

# ASSESSMENT OF ACTIVE LOAD CONTROL APPROACHES FOR TRANSPORT AIRCRAFT – SIMULATION AND WIND TUNNEL TEST

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**Keywords:** load control, wind tunnel experiment, high aspect ratio wing aircraft

**Abstract:** Active flight load alleviation is an important contribution towards lighter wing structures and wings of higher aspect ratios, both important measures to increase the efficiency of transport aircraft. In the DLR project oLAF (optimal load adaptive aircraft), strategies for active and passive load alleviation are developed and validated. In the project, different lines of investigation are followed in parallel – first, a reference configuration of a long-range aircraft is designed on a preliminary design basis, and both aerodynamics and structure of the wing are further optimized using coupled CFD- and finite-element-based design methods. Second, various aspects of load control technologies are studied independently, and the results are applied using the design process of the reference aircraft. Third, a closer look is taken at the aerodynamics of spoilers and control surfaces. Finally, high-fidelity methods are employed for a further development of MDO aircraft design processes.

Outputs of the aforementioned activities form the basis for the definition of a wind tunnel experiment for the validation of active load alleviation approaches in the DNW-NWB low speed wind tunnel. The planform of the wind tunnel wing is derived from the overall aircraft design. Aeroelastic tailoring approaches are used for the design of the wing structure. The active control laws applied in the experiment are derived from the control design approaches developed for the complete aircraft. For the flow excitation, a new gust generator has been developed. The results of the wind tunnel experiment are used for the validation of the numerical approaches developed in the project.

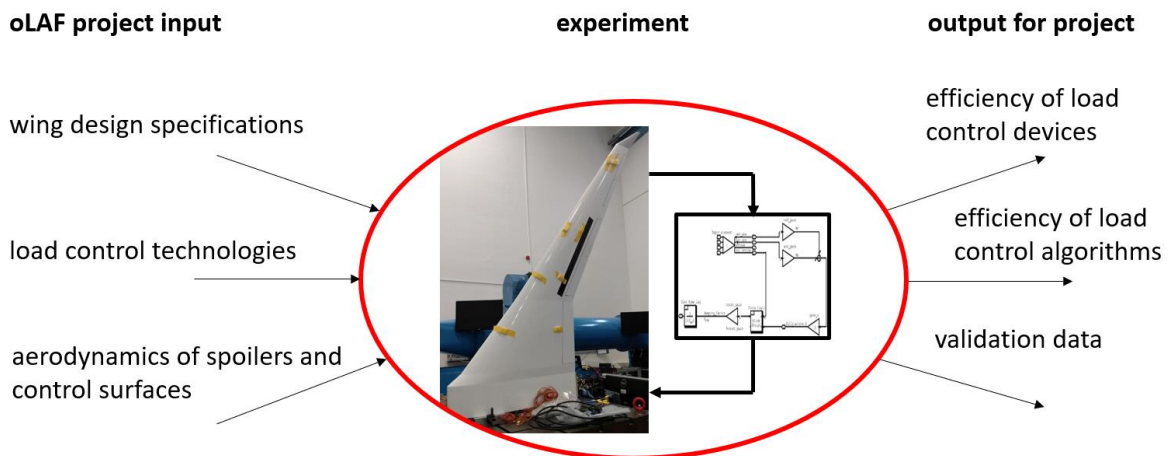
This paper focusses on the specifications of the wind tunnel experiment resulting from the overall project investigations and the contributions of the experiment to the project goals. Further papers will provide detailed descriptions of the wing design and the wind tunnel experiment.

## 1 INTRODUCTION

A major focus of current research world-wide is the evaluation of high aspect ratio wing aircraft with respect to performance improvement and thus the reduction of the ecological footprint, when compared to classical configurations. In the DLR-project oLAF (optimal Load-Adaptive Aircraft), the goal is to evaluate the potential of aggressive load reduction with regard to minimization of structural mass and flight-physical performance improvement for a long-range aircraft.

Active flight load alleviation is an important contribution towards lighter wing structures and wings of higher aspect ratios, both important measures to increase the efficiency of transport aircraft. In oLAF, strategies for active and passive load alleviation are developed and validated. In the project, different lines of investigation are followed in parallel – first, a reference configuration of a long-range aircraft is designed on a preliminary design basis, and both aerodynamics and structure of the wing are further optimized using coupled CFD- and finite-element-based design methods. Second, various aspects of load control technologies (aeroelastic properties of wings and control devices, structural wing design, design of load control algorithms with and without LIDAR) are studied independently, and the results are applied using the design process of the reference aircraft. Third, a closer look is taken at the aerodynamics of spoilers and control surfaces. While spoilers are regularly used as secondary control surfaces, the numerical analysis of deployed spoilers and of the efficiency of control surfaces downstream of the spoilers is still challenging. To assess the applicability of spoilers directly for load control as well as the influence of spoilers on the control surfaces, both numerical and experimental investigations are performed. Finally, high-fidelity multidisciplinary design and optimization methods are further developed and tested in an extended MDO-process.

Outputs of the aforementioned activities form the basis for the definition of a wind tunnel experiment for the validation of active load alleviation approaches in the DNW-NWB low speed wind tunnel. The planform of the wind tunnel wing is derived from the overall aircraft design. Aeroelastic tailoring approaches are used for the design of the wing structure, but whereas for a full aircraft, the objective function is optimal performance, i.e. a combination of minimum structural mass and minimum drag, the wind tunnel wing is optimized for maximum deflection and minimum natural frequency to enable real-time testing of active load control approaches. Another important objective of the wind tunnel test is the application of the numerical descriptions of spoilers and control surfaces to be used in control design. The active control laws applied in the experiment are derived from the control design approaches developed for the complete aircraft. The results of the wind tunnel experiment are used for the validation of the numerical approaches developed in the project.



