International Forum on Aeroelasticity and Structural Dynamics
IFASD 2024
17-21 June 2024, The Hague, The Netherlands

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

Wolf R. Krüger[1*], Holger Mai[1], Thiemo Kier[2], Lars Reimer[3]

[1]DLR – Institute of Aeroelasticity, Bunsenstr. 10, 37073 Göttingen, Germany
[*]Wolf.Krueger@DLR.de

[2]DLR – Institute of System Dynamics and Control, Münchener Straße 20, 82234 Wessling, Germany

[3]DLR – Institute of Aerodynamics and Flow Technology, Lilienthalplatz 7, 38108 Braunschweig, Germany

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. Parallel papers in this conference 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 Last-Adaptives Flugzeug" = 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. 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 it taken at the aerodynamics of spoilers and control surfaces, both numerical and experimental investigations are performed. 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. 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. Another 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.

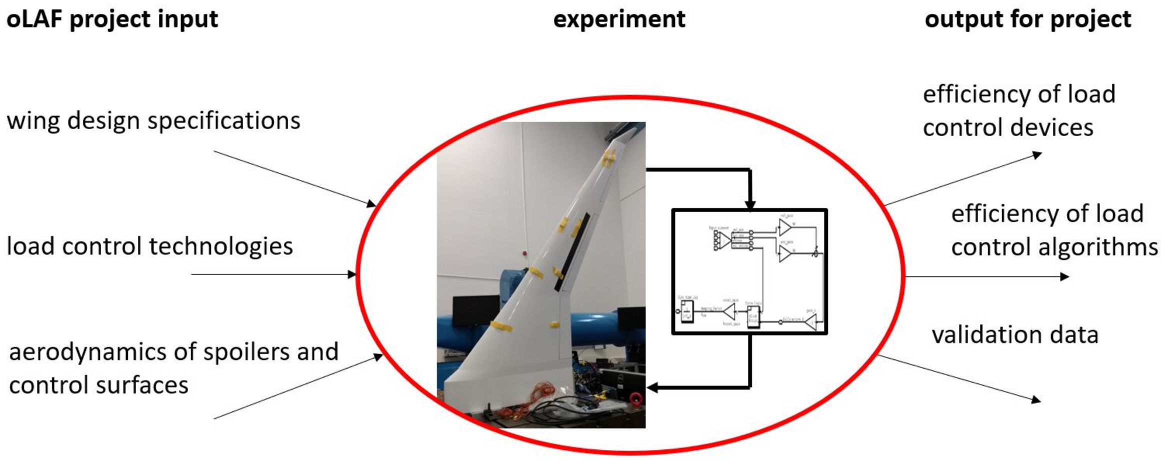

Figure 1. Data flow in oLAF

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 presented at the IFASD 2024 conference 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 and processes from the multidisciplinary aircraft design chain (see Section 4). 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.

