MULTI-DISCIPLINARY ANALYSIS AND OPTIMIZATION OF HYPERSONIC TRANSPORT AIRCRAFTS

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ABSTRACT

The development and first applications to a Mach 6 hypersonic transport configuration of a new multidisciplinary optimization (MDO) process is presented. The coupled treatment of several physical disciplines with focus on aerodynamic performance, flight mechanic aspects, propulsion integration and structure behaviour taking into account hypersonic relevant requirements is shown as well as the integration of multiple mission points.

1. INTRODUCTION

The development of the presented MDO process is strongly linked with EU 6th frame ATLLAS (Aerodynamic and Thermal Load Interactions with Lightweight Advanced Materials for High Speed Flight) project, wherein the identification of critical technologies for external airframe and propulsion units in hypersonic using analytical, numerical and experimental tools and the evaluation of two supersonic aircraft concepts, one for cruise Mach number 3 and one for cruise Mach number 6 are defined as major scientific and technological objectives. In the ATLLAS project 12 partners from 6 European countries are involved. The presented MDO process is applied to the Mach 6 configuration.

Due to high number of possible design parameters of complex hypersonic configurations the ATLLAS MDO process is first splitted into two seperated MDO processes. Hence one MDO is leaded by DLR with concentration on airframe design parameters and the second one leaded by ONERA concentrates on inlet MDO. At the end of the project results, methods and experiences of the inlet MDO process will be added to the airframe MDO for a final combined MDO run.

2. REFERENCE DESIGN ANALYSIS

The MDO process started within the ATLLAS project by the review in literature and past projects to find a configuration as initial point for applying the MDO. At the end of the review process the HYCAT-1A configuration was extracted due to similar mission objectives and the availability of a huge database including wind tunnel tests. Also the promising compromise between hypersonic and subsonic performance as well as good trim capabilities, both major requirements for future hypersonic aircrafts, favour the HYCAT-1A which has classical horizontal tail, characteristic sharp forebody leading edges and it's driven by a combined turbojet-ramjet engine based on hydrogen fuel. The fuselage is 105 meter long with a spanwidth of 28 meters. The HYCAT-1A was designed for a 5000 nm flight distance taking 200 passengers on board. [1][2].

The analysis of the reference design started with mass budget estimation, a turbojet-ramjet study, mission profile arrangement, aerodynamic CFD calculations in subsonic, transonic and hypersonic, dynamic FEM analyses and trim capability calculations. Hence a database including all important configuration data was created by the ATLLAS partners. The most critical issues of the configuration can be indicated and hence major objectives, important system requirements and constraints for the MDO can be formulated.

At the moment the major issues that have to be considered during the MDO are the mandatory integration of the engine due to the lift increase, the identification of the end of cruise point with worst trim conditions and the low frequency lateral and vertical bending of the configuration due to the large dimensions.

3. DLR MDO PROCESS

The major requirement of the DLR MDO tool is the automated computation of the hypersonic configuration by changing geometrical design parameters. The MDO tool consists of several modules for different subtasks which are added to a function chain where at the end a defined objective function is updated. The workflow for a 3-point MDO process is demonstrated in Figure 1 and is generally defined by parameterized geometry generation, mass modelling for component masses and centre of gravity computation, CFD grid generation, numerical aerodynamic flow solving, thrust and trim capability determination, FEM grid generation and dynamic structure analysis, constraints check and objective function update. The most of the modules are also depending on the mission point e.g. transonic or cruise point. Concerning the MDO this has mainly the highest impact on the propulsion system integration. Hence geometrical and physical differences of the engine in different mission points are considered.

The MDO tool includes both, hypersonic critical issues as well as general MDO relevant aspects. So one the side for example the propulsion system is integrated in the MDO in a form that intake and nozzle flow is computed directly in the CFD and the combustion chamber is covered as a black box with given properties so the gross thrust is determined. On the other side to speed up the MDO process special methods are developed like a modular mesh generation procedure which strongly reduces meshing time.

In the MDO tool commercial software is used as well as own developed source codes. All modules are embedded in a new and fully automated PYHTON environment taking over running and monitoring of modules, data exchange and conversion, machine communication and database update. The modular concept of the MDO process allows simple removing, adding and modifying of several modules.

