Tetgen[6]. This mesh has been used to calculate the initial step of the FSI loop, i.e. without any deformation. The flight condition has been chosen to represent a pull-up maneuver with a load factor of n = 3 g. For this, the required lift coefficient C_L was calculated from the MTOW (Maximum Takeoff Weight) of the aircraft. Then, the aerodynamic solver has been set to adapt the angle of attack iteratively in order to achieve a C_L of 0.552 during the calculation. The aircraft was in *dive* condition at sea level, which corresponds to a Mach number of 0.367.

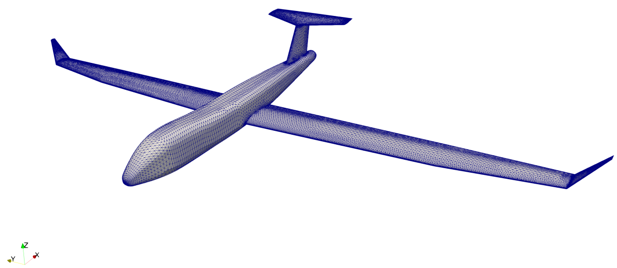

Fig. 9 : Aerodynamic surface mesh

4.1.2 Structural model generation

The structural model was also generated from the CPACS database, with the internal Airbus DS tool *Descartes* [3]. It is shown in fig. 10. The

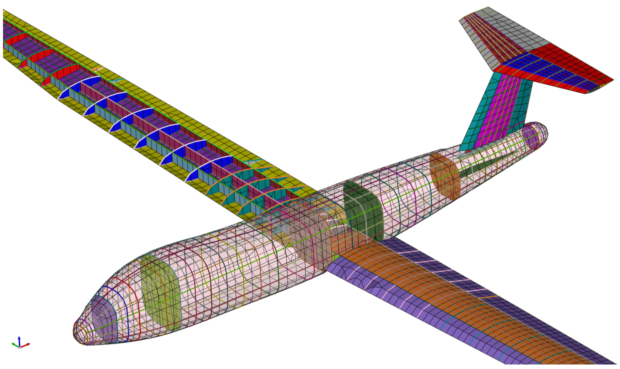

Fig. 10 : Structural FEM model of the *OptiMALE*

wing structure is based on a wing-box with front-, rear- and auxiliary spars in span-wise direction. The spars are supported by several ribs in the chord-wise direction, and the rib pitch increases along the span. The stability of the wing -box skin is maintained by an equally distributed set of one-dimensional stringer elements. The T-tail empennage is essentially constructed in a similar way.

The fuselage structure consists of a web of one-dimensional stringers and frames on the skin. The stiffness of the fuselage is further increased by six bulkhead elements.

The structural model is additionally enriched by the results of a mass model calculation. The masses of on-board systems, payload and fuel are attached to the structural model, and the secondary structural mass is applied to finite-element properties. A more detailed view of the automated structural mesh generation and the mass model calculation is given in [10].

4.1.3 Fluid structure interaction implementation

The mapping of the calculated loads and displacements between the aerodynamic and structural domains is performed at DLR. A mesh-free approach using the moving least square (MLS) technique described by Quaranta et al. [1] or Rendall and Allen [2] is adopted. It allows for the computation of the point displacements on the fluid domain boundary based on the displacements in the structural domain u_{st} using equation 1, where H is the interpolation matrix. Conveniently, the point forces on the aerodynamic surface points can also be mapped to loads at the structural model points using the same approach, due to the principle of virtual work in equation 2.

$$u_{fl} = H * u_{st} \tag{1}$$

$$f_{st} = H^T * f_{fl} \tag{2}$$

The MLS algorithm computes the interpolation matrix by combining a least-squares polynomial fit and a radial basis function interpolation. For the analysis of the *OptiMALE*, a second-order polynomial basis and the Wendland C_0 radial basis function are chosen [1], [2]. Figure 11 shows a typical force distribution from a CFD solution as provided by AIRINNOVA and CFSE being mapped to the Airbus DS structural mesh. In Figure 12, the resulting displacements are given, which are then mapped back to the CFD surface mesh.