**Figure 1.** Data flow in oLAF

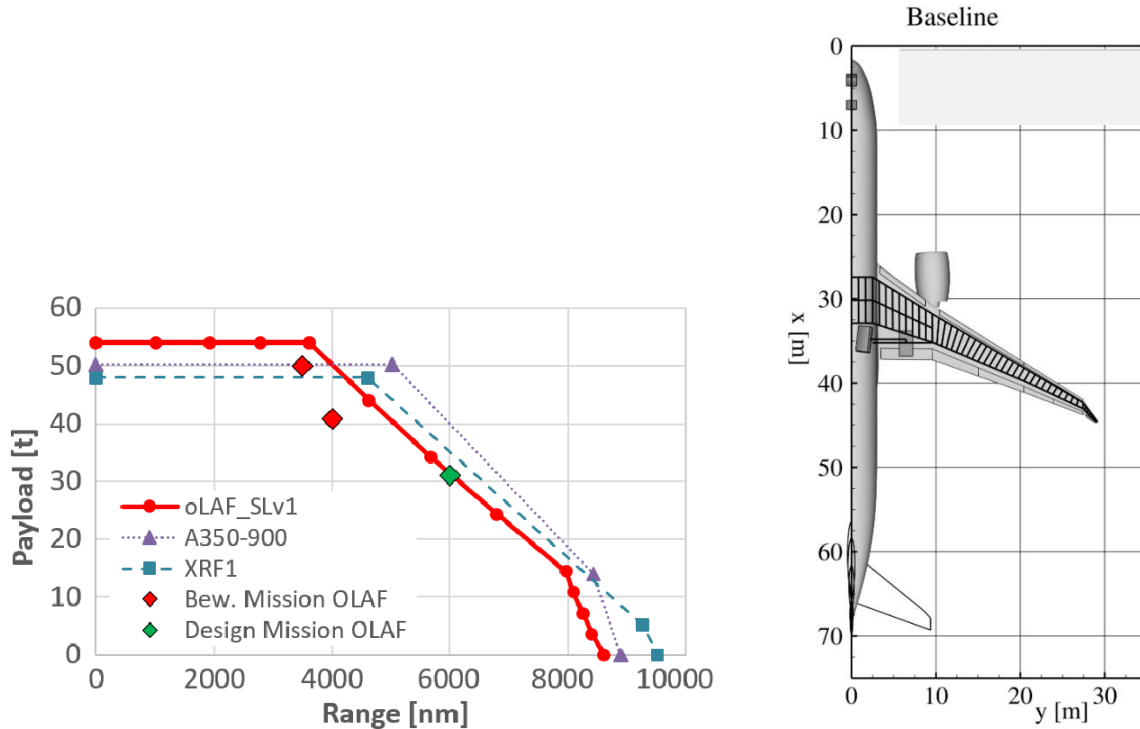
This paper focusses on the specifications of the wind tunnel experiment resulting from the overall project investigations and the contributions of the experiment to the project goals. Further papers will provide detailed descriptions of the wing design [1], the gust generator development [2] and the control design approaches including results from the wind tunnel experiment [3].

In the oLAF project, the respective activities are closely interconnected. The aircraft design with aggressive load reduction (see Section 2) is carried out using the load reduction technologies developed (see Section 3) and selected design and optimization methods/processes from the multidisciplinary aircraft design chain (see Section 4). In addition, the aircraft design package carries out the utility analysis of the integrated "aggressive load reduction" technology at overall aircraft level. The reference against which the technology benefit is determined is a configuration with load reduction according to the state of the art, which is designed in the same package. The wind tunnel experiments (see Section 5) provide validation data for the numerical methods used for the design and evaluation of load control technologies. Furthermore, the experiments provide an experimental demonstration of the efficiency of a selected, purely numerically designed load reduction concept.

## **2 REFERENCE AIRCRAFT**

For the investigation of the potential of aggressive load alleviation a long-range aircraft configuration is developed and taken as a reference. In a first loop, the aircraft is designed assuming classical load alleviation approaches, especially manoeuvre load alleviation, using the standard control surfaces. In a second loop, roughly half way through the project, selected additional load alleviation technologies are implemented on the aircraft and the potential for load reduction of the respective technologies is evaluated. The sizing of the aircraft structure is now repeated with a set of newly determined loads, thus assessing the potential of the load alleviation technologies for a wing mass reduction.

The reference aircraft in oLAF is a wide-body long-range configuration, closer described in [4], [5], [6]. Top level aircraft requirements are an OEM of 118 t, an MTOM of 220 t, a maximum payload of 54 t and a flight Mach number MMO of 0.86. The wing span of the initial configuration is 57.7 m, with an aspect ratio of roughly 10. The design parameters are shown in the payload-range-diagram in Figure 2, taken from [4], compared to parameters of the Airbus research model XRF1, a long-range wide body transport aircraft developed by Airbus as part of the eXternal Research Forum, and publicly available data of the commercial Airbus A350-900.