The MDO tool is linked to the commercial software SYNAPS POINTER PRO [7] which offers several types of optimizers, like scanner, gradient based or genetic methods. In the presented MDO the Subplex optimizer, a function ranking method, is favoured. Below the basic modules of the MDO tool are shortly presented.

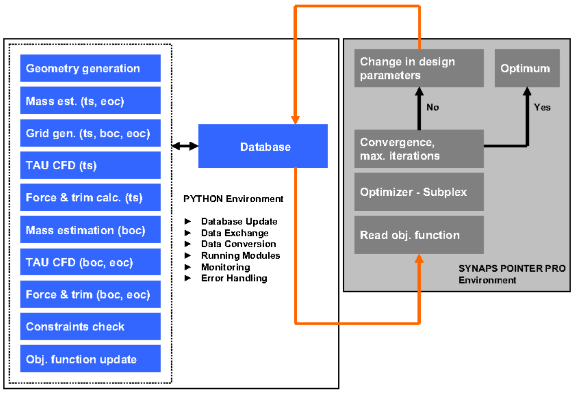


Figure 1: Flow chart for 3-point MDO process

3.1. Geometry Generation

The geometry generation is one of the major modules of the MDO tool due to most of the engaged modules are depending on the geometry. For the geometry generation an own tool is developed based on NURBS curves [3] described by a set of control points. A certain number of NURBS curves are arranged in 3D-space resulting in a surface. The geometry is divided in several surfaces and changing NURBS attributes offers different kinds of surface interfaces by complete smooth to kink. The geometry description is completely parameterized hence the airframe is controlled by about 100 parameters and the engine by 40 parameters. Figure 2 shows the generated geometry of the reference design.

The tool allows global and local geometry changes modifying NURBS control points and guaranties water closed geometry. Additionally inner surfaces for tanks and passenger cabin needed for mass estimation are created. Furthermore the geometry tool can be used directly for structure model node creation.

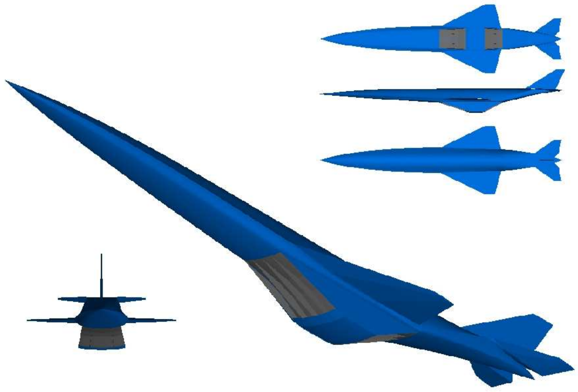


Figure 2: Reference design geometry

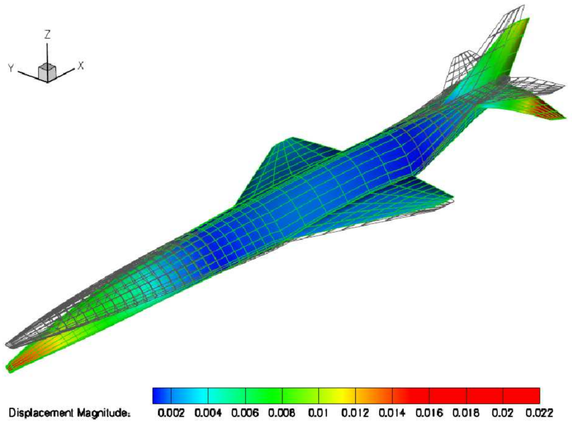


Figure 3: FEM analysis: vertical bending mode

3.2. FEM Calculation

An initial FEM model provided by ATLLAS partner FOI is adapted to the MDO process including automated FEM mesh generation connected to the geometry generation procedure. The model consists of 4-node shell elements for cover plates, bar elements are simulating frame stations, spars and stringers and rigid body elements are used for component connections. Non-structural masses are distributed over the whole structure. For FEM computations the numerical structure solver NASTRAN is used with concentration on dynamic eigenvalue analyses [6] to consider critical bending modes of the configuration as demonstrated in Figure 3.