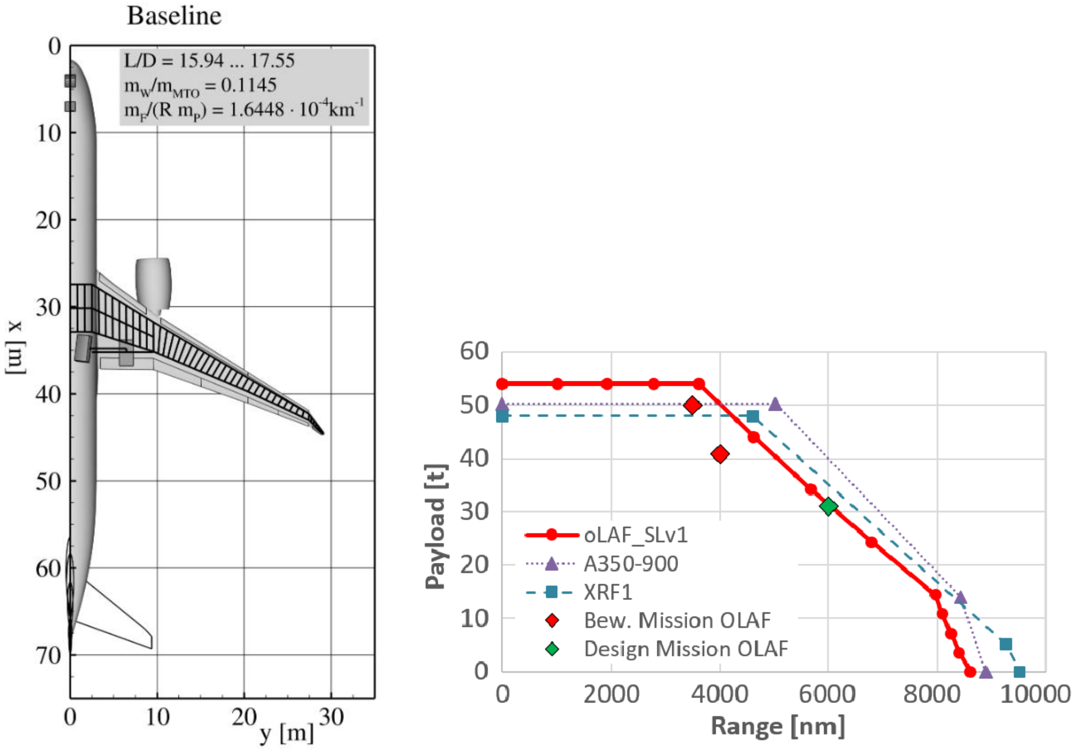

Figure 2. Planform of reference aircraft (left) / payload-range diagram for the oLAF configuration at Ma=0.83 (right)

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.

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]. As a further result, the wing planform of the oLAF configuration was the input for the wind tunnel model wing.

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, the GFEM is shown in Figure 3.

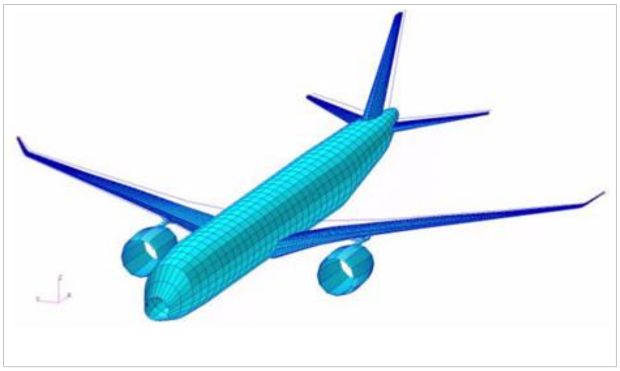

Figure 3. oLAF reference configuration: GFEM model

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 [8].

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.

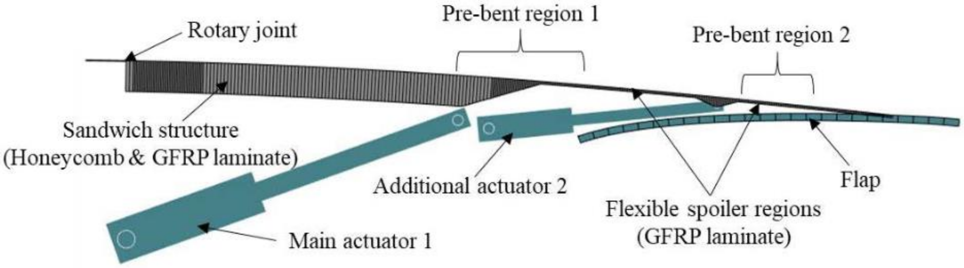

Figure 4. Finite element model of the morphing spoiler made of a glass fibre reinforced polymer

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 4, 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.

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 5 and described in [12]. The LFD substitute model technology is used intensively for the oLAF wind tunnel test concentrating on control surface transfer functions, see Section 5, and for the highly dynamic FlapTab.

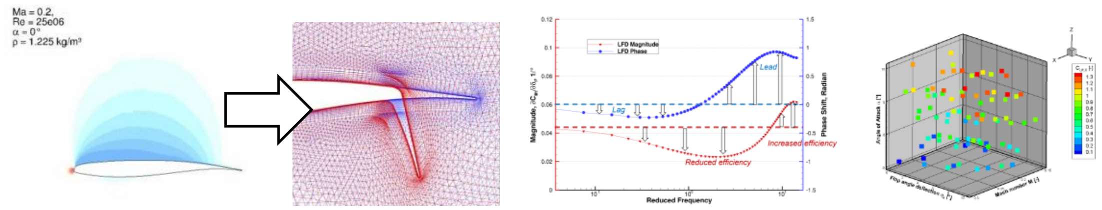

Figure 5. Generation of the database: RANS-Solution → definition of motion → calculation of $\hat{g}$-vector with LFD → include data point

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 6. 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 6. 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 of the aircraft in flight, 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.

