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A PRELIMINARY LOW-FIDELITY MDO APPROACH FOR LOAD ALLEVIATION THROUGH MOVABLES ON HAR WING

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Abstract. *As part of the current efforts targeting further development on cleaner and more efficient aviation, this study proposes a new MDO approach for an optimized High Aspect Ratio (HAR) wing weight using a load alleviation. Load Alleviation Function (LAF) aims at diminishing the peak wing bending moment due to a manoeuvre or a gust by redistributing the lift to a more inboard position on the wing using movables to decrease the overall wing weight. Nowadays, movables are exclusively designed to master the control of the aircraft, and LAF takes advantage of these control surfaces characteristics despite not being designed for it. The challenge of LAF tuning on a HAR will come from the high wing deformation. So this study aims to address the handling qualities (HQ) and LAF aspects in an optimization process of the control surfaces positioning, actuators power, sizes and deflections covering both disciplines, with a wing weight reduction intent. The challenges faced within the project reside in the couplings of the numerous disciplines present in the overall aircraft design: aerodynamics, loads, static aeroelasticity (movable control reversal), HQ, stress, and mass. A highlight will be made on the aerodynamic and loads disciplines, as current MDO publications do not consider a broad number of load cases and flight points with the right coverage of the sub-loads disciplines (such as gust and its aerodynamic specificities), which are crucial in the ranking of different designs, and crucial in the assessment of its feasibility, and finally for certification. This study aims to define the MDO framework by identifying the right compromise between disciplines and fidelities whilst preserving the computational resources. In the first stages, the project focuses on the lower-fidelity approaches through open-source means to verify its feasibility and compile the requirements, targeting to include multi-fidelity approaches at future stages of the research project.*

Keywords: Load Alleviation Function, Multidisciplinary Design Optimization, Multi-fidelity, Handling Quality, Aircraft Control, High Aspect Ratio, Aeroelasticity, Loads

1 INTRODUCTION

In recent years there has been a surge in the interest in HAR aircraft in civil aviation [1]. Thanks to the increase in performance due to the reduction in induced drag. However, this effect is of no use if the wing cannot withstand the load applied, increasing the aspect ratio can only be achieved either by increasing the structural mass or allowing an increase in wing flexibility. The flexibility can be augmented without failure thanks to the use of advanced composite materials, which is already a common practice in recent aircraft designs. The problem arises with the aeroelastic effects that this flexibility implies in the control of the aircraft, as it will be discussed in section 2 and 4.1. The MDO approach to define the control surface concept could be a promising solution to this problem as it is addressing the flexibility effect, handling qualities and the load alleviation opportunity to minimize the weight increase due to the HAR concept. The control surface optimization through MDO is also relevant for classical wing, as sequential computation limits the number of configurations and disciplines that could be considered.

Accordingly, the interest of this study is to develop an MDO framework to optimize the LAF by improving the movables configurations. Some intricacies will arise from the high aspect ratio of the wing, a highly flexible wing will highlight the aeroelastic effects constraining the efficiency of the LAF. To address and illustrate this, two configurations will be assessed to support the comparison of a classical wing configuration versus high aspect ratio.

Load alleviation (LAF) or Maneuver Load Alleviation (MLA) involves the process of structural load mitigation that occurs during flight. The LAF configuration must comply to the European Union Safety Agency (EASA) and the Federal Aviation Administration (FAA) in the United States regulations. A series of specifications for the design and certification of aircraft regarding the maximum loads an aircraft must be able to endure is available in [2] and [3].

Referring now to the sections CS-25.301 Loads: *“Strength requirements are specified in terms of limit loads (the maximum loads to be expected in service) and ultimate loads (limit loads multiplied by prescribed factors of safety). Unless otherwise provided, prescribed loads are limit loads.”* For this case, we will focus on the limit loads, covered as well in section CS-25.321, where is specified the maximum and minimum load factor an aircraft must endure at several flight speeds. The load factor represents the ratio of the aerodynamic component to the weight of the aircraft [2].”

To know on which conditions the limit loads can be achieved during flight, the manoeuvre loads sections CS-25.331 and CS-25.333, specify the design flight speeds and load factors. In section 3.2 further details will be given on the flight envelope the aircraft will be subjected to.

The first load alleviation system was designed for the A320 [4], where it was shown a potential net load alleviation of around 15% at the wing root.

2 LAF/MLA WORKING PRINCIPLE

Knowing the potential benefits of LAF/MLA, it is imperative to know how it works in flight to assess the required disciplines for optimization. LAF in a nutshell intends to create a downward force in the wing to alleviate the increase in loads due to a manoeuvre by deploying the control surfaces. But deploying the control surfaces means a change in the location of the centre of pressure, which can be thought of as the position where the

total lift is applied in an aircraft. This force will generate a moment with respect to the centre of mass of the aircraft which must be counteracted by the Horizontal Tail Plane (HTP) in order to have a stable flight. This presents a challenge, as most of the previous studies that want to tackle aerostructural optimization, only consider the main wing.