3.3. Mass Estimation

The mass estimation is performed by determining surface areas and geometrical centre of gravity of these surfaces resulting from geometry module. Every surface is loaded with a mass distribution and an additional fix mass which is not changed during the MDO. Here the initial mass budget of the reference configuration provides the input and applying new configuration geometry now updates component masses, presented in Figure 4, fuel mass and centre of gravity depending on fuel charging, see Figure 5.

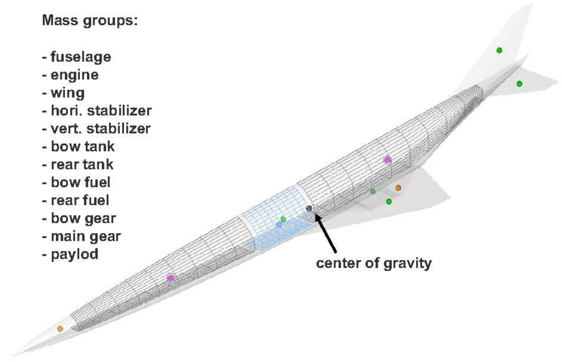


Figure 4: Mass components

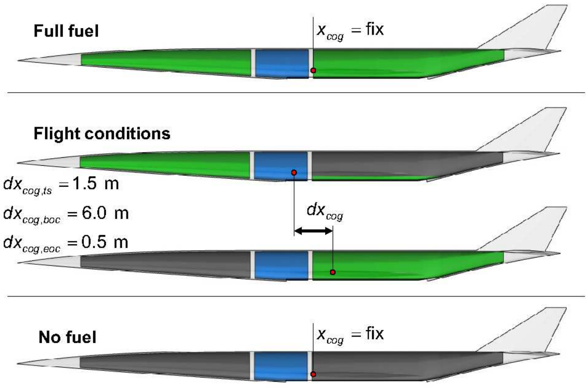


Figure 5: Centre of gravity influence due to fuel charging

3.4. CFD Grid Generation

Allowing global geometry changes during the MDO re-meshing of the CFD grid within every optimization loop is needed. Therefore the commercial unstructured grid generator CENTAUR [5] is used. For higher accuracy grids with about 1.8 million nodes are used whereas almost the half of nodes locate inside the engine zone. Suitable source placement guaranties fix mesh refinement for certain local geometry parts like wing leading edges. It has to be noted that for 3-point MDO also 3 meshes are needed due to different engine modes and horizonal stabilizer deflections and furthermore CFD grid generation is one of the main driver for the overall loop time. So a special modular grid generation procedure is developed by splitting the 3D-field around the configuration into several zones which can be re-meshed independently, see Figure 6. Only zones where the geometry changes have to be re-meshed and then grids for different mission points are created by grid uniting of main, engine and horizontal stabilizer zone. Hence the overall meshing time during one loop is strongly reduced.

