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DESIGN OF A HIGH ASPECT RATIO WINDTUNNEL MODEL FOR TRANSONIC GUST LOAD ALLEVIATION

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Abstract: The Clean Aviation Project called "Ultra-Performance Wing" (UP Wing) develops, matures and demonstrates key technologies and provides the architectural integration of ultra-performance wing concepts for short-medium range (SMR) aircraft with 150 to 250 passengers and 500 to 2000 nm range. One of the key technologies within the UP Wing project is "Novel Control Technologies" leading to a reduction in wing loads by applying manoeuvre and gust load alleviation technologies. To validate and compare different control methods best suited for gust load alleviation an aero-servo-elastic windtunnel test will be performed. This paper describes the design and corresponding analyses for a highly flexible wind tunnel model including several active control surfaces. The wind tunnel model will alleviate the gust loads by means of fast actuating control surfaces. One of the key challenges is to fit actuators within the available space that are both fast and able to overcome the moments generated by the control surfaces in transonic test conditions. To alleviate the loads, several control methods are investigated by different partners using a state space model created from the structural model and the aerodynamic panel model. To test the novel load alleviation function concepts during the wind tunnel test, a disturbance in the flow field will be generated. This is done by means of gust generator ahead of the test section.

The paper provides an overview of the past and upcoming activities related to the design of a flexible high aspect ratio wind tunnel experiment within the UP Wing Project.

1 INTRODUCTION

The short-medium range class is the largest contributor to the emissions in commercial air transport in terms of passenger and cargo kilometers. The transformation of civil aviation is now launched for a full climate neutrality by 2050. As set out in the Green Deal of the European Commission, this transformation requires the development of a new generation of aircraft in this class with radically improved energy efficiency leading to at least 30% reduction of net greenhouse gas (GHG) compared to 2020. A significant contribution to achieve these high ambitious goals is a breakthrough in next generation wing design, as the wing plays a dominant role for a further drastically drag and weight improved aircraft. A wing-oriented Clean Aviation project called

"Ultra-Performance Wing" (UP Wing) is a credible answer of a consortium that consists of 26 partners across Europe, engaged to deliver a wing configuration targeting a Technology Readiness Level (TRL) 4 by the end of the project in 2026, [1]. The project develops, matures and demonstrates key technologies and provides the architectural integration of ultra-performance wing concepts for short-medium range (SMR) aircraft with 150 to 250 passengers and 500 to 2000 nm range.

One of the key technologies within the UP Wing project is "Novel Control Technologies" leading to a reduction in wing loads by applying manoeuvre and gust load alleviation technologies. This is a critical technology for High Aspect Ratio (HAR) wings that experience an increased dynamic response due to external disturbances compared to conventional wings. Different control methods will be compared to estimate which technology is best suited for load alleviation. These control methodologies will be tested in a dynamic wind tunnel test. A flexible high aspect ratio wind tunnel model, featuring multiple active control surfaces, will be designed, manufactured and tested in the German-Dutch High Speed Wind Tunnel (DNW-HST) transonic test facility. This paper describes the design and analyses performed for the wind tunnel model by the partners involved.

2 TEST OBJECTIVES AND CONDITIONS

In the UP Wing project, a transonic wind tunnel experiment using a flexible model wing for the validation of active load control will be performed. The objective of the wind tunnel test is to gather experimental data of the aeroelastic behavior of the flexible wind tunnel model to validate (novel) control strategies aiming at load alleviation. The wind tunnel model will be designed with the aim to have a 15-20% tip deflection of the semi-span in nominal test conditions. The geometry of the model is derived from the DLR-F25 baseline configuration from the LuFo VI-2 project "VIRENFREI", a project funded by the German Federal Ministry for Economic Affairs and Climate Action (funding reference: 20X2106B). The number and placement of wind tunnel control surfaces are based on the full scale UP Wing movable layout configuration from which the trailing edge control surfaces used for load alleviation are selected. Three trailing edge control surfaces will be included for load alleviation. In addition, feasibilities studies are on-going to include static spoilers. The wind tunnel test in the DNW-HST will be performed at the full scale aircraft cruise Mach number (M=0.78 – 0.80) to represent non-linear aerodynamic behavior. The wind tunnel is a closed circuit tunnel able to vary the density. The test section is 2.0m wide by 1.6m or 1.8m height. The scaling factor is set to 1:15.28 in order to get the maximum allowable span length for the wind tunnel model, e.g. 70% of the wind tunnel section width.

Figure 1 provides an overview of the planned test set up, with the model wall mounted and two oscillating vanes in front of the model to generate a disturbance. The two vanes are horizontally mounted upstream of the test section and are actuated to rotate along their span. A rapid and simultaneous rotation of both vanes causes an effective change in angle of attack at the model test location.

