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REDUCTION OF AIRCRAFT DRAG, LOADS AND MASS FOR ENERGY TRANSITION IN AERONAUTICS

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Abstract
This paper provides an overview of research approaches and first results of the Cluster of Excellence "Sustainable Energy Efficient Aviation", SE²A, with respect to the reduction of commercial aircraft drag and load, and therefore mass as a consequence. These approaches are viewed as major enablers of the energy transformation in aeronautics. A sound overall aircraft design is employed for assessment of technological progress in these areas. This approach quantifies snowball effects on overall aircraft level, and it provides data from reference aircraft to the research projects, to guide research directions and detailed scientific analyses within the Cluster.

1. INTRODUCTION

Long-term changes in aviation policies, regulation, and energy sources will trigger considerable changes in aircraft design compared to those of aircraft currently operating. In particular, paradigms will change as a result of the considerable price differential between wind-generated electricity and refined energy sources such as electrofuels, as will be available in future circular energy economics. Drastic reductions in aerodynamic drag and structural mass and exploitation of synergies offered by propulsion systems will be mandatory for obtaining technically feasible and economically viable designs of fully electric and electro-hybrid drive systems for aircraft with lower ranges. Based on preliminary design calculations, the suitable target for aircraft drag reduction is 50% and for structural mass reduction 40% if such advanced concepts are to be utilized for commercial air transport by 2050. Long-range aircraft, on the other hand, will continue to rely on high energy density fuels at prices much higher than the price of kerosene today. These fuel cost increases will provide a strong economic incentive for introducing these advanced technologies to improve aircraft efficiency in both short-range and long-range aircraft.

One of the three research areas of the Excellence Cluster SE²A (Sustainable and Energy-Efficient Aviation) at TU Braunschweig explores the scientific and technological fundamentals of carefully selected aircraft technologies, for enabling next generations of aircraft designers to cope with the challenges of energy transformation. We do not seek to develop new aircraft products nor industrialized techniques. In order to achieve the top-level goals of drag and weight reduction, we identified research areas that are essential for a broad range of applications, ranging from regional, short-range aircraft with purely electric energy systems up to long-range aircraft, that could employ energy efficient fuel cells.

The general research hypothesis of the SE²A Cluster regarding aircraft design states that the expected paradigm change in energy economics will cause large changes in the design and operation of future aircraft, so that viable aircraft designed for operating ranges between 500 km and 16,000 km take advantage of the cost differentials between possible energy supplies. The feasibility and economic value of such aircraft will depend particularly on reduction of aircraft drag and weight.

The SE²A Cluster has identified a set of key technologies needed to reach large improvements in drag, weight, and propulsive efficiency. While some of them do not require new knowledge, such as windowless fuselages for example, there exist high-potential technology areas where the present knowledge base is small and long-term fundamental research is needed.

The general research hypothesis of above leads us to claim detailed working hypotheses, which call for long-term fundamental research into four directions:

- Drag reduction by systematic laminarization of all aircraft components offers the largest potential for reducing aircraft drag and hence energy consumption (see Chapter 3). It also offers large indirect gains by exploiting snowball effects on overall aircraft design level.
- Research on composite materials and function integration into multi-shell structures will advance the key structural enablers, leading to considerable weight savings.
- Research on new multidisciplinary means of aircraft control will pave the way towards considerable reductions of structural weight by means of load control (see Chapter 4).
- Considerable additional weight reductions appear possible by revising current design criteria for composite structures.

The paper presents the ideas and first results on drag reduction and load alleviation. The analysis of the advances in aircraft technology requires an assessment at the over-

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all aircraft design level. Such approach requires flexible overall design simulations for the entire aircraft that take into account life cycle and noise impact. These simulations will not only allow quantifying possible snowball effects resulting from the introduction of new technologies, they will also identify the need for configuration changes that might otherwise be overlooked (cf. Chapter 2). While overall aircraft design simulation must model the energy supply system on board, the design of this system must simultaneously consider detailed overall aircraft design data.

2. AIRCRAFT DESIGN AND ASSESSMENT METHODOLOGY

The goal of aircraft design research activities of the SE²A Cluster of Excellence is to investigate the potential and influence of combining novel technologies, of e.g. airframe, propulsion, and energy supply, and novel aircraft configuration in reducing emissions and noise. For this purpose, three different reference aircraft are designed, i.e. a short-range, a mid-range, and a long-range passenger aircraft. These aircraft are designed for an assumed entry into service at the year 2040.

2.1. Airframe and energy network technologies

The following technologies are considered in the SE²A Cluster:

- Active flow control, see Chapter 3
- Active load alleviation, see Chapter 4
- New materials and structure concepts, see Chapter 3.3
- Boundary layer ingestion, see reference [1]
- Electric / hybrid-electric propulsion system [2]

Since the applicability of each of the airframe technologies mentioned above depends on the aircraft configuration, different assumptions are used for different reference aircraft to simulate the influence of the novel technologies. FIGURE 1 summarized the assumptions used for the influence of each of these technologies on aircraft drag, weight, load, and propulsion. It needs to be mentioned that these assumptions are initially used for designing the reference aircraft, but will be updated once the research teams of the Cluster succeed in consolidating the outcome of these technologies in greater detail. A more detailed discussion about the modeling approaches of the novel airframe technologies is presented in [3].

2.2. Aircraft design framework

To design the reference aircraft of the SE²A Cluster, a multilayer aircraft design framework named ADEMAO (Aircraft Design Engine based on Multidisciplinary Analysis and Optimization) is developed. The framework builds on the integration of four different layers:

- Layer one: An aircraft conceptual design tool, which can be used for clean-sheet design. This layer includes all the different disciplines involved in aircraft design.
- Layer two: A surrogate modeling toolbox, which can be used to generate surrogate models based on the outcomes of different research teams and integrate it with the aircraft conceptual design tool. This layer will also enable a multi-fidelity optimization between layers one, three, and four.
- Layer three: A coupled-adjoint physics-based MDO toolbox, which is used to improve the initial design provided by the first and second layer, and also generates more detailed information about the design. This layer is based on medium-level fidelity, but physics-based analysis, which allows us to integrate more design disciplines in a computationally affordable way compared to high fidelity methods. This toolbox will be used for more detailed optimization of the output of layer one such as aeroelastic tailoring of the wing including boundary layer suction and active load alleviation.
- Layer four: High fidelity MDO including a few main disciplines involved in the aircraft design.

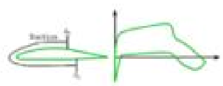
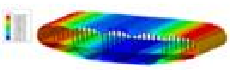
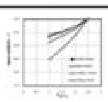
Technology integration and explanation		Short Range	Mid Range	Long Range (BWB)
Laminar flow control		Modelled through equivalent skin-friction coefficient which should further decided by the percentage of laminarization (Xfoil-suction, TAU, etc.)		
		Wing and tailplane transition location at 80%, fuselage up to the wing intersection	Wing and tailplane transition at 80%, fuselage up to wing	BWB wing transition location at 80%
Advanced structures		15% structure weight reduction in main wing, fuselage, tailplane	15% structure weight reduction in main wing, fuselage, tailplane	20% structure weight reduction
Active load alleviation		Modelled with the structure mass of aircraft wing		
		Ultimate load factor = 2.0 (1.5)		
Boundary layer ingestion		Modelled with the propulsion efficiency		
		No impact	5% improvement in propulsive efficiency	

FIGURE 1. Assumptions used to simulate the influence of different technologies in aircraft overall design

The ADEMAO framework is illustrated in FIGURE 2. Moving from left to right the level of fidelity of the analysis and optimization tools increases, however, the number of components and disciplines considered in design optimization is reduced. The first layer in the left has the maximum width, which includes the whole aircraft design, while the layer in the right has the maximum depth, which includes the most comprehensive physical model of the selected disciplines.

These four layers are connected to exchange information, which can be used for multi-fidelity design optimization.