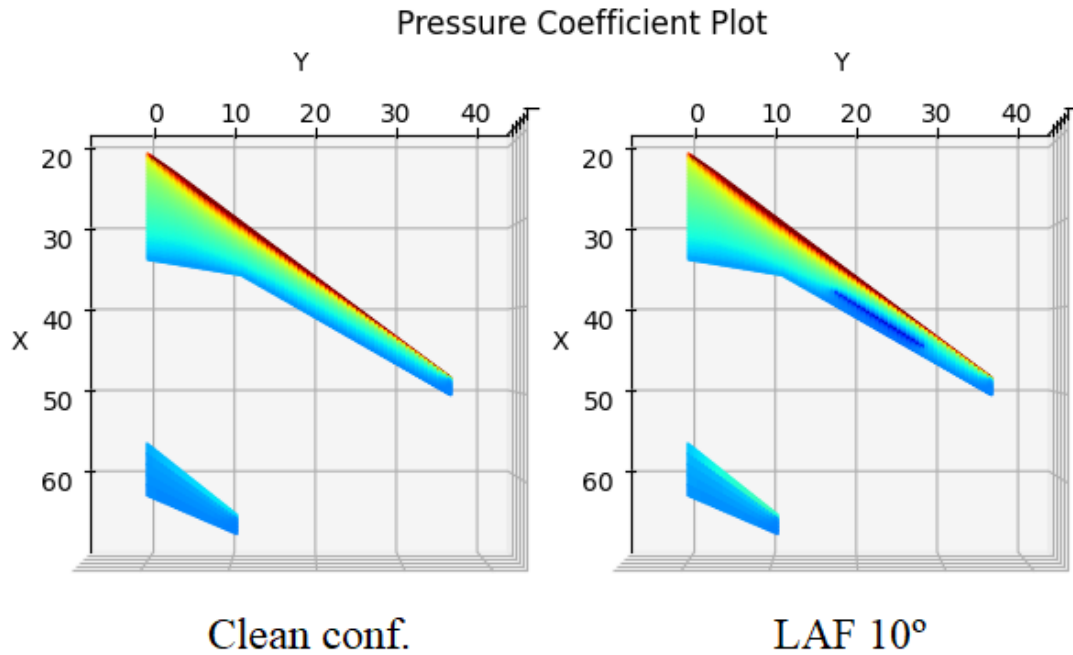


Figure 1: Comparison of pressure distribution between deployed aileron and clean configuration.

In figure 1 it has been plotted the pressure distribution of both configurations, with and without the aileron deflected. This contour plot presents the pressure difference for what would be the upper and lower surface of the wing. The slight decrease in pressure in the region where the aileron is deflected, means a local loss in the lift over the area, alleviating the load at which the wing is subjected.

As it can be seen in 2, there is already a 6.6% improvement in loads with just deploying the default aileron configuration.

3 PROBLEM DESCRIPTION

The objective of this study is to devise a preliminary MDO architecture to attain the best control surface configuration for the least wing bending at the root. The problem could be read as:

$$\begin{aligned}
 &\text{Minimize} && M_x(\text{pos}, \text{size})_i \\
 &\text{w.r.t.} && \text{pos}, \text{size} \\
 &\text{subject to} && F_z(\text{pos}, \text{size}) < \text{Limit Loads}
 \end{aligned} \tag{1}$$

Where $M_x(\text{pos}, \text{size})_i$ is the wing bending moment for a given manoeuvre_{*i*} and F_z is the vertical loads. The wing box should be subjected to an extensive flight envelope for its

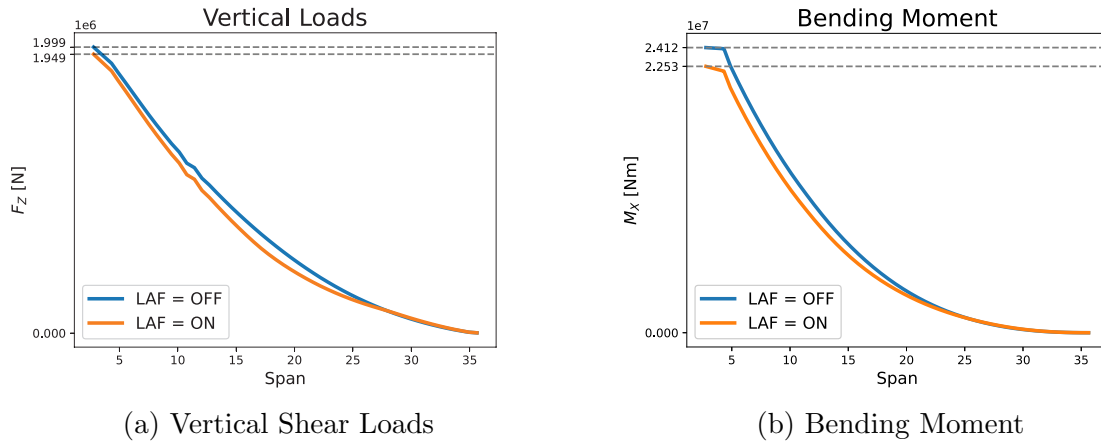


Figure 2: Effect of LAF on vertical load and bending moment (uCRM13.5 [5] with 10° aileron deflection).