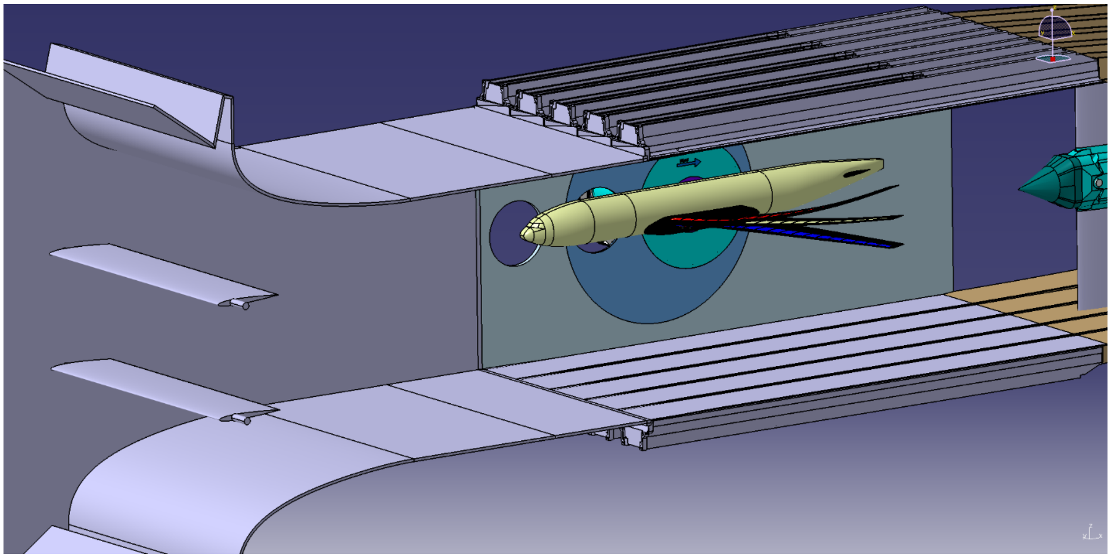
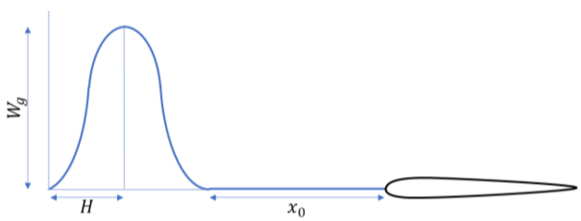


Figure 1: Wind tunnel test experiment set-up in the DNW-HST wind tunnel

Two types of disturbances are currently investigated and analyzed namely a 1-cos discrete gust type profile and a continuous turbulence profile as specified in the Certification Specifications for Large Passenger Aircraft (CS-25). The focus is currently aimed at the 1-cos discrete gust profile, see Figure 2. For the gust profile, the amplitude is determined by the reference velocity (U_{ref}) as provided in the CS-25, the flight alleviation factor F_g which is aircraft depended and half the gust length H (ranging from 0ft to a maximum of 350ft).



$$W_g = U_{ref} * F_g * \left(\frac{H}{107}\right)^{\frac{1}{6}}$$

Figure 2: 1-cos gust profile

The scaling of the gust length in wind tunnel test conditions is based on the geometric scaling factor of the wind tunnel model. This results in the following target gust length conditions in the wind tunnel, see Table 1. The longest gust length is set to 18-20Hz. The shortest gust length is limited by the capability of the actuators driving the gust vanes as shown in Figure 1. These numbers are comparable to the gust specifications of the ARA wind tunnel in the United Kingdom capable of generation discrete gusts with a duration of 25ms to 50ms under transonic conditions, [2].

Table 1: Wind tunnel gust lengths

Full scale gust (2H) [Ft]	Wind tunnel gust (2H) [Ft]	Gust duration [ms]	Gust frequency [Hz]
700	45.8	54.3	18.4
350	22.9	27.2	36.8

The gust amplitude (W_g) is estimated from the total increase in force due to the gust for a typical transport aircraft. Taken into account the difference due to inertia relief for a free flying aircraft, a target of 4m/s is set for the vertical velocity resulting in a 1deg Angle of Attack increase under the testing conditions (M=0.78 under atmospheric conditions).