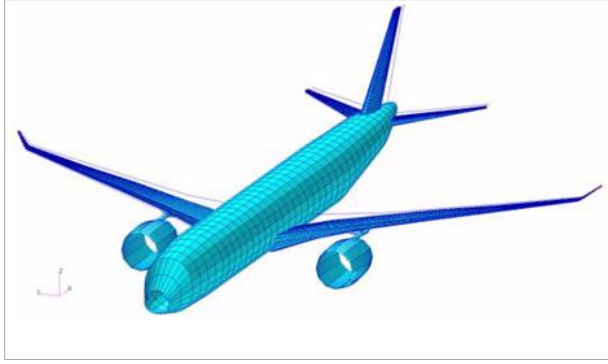


**Figure 2.** Payload-range diagram for the oLAF configuration at  $Ma=0.83$  and the reference aircraft, taken from [4]

For the conceptual design, the aircraft design tool openAD is used. The process consists of a single loop converging the maximum take-off mass and fuel mass. OpenAD is used to obtain the main geometrical parameters for the wing, fuselage, and tail planes, an initial mass-breakdown, a costs estimation and a simplified aerodynamic performance map. The tool has the additional functionality to generate a CPACS file which is the basis for aircraft data exchange in the project.

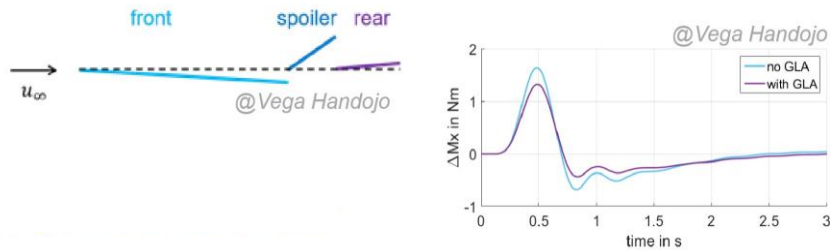
Based on the result of the overall aircraft design, parametric models for the aero-structural wing optimization are built. This design step consists of an optimization process which is based on using CFD and finite element analysis methods, with requirements from a multi-mission analysis. The conceptual design is enhanced by introducing more aerodynamic performance driving profiles and twist distribution based on previous wing planform optimization results [5].

In a subsequent analysis, the aeroelastic design and assessment is performed, including an extensive flight load analysis campaign of the flexible aircraft and a structural optimization of the wing structures taking loads as well as aeroelastic requirements like sufficient control surface efficiency into account [5]. The analyses are performed using a so-called GFEM model, created with the parametric model generation process cpacs-MONA of DLR [7]. The result of the first design loop is the reference aircraft configuration shown in Figure 3.



**Figure 3.** oLAF reference configuration: GFEM model (left), wing FE model (right)

The wing planform of the oLAF configuration was the input for the wind tunnel model wing.



For a concluding assessment of the potential of load alleviation, the baseline aircraft configuration has been re-designed including various load alleviation technologies, leading to the final aircraft design. The comparison of baseline and final design delivers the assessment for the potential of designing an aircraft with aggressive load alleviation.

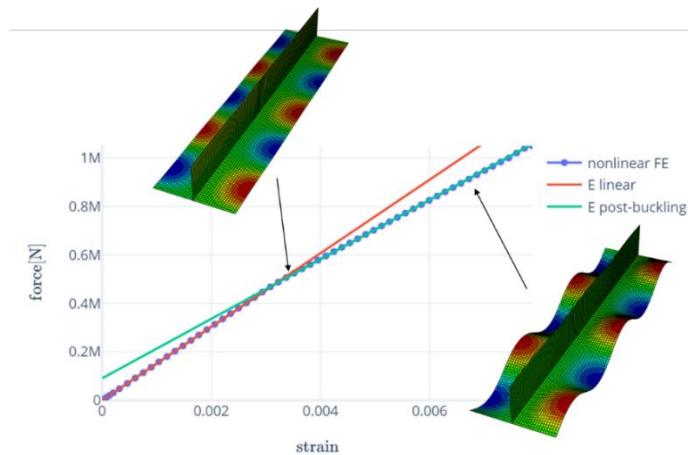
### 3 LOAD ALLEVIATION TECHNOLOGIES

In a parallel activity, individual load reduction technologies are developed, and their respective effectiveness analyzed. Promising approaches include the extended use of spoilers for load control, the application of materials with non-linear properties for load reduction in wing design, and the admission of skin buckling at high loads, softening the wing and thus reducing peak loads. In addition, active load control laws, both feedback strategies and feed-forward strategies (assuming a LIDAR) have been analyzed. Finally, CFD-based simulation methods to support load control have been advanced. The investigations include the following areas:

#### *Application of non-linear stiffness in wing structures for load alleviation*

With non-linear stiffnesses behaviour, the deformation of the wing structure can be influenced in such a way that a favourable lift distribution can be achieved for sizing load cases, due to a (passive) increase of the effects of bending-torsion coupling. As a result, more lift is produced in the root area of the wing, which leads to a reduction in the root bending moment. In the project, a methodology for the introduction of materials with non-linear stiffness properties has been developed and documented in [8]. Another approach to realize a non-linear increase of the bending-torsion coupling is the utilization of buckling to influence structural flexibility. In the

post-buckling regime, the structure softens, potentially increasing the bending-torsion coupling and reducing outboard lift, see Figure 4 from **REF**.