correct sizing, for that a broad set of flight points will be evaluated to retrieve the worst scenario, see section 3.2. The variables *position*, *size* refer to the position and size of two adjacent ailerons present in the original design. Being this architecture just a preliminary study, many other constraints must be taken into account for it to reach certification-level requirements, such as Control Reversal (CR), Handling Qualities (HQ), Gust, Horizontal Tail Plane (HTP) Overloading and Failure Conditions. These constraints need to be assessed and this project targets their assessment as separate disciplines in the future (see section 6).

3.1 Model description

As a target for this study, the uCRM9 and uCRM13.5 were selected [5] as they perform as great examples for this test case. The uCRM9, representing a standard long-range aircraft with a wing aspect ratio of 9, will be used as the baseline for the optimization. To validate the results, [6] has a great compilation of the static aeroelastic performance of both uCRM9 and uCRM13.5.

These models were conceived for aerostructural optimization, so there are no specifications for the control surfaces. To have some reference, the model CRM-HL (Common Research Model in High Lift configuration) is practically the same as the uCRM9, and following the design specifications of the technical report of Shmilovich et al.[7] the position and size of the reference model were determined for the uCRM9. For the uCRM13.5 since there is no available information, the same nondimensional aileron size and position from the CRM-HL was used.

Both models share the same centre of mass (presented in yellow in figure 3). The relevant design criteria for the aircraft are depicted in table 1.

3.2 Flight envelope

The definition of the flight envelope is another important step in the optimization, as they will be the test cases for the model. For this reason, real sizing test cases for long-range aircraft are used, shown in table 2. At every iteration, all manoeuvres are evaluated, and the worst case will be the output to minimize, as the manoeuvring sizing

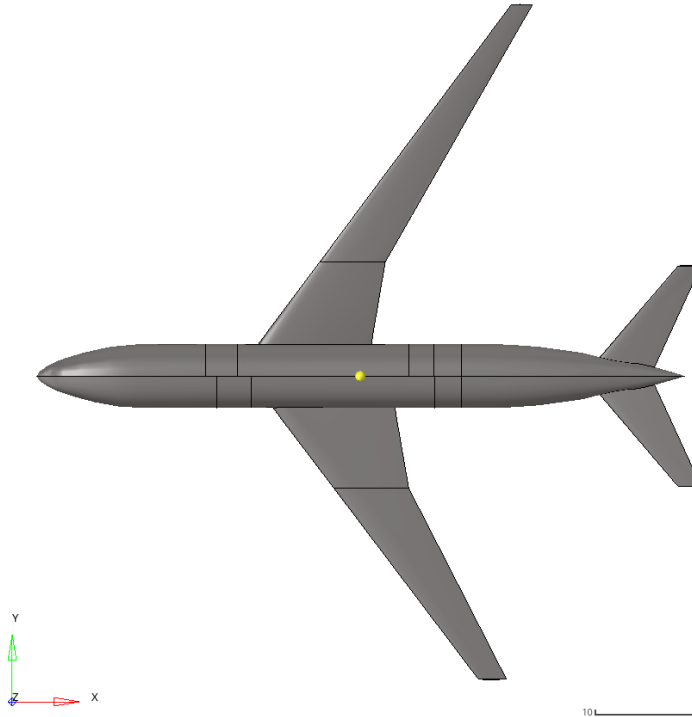


Figure 3: Aircraft model comparison, uCRM13.5 (Top) and uCRM9 (Bottom).

Table 1: Design properties for both aircraft.

Aircraft	uCRM9	uCRM13.5
AR [-]	9	13.5
Span [m]	58.76	72.00
MTOW [ton]	297.5	284.256
Mach Cruise [-]	0.85	0.85
Cruise alt. [kft]	37	37

case may not be the same for different LAF configurations.

In 2 also includes the cruise conditions as a reference. V_C and V_A stand for design cruising and manoeuvring speeds, respectively. n is the load factor.

4 COMPUTATIONAL APPROACH

Given the design criteria and constraints, an aerodynamic and structural model is required for the main Multidisciplinary Analysis (MDA) of the optimization loop.

4.1 MDA and Static Aeroelasticity

As mentioned in section 2, a simple Fluid-Structure Interaction (FSI) with just aerodynamics and structure will not suffice. It is required to take into account the contribution of the tail. The interest of the study will be just static aeroelasticity, so NASTRAN will be selected for its capability of not only solving the FSI but also solving the longitudinal stability problem.