3 WIND TUNNEL MODEL PRELIMINARY DESIGN

3.1 Wind tunnel model aerodynamic design

For the aerodynamic design of the wind tunnel model, the shape is derived from the wing of the full-size reference aircraft DLR-F25, used in other work packages of the UP Wing project, e.g. in WP 2.1. However, during the specification process for the wind tunnel experiment it became clear that a pure down-scaling of the full-size aircraft wing was not suitable for the wind tunnel model. First, the maximum thickness of a scaled model wing would have not have been sufficient to accommodate sensors and actuators in the model. Second, the scale factor between full aircraft and wind tunnel model leads to a reduced Reynold's number of the wind tunnel wing, creating a distinct difference in aerodynamic behavior of full-aircraft wing and model wing at the transonic test speeds. Most notably, the wind tunnel wing in scaled aircraft shape would not show sufficient aerodynamic robustness around the design point to be suitable for the testing purpose. During the adaptation process, several geometric parameters have been modified and the influence on the aerodynamic properties of the wing investigated by extensive CFD analyses. First, an adaptation of the wing twist distribution has been performed with respect to the original DLR-F25 variant from VirenFrei. Second, a planform modification has been suggested, increasing the tip chord by 18% and, at the same time, removing a kink at the trailing edge which was located close to the span-wise engine position in the full aircraft. Third, the absolute thickness of the profile at the wing tip has been increased, thus also increasing the internal space in the model for sensors and actuators.

The first design step included an increase in absolute chord for various span stations while keeping the absolute thickness constant. In this step, also the trailing edge kink has been smoothed out. In addition, a re-twist was applied compared to the full scale flight shape twist distribution, see Figure 3.

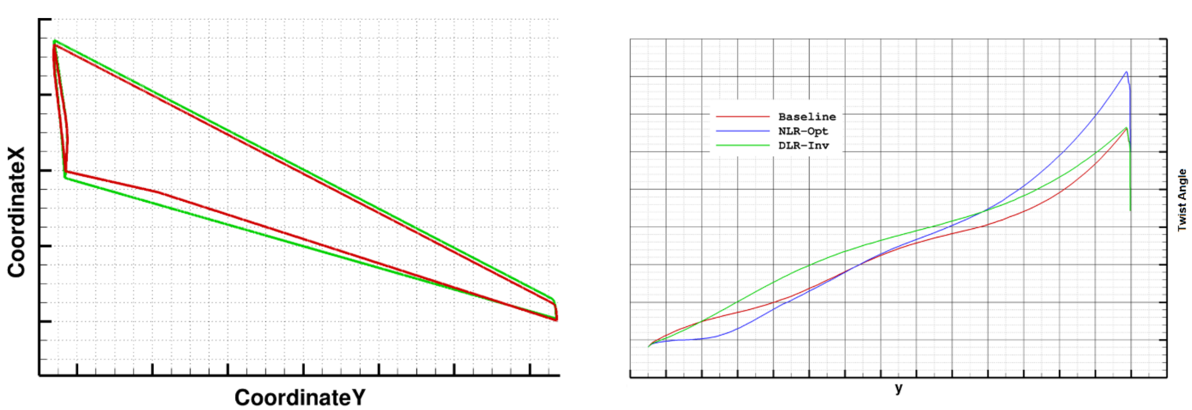


Figure 3: (left) Planform modifications of the wind tunnel wing (red is the scaled DLR-F25 planform and green the final wind tunnel planform), (right) twist adaption from the Baseline (DLR-F25) to DLR and NLR variants in the design process.

Figure 4 shows the effect of the planform modifications on lift and drag of the wind tunnel wing. The influence of the modification is considerable, increasing total lift and extending the linear range of the relation between C_L and angle of attack.

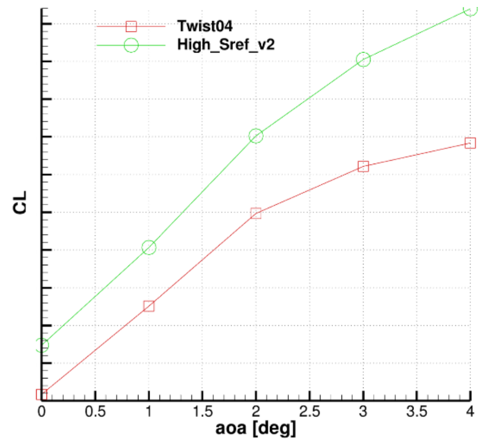


Figure 4: C_L alpha curve comparison between the baseline (DLR-F25) and updated planform geometry named High_Sref_v2.

In a second step, the airfoils have been optimized to further increase the aerodynamic robustness at higher angles of attack, by extending the linear region of the CL-alpha curve, and therefore delaying buffet-onset. Both DLR and NLR worked separately on numerical optimization approaches. For NLR, all the CFD simulations were performed using ENFLOW, which is a high-fidelity CFD RANS code developed in-house. NLR used an adjoint method for design optimization to optimize the wing profile at a number of spanwise locations [3]. DLR used the DLR TAU code in combination with the inverse design method to compute the wing geometry for a prescribed target pressure distribution [4].