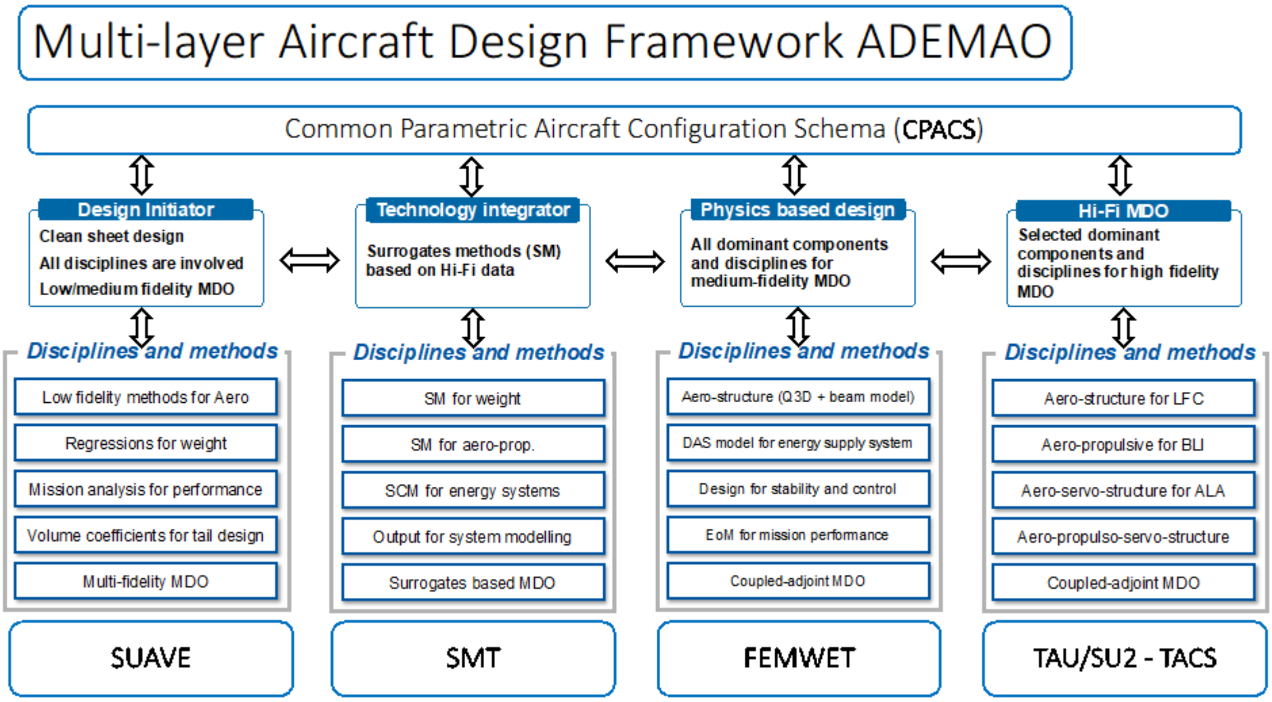


FIGURE 2. The multi-layer structure of ADEMAO. The last row shows the tools being used in each layer.

2.3. Preliminary results

As the short-range reference aircraft, a full-electric aircraft was designed based on the top-level requirements of the ATR-72 (class) aircraft. Three different designs were initially developed and after the initial sensitivity study, the best design was selected, see FIGURE 3. A comparison between the SE^{2}A short-range and the ATR-72 characteristics is presented in TAB 1.

The same approach is used to design the mid-range reference aircraft. The top-level requirements are defined based on Airbus A320 (class) aircraft. The final goal is to design a hybrid-electric aircraft for this class, however in the first step only gas-turbine propulsion by an ultra-high bypass ratio turbofan is used. In the next step, electric propulsion will be added to this design. For the mid-range aircraft, boundary layer ingestion technology is used, by placing two engines on top of the wings. Two different configurations were developed, a forward swept wing and a backward swept wing. The main reason for using the forward swept wing is the need for a low leading-edge sweep to maximize laminar flow over the wing with minimum boundary layer suction. It can be shown that for the same mid-chord sweep (or quarter-chord) a forward swept wing has a lower leading-edge sweep angle compared to a backward swept wing. The initial assessment of the two configurations showed that the aircraft with forward swept wing has superior performance due to its larger extent of laminar boundary layers at the fuselage. The two configurations and the selected one are shown in FIGURE 4. TAB 2 summarizes the comparisons between the characteristics of the SE^{2}A mid-range aircraft and the Airbus A320.

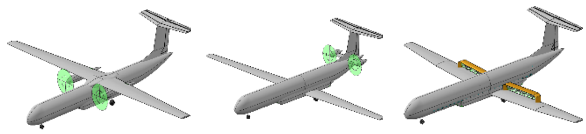


FIGURE 3. Three initial configurations for the SE^{2}A short-range aircraft (top) and the final design (bottom)

Parameter	SE^{2}A-SR	ATR 72	Change (%)
MTOW (kg)	45942	23000	99.7
OWE (kg)	36479	13311	174.0
L/D_{max}	33.0	17.14	92.5
Cruise average L/D	32.5	16.0	103.1
Block fuel (kg)	0	1377	-
Fuel efficiency (kg/seat/100 km)	0	2.07	-

TAB 1. Comparison between SE^{2}A short-range and ATR-72.

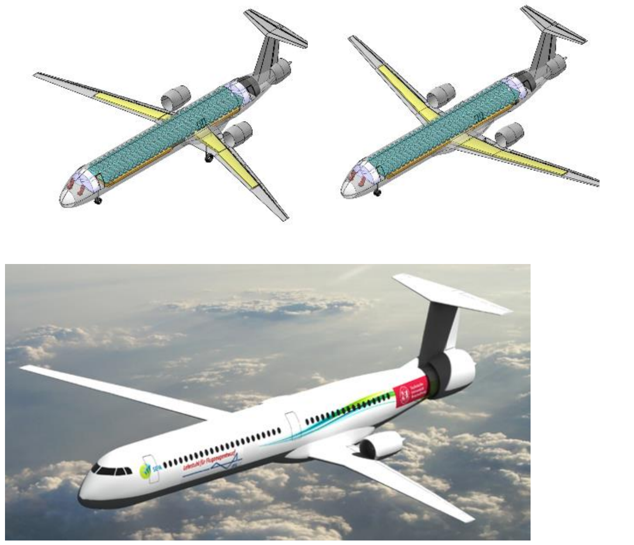


FIGURE 4. Two initial configurations for the SE²A mid-range aircraft (top), and the final design (bottom)

Parameter	SE²A-MR	A320	Change (%)
MTOW (kg)	61765	77722	-20.5
OWE (kg)	36545	41487	-11.9
L/D_{max}	34.2	18.75	82.4
Cruise average L/D	26.2	16.5	58.8
Block fuel (kg)	4886	13325	-63.3
Fuel efficiency (kg/seat/100 km)	0.612	1.669	-63.3

TAB 2. Comparison between SE²A mid-range and Airbus A320.

The long-range reference aircraft is planned to be designed using liquid hydrogen and fuel cells for energy storage and power conversion, respectively, combined with a Blended Wing Body (BWB) configuration. However, in the first step, a preliminary version of the BWB aircraft was designed using a conventional propulsion system, to investigate the influence of the novel airframe technologies on the performance of the aircraft. The aircraft was designed based on top level requirements similar to the Boeing 777 (class) aircraft. The configuration of the aircraft is shown in FIGURE 5 and the characteristics of the aircraft are compared with the Boeing 777 in TAB 3.

FIGURE 5. Configuration of the SE²A BWB aircraft

Parameter	SE²A-LR	B777	Change (%)
MTOW (kg)	169904	347452	-51.1
OWE (kg)	88251	145150	-39.2
L/D_{max}	44.0	21.0	109.5
Cruise average L/D	22.5	18.5	21.6
Block fuel (kg)	48634	109290	-55.5
Fuel efficiency (kg/seat/100 km)	1.08	2.72	-60.3

TAB 3. Comparison between SE²A long-range and Boeing B777

To investigate the influence of novel airframe technologies on the performance of full-electric aircraft, a series of sensitivity analysis has been performed. The goal is to investigate the effect of boundary layer laminarization as well as reducing the limit load on the wing by the use of the active flow control and active load alleviation technologies. For this purpose, the (full electric) short-range aircraft is resized for various values of boundary layer laminarization (from 50% to 80% of the wing area) and limit load factor (from 1.5g to 2.5g). FIGURE 6 illustrates the contours of aircraft Maximum Take-off Weight (MTOW) for the mentioned range of laminar flow and limit load factor. Assuming 50% laminar flow using natural laminar flow control and a limit load factor of 2.5 for conventional aircraft, from FIGURE 6 one can observe that about 30% reduction in MTOW can be achieved using an 80% laminar flow and a limit load factor of 1.5 (comparing top left and bottom right corners of FIGURE 6).

