AERODYNAMIC DESIGN OF A HIGH-LIFT SYSTEM COMPATIBLE WITH A NATURAL LAMINAR FLOW WING WITHIN THE DESIREH PROJECT

Henning Strüber, *, Jochen Wild **
***Aerodynamic Design – High Lift Devices, Airbus Operations GmbH, Bremen, Germany,**
**** DLR Institute for Aerodynamics and Flow Technology, Braunschweig, Germany**

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Abstract

The paper describes the aerodynamic design of a high lift system suitable for a Natural Laminar Flow wing. 2D & 3D numerical optimization has been used in the design process and the outcome has been tested at flight Reynolds Number in the European Transonic Windtunnel (ETW), where various measurement techniques have been applied. An analysis on aircraft level has been performed to assess Natural Laminar Flow (NLF) wing's drag benefits.

1 Introduction

Because of today's problem of carbon emissions and climatic changes, the aircraft industry is facing new challenges. In its Vision 2020, the advisory group ACARE gave new objectives: greener aircrafts and a reduced time to market. The European research project "Design, Simulation and Flight Reynolds Number testing for advanced High Lift Solutions" (DeSiReH) addressed these issues with the development of an advanced compatible high-lift system enabling natural laminar flow (NLF) on the wing in cruise flight.

The Project was funded by the European Commission within FP7 (Contract no: ACP8-GA-2009-233607) running from 2009-2013. The consortium consisted of 20 partners including aircraft manufacturers, research organizations, universities and medium size enterprises from all over Europe.

Natural laminar wings will lead to significant environmental improvements, but NLF technology also introduces new design constraints for the high-lift system and broadens the design space. Hence it implies development of automated optimization algorithms. Thus DeSiReH focused on the development and application of new numerical methods to design a NLF compatible high-lift system.

As high Reynolds number wind tunnel tests are very important in the industrial high-lift design process, DeSiReH also tackled the applicability of advanced measurement techniques in cryogenic testing conditions in an industrial context.

The quantified objectives of DeSiReH were the following:

- Reduction of industrial A/C development costs by 10% by reduced and more efficient wind tunnel testing
- Decrease time-to-market by 4% by improved aerodynamic design turnaround time
- Improve industrial high-lift design process efficiency by 15%
- The design of a NLF compatible high-lift System enabling the NLF-potential to reduce A/C drag by 5%

The DeSiReH project consisted out of four work packages (Fig. 1). In work package WP1, existing high-lift design methodologies were assessed and improved for an industrial application. These matured design strategies were then applied in work package WP2 to design a high-lift system for the TELFONA performance wing. Within work package WP3 the optimized design was tested in ETW at flight Reynolds number, applying advanced measurement techniques in order to assess its aerodynamic performance. Finally in work package WP4 the project achievements in terms of design process improvements were assessed with respect to industrial expectations. Environmental benefits resulting from an NLF wing application were assessed on aircraft level.

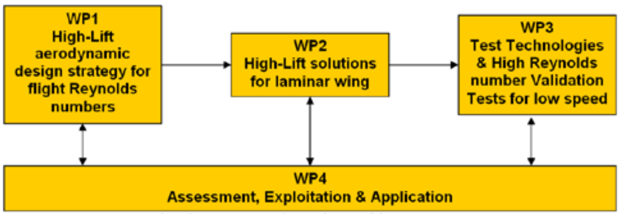

Fig. 1. Work package structure and interrelations of the DeSiReH project

2 High-lift aerodynamic design strategy for flight Reynolds numbers

From the beginning of the project, work concentrated on evaluating and assessing numerical methods for the design and simulation of high-lift systems. CFD-based optimization activities were carried out in two phases of the. In a first "analysis" phase, reported in detail in [1][2], a realistic multi-objective/multi-point optimization problem was defined and solved by a group of partners adopting different approaches in terms of employed flow model, meshing techniques, geometry parameterization, and optimization strategies. The results obtained were compared and efficiencies/deficiencies of the adopted approaches were highlighted. A broader understanding of the problem to design high-lift systems within an industrial context was achieved in three ways. First, industrial recommendations for the design process were specified by the main industrial partners. Second, the various design targets of high-lift systems were derived by screening certification regulations and evaluating the aerodynamic importance during the different flight phases during take-off, approach and landing. Third, a common understanding of the design space of high-lift systems was generated.