Both the DLR and NLR optimization approaches include geometry constraints at all locations where (i) the maximum thickness, (ii) the thickness in the aft region up to the trailing edge, and (iii) the leading edge radius are not allowed to be less than the values set by manufacturing constraints. Stringent constraints were also imposed on the boundary layer loading, in terms of the shape factor near the trailing edge of the wing, to inhibit flow separation.

Figure 5 shows the final C_L versus angle of attack curve for the two different designs and the baseline design. In the end, the geometry labelled NLR is selected to continue the wind tunnel model design due to the extended linear C_L-alpha region. In addition to the optimized wing, a slender body and fairing are added, see Figure 6. On the right side of Figure 5 the final surface pressure distribution for C_L=0.50 is shown including the fairing and slender body (not shown in the picture).

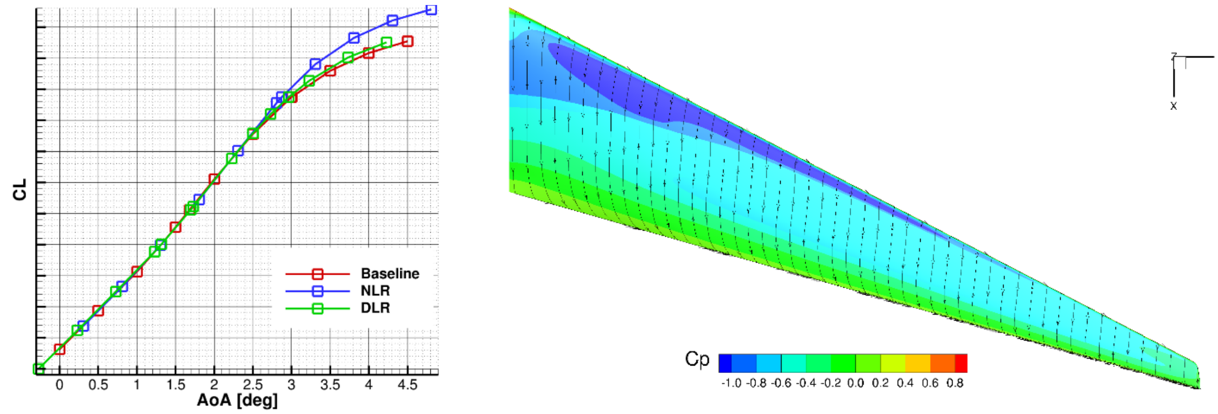


Figure 5: (left) C_L alpha curve comparison between the baseline (DLR-F25) and final NLR and DLR wind tunnel geometries, (right) top surface pressure distribution at C_L=0.50.

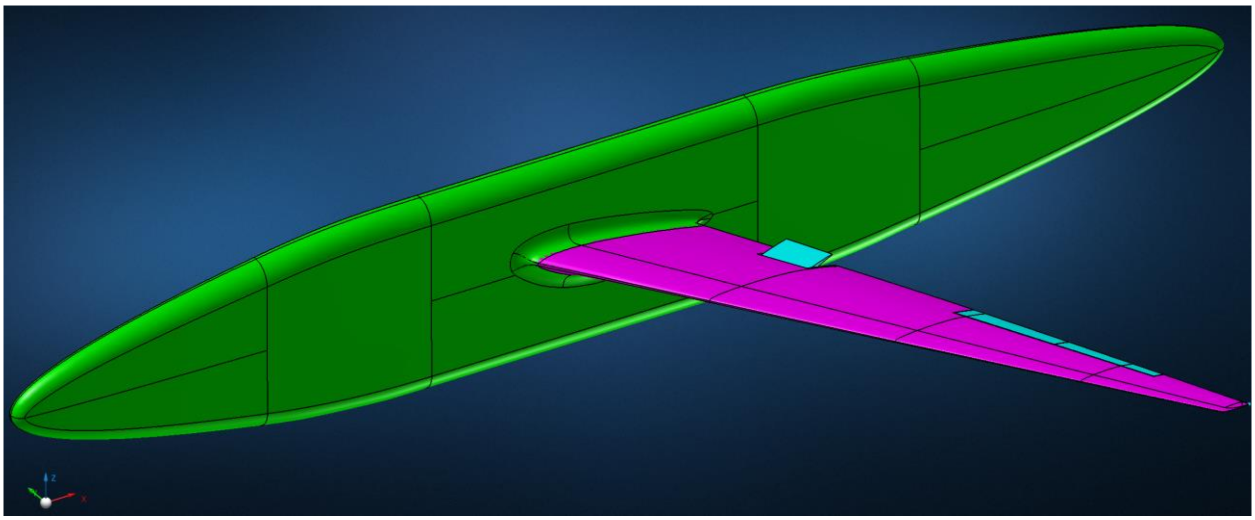


Figure 6: Preliminary CAD model of the wind tunnel model including a slender body, fairing and optimized wing geometry

3.2 Wind tunnel model structural design

The main design target for the wind tunnel model is the required high-flexibility and target twist distribution under the prescribed loading conditions. To accomplish this design target and comply with the safety requirements as set by DNW for operating a model in the tunnel, requires significant design work for the structural properties. The structural design is separated in three phases, conceptual design, preliminary design and detailed design.