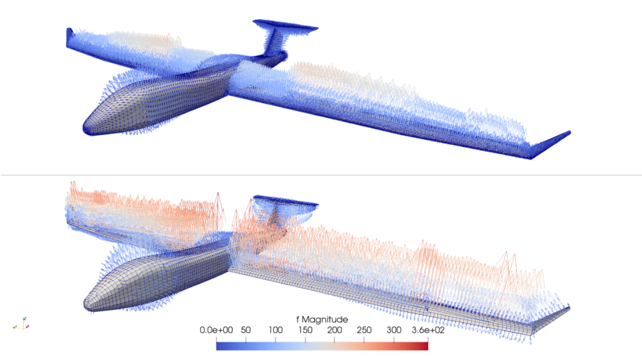

Fig. 11 : Aerodynamic forces

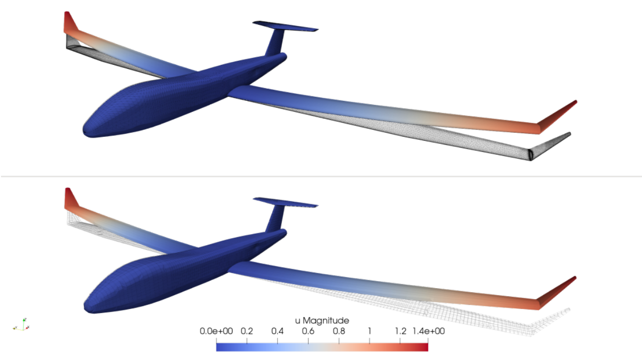

Fig. 12 : Structural displacement

4.2 Optimization work-flow application

The structural sizing optimization is mainly a functionality of the internal Airbus DS software *Lagrange* [12]. The objective function is to minimize the structural weight by altering the thicknesses and areas of the finite element properties. The optimization is constrained by stress, strain and stability allowables with safety factors applied.The optimization is then started with a converged set of forces from the aeroelastic loop.
After the structural sizing optimization converged with minimal structural weight, the stiffness of the aircraft has changed and this invalidates the initial aeroelastic loadcase. For this reason, the aeroelastic loop is repeated with updated structural model, and the converged set of forces from the last aeroelastic loop is taken as a starting point.
After a convergence of the structural weight is achieved, an evaluation of the endurance has to be performed with eq. 3[13]. The actual $\frac{L}{D}$ ratio is taken from another run of the aeroelastic loop in cruise flight condition and the actual fuel weight fraction can be calculated with the MTOW kept constant and the converged structural weight from the second sizing optimization step.

$$E = TSFC^{-1}\frac{L}{D}\ln\frac{MTOW}{MZFW} \tag{3}$$

where:

TSFC	Thrust specific fuel consumtion
MTOW	Maximum takeoff weight
MZFW	Maximum zero fuel weight

The target function for the shape optimization is to maximize this endurance value. With a set of geometric design variables of the main wing e.g. the span, the chord or the aspect ratio, the $\frac{L}{D}$ ratio can be increased directly or the $MZFW$ can be decreased indirectly.

4.3 Analysis model update

After the geometric shape design variables are changed by the optimizer, they have to be propagated to the analysis models to the analysis models as well. This is the task of the internal Airbus DS tool *Descartes* by morphing the FEM model. The structural mesh is kept constant with respect to the number of elements and nodes and their connectivity. Only the coordinates of the grid points are changed. The aerodynamic mesh is based on a different geometry, so it was decided to reuse the method from the FSI loop by applying a structural shape change to the aerodynamic model, as it would be a displacement value. The robustness of this approach to update the analysis model is a limited, as it is very sensitive to topological changes.

4.4 Surface Mesh Deformation: An Alternative

AIRINNOVA provides an automation of coupling the CFD and structural deformation to carry out the static FSI, via an automated application of the (structural) deformation on the surface mesh, and re-generate the volumen mesh for CFD computation. This is an alternative to the volume mesh deformation using the built-in FFD technique in SU2. The advantage of treating surface mesh instead of volume mesh is that, as all the aero-structural interaction happens *only* on the aircraft/wing surface, it is more natural that we focus on the surface instead of the whole flow field (volume). It will be a waste in terms of computational resources, transferring and storing the volume mesh between partners is an obstacle and actually not necessary. To this extend, in the FSI loop, it is better to let the surface information travel.

The overall FSI automation loop is shown in Figure 13. This section will detail how the automation loop is working by emphasizing the CFD part, using surface mesh deformation for mesh updating.