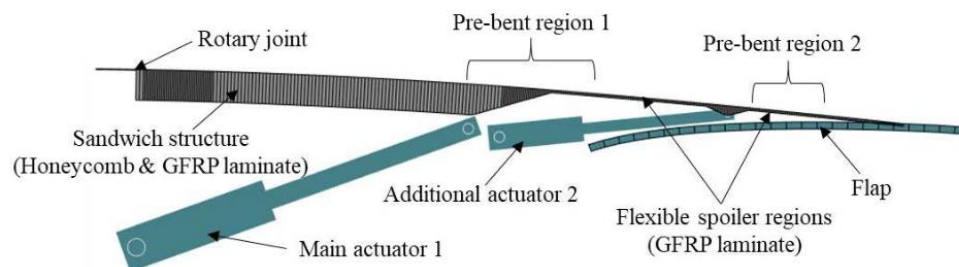
**Figure 4.** Stiffness of element prior to and during buckling

Both approaches have been investigated on dedicated wing models. However, a numerical assessment of these approach on the oLAF reference aircraft is not planned inside the project as a structural sizing process taking advantage of non-linear structural behaviour is not state-of-the-art and needs a significant development of the current sizing process.

#### *Investigation of control surfaces*

Lift is conventionally reduced by the deflection of control surfaces. In addition to control surface-based technologies, bumps and microtabs are also being investigated with regard to their load reduction potential. Among other things, the focus in the process is on the provision of substitute models. Here, the POD proved to be the best method. With the help of POD, the lift of a spoiler deflection can be determined very quickly with any angle/speed combination within the previous simulation range.

A specific development in oLAF is the so-called morphing spoiler, which fulfils both the conventional functions such as the air brake and can also enable additional functionalities through its shape variability. These functionalities include the formation of a shock control bump, which can attenuate the transonic shock and thus reduce drag. In addition, this morphing spoiler is investigated to determine whether a comparatively high bump can be structurally realized in order to reduce loads (destroy lift) with such a so-called load alleviation bump. The design is realized with the objective of load reduction with as little additional weight as possible. Figure 5, taken from [9], shows the finite element model of the morphing spoiler made of a glass fibre reinforced polymer (GFRP) using shell elements with two actuators that can form a position and height variable shock control bump.



**Figure 5.** Finite element model of the morphing spoiler made of a glass fibre reinforced polymer

#### *Load alleviation control laws*

Two groups of active load control algorithms are investigated in oLAF, first feed-back control laws, working on the basis of immediate feed-back of measured data, e.g. accelerometers on the wing, second feed-forward control algorithms making use of data acquired before an excitation hits the aircraft and the wing.

The feed-back control laws are developed to design a robust gust load reduction controller. The aim of the controller is to minimize the loads at control points specified by the user (e.g. the bending moment at the wing root) due to a gust input (= external disturbance). For this purpose, the controller commands the corresponding control surface deflections, based on the sensor signals available to it (e.g. rotation rate and acceleration sensors distributed along the structure, angle of attack sensor). The optimization methods require a linear time-invariant state-space model of the aircraft as input. This results from trimming and linearization of the non-linear differential equations in a previous modelling step. The output of the optimization methods is in turn a linear time-invariant state-space model of the controller. Various optimization methods were implemented based on the framework of linear matrix inequalities (LMIs) and the loop shaping procedure of McFarlane and Glover [10]. All methods are implemented in Matlab. Controllers were designed at individual flight points and successfully tested by simulation. The model design approaches are presented in [3] in more detail. Those approaches were the input for the controllers used in the wind tunnel experiment.

The technology of the Doppler wind lidar with wind estimation algorithm is the prerequisite for all feed-forward control methods applied in the project. From the relative speeds of the wind field measured with the lidar sensor in relation to the aircraft (or the sensor), a vertical wind profile is created with the wind estimation, which is made available to the feedforward controller as an input signal. This allows the lift distribution, particularly on the wings, to be changed before the aircraft reaches the wind field, thus reducing the aerodynamic loads.

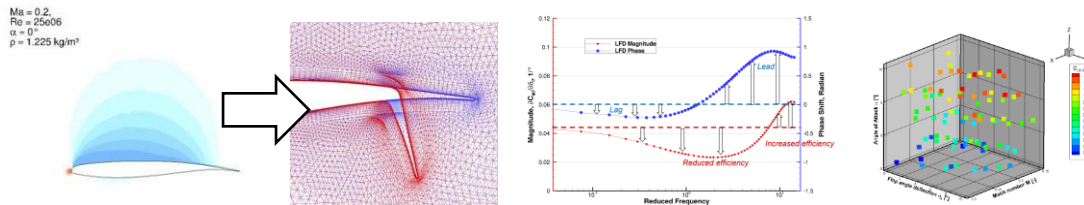
A comprehensive simulation module was created that includes the lidar sensor mentioned above and the wind estimation algorithm. The model of the lidar sensor was extended in collaboration with the DLR Institute of Atmospheric Physics as part of the COLOCAT project by a so-called "substitute model", which contains a realistic representation of the measurement process [11]. This substitute model was created on the basis of a very complex simulation of the lidar ("end-to-end simulator"), which represents the measurement process on a physical level and on the basis of Monte Carlo calculations and is therefore too complex (computationally expensive) for direct integration into a simulation environment with an aeroelastic aircraft, controllers, etc. The use of the substitute model thus enables a realistic simulation of the lidar with low computational effort. Findings from COLOCAT also allow an assessment of the optimal parameter range of the lidar with regard to load reduction performance, which are incorporated into the work in oLAF. The feed-forward control laws are used in the second loop design of the reference aircraft described in Section 2.