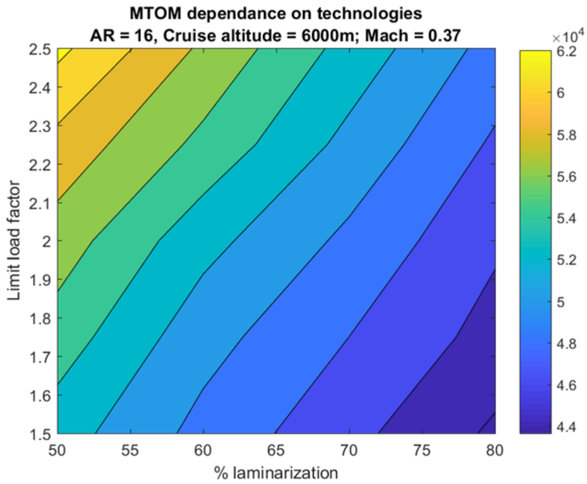


FIGURE 6. Contours of aircraft MTOW for different values of laminar flow area and limit load factor.

More detailed results are presented in FIGURE 7, where the values of aircraft battery weight, empty weight, and MTOW are plotted for different values of laminar flow area and limit load factor. The results indicate that battery weight depends strongly on drag reduction due to laminarization, while aircraft empty weight depends much more on the limit loads.

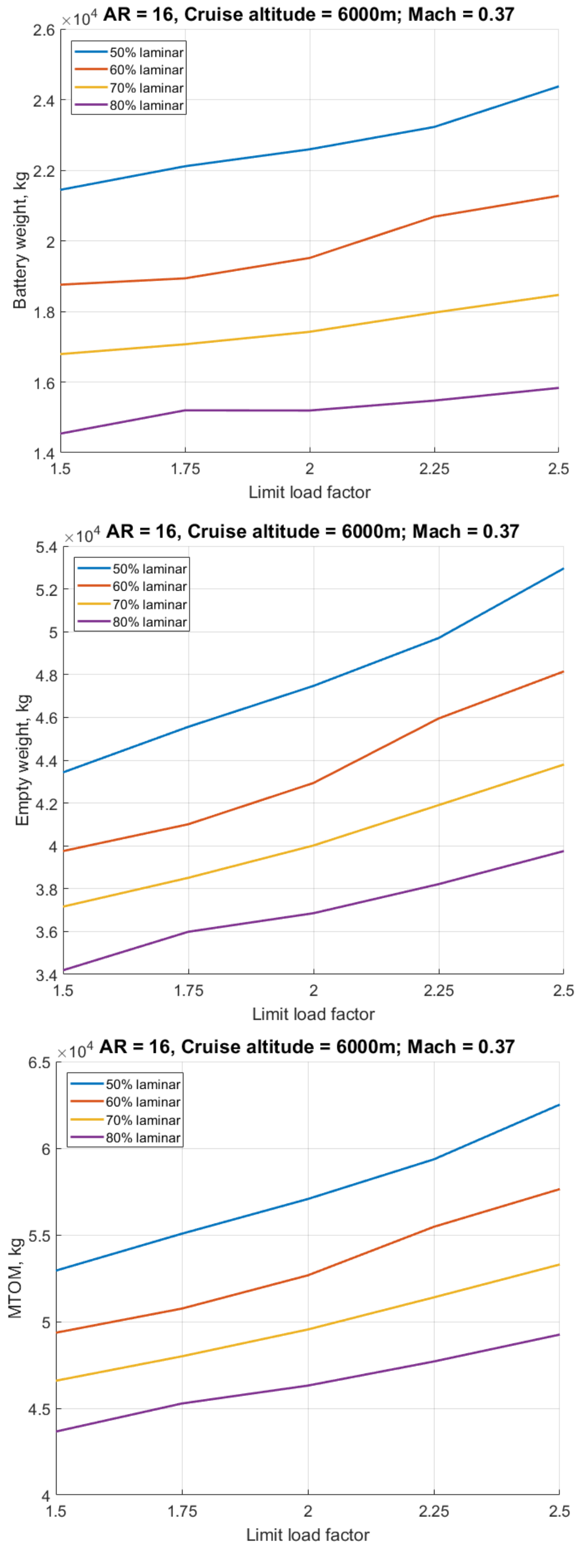


FIGURE 7. Influence of laminarization and load alleviation on battery weight, empty weight, and MTOW of the SE²A short-range aircraft.

3. AIRCRAFT DRAG REDUCTION

The general research hypothesis of the SE²A Cluster regarding aircraft design states that the expected changes in energy economics will cause step changes in the design requirements and operation of future viable aircraft. Aircraft drag does not only affects the flight performance of commercial aircraft; it will assume a much stronger contribution to direct operation costs in the future, due to the structural changes in energy supply economics. Therefore, the research strategy of the SE²A Cluster views drag reduction of commercial aircraft as a major enabler for sustainable aviation.

3.1. Drag Reduction Potentials and Challenges

Technologies for drag reduction have always been on the research agenda. The aircraft drag comprises induced drag, wave drag, viscous drag, and miscellaneous, smaller parts. The potentials of technologies for reducing the lift dependant induced drag are rather limited as long as viscous drag dominates the overall drag balance. A similar statement holds for the wave drag of cruise flight at high Mach numbers. It is also known that passive and active means for reducing the friction drag of turbulent boundary layers are rather limited in their effect.

Systematic laminarization of the major aircraft components offers the largest potential for reducing aircraft drag and hence reducing energy consumption. It also offers large indirect gains by exploiting synergy effects on overall aircraft design level. This is demonstrated by recent preliminary design computations of Beck et al. [4], who assessed boundary layer suction rates and the component drag of wing, tail and fuselage for a mid-range commercial aircraft. FIGURE 8 shows drastic drag reduction potentials if comprehensive laminarization of all major aircraft components is introduced. Significant is also the so-called snowball effect on overall aircraft with respect to re-designing the wing planform and re-sizing the overall aircraft.

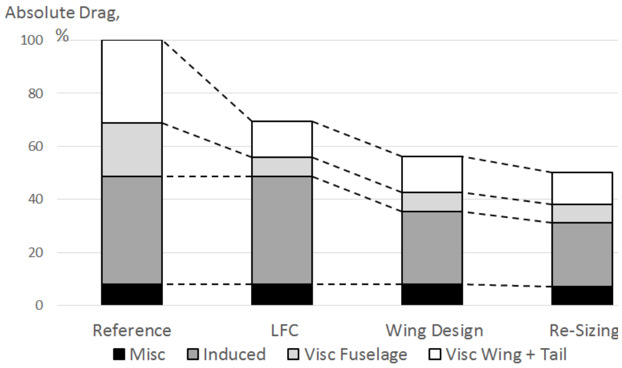


FIGURE 8. Viscous drag reduction by laminarization and effect on overall aircraft drag according to [4]

Comprehensive laminarization goes far beyond designing the aircraft geometry for maximum natural laminar flow (NLF). NLF can only reduce the viscous drag of the wing and the tail, by about 40-50%. Further drag reductions are accessible only with active flow control by boundary layer suction (BLS). We note that BLS should be applied only where absolutely needed, as the required installation of suction devices increases aircraft complexity, and adds to the required suction power on board. This constitutes the so-called hybrid laminar boundary layer control (HLFC). BLS would typically be installed between 60 and 80 percent of the wing chord in order to yield the ultimate laminar wing.