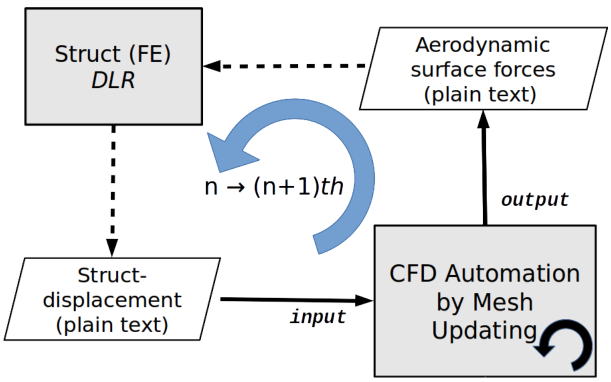

Fig. 13 : The FSI loop.

4.4.1 Surface Mesh "Deformer"

The *Surface Mesh Deformer* was initially created to tailor the CFD computation of a static structural deformation problem, aiming to compare the aerodynamic differences between the jig-shape and the shape which is deformed by the aerodynamic forces on the jig-shape. It is written in Matlab and to compute the *deformation map* by degree n polynomial P_n ($n = 4$ in this paper). The surface mesh is thus deformed and output as STL format using the computed deformation map in two steps:

- compute deformation map;
- deform the desired surface mesh using the map.

The inputs for computing the deformation map are (1) the jig-shape surface mesh (points close to the geometry surface) x_i as STL ascii file; (2) the maneuver-shape (deformed) surface mesh dx_i which has the same surface coordinates as the jig-shape surface. The coefficients P_n are saved to be used in the following step to deform the desired surface mesh given by the user. In the *OptiMALE* case, the (1) jig-shape surface mesh, $x_{s,i}$,is created by CFD partners CFSE/AIRI, and the structural displacement of $x_{s,i}$ is provided by the DLR. This displacement is as a result of the aerodynamic forces applied to the surface $x_{s,i}$, namely, $dx_{s,i}$ as plain text file saved with identical surface point IDs as the un-deformed surface mesh file. The deformed surface mesh is computed by the saved deformation map coefficients $P_n(x_{s,i})$:

$$x_{s,i(def)} = x_{s,i} + P_n(x_{s,i}) \tag{4}$$

The deformed surface mesh $x_{s,i(def)}$ is saved in the same format STL as the jig-shape surface mesh $x_{s,i}$.

4.4.2 The Automated Mesh Update Loop

Figure 14 shows the details of the CFD part of the FSI automation loop by transferring surface information. Once the working volume mesh is created, only the structure displacement is required from the external partner, and volume mesh for CFD analysis is self-updated by updating the surface mesh by the surface displacements using the "surface mesh deformer" and re-generate the volume mesh by Tetgen/Pentagrow [6, 14].
The CFD analysis is carried out by Euler solver in SU2 [7, 16, 15] and it gives the surface flow solution in vtk format.
A Python script is used to read this vtk file and save the surface forces on the surface nodes in a

plain text file, which is to be sent to the structure partner for the next displacement computation. The loop is automated by executing and linking the respective tools, reading/writing the I/O by Python and Bash scripts.
Note that, in this automation loop, the SU2 computation is carried out in clusters by automatically sending and receiving jobs via bash scripts. This accelerates the computation significantly and the FSI can get converged within 1 day. For the test case carried out in this paper, the volume mesh has 6.6 million cells, it needs 84 min for one run on 64 cores on a Cray XC40 machine.

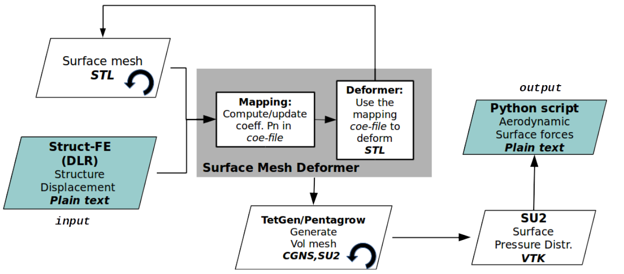

Fig. 14 : The details of the CFD part of the FSI automation loop by surface mesh deformation.

4.5 Automated workflow execution

Enabling process automation is a major topic of the AGILE project. The inner aeroelastic loop is automated via Brics[9] and RCE[8] in the following steps by CFSE as shown in fig. 15.