Based on these results common design cases were specified for activities to evaluate design procedures for a more globally optimal design, accounting for all flight phases simultaneously in contrast to the state-of-the-art stepwise approach. Regarding the comparative analysis of optimization approaches for the classical optimization methods all optimizations were performed and the solutions were compared by crosschecking partners' results [3]. Some partners also made comparisons especially for the optimizations using adjoint techniques [4]. Although very promising, the real world application turned out to be not as straight-forward and the robustness of the methods have to be increased before usage in an industrial context.

The objective to accelerate the numerical flow simulation for a better efficiency in aerodynamic design, most important in high-lift design due to a specifically high computational effort, had been initiated by selecting common cases and providing common computational grids. A significant efficiency enhancement of URANS methods has been obtained through improving the initialization procedure for the flow solution at next time level, by introducing implicit techniques, and by implementing zonal/fractional time-stepping (for more detail, see [5]). 20% to 90% speed up of unsteady RANS calculations has been demonstrated. The evaluation of gridding strategies additionally showed a possible reduction off computational effort by up to 75% due to reduction of the number of grid nodes and the use of wall functions. Grid adaptation methods (based on flow sensors, entropy, and adjoint fields) have been evaluated, giving clear indications about meshing strategies for more efficient CFD application for high-lift flows [6].

3 High-Lift solutions for laminar wing

Work package 2 addressed the design of innovative high-lift solutions to enable laminar wing technology. The matured design methods and strategies found in work package WP2 were applied to design a high-lift-system for a wing featuring NLF at cruise condition. The design of such an innovative high-lift-system is a highly industrial relevant problem and consolidates two requirements:

1. The qualification of the matured methods and strategies for their implementation in the industrial design process;
2. provide an important contribution to enable the NLF-technology by designing a compatible and efficient high-lift system.

The first major aim was to assess different high-lift concepts and to deliver an aerodynamically designed optimal feasible high-lift solution for a NLF wing. In the first step the focus was put on detecting feasible concepts by means of 2D/2.5D wing section design. For the real design of the high-lift system for the laminar wing, first a baseline wing was obtained from the TELFONA project [7].

The wing was analyzed in its stall behavior to derive recommendations for the design as well as to select an appropriate design wing section for conceptual studies. At this design section several concepts have been designed to see their principal potential for usability for the laminar wing.

At the leading edge Krueger devices, droop-noses or even very long chord slats were investigated. At the trailing edge the concepts range from classical fixed-vane flaps to drooped spoiler flap solutions. The obtained results were cross-computed in order to eliminate solver dependencies. In order to down-select the concepts the best obtainable performance by optimizing the shape, size and setting of high-lift devices including consideration of the NLF constraint of the cruise wing. The receptivity of the laminar boundary layer of the cruise wing at the steps and gaps positions of the retracted high-lift components were evaluated by transition prediction methods.

The design study and their down-selection unveiled the Krueger to be the device of choice at the leading edge. For the trailing edge the spoiler droop flap was initially selected for further integration onto the 3D wing.

In a second step the down-selected concepts were extended to the 3D wing geometry. With the same systematic approach, but now based on full 3D simulations, the high-lift devices were optimized in combination with the most promising leading and trailing edge device (Fig. 2). The 3D wing designs took into account mechanical integration constraints [8] (Fig. 3) as well as insect shielding requirements (Fig. 4). The geometry was delivered for the detailed design of the wind tunnel model to verify the obtained designs.