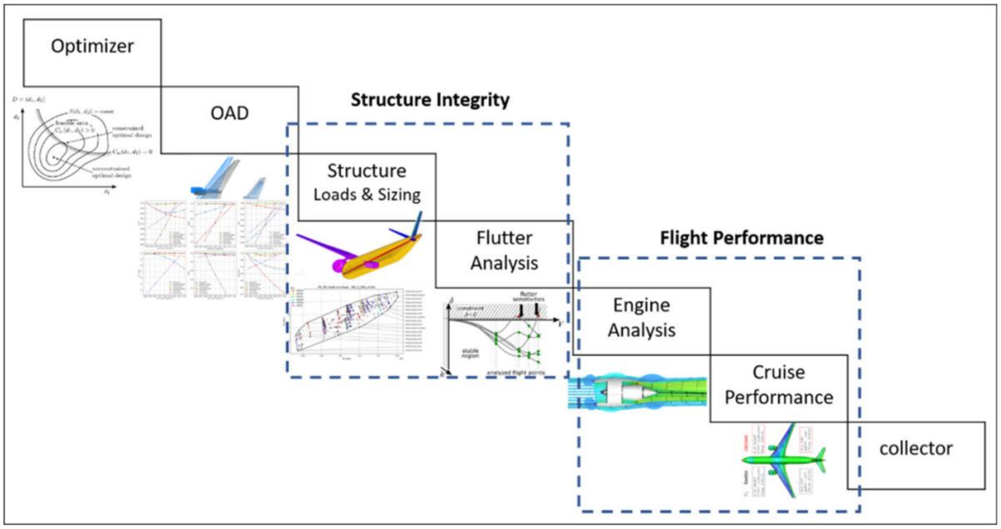

Figure 6. Block diagram of the cross-institute gradient-based MDO chain

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.

An overview of the capabilities of DLR's cross-institute multidisciplinary design optimization chain at the beginning of the oLAF project is given in [15]. A summary of the developments and results achieved in oLAF will be presented in [16].

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.

Control surface transfer functions

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 transfer behaviour of the corresponding control surfaces across all flight ranges is of decisive importance. Measurement data from past principle experiments in the DNW-NWB (e.g. subsonic for spoilers) and transonic wind tunnel DNW-TWG (e.g. transonic for dynamic rudder oscillations) already exist for individual devices and ranges of application and have been evaluated in the first phase of the project.

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, France, and with JAXA, Japan. The aim 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 [17].

Second, a dedicated wind tunnel campaign was performed for the identification of unsteady spoiler aerodynamics, validating the numerical simulations described in Section 3 above. 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 chord of 0.6 m has been fitted with a camber tab. With this model setup, the dynamic response behaviour of the flow is measured and analyzed 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 to be validated.

Demonstration of active load alleviation functions

In a second wind tunnel experiment the effectiveness of different active control approaches with regard to the reduction of structural loads has been evaluated. The aim of the experiment was to demonstrate that a wing designed for load reduction, with the dynamic properties of the control surfaces determined numerically and applying the corresponding controller synthesis methodologies, is capable of reducing gust and manoeuvre loads as predicted.

The basis for the wing design is the long-range reference aircraft described in Section 2. The planform of the wind tunnel wing is derived from the overall aircraft design, see Figure 7, scaled to wind tunnel dimension. However, the implementation of the active components requires a certain model size, thus the demonstrator test is carried out with a half-model configuration. The choice of a half model is also favourable in another context as it allows a more flexible wing to be designed for the given strength requirements.