However, it is crucial to understand beforehand how the static aeroelastic analysis

Table 2: Flight envelope.

V_A			
Mach	Alt. [kft]	Q [Pa]	n [-]
0.512	10.0	12783.5	2.5
0.780	25.0	16012.1	2.5
0.780	38.0	8815.7	2.5

V_C			
Mach	Alt. [kft]	Q [Pa]	n [-]
0.85	37.0	10984.4	1.0
0.594	10.0	17206.1	2.5
0.860	26.0	18630.9	2.5
0.860	38.0	10717.4	2.5

is performed. In this problem two disciplines take part: structures and aerodynamics. Both are heavily coupled since the deformation of the wing depends on the load applied, which, in turn, is obtained from the pressure distribution of the aerodynamic surfaces. This circles back to the structural part, as the aerodynamic shape, consequently, will vary depending on the load applied. This loop is what static aeroelasticity aims to solve.

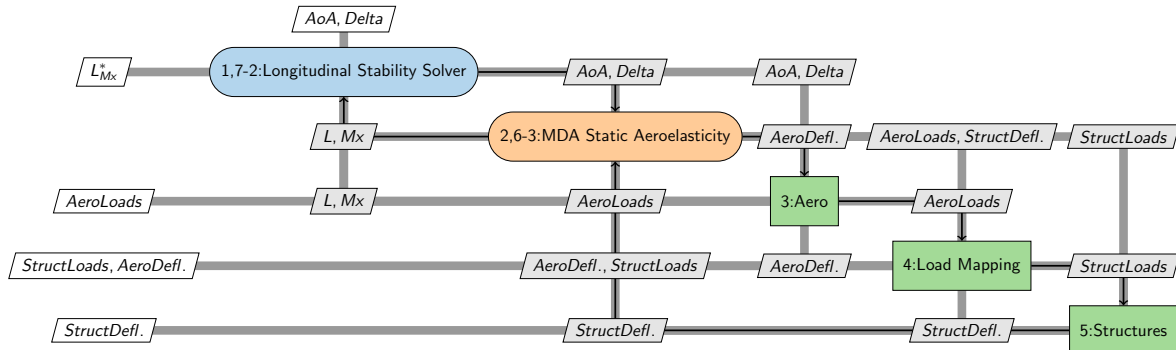


Figure 4: MDA XDSM for a static Aeroelastic problem with a longitudinal stability solver.

As shown in figure 4, the MDA Static Aeroelasticity (Sol 144 in Nastran) not only has to solve the aero-structural problem but on top of that equilibrium must be satisfied. Where the total lift given by the aerodynamic surfaces must equal the weight of the aircraft, as well as having no pitching moment at the Center of Mass (CoM).

4.2 Structural Model

The models uCRM9 and uCRM13.5 [6] NASTRAN Finite Element Model (FEM) are readily available, only for the wingbox. But with some modifications, it is possible to adapt the model to satisfy the problem needs.

First of all, it is imperative to find and specify the CoM of the aircraft. NASTRAN requires as input the centre of mass to be used as a pivot point for longitudinal stability. From the results of [6], it can be assumed that the CoM is placed near the reference point

used to obtain the pitching moment, as it is close to zero. Once this point is known, the centre of mass of the wing box plus fuel is obtained from the FEM. To force a CoM at the desired point, the approach taken was to include a third concentrated mass point as depicted in figure 5, this mass will equilibrate the wing box on the CoM and the remaining aircraft mass will be placed at the CoM. This workaround will suffice for static aeroelasticity, but it will not work for any dynamic analysis.

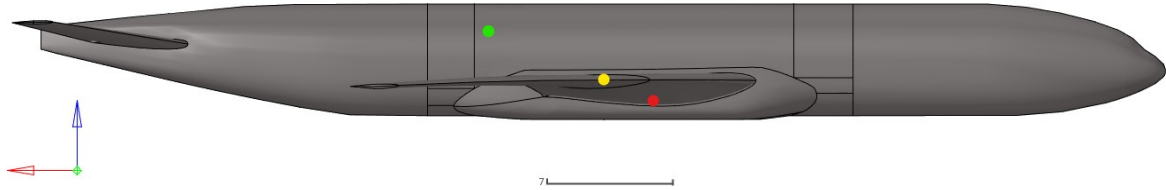


Figure 5: uCRM9 point mass locations, the aircraft CoM (yellow), aircraft trim mass point (green), and wingbox CoM (red).

4.3 Full Aerodynamic Model: Wing and HTP

The aerodynamic model will be in this case the Doublet Lattice Method (DLM) present in NASTRAN. Its simplicity will present a great advantage in the optimization process, as it will rapidly provide aerodynamic loads to the structural discipline reducing considerably the run times, compared to other flow solvers such as Computational Fluid Dynamics (CFD). The DLM model available in NASTRAN will as well account for compressibility effects, via the Prandtl–Glauert transformation [8].