#### *CFD-based analysis*

The technology development described so far is supported by improvements in CFD-based simulation approaches. Active load control devices operate by introducing a local influence on the flow field which can only be analysed with sufficient quality using CFD analyses. This is

especially true in the transonic regime. The aim of the work on oLAF is to create suitable CFD-based unsteady aerodynamic models that can be used with parametric structural models to evaluate the various load control approaches.

A substitute model is developed to calculate and determine the static and dynamic response behaviour for any flight conditions of moving geometries, such as flap deflection or the pitching motion of an aircraft, and set up pre-calculated databases. The data generation is performed using the Linear Frequency Domain Solver (LFD) developed at DLR to achieve a high level of accuracy for dynamic response, based on a RANS calculation. In this way, aerodynamic coefficients and surface pressure distributions for any control surface deflections can be efficiently calculated and reused. From the databases, a calculation of those data is performed within milliseconds and therefore enables a wide range of applications, whether for optimisation or in real-time experiments. The process is depicted in Figure 6 and described in [12]. The LFD substitute model technology is used intensively for the oLAF wind tunnel test concentrating on control surface identification, see Section 5, and for the highly dynamic FlapTab.



**Figure 6.** Generation of the database: RANS-Solution → definition of motion → calculation of  $\hat{g}$ -vector with LFD → include data point

As a further development, the application of the Loewner framework-based techniques was applied to a gust input and, as expected, showed excellent agreement of the reduced-order state-space model with the LFD reference data, although the complex LFD data show the spiral behaviour caused by the gust penetration effect. This is due to the fact that the proposed method does not require the user to select the aerodynamic lag poles, but instead generates them automatically from the tangential interpolatory conditions [13]. The reduced-order model contains the aerodynamic data, allowing analytical coupling with a range of parametric structural models, which enables the potential of load reduction achieved with different designs and with existing control laws for active load reduction to be determined.

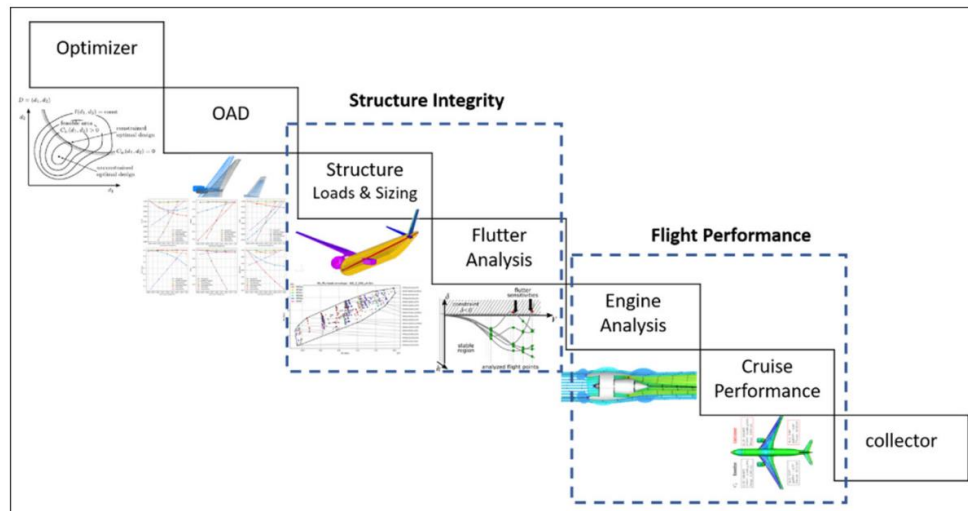
A wing designed with aggressive load alleviation must still be free from flutter. Thus, methods are developed at DLR to determine the flutter sensitivities for a 3D wing model. The aim of the analyses is to precisely determine the flutter sensitivities with regard to the planform parameters. The analyses of the flutter sensitivities when using the p-k method and the results of the studies of 2D and 3D configurations and the planform parameters were published in [14]. Furthermore, calculations for the CFD-supported flutter analysis were prepared and transferred to the MDO activities in oLAF, see Section 4.

#### 4 LOAD ALLEVIATION IN THE MULTIDISCIPLINARY WING DESIGN AND OPTIMIZATION PROCESS

Multidisciplinary design optimization (MDO) has been much advanced in the past years. In oLAF, the existing cross-institute multidisciplinary aircraft design tools are improved by adding new technologies and applying them to a new configuration. Furthermore, the tools' capabilities



towards dealing with load alleviation during the automatic multidisciplinary wing design process are extended. DLR's cross-institute gradient-based multidisciplinary design optimization (MDO) chain is presented in Figure 7. The process involves mainly two parts; the first ensures the structure integrity and the second predicts and improves the flight performance, mainly at cruise and off-design points. The structure integrity is handled via the Structure Loads and Sizing and Flutter Analysis components shown in Figure 7. The flight performance is predicted here via coupling a RANS-based flow solver (DLR's TAU) with the structure solver NASTRAN in order to account for the elastic deformations the aircraft undergoes, and with the 1D thermodynamic engine model, to exchange thrust and engine boundary conditions while trimming the aircraft forces. The shape improvement is predicted based on the design sensitivities, which require a differentiation of the numerical models engaged.