To obtain the first set of design loads a lower fidelity panel method model is created based on the final aerodynamic design Commercial software suite ZAERO is used for analysis. ZAERO is a panel method that solves the (incompressible) potential flow equation whereas Mach effects are being accounted for through Prandl-Glauert corrections. Wing profiles are incorporated by means of placing the panels adjacent to the camber line of the airfoil. This model is used for static and dynamic load analyses. The design lift coefficient of C_L = 0.50 results in a total force of approximately 4100[N] static load on the model. On top comes the loads generated due to the gust in the tunnel.
The gust spectrum in this preliminary design phase is obtained from Computation Fluid Dynamics (CFD) analyses in which the gust generator vanes are included, see Figure 8. On the left side of

the figure, an indication is provided for the resulting gust angle versus time. The amplitude and frequency of the resulting gust is depended on the vertical placement on the vanes, the chord and profile of the vanes and the rotational frequency. As noticed from the gust angle plot in Figure 8 the gust is characterized by negative peaks before and after the main positive peak. The starting and stopping vortices of the vanes seem to be the primary reason behind this difference [Refx].

On the right of Figure 7, the resulting gust load shear force is plotted for three different gust cases varying in gust frequency and amplitude. The maximum shear load obtained is close to 20% of the static load.

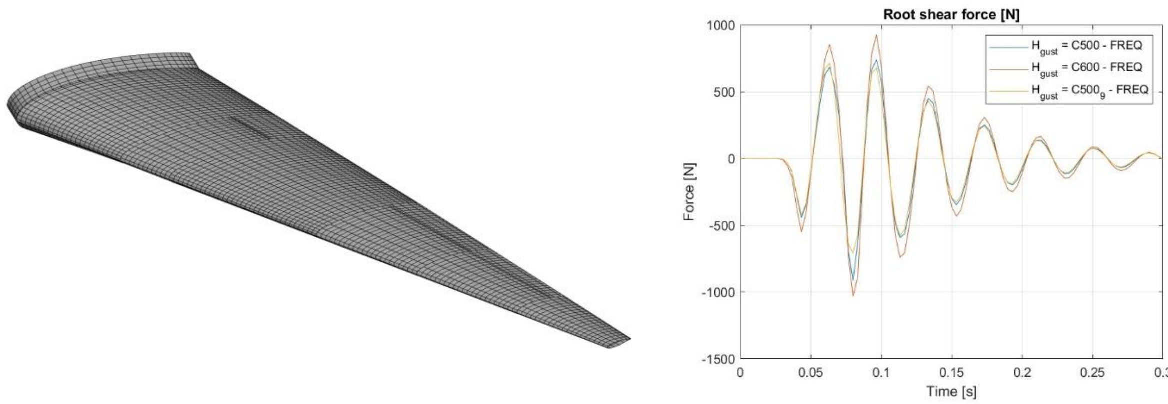


Figure 7: Panel model including chamber correction used for ZAERO analyses.

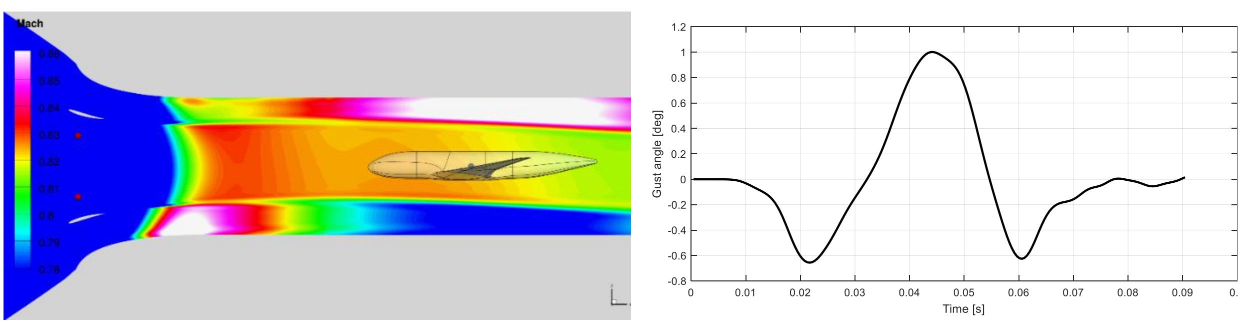


Figure 8: (left) CFD simulations of the gust characteristics in the wind tunnel, (right) resulting angle-of-attack increase a function of time.