The general approach towards HLFC is not new. A number of HLFC variants have been researched for several decades, and a significant number of successful tests in wind tunnel and in flight have been reported. Well known problem areas are high manufacturing costs of wings with HLFC systems and their additional weight, as well as operational issues. Comprehensive laminarization of a wing as discussed above has not yet been demonstrated. The rather slow technological progress appears to be mainly caused by the interdisciplinary nature of the required engineering solutions. A major problem has always been the compliant structure design that provides the flow control function with acceptable weight.

Designing genuinely three-dimensional aircraft components with laminar flow along its surface such as fuselages and blended wing bodies requires tools for laminar-turbulent transition prediction on 3D shapes and for optimizing the laminar extent by HLFC. These do not exist today either.

3.2. Aerodynamic Design Approach for Comprehensive LFC

3.2.1. Design of Laminar Flow Control for High Aspect Ratio Wings

The aerodynamic design of HLFC on wings with high aspect ratio takes advantage of the infinite swept-wing approximation. That is, the aerodynamic design effort focusses on identifying an airfoil shape that is best suited to yield low wing drag at low suction power input for best overall efficiency. Optimization including suction power is of particular importance for wings with comprehensive laminarization over most of its surfaces.

The current research of the SE²A Cluster aims at identifying optimized airfoil and wing shapes that sustain laminar flow on at least 80% of the chord length using BLS. The concept is inspired by recent developments in sailplane technologies [5]. A coupled optimization of airfoil shape and the suction distribution is performed to strike the right balance of the dampening effect of BLS and favourable pressure gradient region of the airfoil geometry on Tollmien-Schlichting instabilities (TSI). The objective here is to minimize the total aerodynamic drag which encompasses the profile drag of the airfoil and the suction power necessary by the BLS. Such a coupled optimization provides an additional degree of freedom to control the pressure distribution, C_p, over the airfoil. In addition, the airfoil must have robust performance in off-design conditions. The current optimization loop involves three blocks: (a) shape parameterization (b) optimizer, and (c) flow solver. Reference airfoil shapes and suction distribution are parameterized using Class Shape Functions (CST). Optimization is performed with NSGA II Genetic algorithm using the CST control points as the design variables. The advantage of employing the infinite swept-wing approximation is that computationally efficient flow solvers can be used such as XFOIL for subsonic flow fields or MSES for transonic flow. The present flow calculations are performed using an extended version of XFOIL for BLS, XFOILSUC [7], with an improved e^N-method according to Van Ingen [6] to predict boundary layer transition.

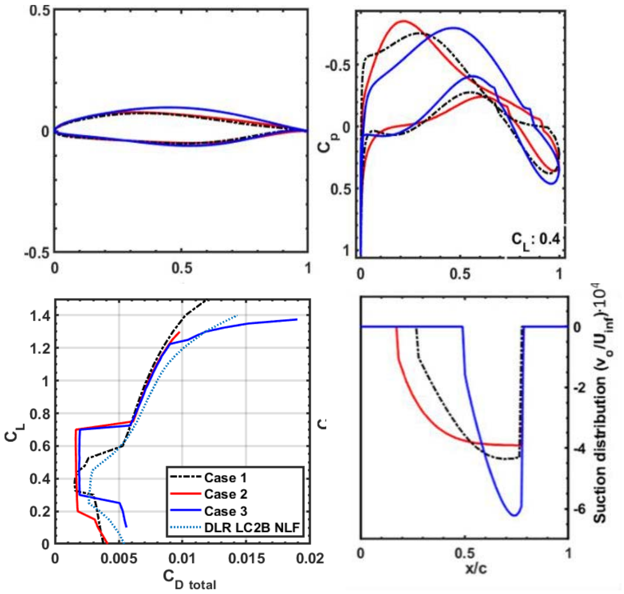


FIGURE 9. Optimization of airfoil, design point C_L=0.4 (black), design range C_L=[0.3 0.7] (red), constrained design with suction onset at x/c=0.5 (blue), reference DLR LC2B NLF airfoil (dotted)

As first object, an airfoil is optimized for a short-range subsonic aircraft at Reynolds number of 16 million and Mach number of 0.4. The computation set-up assumed BLS on the upper surface up to 80% of airfoil chord while NLF was the design objective on the lower surface. The results are displayed in FIGURE 9, where the optimization loop showed its applicability for single-point optimizations, for covering specified design ranges, and for treating constrained optimization, e.g. a restriction on allowed suction locations. The drag values shown include the major contributions to suction power, but without losses in suction ducts and turbomachinery. It is seen that BLS brings about a 35% reduction of total airfoil drag relative to a state-of-the-art NLF airfoil.

3.2.2. Laminar Flow Control for 3D Geometries

The aerodynamic surface of blended aircraft configurations, e.g. the centre portion of blended wing bodies as well as conventional aircraft fuselages feature fully 3D flow fields. The prediction of laminar flow along on such geometries and the optimization of the laminar flow extent by HLFC requires new, computationally efficient design tools with an adequate representation of flow physics. Currently available transition prediction capabilities and HLFC design tools employ either classical linear local stability theory (LST) or more advanced transition prediction approaches based on standard parabolized stability equations (PSE), which both neglect any spanwise gradients (infinite swept-wing approximation). They provide satisfactory results about the expected transition location for high-aspect-ratio wings only. Moreover, for effective design applications an iterative procedure for gradient-based shape optimization with efficient computation of the required gradients needs to be established [8], using information from direct and adjoint Euler, direct and adjoint boundary-layer, and direct and adjoint PSE computations, respectively.

The SE²A Cluster develops the required know-how and an efficient optimization tool chain for HLFC at 3D configurations. Since the spanwise gradients in the boundary layer are no longer negligible, a generalized PSE approach, PSE-3D, suitable for fully 3D boundary-layer flows is required for boundary-layer stability analysis, and concepts for an N-factor based transition prediction in fully 3D flows have to be established and tested. An extended version of the NOLOT/PSE code [9] with a marching procedure in both surface-parallel directions, as originally proposed by Herbert [10], will be used for transition prediction. When linked with a corresponding adjoint version of the PSE-3D code and direct and adjoint solvers of 3D Reynolds-averaged Navier-Stokes equations (RANS) sketched in FIGURE 10, an efficient gradient-based optimization tool chain suitable for HLFC on e.g. BWB configurations can be set up. The DLR TAU code [11] will provide the required direct and adjoint RANS solver capabilities. The tool chain aims at minimizing the measure E of the overall boundary-layer disturbance growth and provides ∇E, the sensitivity of E to small changes in suction distribution, and hence the shape of e.g. the blended wing body.

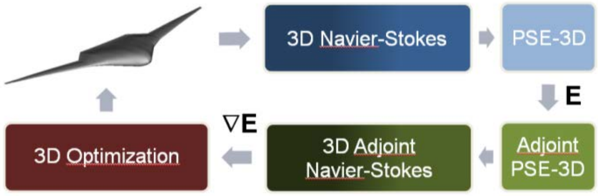


FIGURE 10. Tool chain for gradient-based optimization of 3D configurations with hybrid laminar flow control

3.2.3. Suction flow design

For HLFC systems the outer flow must be distinguished from the interior flow. The outer-flow on the surface is laminarized by shape design and by taking advantage of the effect of the interior flow - the sucking of air through the porous skin into some collector duct that has pressure loss due to flow resistance. To drive the air through the porous skin, a pressure difference is applied between the interior and the outer surface of the skin design. The actual suction velocity depends on the flow resistance through the porous skin. Recent improvements in wing surface materials and the technologies capable of machining them, have resulted in good quality of micro-holes perforated materials, as demonstrated in FIGURE 11.

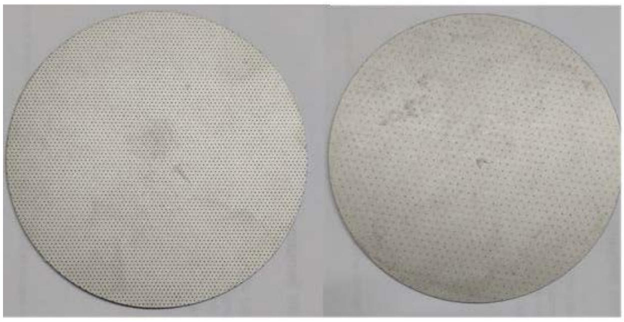
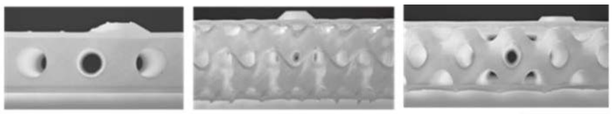


FIGURE 11. Laser drilled micro hole samples of 120µm (left) and 240µm (right)

The first objective of suction flow design is to quantify the pressure loss behaviour of the micro perforated metallic sheet as function of the suction velocity using calibrated flow meter.