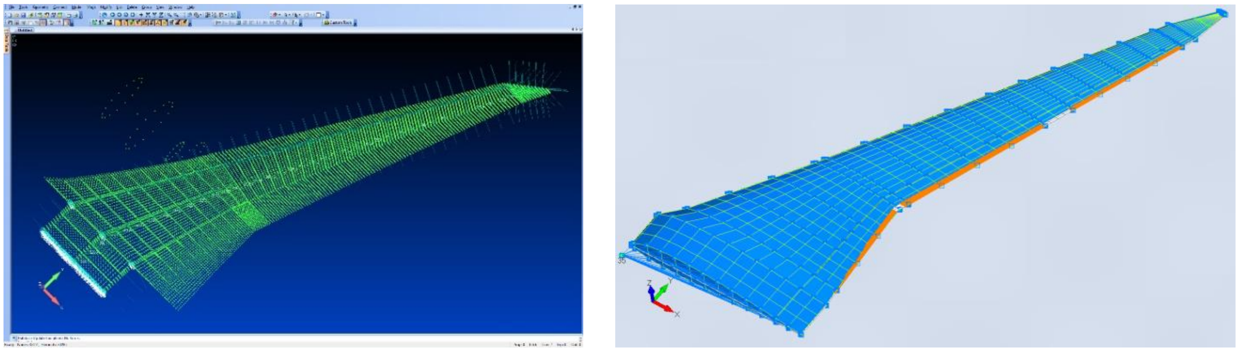

Figure 7. FE model of full aircraft wing (left) / FE model of wind tunnel model wing (right)

The wind tunnel model wing has a semi-span of 1.75 m and is manufactured from glass fibre composite material which allows high deformations at high strength. 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.

The model is designed with five control surfaces (flaperons/ailerons) along the trailing edge and two spoilers in front of the inner control surfaces. However, the spoilers have not been used in the current wind tunnel campaign. The sensors built into in the wing include 12 accelerometers, 10 pressure sensors and a fiber-optical sensor for strain measurements. Furthermore, the forces and moments of a piezo-balance in the wind tunnel mounting are available for feedback, and a marker-based optical measurement system has been used for the high-speed tracking of wing and control surface deflections.

The wind tunnel model structure was designed, manufactured and equipped using the DLR in-house aeroelastic model design process. The transfer functions of the actuators, required for the control design, are identified in a specific set-up of the model prior to the wind tunnel campaign, see Figure 8. The dynamic properties of the model structure are identified both wind-off in a standard GVT, and wind-on at specific test points for identification. A comprehensive description of the model design can be found in [1].

The wind tunnel campaign took place at the DNW-NWB subsonic wind tunnel in Braunschweig [18]. The wind tunnel has a cross section of 3.25 m x 2.8 m and is operating at a maximum flow speed of 90 m/s. For the gust experiment, the set-up was designed for flow speeds of up to 50 m/s.

To simulate gust and manoeuvre loads, it was originally planned to mount the model on the movable model support (MPM) of the DNW-NWB. However, it was found that the excitation frequencies of the MPM were not sufficiently high to emulate a gust excitation near the elastic natural frequencies of the wing.

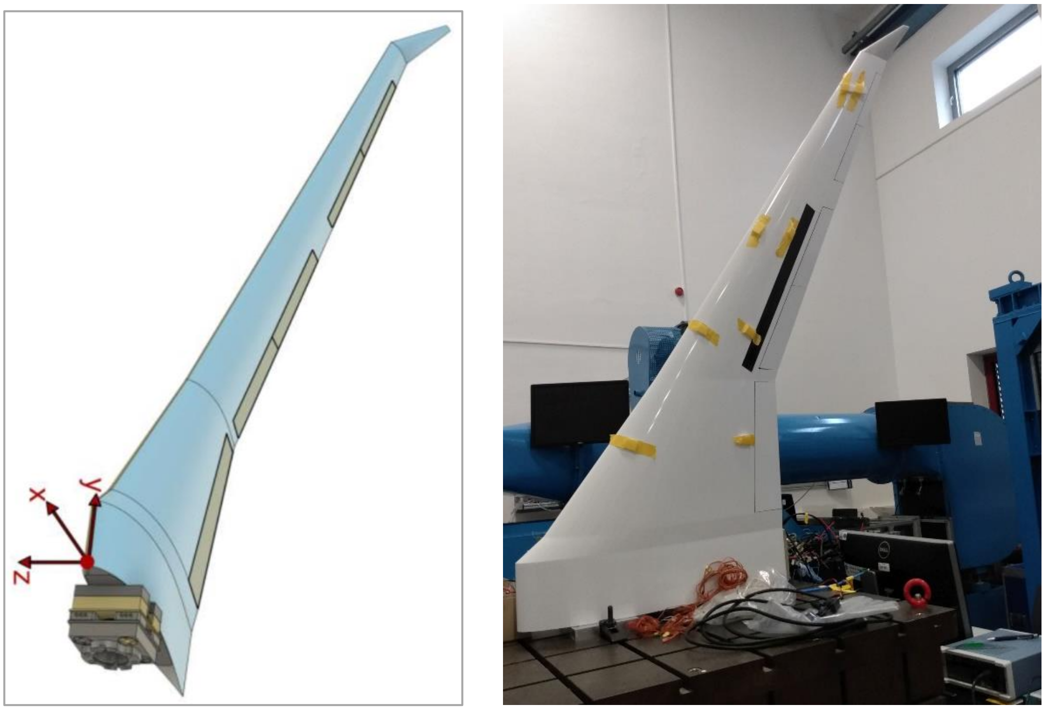

Figure 8. CAD model of the oLAF wind tunnel model including the balance (left) /
Wind tunnel model wing mounted on the test rig for sensor and actuator calibration (right)