To include the aerodynamics in NASTRAN, the projection of the wing was used as a reference. The mesh will consist of a series of horizontal panels representing idealised wetted surfaces, depicted in figure 6.

The element density of the DLM panels in the wings is much greater than the HTP, as it will be the focus of the optimization. As the aileron is defined as a subset of the panels that make the wing, the precision of the mesh must be high enough to avoid aliasing.

The main issue for using DLM as the aerodynamic solver is the linear behaviour, this means that there will not be any viscous effects that may lead to flow separation, which is the case in manoeuvres with a high load factor as the angle of attack is high as well. Apart from that the aerodynamic forces will not include the contribution due to camber or airfoil thickness.

4.4 Load Mapping

The last discipline in the MDA is the load mapping, often referred to as load and displacement interpolation. Both aerodynamic and structural meshes are essentially different, not only for the different physics involved but also because the nodes for both do not coincide. Within NASTRAN, the splining cards have as its purpose collecting the load applied at a given aero-node and applying it to the correct structural nodes, and, at the same time, retrieving the displacement of each structural node to be applied in the respective aero-node so the aerodynamic mesh can be deformed in parallel to match the structural mesh. Being the splining essentially an interpolation, it is important to always validate the loads introduced, as the total load from the aerodynamics must be equal to the load applied in the structure so that the interpolation is conservative. Many radial

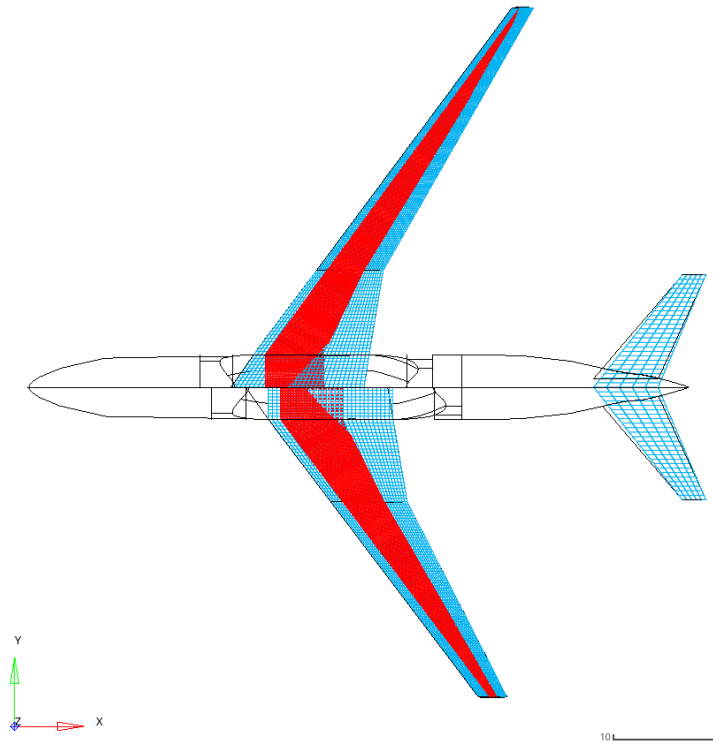


Figure 6: Aircraft FEM (Red) & DLM (Blue) model comparison, uCRM13.5 (Top) and uCRM9 (Bottom).

basis functions for load interpolation are available, some of which are discussed in [9] and will serve as a foundation for accurate load interpolation.

For NASTRAN, many options are available for the splining. SPLINE1 is the preferred solution as it will interpolate the loads in a defined surface [10], this Thin Plate Splines will transfer the load from the aerodynamic panels to the rigid connections to the structure, see figure 7. For this reason, rigid connections from the leading edge to the geometrical centre in between ribs and to the trailing edge were created, aiming at capturing the local twist of the wing and tail. The loads are distributed from the SPLINE1 surface to the structural FEM via radial interpolation through the RBE3 card [10], as shown in figure 7.

4.5 Result Validation

Once the model is ready, using the results from [6] as a reference, knowing that the model is rather low-fidelity it is not expected high accuracy regarding the CFD/CSM results obtained in [6]. The objective is to validate if the results are coherent with the study test cases. Only the maximum deflection of the wing and angle of attack for trim was used, see table 3, where the results from the static aeroelasticity from NASTRAN are compiled under Sol144.