The second objective is to study different concepts of inner structures based on analytical and empirical correlations of flow resistance. With the help of 3D printing technology different concepts of the internal sandwich core structure to support the porous sheet are being explored and a suitable reduced order model of the flow through the core is proposed to facilitate aerodynamic design. FIGURE 12 shows 3 different concepts of the internal design. Special flow bench tests are carried out to study the pressure distribution (loss) based on the design variables.



(a) Base- Channel core (b) TPMS - Gyroid (b) TPMS - Schwarz

FIGURE 12. Samples of suction flow sandwich structures including Triply Periodic Minimal Surface Structures (TPMS)

3.2.4. Validation Concept

Comprehensive laminarization of aircraft wings, bodies and also blended aircraft components using new technologies in aerodynamics and structures makes thorough technology validation necessary. The SE²A Cluster follows a stepwise approach to validation that takes technical needs and available research infrastructure into account. The approach comprises fundamental transition studies on a flat plate, intermediate experiments of a research airfoil in a medium-size wind tunnel, and finally, thorough technology testing in a large world-class wind tunnel facility.

The flat-plate tests aim at measuring the quantitative effect that suction has on laminar turbulent transition and validate the ability to predict that effect by computation. They also address the possible problem of aerodynamic roughness created by suction through micro holes of different size. The flat-plate tests further aim at quantifying porous-skin flow resistance under realistic outer flow conditions. HLFC experiments on a dedicated research airfoil will verify the integrated design capability of porous skin and sandwich core. They also address the problem of rapid boundary layer transition in flow regions with strong adverse pressure gradient, downstream of the chosen suction interval. This is a new research question associated with comprehensive laminarization of the wing towards the trailing edge. Finally, the airfoil tests will demonstrate the low drag of an airfoil with 80% laminar flow. The third validation step aims at fulfilling the needs to test at elevated Reynolds numbers and to simulate the aerodynamic effects of wing sweep. A suited facility for that purpose is the DNW-NWB 3m wind tunnel.

The SE²A Cluster has recently completed its first flat-plate experiments. Here, the modal growth of Tollmien-Schlichting waves causes large, primary disturbances of the boundary layer. This sets the stage for break-down to turbulence. With suction, boundary layer transition can be delayed, by attenuating or suppressing the growth of these primary disturbances. The experiments of the flat plate with a suction insert were conducted in the low-speed wind tunnel, MUB, of the Technische Universität Braunschweig. The setup is shown in FIGURE 13. With a test cross-section of 1.3m ×1.3 m, Reynolds number varies between 3 – 10 Million.

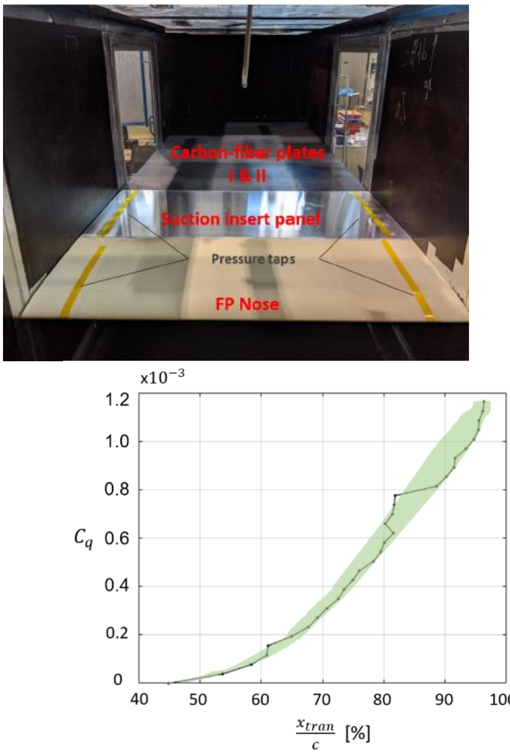


FIGURE 13. Flat plate test set-up in wind tunnel MUB and measured transition delay with suction for 240µm holes

Infrared images are used to detect the region where final break down to turbulence occurs, and deduce the nominal location of the transition line, while static steady pressure measurements on both sides of the suction panel provide the data needed to perform stability analysis. The experiments tested two suction inserts with moderate and large hole diameters (120µm and 240µm) and a solid-plate insert for reference. The first results indicate a significant and continuous transition delay as a result of increasing the suction coefficient, C_q. Further, N-factors of around 8 are obtained for the solid reference, while suction through the large holes reduces this number significantly. Detailed analysis of these results is underway.

3.2.5. Combined Effects of Laminarization and Boundary Layer Ingestion

The SE²A Cluster explores the potentials of boundary layer ingestion (BLI) for improving the propulsive efficiency for future commercial aircraft. This includes the examination of power benefits on overall aircraft level, when combining BLI with LFC upstream of the engine inlet. Therefore, a joint power saving coefficient (PSC) is defined, that quantifies the relative fuel power saving compared to a reference case.

Flow data of the boundary layer upstream of the inlet are taken from 2D XFOIL calculations by Beck et al [4] for the NASA SC(2)-0518 profile, which was used to represent the initial aerodynamic shape of the blended wing body fuselage. The assumed angle of attack was -0.75° at M=0.7. Aerodynamic losses of the fan stage due to inlet distortion by BLI are estimated by employing a parallel compressor model [1]. This model is applied to a propulsor that was previously designed in UHBR research of the CRC 880 [12]. FIGURE 14 displays PSC for different thrust levels and for different flight altitudes. Solid lines indicate the PSC of a BLI propulsor relative to a non-BLI propulsor with the same thrust. Dotted lines represent the PSC of a BLI propulsor with LFC upstream compared to a non-BLI propulsor without LFC, and hence, turbulent flow. The angle of attack is adjusted in the BLI-LFC case to provide the same lift coefficient, and the propulsor thrust is reduced to reflect the decreased drag of the laminarized profile, that included the equivalent drag of the suction power needed to overcome static and dynamic pressure losses of BLS.

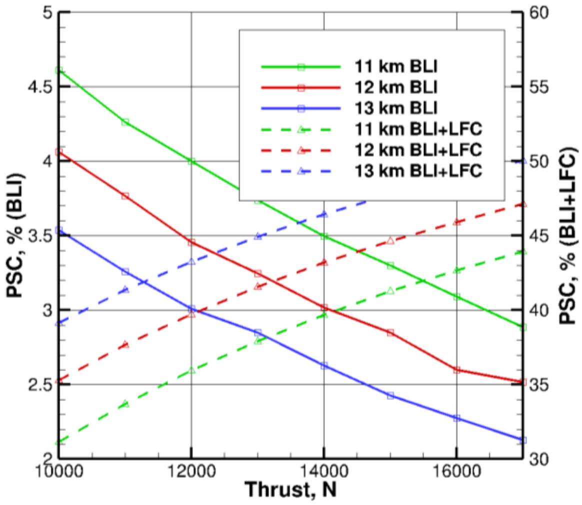


FIGURE 14. Effects of thrust, flight altitude and LFC on Power Saving coefficient for BLB propulsor

The power saving effect of LFC clearly dominates overall power savings yielded by LFC and BLI. The dependence of the PSC on thrust and altitude is contrary to the case without LFC, while the effect of BLI contributes only about 0.1 absolute percent points to the overall PSC. Further computations assumed drastically increased fan efficiency and an increased suction power requirement (leading to reduced areas of LFC application). These sensitivity studies confirmed that BLI has only a minor share in overall power savings of combined applications of LFC and BLI. Focussing on LFC for overall power saving optimisation therefore seems useful for the current approach.