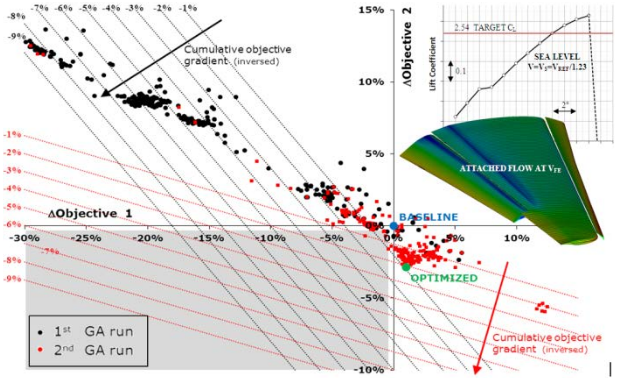

Fig. 2: NLF high-lift wing designed by numerical optimization

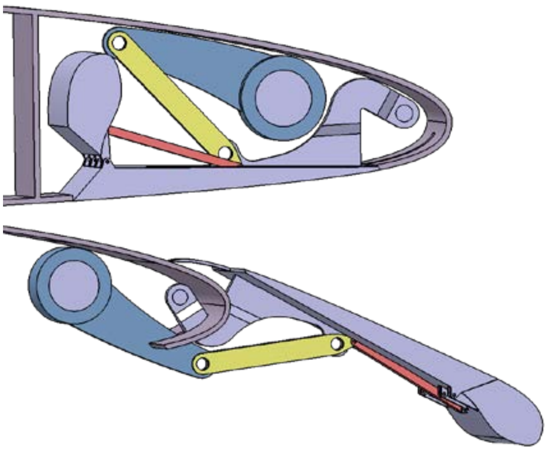

Fig. 3: Mechanical integration concept of slotted and folding Krueger kinematics

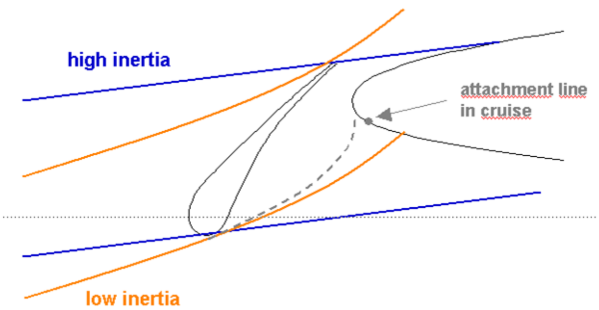

Fig. 4: Insect shielding requirement for Krüger deployed positioning

The geometries have been used to setup detailed CFD analysis of the performance and the deviations due to wind tunnel installation effects. The activities identified the effects of wind-tunnel walls (Fig. 5), model mounting, and the wing flexibility of the model (Fig. 6) in the pressurized tunnel, reported in detail in [9]. The flow models were based on the RANS and/or URANS equations. The structural model for the prediction of wing deformations was based on a FEM description of the wind tunnel model. After the wind tunnel tests described in the next section comparisons were made to evaluate the accuracy of the predictions

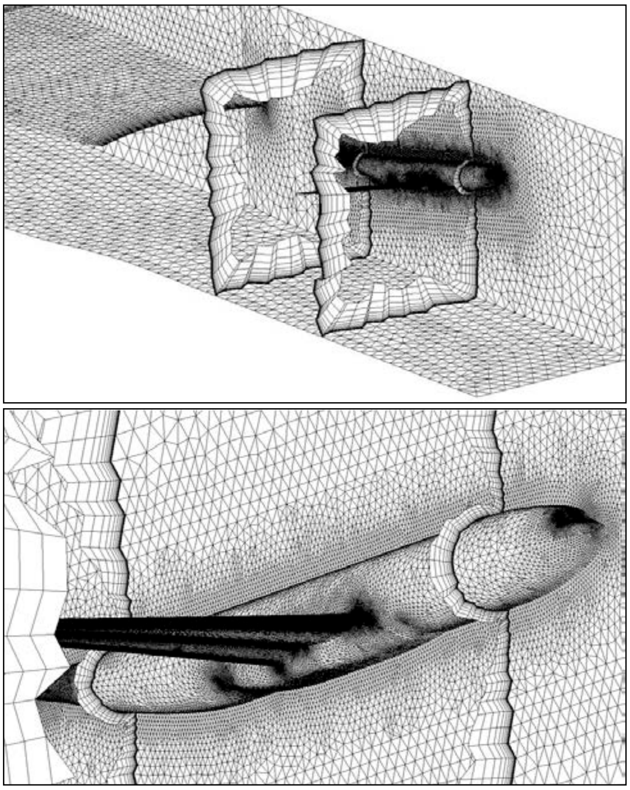

Fig. 5. grid of high-lift configuration inside ETW wind tunnel; surface grid & cuts through the prismatic grid

4. Test Technologies & High Reynolds Number Validation Tests for Low-Speed

Nowadays, aircraft engineering offices aim at reducing the overall wind tunnel process time and cost and provide reliable data for direct flight application. In the future classical wind tunnel testing for specific aircraft development will be reduced, while developing synergies between physical and numerical simulation with an overall aim to optimize data production, to best explore flight physics of new configurations and to open the envelope for industrial application of new test technologies.