As expected, the displacement results differ from the reference from 26.42% to 39.67%. For the same wing box model, previous studies [11] have shown large discrepancies between low-fidelity and high-fidelity aeroelastic analysis. This is to be expected, not only because of the low fidelity aerodynamics, but it can be also due to the contribution of the tail might be different. Finally, the angle of attack (AoA) results are also different. This is

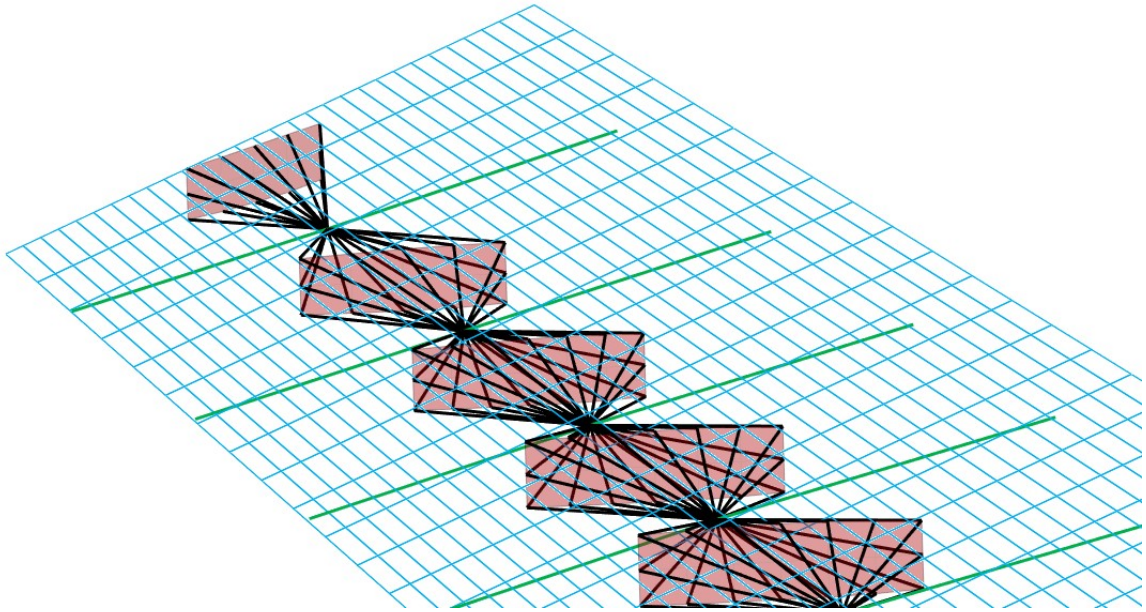


Figure 7: SPLINE1 configuration (green), ribs (red), RBE3 (black) and CAERO1 (blue) entries.

Table 3: Result validation in cruise flight conditions.

uCRM9	Brooks et al.[6]	Sol144
Max Vertical deflection [m]	2.524	1.857
AoA [deg]	2.044	5.389
uCRM13.5	Brooks et al.[6]	Sol144
Max Vertical deflection [m]	6.02	3.632
AoA [deg]	-	5.083

due to the fact that only the wing and the tail are considered.

Nevertheless, the results obtained, compared to reference single-aisle aircraft publications, are representing the right baseline for this analysis. The final deformation can be seen in figure 8.

4.6 Optimization Process

Given that the MDA is currently contained in just one discipline and handled by NASTRAN, the optimization can be achieved simply by introducing an optimizer such as Sequential Least Squares Programming (SLSQP) or Constrained Optimization By Linear Approximation (COBYLA), these optimizers have the advantage that they do not require gradient input, as the sensitivities are computed through the execution. This allows treating NASTRAN as a "black box", which is not the most optimal process, but given the simplicity of the architecture, as a first approach, it will suffice. The eXtended Design Structure Matrix (XDSM) is presented in figure 9.

For the execution of the optimization, GEMSEO [12] was utilized for its simplicity to create and define a multidisciplinary analysis and optimization process.