**Figure 7.** Block diagram of the cross-institute gradient-based MDO chain

On the structure integrity side, two main aspects are pursued. The first one is to model the structure via composite materials, either while dealing with it as a smeared thickness or while giving the designer more freedom to tackle the different layers nearly independently. The second aspect is to enhance the loads prediction process with load alleviation tools that allow the designer to investigate the feasibility of such systems in a robust and automatic design process. On the flight performance side, the focus lies on enhancing the aircraft trim process, while engaging the sizing of the engine and all the modelling complexities related to that, in the design loop.

## 5 WIND TUNNEL EXPERIMENTS

The design of efficient load control approaches requires detailed knowledge about the involved physical effects. For the current investigations, the focus of the experimental, i.e. wind tunnel, activities was on the identification of unsteady control surface aerodynamics and the validation of respective CFD analyses, and on the validation of control design algorithms suggested for use in load control on a full aircraft scale.

For the evaluation of the effectiveness of control surface-based measures for load reduction and adequate controller design, precise and well-founded knowledge of the transmission behaviour of the corresponding control surfaces across all flight ranges is of decisive importance.

Measurement data from past principle experiments in the DNW-NWB and DNW-TWG (e.g. transonic for dynamic rudder oscillations, subsonic for spoilers) already exist for individual devices and areas of application, which will be viewed and analysed for the project and used to validate the methods in HAP 2.

#### *Control surface transfer functions*

First, available data for dynamic control surface motion in transonic speed was evaluated. The data originates from the so-called COSDYNA (Control Surface DYNAMics) experiments, a series of experiments conducted in collaboration with the former Département Aéroélasticité et Dynamique des Structures (DADS) of ONERA **REF** and with JAXA **REF**, was to create a high-value experimental database for motion-induced forces on trailing-edge control surfaces in transonic flow. The data is intended for the validation of numerical simulation methods and as a reference data set for flutter and load prediction for aircraft structures and control surfaces. The data base was XXX

Second, a dedicated wind tunnel campaign was performed for the identification of unsteady spoiler aerodynamics, validating the numerical simulations described in **Section** above, and setting up a data pool for fast XXX

To expand the experimental database in the low-speed range, the aerodynamic response behaviour is measured during dynamic deflections of control surfaces (optionally with a deflected spoiler). For this purpose, the trailing edge flap of the 2D airfoil model of the DLR-F15 with a span of 2.8 m and an airfoil depth of 0.6 m is fitted with a camber tab. With this model setup, the dynamic response behaviour of the flow is measured and analysed in detail at speeds of up to 90 m/s in the DNW-NWB. The data obtained allow the calculation methodology and the dynamics of the control surfaces predicted in HAP 2 to be validated. They therefore primarily serve to validate the numerical predictions of the transmission behaviour and the input variables based on them, which form the basis for the design of the control loop for load reduction, which is used in the experiment in WP 3.2.

#### LA-Demonstrator

Using the methods from HAP 2, which were validated on the basis of experimental data from WP 3.1, a long-haul aircraft with load reduction measures is designed in HAP 1. In addition to the aerodynamic and aeroelastic design, control surface and structural concepts as well as control systems for load reduction will be designed.

This work package will experimentally demonstrate the effectiveness of such an integrated design with regard to the reduction of structural loads. In particular, the design of the controller system for load reduction can also be validated experimentally. The aim of the experiment is to demonstrate that a wing designed in HAP 1 for load reduction with the dynamic properties of the control surfaces determined in WP 2.2 and the corresponding controller developed in WP 2.4 is capable of reducing gust and manoeuvre loads as predicted.

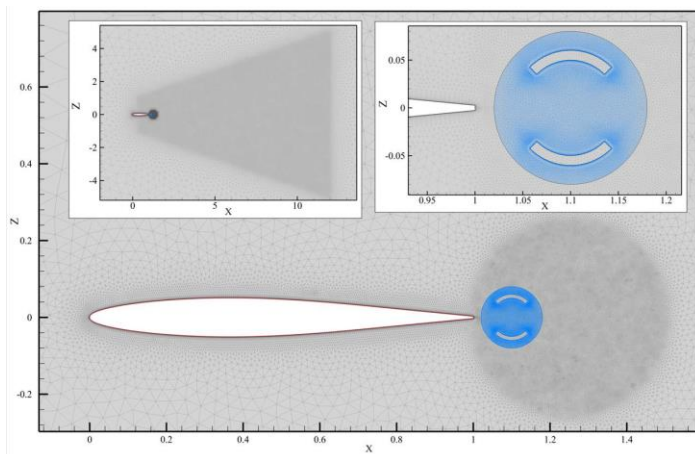
Due to the model size required to implement the active components, the demonstrator test is to be carried out with a half-model configuration in the DNW-NWB. The wind tunnel model will be equipped with a representative flexible wing and with controlled load reduction measures. To simulate gust and manoeuvring loads, the model will be suspended from the movable model support MPM of the DNW-NWB.

To design the controller for load reduction, a simulation model is created that represents the transfer functions identified from control surface deflections to the sensor signals. In order to be suitable for the multi-variable controller design, the model should be of the lowest possible order and at the same time have sufficient accuracy. Appropriate control-oriented modelling methods are applied and further developed. The simulation model is then used to design the load reduction controller, for which suitable target functions, such as a balanced reduction of torsional and bending loads, must be formulated. Furthermore, sufficient robustness and compliance with the manipulated variable limitations of the closed control loop should also be guaranteed. For this purpose, a comprehensive simulation environment is being set up that enables automated tuning of the controller at selected operating points and for predefined excitations. For the operation of the model with both open and closed control loops, the flutter safety must be checked. To enable control and monitoring of the individual controller functions during the experiment, a reusable user interface is also to be implemented.