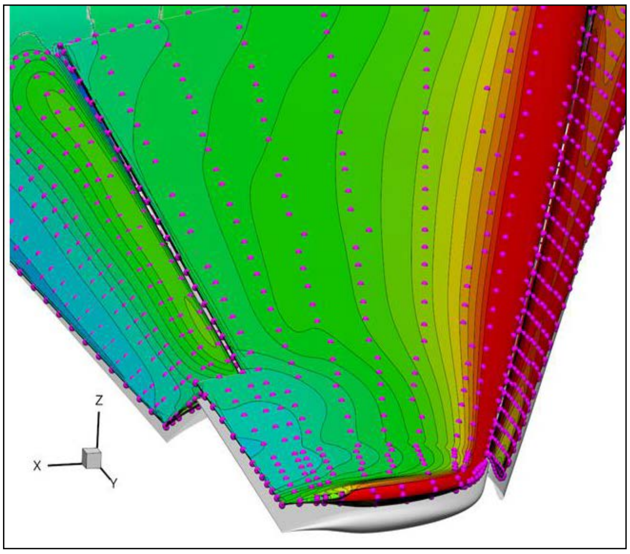

Fig. 6. Rigid and deformed wing shape predicted by CFD-CSM coupled simulations

DeSiReH was aligned with such expectations with a typical application aiming to design a high lift system achieving the required high-lift performance in take-off and landing while being compliant with a NLF wing in cruise. In the frame of the third work package WP3, the design process applied before was validated in a wind tunnel test with a half model. In order to test at true flight Reynolds number conditions, it was performed under pressurized cryogenic conditions at the European Transonic Wind tunnel (ETW) (Fig. 7).

The wind tunnel test provided high fidelity experimental data for verification of the high-lift design performed in the previous work package and validation of the CFD predictions [10]. To overcome potential limitations of CFD predictions on still challenging topics as high lift aerodynamic behavior at the edge of flow separation, or boundary layer turbulent transition, the wind tunnel test included advanced non-intrusive optical measurement techniques providing local information on the flow field.

At last this measurement technique had to be compliant with the pressurized cryogenic environment of ETW. The work package aimed at improving the capability to use in an industrial way such advanced measurement techniques within the same test campaign. In parallel with conventional techniques (balance and pressure measurement) these advanced techniques used in DeSiReH were [12]:

- Model deformation measurement by Stereo Pattern Tracking (SPT) [12]: since high Reynolds numbers are partly obtained at the expense of high pressure increasing model deformations. Resulting geometry changes affect the local flow and any comparison with sophisticated CFD methods has to be based on an exact knowledge of the geometry during testing.
- Flow visualization by Particle Image Velocimetry (PIV) [13], in particular downstream the wing trailing edge, enhances the understanding of the aerodynamic behavior and potentially enables to assess the local drag (Fig. 8).
- Boundary layer transition detection by Temperature Sensitive Paint (TSP) [14], as the transition position has also an impact an achieved aerodynamic performance (Fig. 9).

5 Assessment of environmental benefits on Aircraft level

Work package WP4 identified benefits of the results of the DeSiReH project against ACARE targets for a typical narrow body transport aircraft. To ensure that all relevant effects are included, this was done by comparing two aircraft conceptual designs [15]. One was set up with the laminar flow wing including the optimized high lift system resulting from the DeSiReH design work. The other was based on a conventional turbulent flow wing technology, but in all other aspects with identical technology levels. Both designs met the same transport requirements: payload, range, cabin comfort standards and field performance.

Fig. 7. DLR-F11 wing (scaled 1:11.75) with DeSiReH high-lift wing mounted in ETW test section