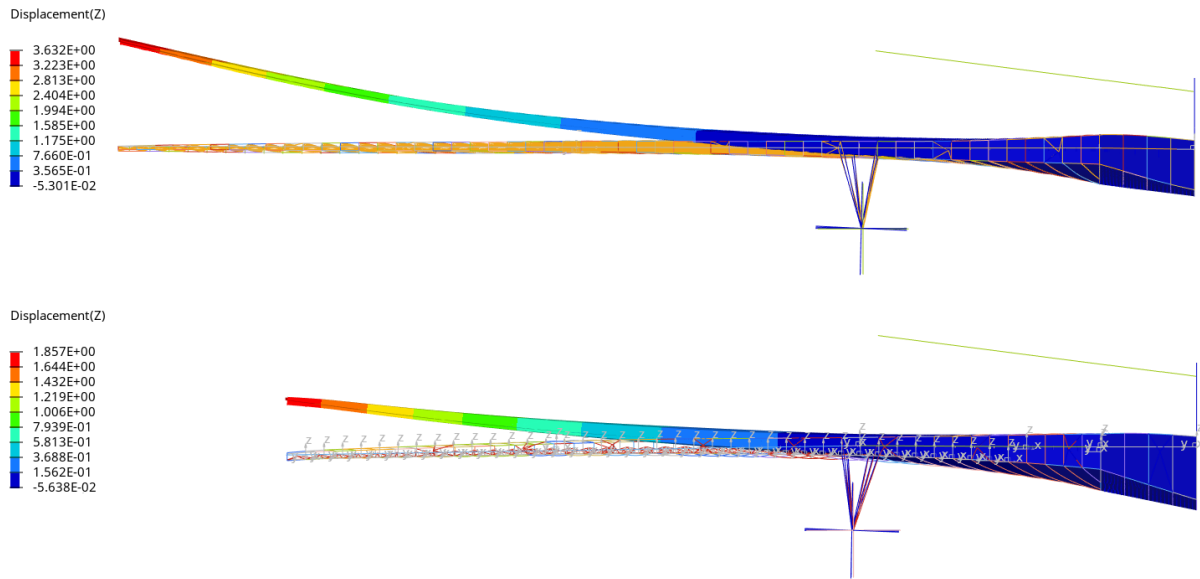


Figure 8: Wingbox cruise deflection comparison, uCRM13.5 (Top) and uCRM9 (Bottom).

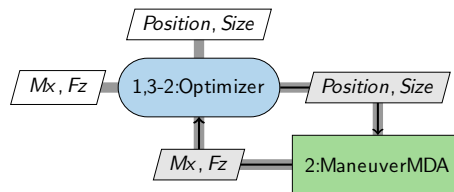


Figure 9: MDAO XDSM for aileron LAF optimization.

5 RESULTS

The first iterations of the optimization had two design variables, the position and size of the two adjacent ailerons. And it comes as no surprise that the optimizer will attempt to reach the maximum size it can for the control surface. The linear aerodynamics present in the DLM solver does not penalize the size of the aileron, so for the final results, a final size of 0.2 was set. It is for this reason as well the deflection angle was not taken into consideration and all the tests were run with 10° deflection. As a design variable for the optimization, the optimizer will always be inclined to the greatest value as no flow separation will appear.

Apart from that, the optimizer has given some interesting insight on what is the preference for the placement of the ailerons. As it can be seen in figure 10, contrary to what it may be most intuitive, the aileron is not placed near the wing tip where the lever arm respect to the root is greatest, but it tends to 60-70% respect to the wingspan. This is due to the fact that near the wingtip the wing box is more flexible, which means that the bending effect will not be as apparent in the root. So for LAF to be effective, it must be closer to the root, finding a compromise between the lever arm and structural flexibility. Less benefit with LAF is anticipated in HAR configuration, the increase in flexibility diminishes the effectiveness of the control surface. And, on top the wing deflection, the aileron induces a torque reducing the local angle of attack, and thus decreasing the intended effect by the aileron deployment. The overall weight impact should be assessed to

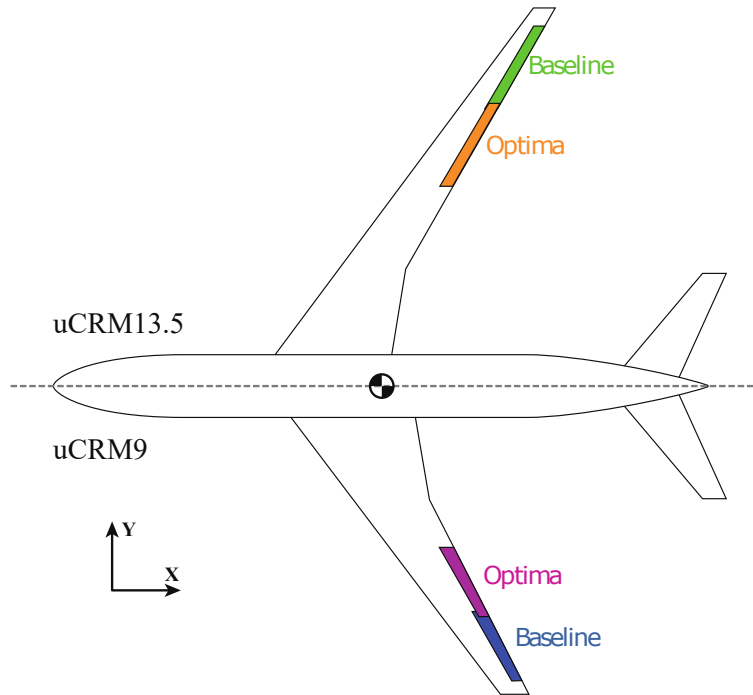


Figure 10: Aileron position optimization, baseline vs optima.

Table 4: Results, nondimensional reference and optimal geometrical aileron placement. Showing the inboard relocation for optimal load alleviation. Maximum bending moment found at $M=0.78$ at 38kft with $n=2.5$ for both cases.

uCRM13.5	Reference	Optimal
Position [-]	0.8	0.624
Size [-]	0.2	0.2
M_X Reduction [%]	-	3%

uCRM9	Reference	Optimal
Position [-]	0.8	0.708
Size [-]	0.2	0.2
M_X Reduction [%]	-	2%

identify the real ranking between HAR wings and the classical configuration (AR9).