We note that the present analysis assumed a quasi 2-dimensional setup for computing the interactions of BLI and LFC. In future works, the 3D flow over the BWB fore-body will provide a more realistic inflow to the inlet, see FIGURE 5. This set-up will allow studies which account for the interaction of BLI and LFC only in the region upstream of the engines. This should increase the relative impact of BLI on overall power savings and may result in different design trades regarding the combination of both technologies.

3.3. Compliant Structures

3.3.1. Multiscale Design Concept

Compliant wing structure design aims at integrating multifunctional suction panels, as discussed in Section 3.3.3 while reducing structural weight as much as possible. The structural design approach to meet these objectives is illustrated on the basis of the non-swept wing of the short-range aircraft configuration presented in Chapter 2. This restriction does not limit the insight gained; the challenges for the two other reference configurations of the SE²A Cluster are quite similar.

In order to cope with the complexity of the multidisciplinary design task, the design approach follows a multiscale path with parametrized representations of the overall wing structure (coarse grain) and the integrated suction panel (fine grain). As changes of the wing loads, the suction panel dimensions and the interior suction flow design must be taken into account when new knowledge and new design methodologies become available, the SE²A Cluster seeks automated processes in structural design with standardized interfaces to exchange aerodynamic and structural design data updates.

The passive structural solutions for load reduction discussed in Chapter 4 are not taken into account at this point, since the combination of advanced HLFC and passive load reduction is extremely challenging, and should be investigated only when mature solutions are available. Some practical aspects, as e.g. lightning strike protection, details of flight control systems etc. are also not detailed during the present fundamental research works.

3.3.2. Overall Wing Structure

The main part of the load carrying structure, i.e. the wing box, is assumed to be made of CFRP, by which the advantage of CFRP thin-ply material with respect to weight reduction is accessible, see Section 3.3.4. The basic structural design is assumed conventional, using flat shear webs in spars and ribs, as well as straight stringers. The distinction from conventional wing design is the beaded area where the suction panels are to be integrated. FIGURE 15 shows a sketch of a wing box section with only one symbolic suction panel shown. Elements like stringers and ribs are just indicated without taking pitches, shapes and sizes as fixed. Also the position of the aft spar and possibly further spars in relation to the suction panel runout is the result of parametrized input.

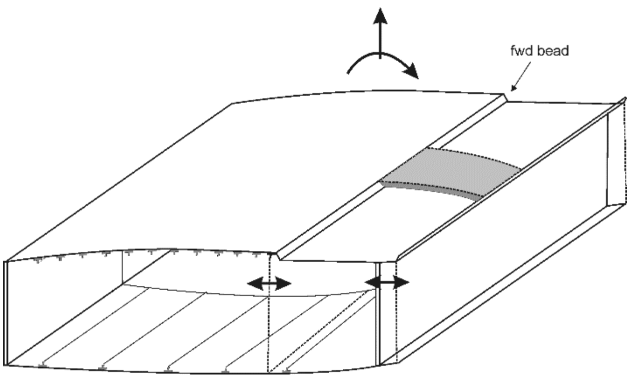


FIGURE 15. Sketch of wing box section with suction panel

First design computations that take into account bending and torsion, reveal particular features of the overall wing structure:

The forward bead initiates disturbances, both in the stress distribution as well as out-of-plane displacements, according to FIGURE 16. Depending on the suction panel concept this area may also comprise highly loaded joints. Hence, the adjacent stringer or spar needs additional stiffness, possibly an adapted directional stiffness, for complying with aerodynamic geometry requirements. The impact is not only expected at the global level, but also detrimental stresses will occur at the laminar level, possibly resulting in inter-fibre failure or delamination. Here, careful shape design of the bead profile will be essential. In addition, the bead profile affects the resulting layer orientation in this region, and automated fibre placement (AFP) is also an issue.

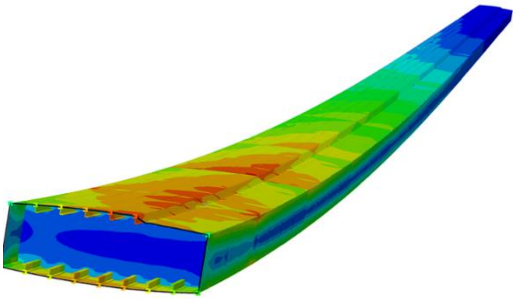


FIGURE 16. v. Mises stress distribution of the SE²A short-range reference aircraft wing box

Due to the fact that the cover plate of the suction panels must be prevented from buckling (under compression and shear), these parts of the suction panels must be widely load free. This means that the underlying wing skin structure must carry the bulk load, and further measures have to be taken to unload the suction panel skin. This may be achieved by separating the individual suction panels without creating unwanted surface disturbances. One of the research questions addresses the use of the lower skin of the suction panel (at least) to act as stiffening members against buckling of the wing skin. Connected with this is the question of how to achieve a detachable joining of the suction panel with the wing skin, which is needed for maintenance. Whether additional stringers are needed in the region of this joint remains to be determined.

A further concern is the fluidic connection of the suction panel with the pump system. Depending on the necessities from the aerodynamic design it could be advisable to locate the required throttle holes in part of the forward bead and in the load carrying wing box skin. This would mean that the highly loaded areas have to be significantly severed, while accessibility may be hampered by the adjacent stiffeners mentioned above. Hence, the fluidic connections will have a significant impact on the local stresses. Due to these disturbances, fatigue will play an important role. Obviously, multidisciplinary trade-offs are needed to balance aerodynamic efficiency and structural weight penalties.

3.3.3. Thin Ply Material

The positive effect of using thin plies on static and fatigue parameters, and on impact resistance is known since beginning of this century. A comprehensive review has recently been provided by Arteiro et al. [13]. Some features of thin plies have already been found in the ‘70s, see e.g. Parvizi et al. [14], and interpreted by Leguillon [15].

The SE²A Cluster carries out a broad test program on the behaviour of CFRP thin ply laminates, including plane tension and compression, open-hole tension and compression and compression after impact (CAI). As an example, comparison of tension failure of quasi-isotropic thin ply material with 0.03 and 0.048 mm layer thickness with comparable material of 0.3 and 0.19 mm showed increased strength of 27% and 36%, respectively. On the other hand, thin ply open-hole tension specimens yielded a decrease in strength. Small decreases were also found under compression and open-hole compression. However, these effects depend on the specific material and on the particular layup, as suited numbers of alternating fibre orientation angles may improve performance.

With respect to stiffness, it seems as if this is slightly reduced compared with traditionally used prepreg layer thickness, but also small increases are found in literature.

It is therefore a research question to foresee where thin ply laminates may be usefully applied. From the data we have, it is obvious that significant gains may be found for the lower wing skin due to the better strength and CAI, whereas the issue of access holes has to be resolved. For the upper wing skin it appears that the slightly reduced stiffness may not be fully balanced by the ideas to use the possible reduction of the coupling elements D_{16} and D_{26} in the ABD-Matrix to improve the buckling strength. On the other hand, thin ply laminates yield higher strengths in the high curvature areas of the beads, see [16]. Nevertheless, the throttle holes required to connect the suction panel to the pump system again call for solving the issue of open-hole strength.

3.3.4. Design of Suction Panel based on ALM

The suction panel consists of a perforated suction sheet as the outer skin surface supported by a core structure which also functions as a duct for the drawn in air, and an inner skin which forms the structure into a closed box. The main function of the panel is to provide suited suction rates in order to damp modal instabilities of the laminar boundary layer, to preserve the outer wing shape under the aerodynamic loads that occur.

The design objectives are to minimize the area of contact between outer sheet and core in order to keep the influence of the connection on the perforated sheet as low as possible, to realize a core structure that is efficient from an aerodynamic and structural point of view, and to make the best possible use of the material by means of a compliant stiffness distribution. FIGURE 17 shows the five individual elements of the structure, these are the inner and outer skin, core, and core-skin connections, which span the solution space with their design, material and manufacturing processes.