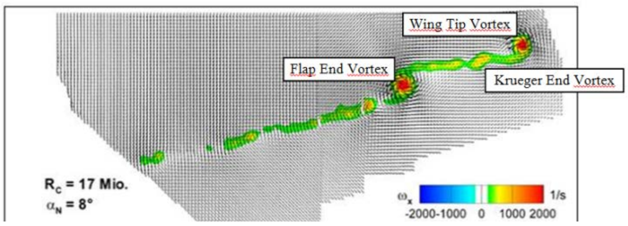

Fig. 8: PIV image of flow field after trailing edge perpendicular to flow field

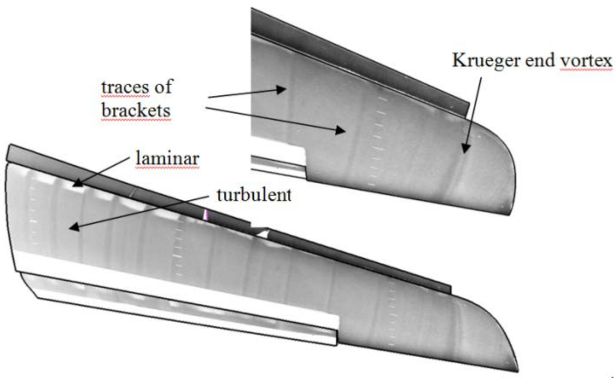

Fig. 9: TSP image visualizing laminar-turbulent transition and vortex structures above surface

Comparing these designs on economic performance enabled to show the benefits of the DeSiReH project, as the application of dual function leading edge devices, which increase lift and shield the wing from low altitude contamination, is considered essential for the success of laminar flow technology. It was respected that laminar flow is expected on the wing upper surface only, as the Krueger flap is stored on the lower side where gaps cannot be avoided and lead to transition of the laminar boundary layer.

5.1 Top Level Aircraft Requirements

The top level aircraft requirements (TLAR), see Fig. 10, give a general indication of the capabilities expected for a transport aircraft in the size of the A320 and match the design envelope of the TELFONA wing. Both the conventional and the laminar flow design comply to these requirements, or deviate in the same way if deemed necessary.

	Transport AC
Seats	162
Design Ma Number	0.75
Max operating Ma Number	0.78
Init cruise altitiude	35000ft
Max altitude	39000ft
Range	2500nm
Field performance	1500m – 2500m (depends on TOW and dISA)

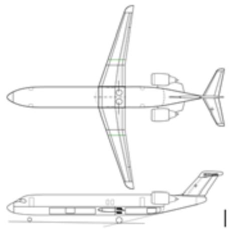

Fig. 10: TLARs and mission for Commercial Transport aircraft, sketch of aircraft

5.2 Fuel reserve policy

A commercial transport aircraft with NLF wing must be able to finish most of its missions, even when loosing laminarity on parts on the wing. Diverting to alternate destinations would mean high additional costs for the airline, which must be avoided.

Reserve fuel policy proves to have a significant impact on the derived benefit of laminar flow technology and it also affects the overall sizing of the aircraft.

Assuming the sizing mission with full turbulent flow leads to a large amount of reserve fuel. A 2% higher MTOW and proportionally larger wings and engines vs. a standard reserve fuel policy are the effect on aircraft level. This causes 1% higher fuel burn on a typical 500 NM trip.

Airline and industrial operational practice is to derive reserve fuel requirements from statistical data. Occasional loss of laminarity would then be weighted by its average occurrence. Due to the shielding function of the DeSiReH Krueger flap a significant source of loss of laminar flow is avoided. For this study an assumed scenario of an additional fuel of20% of the difference between fully turbulent and design laminar fuel burn is included in the fuel burn evaluation.

5.3 Fuel burn and emission benefits

Missions with ranges from 300-2000NM have been analyzed for the turbulent reference aircraft and for the NLF wing aircraft. Three different fuel reserve policies have been studied:

- Standard Reserve (no additional fuel for loss of laminarity)
- Full Reserve (enough additional reserve fuel to finish a mission with 100% loss of laminarity
- 20% Reserve (20% of the Full Reserve fuel is taken on board)

The overall aircraft size has been the same for turbulent and laminar wing. The engines have been downsized to cash in the effect of reduced drag on the laminar wing. This also results in reduced aircraft weight.

The resulting fuel burn benefit (reduction of block fuel) for different mission ranges is shown in Fig. 11. It spreads from 4% for a 300NM mission to almost 7% for a 2000NM mission. The benefit increases with trip length as the cruise portion becomes longer compared to climb, hold and descend portions, where the NLF wing has no great benefit compared to a turbulent wing.