Consequently, a gust generator was specifically designed for the experiment, using rotating cylinders at the trailing edge of stationary profiles, a concept already suggested by Tang, Cizmas, and Dowell in the 1990ies [19]. An important reason for the choice of this design for the current experiment is the fact that no oscillating inertial forces occur during the excitation, requiring a much smaller torque of the driving mechanism and resulting in smaller mechanical forces on the support when compared to an oscillating-vane concept. The slotted-cylinder design results in an excitation frequency twice of the cylinder rotation frequency. While the system is mainly designed for period excitation, it was possible, using drive motors from a robotic background, to also generate non-periodic excitation signals. The design of the gust generator has been supported in the project by comprehensive numerical studies, see Figure 9. The gust generator rigged in the wind tunnel can be seen in Figure 10 below. The development of the gust generator is described in detail in [2].

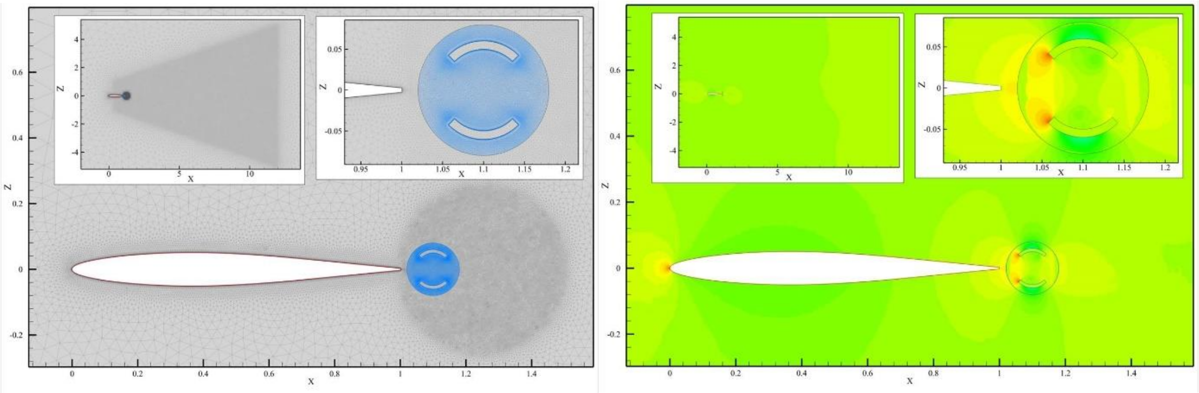

Figure 9. Conceptual CFD-study of a gust generator with a rotating cylinder concept

Load control is implemented on a real-time environment based on control laws being developed in MATLAB/Simulink. To design the controller for load reduction, a simulation model is created that represents the transfer functions identified from control surface deflection and gust input to acceleration sensor signals and wing root loads. 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 challenges regarding uncertainties are addressed by employing robust control. µ-synthesis is chosen as a baseline controller, as it allows to balance conflicting requirements for load reduction, control activity, and robustness [20]. Additionally, the control allocation is optimized within the synthesis. The simulation model has then been 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 of the closed loop and compliance with the limitations of actuator amplitude and speed should also be guaranteed. After the controller has been designed, it is validated in a comprehensive simulation environment that contains non-linearities, limitations, sensor noise, and can be set to different operating points (wind tunnel speeds). For the operation of the model with both open and closed control loops, the stability was checked. To enable control and monitoring of the individual controller functions during the experiment, a reusable user interface has been implemented. This interface enabled a quick exchange of the load controller structure so that besides the µ-synthesis controller, two other controller designs could be tested.