In the conceptual design, the structural concept is selected together with a material. The key drivers for the structural concept is the flexibility target of 15-20% semi span deflection in combination with the design load of roughly 4100[N] plus the resulting gust load. The wing will consists of an upper and lower skin with a foam core. The wing skins are made from Glass Fibre Reinforced Plastic (GFRP) materials. The GFRP material has a lower strength and stiffness than Carbon Fibre Reinforced Plastic (CFRP) materials, but a higher strain to failure thereby enabling larger deflections of the wing. The foam core is not really intended to be a structural part of the wing design but its function is to prevent buckling of the (relatively thin) GFRP skins.

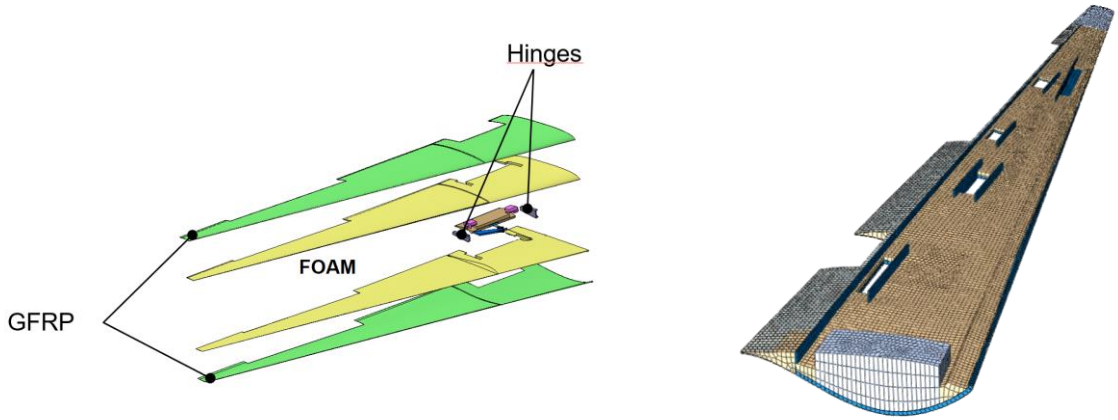


Figure 9: (left) structural concept of the wind tunnel model, (right) conceptual design finite element model including holes and local spars for accessibility of actuators and hinges.

The conceptual design is used as input for the preliminary design featuring an aeroelastic stiffness optimization process developed at the DLR – Institute of Aeroelasticity (DLR-AE), [refX]. The goal of optimizing the base-stacking and its staggered application were threefold:

1. meeting the target loaded twist under loading conditions as provided from the aerodynamic design in chapter 3.1.
2. reaching a tip deflection of at least 15% semi span deflection under loading conditions
3. maintaining a safety factor a set by DNW including static and dynamic components.

The Nastran finite element (FE) model used for the computation of all structural and aeroelastic responses to be considered is generated using the DLR in-house parametric modelling software ModGen [5]. A representation of the FE model is shown in Figure 10.

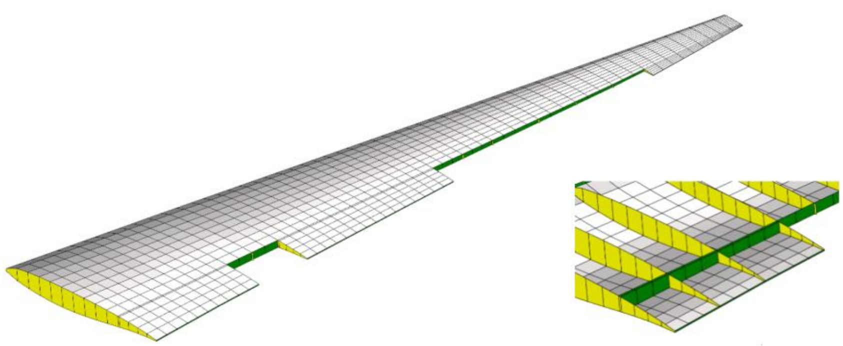


Figure 10: ModGen finite element model.