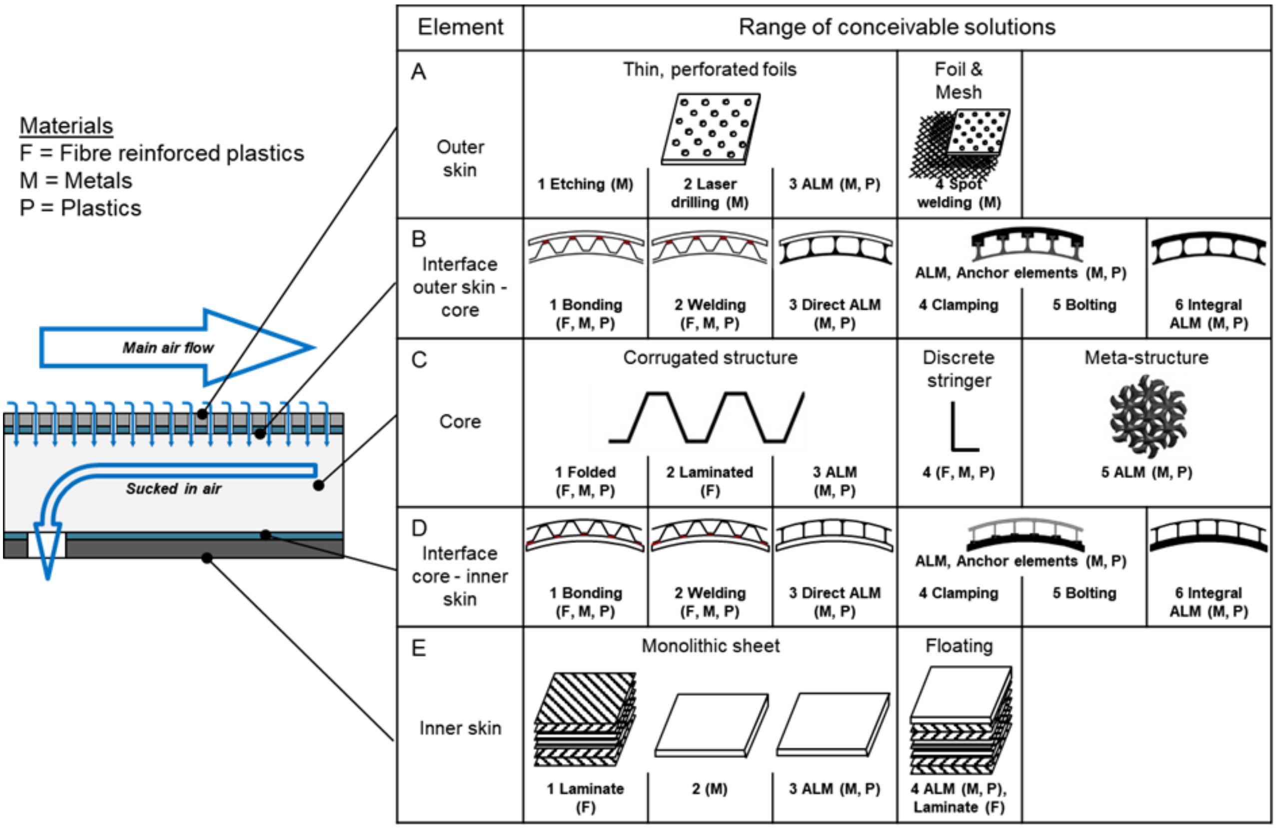


FIGURE 17. Solution space of suction panel

In previous research programs, various suction panels were developed using conventional designs and manufacturing processes (ECHO [17][18], TSSD [19][20], ALTTA [20]). These existing solutions are contained as specific tuples in FIGURE 17. However, it turns out that these known solutions can hardly be employed as an integrated part of a load-carrying structure. Hence they would lead to an excessive weight increase, if comprehensive laminarization of aircraft is sought. Recent additive manufacturing technologies, on the other hand, offer a huge potential regarding function integration and integral part design. Therefore, the focus of SE^{2}A Cluster research is to exploit the potentials of ALM technology for suction panels. ALM technology has the ability to produce highly complex, integral structures with closed-up hollow systems in a one-shot manner. While several concepts of providing multifunctional core structures are investigated by the Cluster, here, we will elaborate on the novel ALM-driven approach “minimal surface concept” as described by tuple (A3, B6, C5, D1, E1) in FIGURE 17 only.

The core is a so-called “Triply Periodic Minimal Surface Structure” (TPMS), which consists of small, recurrent volume elements with 3D surfaces with zero mean curvature at every point. Therefore, the TMPS's surfaces are free of lateral forces and respectively act mechanically as membranes. Typical TPMS structures like Gyroid or Schwarz Primitive are promising approaches since they provide both, a lightweight but dense structure [21] as well as a channel system enabling internal air flow. However, complex, integral structures like TPMS can only be realized with ALM in terms of production technology and cost-effectiveness.

The outer suction surface as well as the TPMS core are manufactured integrally by ALM-technology, without any assembly. This element is bonded to the load carrying wing surface, the inner skin, which is made from CFRP. In this way, a lightweight, intrinsically stable structure is generated. Since using stainless steel or titanium within the Selective Laser Melting (SLM) process, the structure is resistant against most environmental impacts, such as UV radiation, corrosive media, and other.

Currently, this concept is being investigated from the point of view of mechanical and aerodynamic performance through tests. The achievable surface quality, shape retention and reproducibility of the holes are quantified. The perforated suction skin is evaluated by flow meter tests, the TMPS are evaluated by flow bench tests in comparison to the corrugated cores. The structural performance of the TPMS is also investigated and the limits of the ALM technology in terms of manufacturing parameters such as minimum wall thicknesses are determined in order to realize efficient lightweight structures.

4. LOAD ALLEVIATION

Several approaches to reach load alleviation are investigated in the SE^{2}A Cluster. The issue is to find solutions to reduce limit loads to 2.0g or even 1.5g, as this generates large OWR reductions, according to Section 2.3. The general idea of load alleviation is well known, and active and passive approaches may be distinguished. Primarily, means are investigated to change the wing load distribution in a beneficial way, as schematically shown in FIGURE 18. Section 4.1 presents a range set of passive approaches to achieve this goal, while Sections 4.2 and 4.3 investigate active measures.

The SE^{2}A Cluster has defined its mid-range reference aircraft as its initial, joint application scenario for load alleviation. Furthermore, the Cluster research focusses on wing load reduction as its primary objective. Note, that load alleviation of the wing will also reduce the weight of fuselage and empennage. Obviously, all approaches of load alleviation generate certification issues; these should be addressed in detail once technically sound concepts are identified.

4.1. Load reduction potential of nonlinear stiffness and damping technologies

Nonlinear stiffness can be employed to gain load reduction. The way nonlinearity is achieved, distinguishes different concepts of the Cluster from each other. They range from steered material nonlinearity to advanced combinations of technological effects and localized drastic morphing. In addition, viscoelastic damping may turn out as a further means. In all cases these approaches have to be matured, and trade-off studies are needed to check their feasibility in application and possible coupling with other techniques developed, e.g. hybrid laminar flow control.

4.1.1. Nonlinear stiffness design

According to statistical load data, intense load cases (-1.0 g and 2.5 g) occur seldom [22], [23]. The load factor stays between 0.5 g and 1.5 g for the most part of the aircraft's lifetime. Consequently, the load cases appear imbalanced. In contrast, the stiffness of the wing behaves linear. However, rubber-like materials show nonlinear elastic behaviours, as can be seen in the work of Brojan et al. [24]. The idea considers the use of such nonlinear elastic relations (see FIGURE 18) for two objectives: firstly, the lift distribution may be shifted towards the wing root during high load cases. Secondly, aerodynamc performance may increase during low load cases. Hence, the aim is to create passive load alleviation with a nonlinear elastic relation. To analyse the aeroelastic behaviour of such wings, the Ludwick's-Law represents the stiffness in a coupled iterative process with trimmed solutions of the vortex-lattice method (VLM) for quasi-steady manoeuvres.