Figure 10. Wind tunnel set-up with gust generator and wind tunnel model

The complete wind tunnel campaign consisted of two parts. As the gust generator was a newly developed system, the performance was qualified in a separate campaign. The flow excitation was measured for different flow speeds, excitation frequencies and phase angles of the rotating cylinders. Non-periodic excitations were also tested. Subsequently, the actual load control experiment was performed, starting with a structural qualification of the wind tunnel model, and an extensive campaign exploring the potential of the load control algorithms. Figure 10 shows the gust generator, and the wing mounted downstream.

A sample result is given in Figure 11. At a wind speed of 30 m/s, the wing is excited at its resonance frequency of 9 Hz. The root bending moment is effectively reduced by the load control law. The control design approaches and selected results are presented in [3].

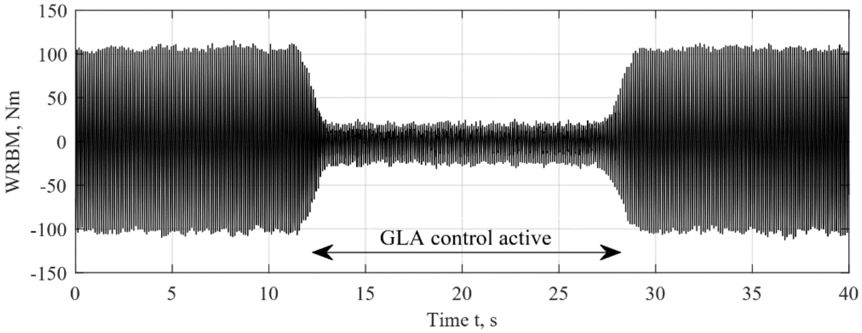

Figure 11. Sample load alleviation result

6 CONCLUSIONS AND OUTLOOK

The oLAF load alleviation wind tunnel experiment successfully demonstrated the efficiency of the design approaches developed for aggressive load control for aircraft with high aspect ratio wings. Inside the project, the results of the wind tunnel experiment feed into the design of the improved reference aircraft configuration, set up to quantify the performance benefit of using extensive load alleviation in the aircraft design.

Evidently, the specific control laws tested on a wind tunnel model cannot be transferred unmodified to a full aircraft, as the conditions arising from free flight, e.g. the interference between the requirements for maneuvering and load control, have not been addressed in the wind tunnel test. However, the control synthesis approaches will be comparable and could be validated in the experiment.

Furthermore, a flexible real time environment was established which allowed both a comprehensive monitoring of data as well as the online modification of control parameters and quick interchange of control laws for a given wind tunnel set-up.

The initial goal of testing control surfaces downstream of spoilers in the load control experiment could not be fulfilled. Due to testing time limitations, the spoilers were not deployed in the campaign. This aspect will have to be tested in a follow-on activity.

The gust generator proved to be very effective. The excitation amplitude was significant, and the possible variation of rotational frequency and phase between the profiles allows a variety of excitation signals to be generated, including non-periodic signals. For the DNW-NWB, the gust generator represents a new module extending the capabilities of the facility which will be used in further projects. While the oLAF experiment was performed using two profiles, which already performed well, the final gust generator set-up will consist of four profiles.

The oLAF gust load alleviation experiment has a predecessor in the so-called KonTeKst wind tunnel experiment, presented e.g. at the IFASD 2019 [21]. A straight wing with three control surfaces was tested in the SWG low speed wind tunnel to demonstrate load control with a re-allocation of control authority in the case of malfunction of a control surface. Excitation was generated by mounting the wing on a pitch oscillator. In oLAF, the configuration was extended to a representative aircraft wing with a realistic control surface layout and aerodynamic excitation by a dedicated gust generator, still at subsonic speeds. The next step is the demonstration of novel load control approaches on an elastic wing in transonic flow. This demonstration is planned in the project UP Wing [22] in the framework of the HORIZON Europe - Clean Aviation programme. A wind tunnel campaign is planned for the year 2025 in the DNW-HST transonic wind tunnel in Amsterdam, demonstrating control schemes and corresponding simulation approaches developed by eight partners from four countries, from industry, research and academia. As DLR is part of the project team, the transonic test will benefit from the experience gained in the oLAF wind tunnel experiment. A publication at this IFASD conference will present the status of the model development for the UP Wing test [23].