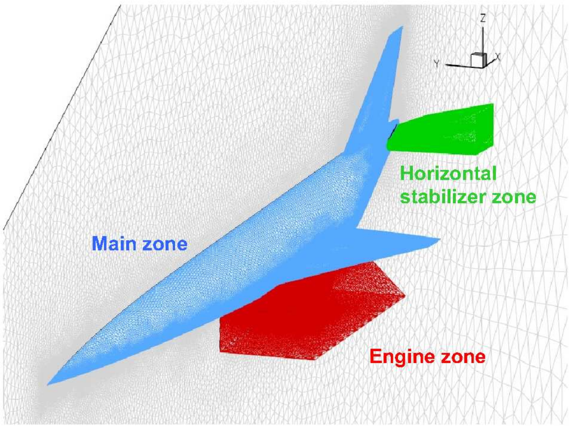


Figure 6: Grid zones of modular CFD grid

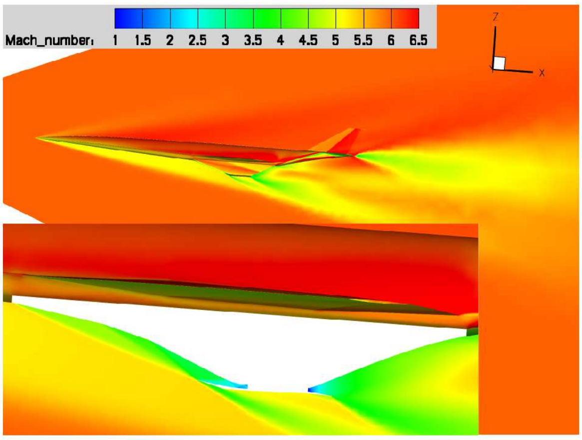


Figure 7: Mach number plot for M = 6.0

3.5. CFD TAU Calculation

The CFD calculations are performed using the DLR TAU code [8], a Reynolds-averaged Navier-Stokes flow solver applicable for subsonic as well as hypersonic cases. For reducing flow solver time TAU is running in Euler mode in addition with large parallel computing. The skin friction is taken into account by turbulent flat plate theory after CFD calculation. Fast convergence is reached using three level multigrid, 2nd order AUSMDV upwind scheme for flux discretization and three step Runge-Kutta method for relaxation solving. The targeted lift is provided by the mass estimation hence the resulting angel of attack and flow field is computed numerically. Figure 7 shows the Mach number plot for cruise conditions including intake compression and nozzle expansion.

3.6. Force and Trim Calculation

Force balance is calculated from the CFD results plus a force model for the black box combustion chamber presented in Figure 8 including the gross thrust and small intake corrections. Forces for intake and nozzle are already included in the CFD calculation. Hence the main force coefficients for lift, drag, thrust and pitch moment are determined. Now on the one side determination of the pressure point is possible and compared to centre of gravity, an important constraint to describe the trim capability of the configuration whereas the influence of horizontal stabilizer deflection plays an important role as Figure 9 brings out the decrease of performance at high Mach numbers. On the other side the specific fuel consumption is calculated from the net thrust given by intake, combustion chamber and nozzle force and fuel mass flow for the current engine mode. This is needed for later range estimation.

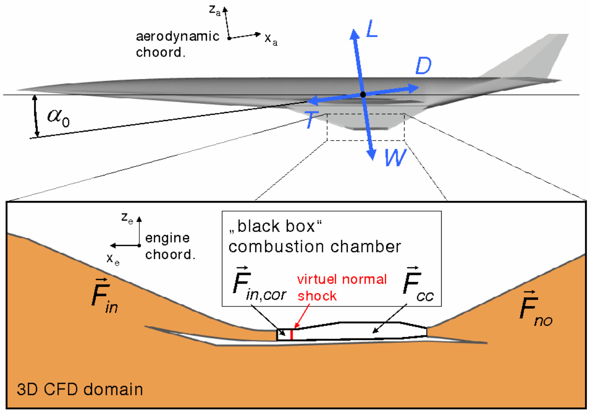


Figure 8: Forces and 'black box' combustion chamber

3.7. Objective Function and Constraints Handling

As objective function for the MDO process the range is chosen due to linkage of aerodynamic and engine performance as well as fuel and operating empty mass.
For 1-point MDO the Breguet range is used but also new range estimations for multiple cruise points are evaluated by integration of the basic range equation for unaccelerated horizontal flight.

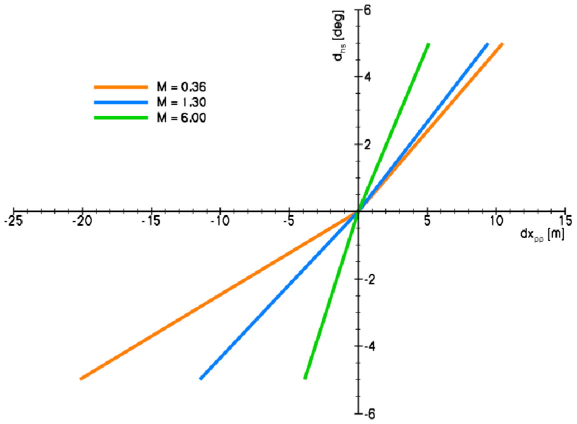


Figure 9: Horizontal stabilizer influence on centre of pressure depending on Mach number

The configuration constraints which can not be found in the range equation are added to the objective function in form of a penalty function which gives the final objective function. Hence the constrained optimization problem is changed to an unconstrained optimization problem and further constraints can simply added to the MDO process in future. So far main constraints are the intake air mass flow for begin of cruise, the distance between centre of gravity and pressure point for all calculated mission points, gross lift off weight and the resulting force in flight direction for all cruise points. As a disadvantage of this method a noisy objective function characteristic is expected.