It comprises load carrying wing skins, extending from leading to trailing edge. The skins are supported by a foam core to prevent it from buckling under compressional loads. While the skins are represented by shell elements in the FE model, the foam is modelled by volumetric elements. The aerodynamics are represented by a doublet lattice model (DLM) including a camber and twist correction, available in Nastran via the so-called W2GJ correction matrix. Coupling between the structural and the aerodynamic model is achieved by a dedicated set of coupling nodes. To this end, ribs connecting directly to the wing skins are introduced in nearly equidistant positions along the span. This technique is required by the ModGen modelling process, which necessitates the presence of a rib in order to generate coupling nodes. For the ribs to not add mass or stiffness, they are modelled without structural properties, as so-called dummy-ribs. Each outer node on a dummy-rib and thus wing skin is connected to an RBE3 interpolating element, the central, dependent node of which is placed in the quarter chord. Extending from the central node towards the leading and trailing edge are RBE2 rigid body elements, resulting in three nodes suitable for the aeroelastic coupling per dummy-rib. The entity of central nodes constitutes the so-called load reference axis, which will also be addressed in the monitoring of deformation and twist responses. Eventually, non-structural masses can be included as point masses, attached via rigid body elements. Nastran SOL144 is then used to compute the static aeroelastic deflection of the wing. The preliminary design of the model and its operational shape is shown in Figure 11. The full span of the model equal 1.40[m] meaning a deflection of 17% is achieved.

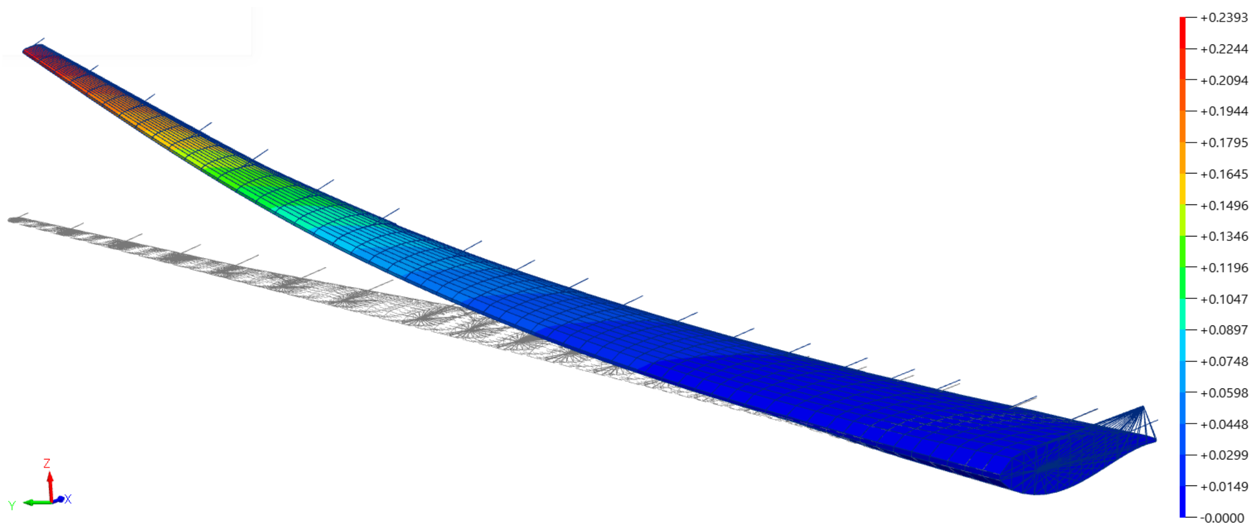


Figure 11: Static aeroelastic load analyses showing the intended deflection of the model under the design loading conditions.

3.3 Actuator requirements for Load Control

In order to evaluate the control surface actuation requirements for gust load alleviation in terms of deflection angles, rotational rates and hinge moments, a preliminary load alleviation controller was built. However, before control design tools could be utilized it was necessary to obtain a state-space model of the wing. A state-space model was created from the initial structural model and the aerodynamic panel model using ZAERO software.

The first 12 structural modes were included in the state-space model covering a frequency range of up to 360Hz. Additionally, during the conversion of the frequency domain model into the time domain using the rational function approximation method, 6 aerodynamic lag states were introduced for each mode. The inputs to the aeroservoelastic model include the angle, rotational rate and rotational acceleration of the control surfaces and also the vertical velocity of the gust. A second order transfer function was used to model the actuator dynamics and convert the control surface angle commands to the angle, rotational rate and acceleration inputs for the aeroservoelastic model. By changing the actuator model bandwidth, it was possible to evaluate the load alleviation performance for different actuation speeds and gain insight into actuation requirements. The outputs of the aeroservoelastic model are the forces and moments at the root of the wing as well as the hinge moments of the control surfaces. Additionally, different sensors such as accelerometers and their locations can be added and different placement locations can be evaluated.