ACKNOWLEDGEMENTS

The authors would like to thank the many contributors to the model design, manufacturing and testing, to the gust generator design, and to the and wind tunnel campaign, who made the experiment possible. This (necessarily incomplete) list includes Johannes Dillinger, Markus Ritter, Martin Tang, Julius Sieg (model design and testing), Martin Weberschock (manufacturing), Thomas G. Schmidt, Charlotte Hanke, Marc Braune, Thomas Büte, Anna Altkuckatz, Tania Kirmse (gust rig development, wind tunnel installation, data acquisition, test plan), Felix Stalla, Kolja Michel, Boris Micheli (the control guys), and the NWB wind tunnel team. The authors would also like to thank all colleagues involved in the oLAF project for their contributions to this paper.

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., Dillinger, J., Ritter, M., Altkuckatz, A., Hanke, C., Braune, M., Krüger, W., Mai, H. (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., Kier, T. M., Looye, G., Michel, K., Schmidt, T.G., Hanke, C., Dillinger, J., Ritter, M., Tang, M. (2024): Wind Tunnel Testing Active Gust Load Alleviation of 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

[5] Wunderlich, T. (2022): Multidisciplinary Optimization of Flexible Wings with Manoeuvre Load Reduction for Highly Efficient Long-Haul Airliners. 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

[7] Klimmek, T., Schulze, M., Abu-Zurayk, M., Ilic, C., Merle, A. (2019): cpacs-MONA – An independent and in high fidelity based MDO tasks integrated process for the structural and aeroelastic design for aircraft configurations. International Forum on Aeroelasticity and Structural Dynamics, IFASD 2019, Savannah, GA, USA.

[8] Bramsiepe, K., Gröhlich, M., Dähne, S., Hahn, D. (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., Goerttler, A., Waldmann, A., Vasista, S., Riemenschneider, J. (2023): Concept of a Morphing Shock Control Bump Spoiler with Two Actuators. 10th 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%20SCB%20spoiler%20with%20two%20actuators.pdf

[10] Glover, K., McFarlane, D. (1989): Robust Stabilisation of Normalized Coprime Factor Plant Descriptions with H_∞-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] Abu-Zurayk, M., Merle, A., Ilic, C., Görtz, S., Schulze, M., Klimmek, T., Kaiser, C., Quero-Martin, D., Häßy, J., Becker, R.-G., Fröhler, B., Hartmann, J. (2021): Sensitivity-based Generation of Pareto Fronts for Design of Powered Aircraft Subject to a Comprehensive Set of Loads. AIAA Aviation and Aeronautics Forum and Exposition, 2021-08-02 - 2021-08-06, Washington DC / USA - Online. doi: 10.2514/6.2021-3025.

[16] Abu-Zurayk, M., Ilic, C., Schulze, M., Häßy, J., Kiehn, D., Wallace, C., Süelözgen, Ö., Kaiser, C., Dähne, S., Wegener, P., Balani, A., Reimer, L. (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).

[17] 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.

[18] https://www.dnw.aero/wind-tunnels/nwb/

[19] Tang, D.M., Cizmas, P.G.A., Dowell, E.H. (1996): Experiments and Analysis for a Gust Generator in a Wind Tunnel. JoA, Vol. 33, No. 1, January-February 1996.

[20] Stalla, F., Kier, T.M., Looye, G., Pusch, M. (2024): Aeroservoelastic Modeling and Robust Control for Gust Load Alleviation of an Experimental Wing. Proceedings of the AIAA SciTech 2024 Forum, 8-12 January 2024, Orlando, FL, USA. https://doi.org/10.2514/6.2024-1442

[21] Krüger, W.R., Dillinger, J., Meddaikar, M.Y., Lübker, J., Tang, M., Meier, T., Böswald, M., Soal, K.I., Pusch, M., Kier, T. (2019): Design and wind tunnel test of an actively controlled flexible wing. International Forum on Aeroelasticity and Structural Dynamics, IFASD 2019, Savannah, GA, USA.

[22] Eberle, A., Stefes, B., Reckzeh, D. (2024): Clean Aviation Ultra-Performance Wing (UP-Wing). AIAA SCITECH 2024 Forum, 8-12 January 2024, Orlando, FL, USA. https://doi.org/10.2514/6.2024-2109

[23] Timmermans, H., Jurisson, A., Eberle, A., Krueger, W., Dillinger, J., Kapeteijn, K., Stalla, F. (2024): A high aspect ratio wind tunnel model for transonic gust load alleviation with active control. International Forum on Aeroelasticity and Structural Dynamics, IFASD 2024, Den Haag, The Netherlands.

COPYRIGHT STATEMENT