3.8. Optimizer

As mentioned in the beginning the Subplex optimizer is applied for the MDO process. The Subplex optimizer is based on the Nelder-Mead simplex (NMS) method which is often recommended as best optimizer for noisy function due to a function value ranking system which is not depending on absolute objective function values. Furthermore no parameter sensivity study is necessary, but NMS is limited to low dimensional problems ($n < 6$). The Subplex optimizer now makes the NMS feasible for high dimensional problems by determining subspaces of the parameter space where the NMS can be applied, a so called subplex cycle is evaluated. Convergence can be observed after three till five subplex cycles [4].

3.9. MDO Applications

First MDO applications and development of the structural module were carried out in parallel hence last one is not included in MDO processes below. A first 1-point MDO for begin of cruise was performed to validate the functionality of the MDO tool. In every loop the lift weight balance is true due to begin of cruise mass estimation gives the targeted lift for CFD calculations. Overall 13 geometrical design parameters, 4 for wing, 4 for horizontal stabilizer and 5 for fuselage were chosen. The result of the 1-point MDO by comparing intial and final design is shown in Figure 10. The cruise range was increased by 10 percent due to increase of L/D and tank volume.

The 1-point MDO then was extended to 3-point MDO as described in Figure 1 by adding transonic acceleration point at Mach 1.3 and the end of cruise point due to the critical trim condition mentioned above. Hence configuration mass at begin of cruise is now depending on transonic performance which determines fuel consumption during acceleration and climb. The number of design parameters was increased up to 22. Assuming lift is proportional to mass, constant cruise velocity and flight height the basic range equation is integrated in a form that aerodynamic performance at end of cruise is included in cruise range calculation. Figure 11 demonstrates the current characteristics of the 3-point MDO. The functionality of various configurations is shown as well as optimizer capability leading out of a penalized system and increase objective funtion by 9 percent.

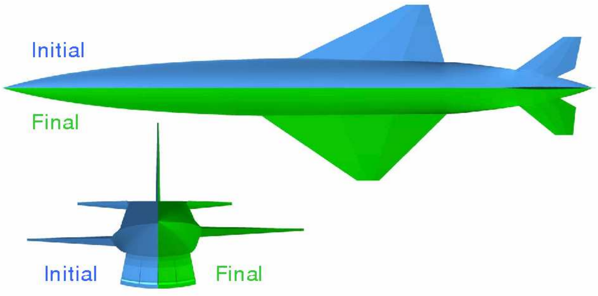
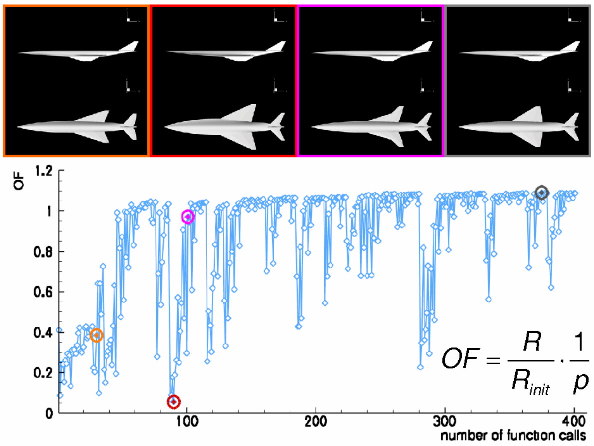


Figure 10: Initial and final configuration of 1-point MDO



$$OF = \frac{R}{R_{init}} \cdot \frac{1}{p}$$

Figure 11: Objective function characteristics of 3-point MDO

4. ONERA MDO PROCESS

4.1. Approach

Within the framework of the ATLLAS project ONERA contributes to the aero-propulsive MDO of the design of a Mach 6.0 vehicle. ONERA is working on the design optimisation integrating both aerodynamic and propulsive considerations. Indeed, if the external shape of the aircraft will have a direct impact on the aerodynamic performance of such a configuration, it is also crucial to optimise in the same time its propulsive performance which has a significant impact on the overall vehicle performance.