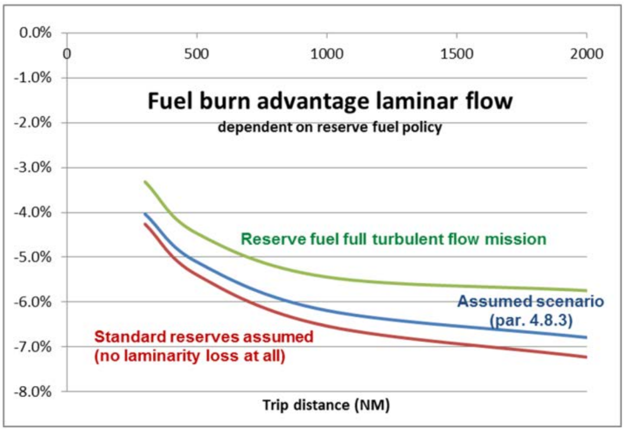

Fig. 11: Fuel burn benefit depending on fuel reserve policy

The reduction of CO2 and NOX emissions is directly related to the fuel burn reduction (4-7%). This statement is valid as both aircraft types use the same engine technology. The up-scaling of the engine for the turbulent wing has a positive effect on the NOX emissions in cruise, for the given example the engine rating is still too high (further up-scaling needed). But due to better climb performance (sealed slat device), the engine can be down-rated in climb, and the overall NOX emission during the full mission equals out. The Krueger Leading edge device is the enabler for the NLF wing technology, which leads to a fuel burn reduction of 4-7%, depending on the mission range.

A reduction in noise during take-off cannot be expected as both aircraft types use the same engine technology and similar engine ratings for take-off. For approach and landing there is yet no available data to compare the technologies. The high lift system of the turbulent wing was assumed to have a better L/D in take off by applying a sealed slat device. That would allow a steeper climb out or lower rating above the noise measurement point, but the overall effect must be seen as small.

6 Potential Industrial benefits out of DeSiReH

Lead-time, cost reduction and efficient design are also targets of the ACARE Vision 2020. Thus a summary of the contributions to those targets out of DeSiReH is given in this chapter.

During the industrial high lift design process, 2D section design plays a major role during the concept finding phase in an aircraft program. Thus, a major improvement can be expected by adopting the results of DeSiReH, where several partners demonstrated the optimization of 2D HL sections in different ways. Different approaches to parameterize and to mesh the high lift section were demonstrated, optimization algorithms were applied to minimize the agreed objective function, giving clear guide-lines for industrial application.

Also the optimization of 3D high-lift configurations was demonstrated. The effort to run a 3D optimization framework is high, but it is worth to apply 3D optimization in the industrial high lift design process to receive the very best result for selected variants in the definition phase, which are then resulting in wind tunnel model or aircraft shapes.

It has become clear that by applying optimizers, the amount of CFD evaluations will increase significantly compared to manual approaches. For the industrial high-lift design process this means that lead-time reduction can be expected only when RANS calculations are accelerated.

But the largest benefit of optimization is the larger amount of design parameters that can be handled at the time and by that the overall design will be more mature. This maturity improves further when multi-disciplinary constraints are included in the objective function formulation.

Due to the automated process, several high-lift concepts can be evaluated in parallel, which allows the designer to down select from a larger variety of devices compared with a manual approach.

For the industrial high lift design process this concludes:

- A lead time reduction per design loop is possible and a significant increase of efficiency can be expected.
- Automation allows increasing the amount and maturity of evaluated high-lift concepts.
- The computational costs will rise due to
    - an increasing amount of studied high-lift system solutions
    - a lot more CPU resources are requested by the optimization process
- The obtained results will have a significant higher maturity. This can be transferred into
    - a possible reduction of design iterations during the overall AC development phase (= lead time reduction potential)
    - less wind tunnel testing time for configuration optimization (= cost reduction potential)

7 Summary

A summary of the work carried out in the DeSiReH project is presented, with a special emphasis on its probable impact on the industrial design work. The design and optimization of a high lift system compatible with the specific requirements and constraints of a natural laminar flow (NLF) wing is described, as well as its verification under flight Reynolds number conditions. The application of non-intrusive optical measurement techniques under cryogenic conditions like Temperature Sensitive Paint for transition detection and Particle Image Velocimetry is demonstrated. Finally the environmental benefit of the application of an NLF wing is assessed, where the designed high-lift system is an enabler for this technology.

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Contact Author Email Address

henning.strueber@airbus.com
Jochen.Wild@dlr.de

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