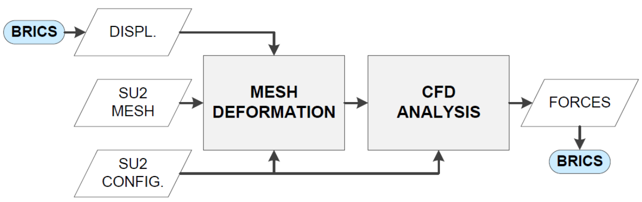

Fig. 15 : Automated aeroelastic process

1. A CSV (Comma Separated Value) file from DLR is received via Brics /RCE at CFSE. It contains a list of displacement along x,y,z axes for each surface node of the aerodynamic mesh (the order of the mesh point remains constant during the complete process).

2. Three inputs are required for the execution of the loop: The displacement received via Brics, the SU2 mesh (undeformed for the first step, and then with converged deformations) and a default configuration file with the calculation parameters.

3. With these inputs, a Python script runs SU2 mesh deformation library. Firstly, it applies the displacement on the surface mesh and then it uses spring analogy to create a new volume mesh which maintains the mesh connectivity. The deformed mesh is saved in SU2 mesh format.

4. SU2 code[7] is used to solve Euler equation on the SU2 deformed mesh with the same C_L as in the initial step. The calculation parameters have been chosen to achieve convergence as quickly as possible. The convergence of the forces is checked in each loop.

5. From the resulting pressure field given as output of the SU2 calculation, the force (in x,y,z direction) on each surface mesh node is calculated and saved in a CSV file.

6. This Forces file is sent via Brics/RCE to DLR.

7. Step 1 to 6 are repeated until the FSI loop convergence is achieved.

5 Workflow results

This section shows the actual advances of the High-fidelity aeroelastic shape optimization work-flow. An aeroelastic force distribution is shown in fig. 16. This load set is the result of the converged aeroelastic loop with a positive $3g$ pull-out.
These loads are used to generate the first results of the structural sizing optimization of the upper wing shell are provided in fig. 17. The thickness distribution shows the solution of the optimizer to handle the wing bending moment with the lowest amount of structural weight.

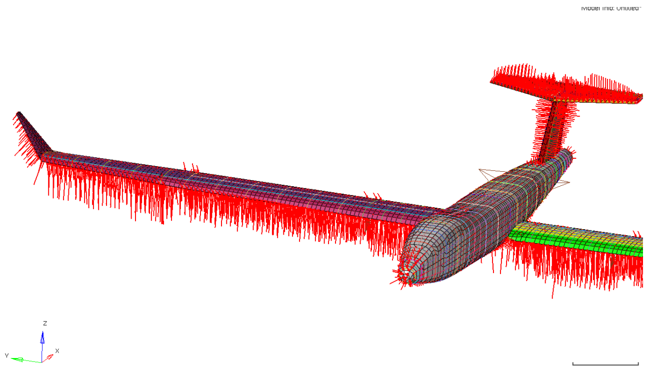

Fig. 16 : $3g$ pull-out aeroelastic force distribution

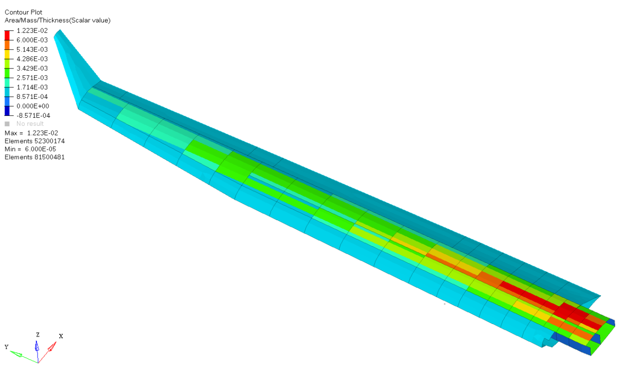

Fig. 17 : Upper wing shell thickness distribution

The next step is to run the aeroelastic loop again with the updated structural stiffness and to converge the structural weight. Now the shape optimization can be performed and the aeroelastic- and the structural sizing loop are repeated with the updated analysis models.

6 Conclusion and future prospects

The AGILE project enables collaboration between tool specialists from different institutes and different countries. This leads to a work-flow of existing methods to improve the *OptiMALE* aircraft. It is not straight forward to find efficient solutions for interfacing tools and communicating data and expertise in a large consortium. This is particularly challenging if there are additional issues for industrial partners as e.g. network security. The present paper shows the work that was done towards overcoming this challenge, in view of achieving the desired shape optimization process. First results are obtained for key components of this process. The automated set-up of the aeroelastic tool chain and the additional sizing optimization is tested successfully and currently there are the last steps towards a successful shape optimization with overall geometric parameters.

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