The first stage consisted in designing a relevant inlet baseline. Then a detailed aero propulsive performance of the glider configuration equipped with this new inlet will be assessed in order to set the reference for the MDO process.

4.2. Preliminary 2D inlet design

The baseline air-intake was designed by Onera using 2D RANS calculations (Spalart-Allmaras turbulence model) on a structured mesh. Firstly a 3D RANS calculation of the Hycat1A forebody was performed at Mach 6 cruise conditions (altitude 27300 m, incidence 4 degrees) in order to give the proper inflow boundary conditions whatever the intake external ramps position.

A mixed compression intake was selected since it allows a good trade-off between kinetic energy efficiency at high Mach number and reduced cowl drag. In the selected baseline configuration, see Figure 12, the flow is supersonically compressed by three external ramps extending between 45m and 55m downstream from the fuselage nose and the internal cowl profile. The flow compression is then achieved by a terminal normal shock and a subsonic diffuser (end of the diffuser at X = 65m). The upper wall internal profile is designed so as to cancel as much as possible the reflected shocks. Only a virtual terminal shock (VTS) is considered at this stage instead of considering complete more realistic throttling device which would require time consuming NS calculations. To take this VTS into account in the efficiency assessment an average one-dimensional flow field conserving the mass flow, momentum and total enthalpy fluxes of the two-dimensional flow has first to be calculated slightly downstream from the intake throat.

With the proposed design, considering 4 rectangular intakes of 2m width each, the engine demand is matched (425 kg/s per intake). The average VTS Mach number is around 1.5. Neglecting the diffuser losses but taking into account the VTS, kinetic energy efficiency amounts to slightly above 0.96, see Figure 13.

Four modules of this baseline intake configuration have been integrated to the Hycat-1A CAD model provided by DLR. The 2D pressure distributions along the external and internal walls have also been used as an input for the structural model improvement.

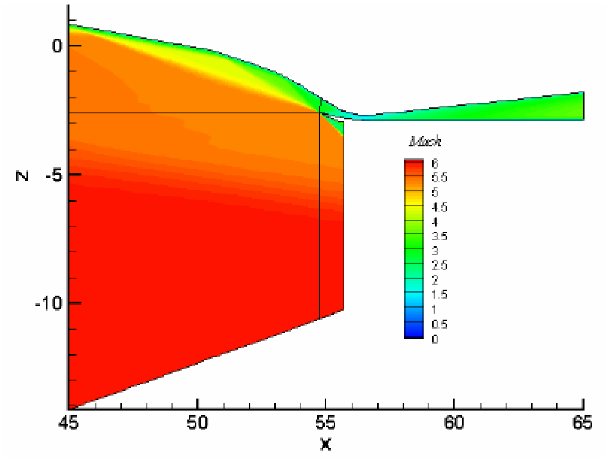


Figure 12: Baseline inlet configuration, iso-Mach contours (2D Navier-Stokes Spalart-Allmaras calculation)