With the aeroservoelastic state-space model it was then possible to construct an initial load alleviation controller for evaluation. A Linear Quadratic Regulator (LQR) controller was implemented for gust load alleviation [6]. A delay of 6 ms was added to the control surface inputs to account for different delays in the wind tunnel setup. State estimation, sensor placement, noise and feedforward information of the gust were not considered for these initial evaluations. Therefore, the achieved load alleviation performance is only a preliminary estimate and will likely change at a later stage. For the disturbance, 1-cosine gust was used with 1 degree amplitude at a 25Hz frequency, which is considered as the most demanding condition in the upcoming wind tunnel test.

For the LQR controller, equal weights were applied on all the control surface inputs together with a weight on the first mode amplitude which was tuned such that the maximum control surface deflection responses would remain under 10deg. With the LQR controller implemented, gust responses were then simulated for varying actuator model bandwidths. In Figure 12, the wing root bending load alleviation performance is presented for varying actuator rotational rates. It can be seen, that the highest rotational rates are used by the outermost flap (flap2) reaching over 600 deg/s while the middle (flap1) and inner (flap0) flap remain around 200-400 deg/s. As the actuator model bandwidth is increased, there is less delay due to the actuator dynamics. This leads to a point where improved alleviation performance can be achieved with lower peak rotational rates.

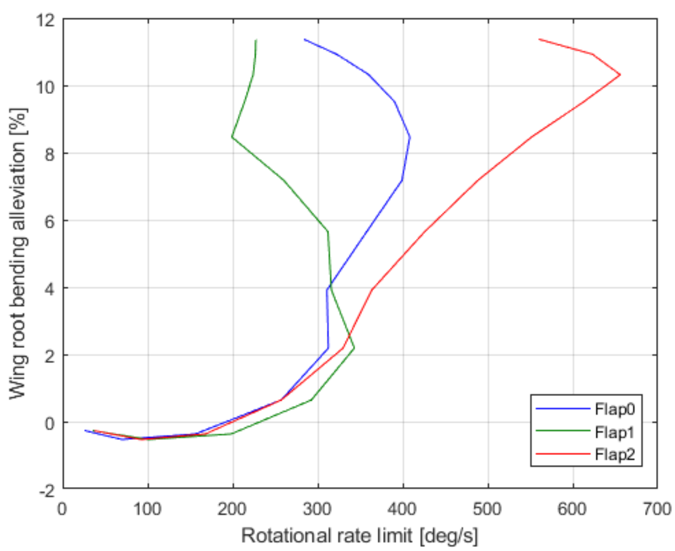


Figure 12: Wing root bending load alleviation for varying actuator rotational rate limits.

In Figure 13, an example control response to a gust excitation is presented. In addition to actuator rotation rate requirements, also the corresponding peak hinge moments were determined. The peak hinge moments were observed to be 0.65 Nm for inner flap and around 0.43 Nm for middle and outer flaps.

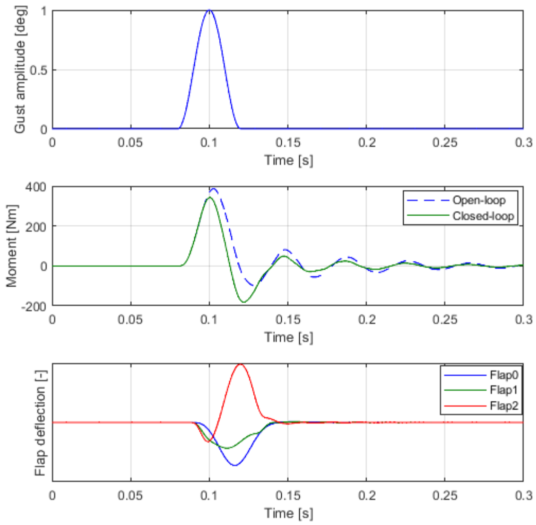


Figure 13: Control system response to a gust excitation.

While different control laws can have very different responses and performance, using LQR it was possible to get an initial estimate of the requirements for the UP Wing actuators.

4 SUMMARY

This paper provides an overview of the Clean Aviation UP Wing project and its technical ambitions with regards to the design of a flexible high aspect ratio wind tunnel model. The aerodynamic shape for the wind tunnel model for load control has been designed and finalized. The steps included a scaling from the full aircraft dimension, an adaptation to the technical requirements from wind tunnel manufacturing, and modifications to obtain a desired aerodynamic performance in the operational range of the load control experiment. The structural design is currently in the preliminary design phase. A material and conceptual design (skin, foam) is selected in order to achieve the required high deflection under nominal operating conditions. The optimization process in in-place to continue the preliminary design in which the required lay-ups are derived to comply with the design targets. Both structural and aerodynamic models are input to the state space models. Initial actuator limits and actuator deflections are provided for the mechanical design of the wind tunnel model.

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