In the DLR project oLAF (optimal load adaptive aircraft), strategies for active and passive load alleviation are developed and assessed. In the project, a wind tunnel experiment for the validation of active load alleviation approaches is conducted, comprising the following elements:

- The design of an elastic wing with five control surfaces along the trailing edge plus two spoilers,
- The development of a gust generator based on a rotating cylinder concept,
- The development of load control algorithms, and
- A test campaign in the DNW-NWB wind tunnel in Braunschweig.
- The wind tunnel model and the load control approaches are derived from numerical investigations of a transonic transport aircraft, performed in other work packages of the project.

Each element is a comprehensive activity with several partners involved. For each of those tasks we would like to submit a paper describing the activities performed.



Flugzeuggrundriss: Planform für Windkanalmodell

WAS GEHT REIN ?

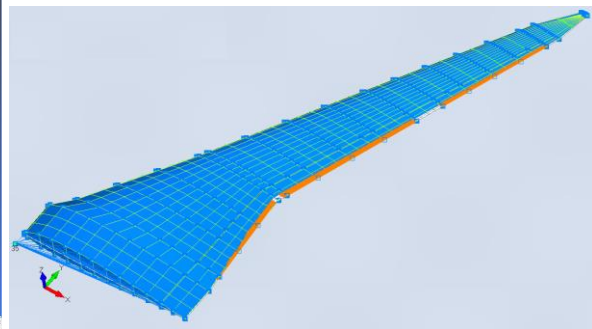
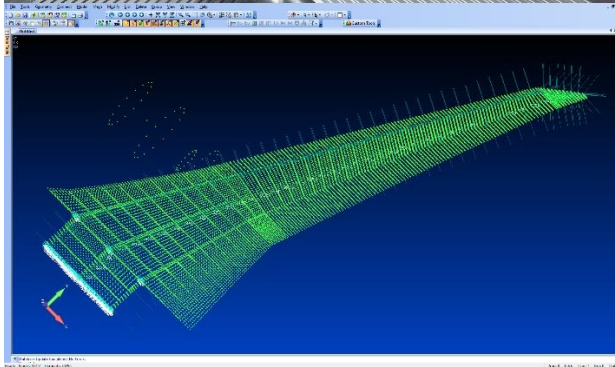
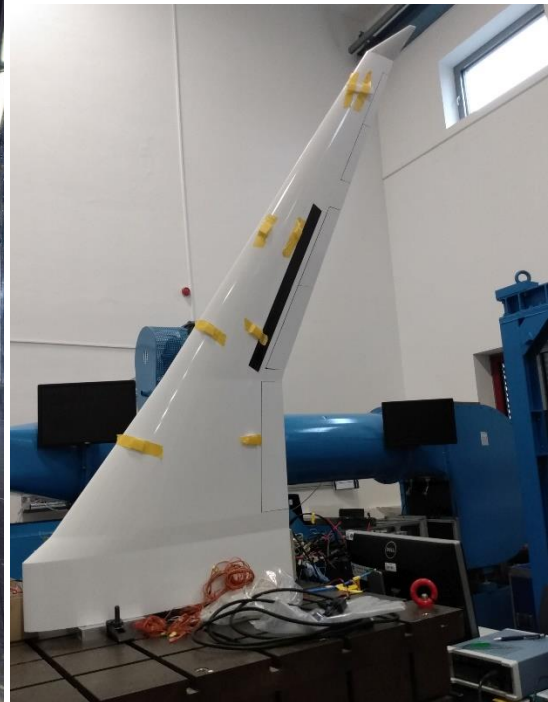
was sind die Unterschiede zwischen Flugzeug und Windkanalmodell?

WIE SIEHT DAS EXPERIMENT AUS?

WAS SIND DIE ERGEBNISSE FÜR DAS PROJEKT?

wie gehen die Ergebnisse in den Windkanalversuch ein?

After the individual development and assessment, the load control technologies have been transferred to be included in the design of the second variant of the long-range aircraft. Furthermore, the efficiency of the active load control strategies was demonstrated on an elastic wing model in a wind tunnel campaign in the DNW-NWB. For this test, a gust generator using a novel excitation concept, using rotating cylinders at the trailing edge of stationary profiles, was developed.



## 6 DATA FLOW

Wie fließen die Ergebnisse der Versuchs in das Projekt zurück, und darüber hinaus (Geschichte mit oLAF / UP Wing / ...?)

## 7 CONCLUSIONS AND OUTLOOK

Here some conclusions and an outlook

Development of reference model was basis for design of wind tunnel model and wind tunnel experiment

different active control laws could be demonstrated (goal: prove design methodology); results showed that control laws are working well

Outlook: UP Wing: transonic experiment planned 2025 (see also other publications on UP Wing, extra session)