Nonetheless, the outcome of this analysis shows an additional 3% benefit on top of the load reduction already present thanks to LAF, this can potentially reduce hundreds of kilograms in the wing structure, and it is targeted as a future part of the project to address the potential weight savings for both wing configurations.

It is worth mentioning that the final placement of the aileron will interfere with the flaps present in the current design. For this study, the optimizer was given the liberty to find the most suitable position in order to get a better insight into the problem. This result also means that it might be interesting in the future to consider as well the use of spoilers, which are closer to the optimal zone for the aileron.

6 NEXT STEPS

As this study is part of a larger project, the next steps to be taken to develop the current MDAO framework by adding other disciplines relevant for feasibility and certification. Firstly, the control reversal effect must be taken into account, by creating a separate discipline that monitors the local lift contribution in the control surface area. Indeed, the capability to control the aircraft is dependant of the control surface efficiency.

Only 2.5g manoeuvres were taken into account in this study, and following the certification specification section 25.335 [2], the aircraft must operate below limit loads under a gust encounter. The control surfaces are susceptible to failure, to fully validate the design it is necessary to validate the loads under failure conditions.

Another important aspect is that ailerons are conceived for the control of the aircraft, if the optimizer does not constrain at some level the effectiveness of the control surfaces to still be able to control the aircraft to fulfil the handling quality perspective.

As mentioned before, the linear aerodynamics present in the current implementation means there is no penalty for high angles of attack and aileron deflection. Fast solutions must be addressed such as [13] and [14], especially for gust computation. And for higher fidelity, finding a nonlinear aerodynamics solver such as CFD or derivatives that is efficient enough to run inside the optimization loop is going to be part of the upcoming challenges. Following previous works like [15], the loads can be interpolated from different aerodynamic flow solvers, which will also present a great opportunity to assess multi-fidelity in the loop.

On top of the flight points, to further enrich the test cases there is an interest to consider different mass configurations with different fuel distributions along the wing which may lead to harsher load conditions.

Finally, it is imperative to address the potential weight savings which ultimately will highlight the true objective of LAF. The MDAO architecture must have, as a final objective, to optimize the wing structure and then be coupled with stress in order to allow the convergence of the aero-loads-stress process.

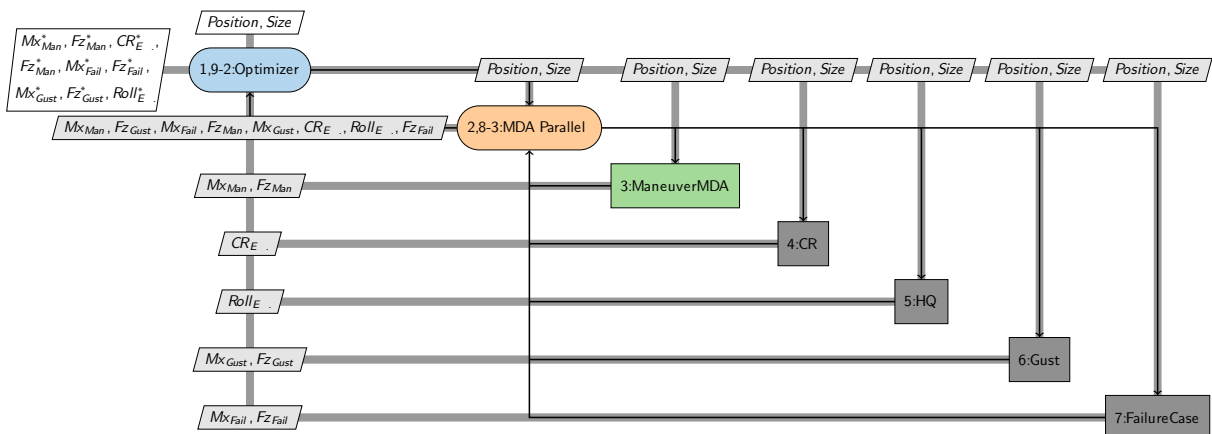


Figure 11: MDAO XDSM for aileron LAF, with future implementations (grey).

In figure 11 the target MDAO XDSM is presented, with the future disciplines to develop in grey color.

7 CONCLUSIONS

This study has demonstrated the LAF/MLA capabilities and how they can be improved by the better distribution of the control surfaces. This MDA process in spite of the fact that it is very simple differs from other wing/wing box optimizations because it requires the HTP, resembling Overall Aircraft Design (OAD). Although it is a very preliminary framework, it has made clear the requirements for the MDA required to perform such optimization, not only for the physics involved but also the requirements that need to be fulfilled as constraints for the optimizer to converge in a feasible design. This study will set the foundation for a greater and more complex framework that will intend to deepen the concept of LAF optimization with greater fidelity and feasibility.

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Figures containing the uCRM aircraft geometry, mesh plots or FEM results were achieved with Altair Hypermesh [16].

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