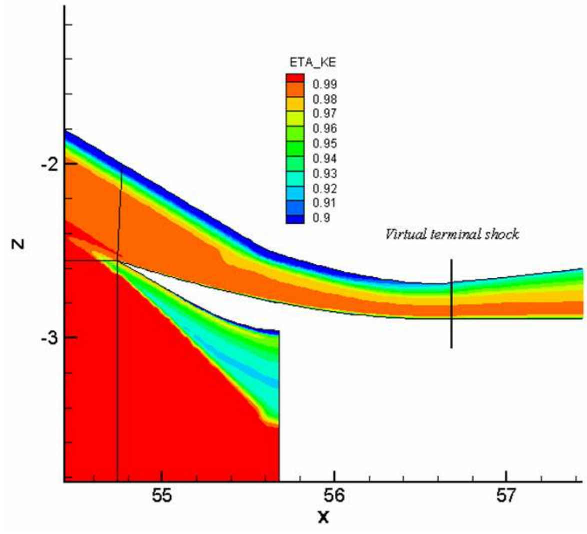


Figure 13: Iso kinetic energy efficiency in the vicinity of the inlet throat

4.3. Aero-Propulsive analysis

The two dimensional inlet baseline defined in the first phase was integrated by ONERA in a three dimensional hypersonic initial DLR CAD model which is shown in Figure 14. Figure 15 presents the corresponding three dimensional structured mesh adapted for RANS calculations is being achieved using ICEM Hexa software. This stage is the most sensitive phase in the CFD computation preparations. Among others, the main challenges are to overcome the topological specificity of the configuration: the very slender peaky nose, the highly stretched inlet lateral walls and the unconventional rear nozzle lateral walls. ONERA elsA [9] solver is used to perform the flow calculations.

The evaluation of the aerodynamic performance of the 3D configuration will take into account both propulsive performance and trim drag corrections. The performance of the engine is evaluated by combination of both interpolations of engine characteristics with the VTS / 1D diffuser technique mentioned above, taking as main input the aerodynamic flow solution. The simulation of the throttling device will give indications whether a bleed system is mandatory or not. On the other hand trim drag correction is modelled using results from CFD calculations of the aircraft for different stabilisers twist orientations.

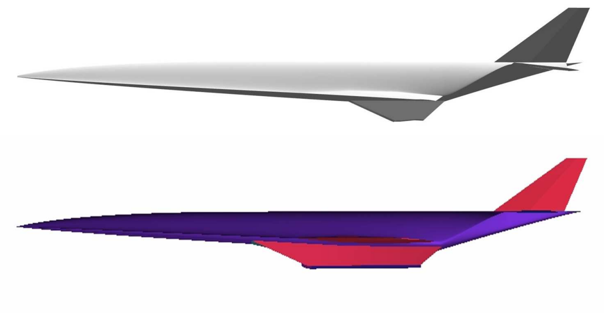


Figure 14: Initial (upper) and final baseline inlet CAD

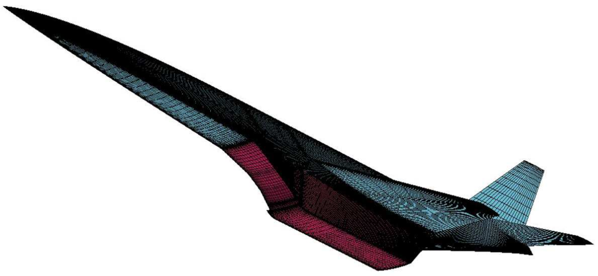


Figure 15: Three dimensional structured multiblock mesh for NS CFD calculations

4.4. Forebody and inlet MDO process

The ONERA contribution to the MDO consists in finding an enhanced inlet geometry satisfying the following problem:

* Objective function: Total drag
* Constraints: Minimum lift, Inlet mass flow requirement

The overview of the corresponding process is illustrated in Figure 16. It can be decomposed into two main parts which are the analysis module and the optimiser. The latter is based on a suitable algorithm, according to the optimisation problem to solve. On the other hand, the analysis module provides the performance in terms of objective function and constraints values for the individual corresponding to a set of design variables on the request of the optimiser. A 16 variables parameterisation is chosen in order to define the most appropriate design space of research of the optimum for the given optimisation problem, see Figure 17. The new mesh corresponding to a set of design variables is generated using a combination of volume mesh deformation techniques such as free form [10] shown in Figure 18 or similar analytical linear deformations, see Figure 19. Furthermore, an optimisation algorithm based on a global (genetic algorithm) approach is chosen to search the optimum in the design space, which is typical for an optimisation problem with a significant number of design variables. The optimisation is performed using an automated PYTHON based program to ensure synchronised communication between the optimiser and the analyser.