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### REFERENCES

- [1] Dillinger, J., Mai, H., Krüger, W. R., Schmidt, T. G., Stalla, F. (2024): Design, manufacturing and identification of an actively controlled flexible wing for subsonic wind tunnel testing. International Forum on Aeroelasticity and Structural Dynamics, IFASD 2024, Den Haag, The Netherlands.
- [2] Schmidt, T.G., Ritter, M., Dillinger, J., Altkuckatz, A., Braune, M., Mai, H., Krüger, W. (2024): Design of a Gust Generator for Aeroelastic Experiments in the Subsonic Wind Tunnel DNW-NWB. International Forum on Aeroelasticity and Structural Dynamics, IFASD 2024, Den Haag, The Netherlands.
- [3] Stalla, F., Looye, G., Kier, T., Krüger, W.R., Mai, H. (2024): Wind Tunnel Test of Robust Gust Load Control on a Flexible Wing. International Forum on Aeroelasticity and Structural Dynamics, IFASD 2024, Den Haag, The Netherlands.
- [4] Schulze, M., Klimmek, T., Torrigiani, F., Wunderlich, T.F. (2021): Aeroelastic Design of the oLAF Reference Aircraft Configuration. Deutsche Luft- und Raumfahrtkongress, DLRK 2021, Bremen, Germany. [https://elib.dlr.de/143642/1/DLRK2021\\_550157.pdf](https://elib.dlr.de/143642/1/DLRK2021_550157.pdf)

- [5] Wunderlich, T. (2022): Multidisciplinary Optimization of Flexible Wings with Manoeuvre Load Reduction for Highly Efficient Long-Haul Airlines. Deutscher Luft- und Raumfahrtkongress 2022, Dresden. <https://doi.org/10.25967/570055>.
- [6] Schulze, M., Handojo, V. (2023): Aeroelastic Design of the oLAF Configuration using Load Alleviation Techniques within cpacs-MONA. Presentation at the Deutsche Luft- und Raumfahrtkongress, DLRK 2023, Stuttgart, Germany. [https://elib.dlr.de/198111/1/DLRK2023\\_610369-Schulze\\_und\\_Handojo\\_Vortrag.pdf](https://elib.dlr.de/198111/1/DLRK2023_610369-Schulze_und_Handojo_Vortrag.pdf)
- [7] T. Klimmek, M. Schulze, M. Abu-Zurayk, C. Ilic, A. Merle, “cpacs-MONA – An independent and in high fidelity based MDO tasks integrated process for the structural and aeroelastic design for aircraft configurations,” in: International Forum on Aeroelasticity and Structural Dynamics, IFASD 2019, Savannah, GA (USA).
- [8] Bramsiepe, Kjell und Gröhlich, Martin und Dähne, Sascha und Hahn, Daniel (2022) *Structural Concepts for Passive Load Alleviation*. AIAA SCITECH 2022 Forum, 3.-7. Jan. 2022, San Diego, CA & Virtual. doi: 10.2514/6.2022-0687
- [9] Künnecke, S.C., Schäfer, M., Goertler, A., Waldmann, A., Vasista, S., Riemenschneider, J. (2023): Concept of a Morphing Shock Control Bump Spoiler with Two Actuators. 10<sup>th</sup> ECCOMAS Thematic Conference on Smart Structures and Materials, SMART 2023, 3-5 July 2023, Patras, Greece. [https://elib.dlr.de/196950/1/K%C3%BCnnecke2023\\_Concept%20of%20a%20morphing%20OSCB%20spoiler%20with%20two%20actuators.pdf](https://elib.dlr.de/196950/1/K%C3%BCnnecke2023_Concept%20of%20a%20morphing%20OSCB%20spoiler%20with%20two%20actuators.pdf)
- [10] Glover, K, McFarlane, D. (1989): Robust Stabilisation of Normalized Coprime Factor Plant Descriptions with  $H_{\infty}$ -Bounded Uncertainty. IEEE Trans. Autom. Contr., Vol. 34, 1989.
- [11] Kiehn, D., Fezans, N., Vrancken, P.S., Deile, C. (2022): Parameter Analysis of a Doppler Lidar Sensor For Gust Detection and Load Alleviation. International Forum on Aeroelasticity and Structural Dynamics, IFASD 2022, Madrid, Spain.
- [12] Seidler, R.B., Marten, S., Widhalm, M., Wild, J. (2020): Efficient Prediction of Aerodynamic Control Surface Responses Using the Linear Frequency Domain. AIAA Journal, 58 (5). American Institute of Aeronautics and Astronautics (AIAA). doi: 10.2514/1.J058840
- [13] Quero, D., Vuillemin, P., Poussot-Vassal, C. (2019): A generalized state-space aeroservoelastic model based on tangential interpolation. Aerospace 6, 1. doi: 10.3390/aerospace6010009
- [14] Kaiser, C., Quero, D.: Effect of Aerodynamic Damping Approximations on Aeroelastic Eigensensitivities. Aerospace 2022, 9, 127. <https://doi.org/10.3390/aerospace9030127>
- [15] M. Abu-Zurayk, C. Ilic<sup>1</sup>, M. Schulze<sup>2</sup>, J. Häßy<sup>3</sup>, D. Kiehn<sup>4</sup>, Ch. Wallace<sup>4</sup>, Ö. Süelözgen<sup>5</sup>, C. Kaiser<sup>2</sup>, S. Dähne<sup>6</sup>, P. Wegener<sup>1</sup>, A. Balani<sup>1</sup>, L. Reimer (2024): Development of Methods for Multidisciplinary Wing Design and optimization under Load Alleviation. Deutscher Luft- und Raumfahrtkongress, DLRK 2024, 30.9.-2.10.2024, Hamburg (accepted).

- [16] Altkuckatz, A., Braune, M., Mai, H. (2022): Management, archiving and provision of aerodynamic and aeroelastic data - A new database concept. 19th International Forum on Aeroelasticity and Structural Dynamics, IFASD 2022. International Forum on Aeroelasticity and Structural Dynamics (IFASD) 2022, Madrid, Spain.

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