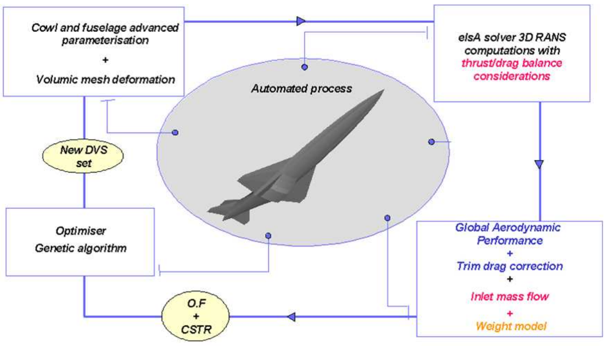


Figure 16: Global MDO optimisation process

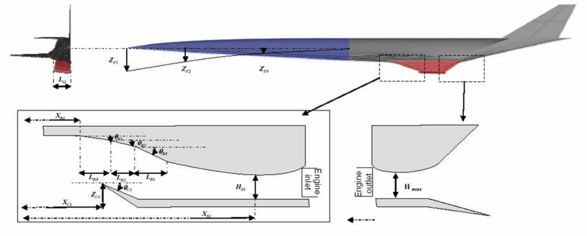


Figure 17: Three dimensional parameterisation

5. CONCLUSIONS

A new developed DLR MDO tool as well as ONERA inlet MDO strategy with application to a Mach 6 hypersonic configuration was presented. At the moment working seperately both MDO procces will be joined at the end of ATLLAS project. An intensive review and analysis process on the HYCAT-1A configuration was performed resulting in initial design, major requirement and important constraint formulations for both MDO processes. DLR MDO requirements were formulated followed by the description of modules for different subtasks which are combined in a fully automated multidisciplinary analysis environment. So far three of four targeted disciplines are considered and strucural modelling concerning dynamic eigenvalue analyses is prepared for implementation to the DLR MDO tool. The functionality of the DLR MDO tool could be shown for a 1-point MDO resulting in 10 percent cruise range increase. Furthermore integration of multiple mission points works successfully. The modular build-up of the MDO tool allows modifying several modules for future improvements.

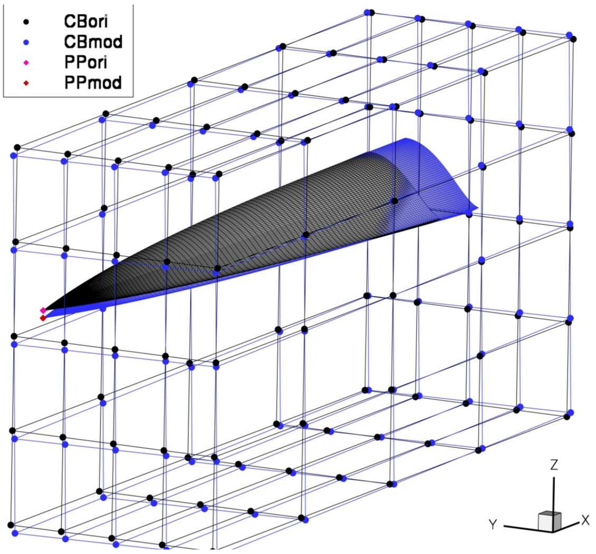


Figure 18: Free form nose deformation

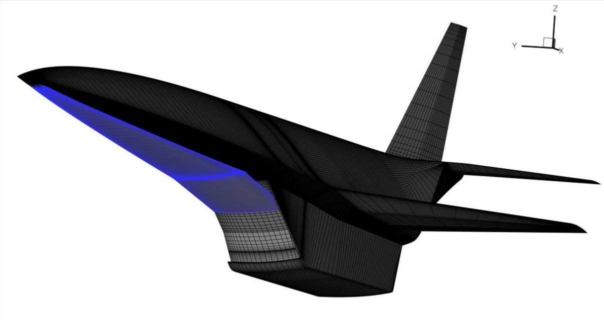


Figure 19: Inlet ramps analytical deformation

Furthermore ONERA developed a baseline inlet design based on 2D Navier-Stokes calculations. The three dimensional structured multiblock mesh for viscid CFD calculations is shown where freeform deformation techniques can be applied during the inlet MDO process taking into account aerodynamic performance, inlet kinetic energy efficiency and inlet mass flow requirements.

6. ACKNOWLEDGMENT

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