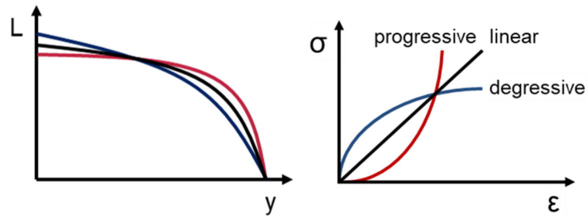


FIGURE 18. Schematic lift distributions of load alleviation and generic nonlinear stiffness relations

4.1.2. Viscoelastic damping design

Another possibility of load reduction is the effective layout of vibration damping. In this context, Constrained Layer Damping (CLD) treatments are promising. A CLD treatment consists of a viscoelastic core layer that is constrained between the primary wing structure and a stiff face sheet (see FIGURE 19).

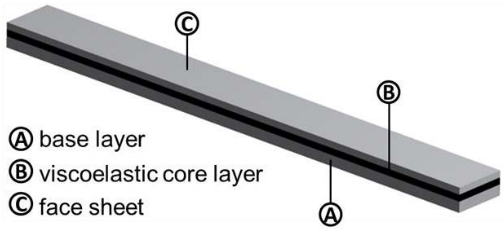


FIGURE 19. Composition of a constrained layer damping treatment.

If the wing is subjected to bending vibrations as a consequence of gust loads or flight maneuver, the viscoelastic layer is forced into shear deformation. Based on the specific viscoelastic properties, a significant amount of vibrational energy can be dissipated. However, the properties of viscoelastic materials are highly dependent on temperature and frequency. The frequency dependence, in particular, causes numerical issues, since corresponding eigenvalue problems are not directly solvable. Therefore, an iterative eigenvalue solver has been developed, allowing for assessing the damping performance of vibrating systems with frequency dependent viscoelastic materials [25]. The impact of temperature changes on damping provided by CLD treatments has been simulated on the basis of a dedicated damping material for aeronautic applications. It could be demonstrated that temperature-related property changes of the viscoelastic material result in considerable changes in damping [26]. In addition, damping is also influenced by the geometry of the CLD treatment. Damping is also sensitive to topological parameters as the width or thickness of the different CLD layers. These design variables can be optimally adjusted regarding maximum damping of a selected mode shape. Mass restrictions have to be included in order to prevent a non-justifiable mass gain of the wing structure. Therefore, a topology optimization algorithm that maximizes damping under mass constraint is a major objective of future research.

4.1.3. Structural technologies enabling load alleviation

Identification of promising aeroelastic tailoring technologies is a further objective of the Cluster. A numerical model of the mid-range reference configuration of the Cluster, as shown in FIGURE 20 was created and a multidisciplinary design process that includes aero-elastic analysis was established. Hereby, detailed structural constraints like strength and stiffness are considered and sensitivities of structural design parameters regarding mass, bending and twist stiffness are identified based on structural optimization [27]. The research considers comprehensive structural details to evaluate the feasibility of load control.

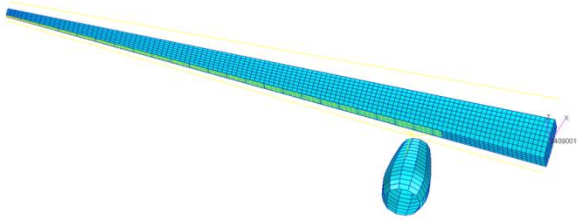


FIGURE 20. Model of the mid-range configuration

Passive load alleviation through stiffened panels in post-buckling regime aims to identify meaningful applications on wing covers. In order to achieve that, a new methodological approach for analysis and sizing is developed and applied that allows analysis of unconventional structural designs. Note, that the tailoring of stiffness by using composite properties is included to achieve desired twist distributions for load alleviation. The latter already resulted in overall benefits [28].

An overview of structural technologies investigated here is shown in FIGURE 21. The technologies under consideration also include pressure-actuated cellular structures (PACS) that could be particularly attractive for movable design.

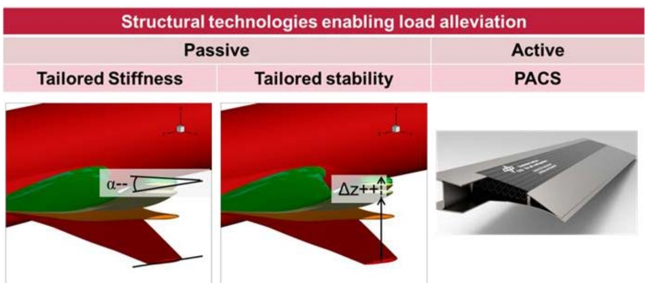


FIGURE 21. Structural technologies to enable load alleviation

4.1.4. Locally Morphing structures for the 1g-wing

This part of Cluster research aims to extend the aeroelastic design space using strong nonlinearities such as buckling for passive load alleviation. The challenging concept is to design structural components with a deliberated structural nonlinearity that comes into play at a defined load level. The nonlinearity affects the deformation of the wing for reducing aerodynamic load. One intended deformation is torsional rotation of the wing, for lowering the effective angle of attack. A second suitable deformation is a change of the airfoil shape. Note, that for backward swept wings, upward bending also reduces the effective angle of attack.

The research is structured in three phases. In the first phase the nonlinear structural behaviour of representative parts of wing design is explored. The target is to gain fundamental understanding how to tailor such parts to meet given needs. The second phase comprises high-fidelity numerical simulations of fluid structure interactions for quasi-2D wing sections that include the previously identified structure parts with defined nonlinearities. This allows an exploration of the wing section’s response under gust loads in the time domain and quantification of the resulting load alleviation due to airfoil changes. In the last phase the aeroelastic model is extended to a full 3D wing to cover all possible deformations such as torsional twisting.

For the first project phase finite element models of generic wing structure elements like skin panels and unstiffened and stiffened wing boxes have been derived from the mid-range reference configuration. The geometrically nonlinear dynamic simulations represent an assumed ‘1-cosine’ gust up to a maximum load of 2.5 g. Material failure is not taken into account up to now. The models are used for sensitivity studies regarding anisotropic composite layups, thicknesses and stringer applications. Additionally, parameters such as static pressure variations and load duration are varied. The loads feature a bending moment and a shear force in the centre of the symmetric profile as well as an equally distributed static pressure on the skin surface. Therefore, the observed torsional rotation is induced by the reaction of the structure and not by external torsional load. The intended nonlinear behaviour is measured by the ratio of the initial stiffness and the stiffness after the nonlinearity sets in.

According to the current results a wing-box with an intended nonlinear behaviour can be designed by modifying the upper skin and rear spar. Typical aircraft design laminates for skins have a layup with a dominating 0° layer and additional 90° and ±45° layers. To achieve the desired behaviour, the initial 0° and 90° layers of the upper skin are rotated by 35°. Using the same layup in the lower skin increases the twisting but reduces the grade of the nonlinearity. Additional nonlinear rotation is achieved when the rear spar is thinner than the front spar. Due to reduced stiffness, the rear part raises more under load. The reduced stiffness and resulting rotation further increase when the rear spar starts to buckle. The deflection at 2.5 g load factor of such a wing box design is depicted in FIGURE 22, whereas the resulting nonlinear load-displacement curve for the twisting is shown in FIGURE 23. This design also shows significant bending and is therefore suited for backward swept wings. Straight stringers in spanwise direction reduce bending more than twisting, but also reduce the nonlinearity, and are therefore not beneficial for the proposed load alleviation technique.

These results show that a wing box with a nonlinear behaviour that contributes to load alleviation can be designed. The real load-alleviation capabilities will be evaluated in the second and third project phases with detailed fluid structure interaction simulations.

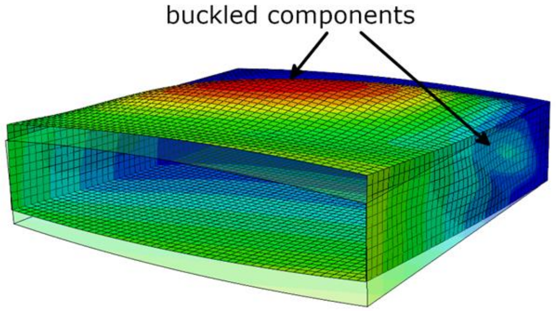


FIGURE 22. Deformation of a wing-box with nonlinear upper skin and rear spar behavior

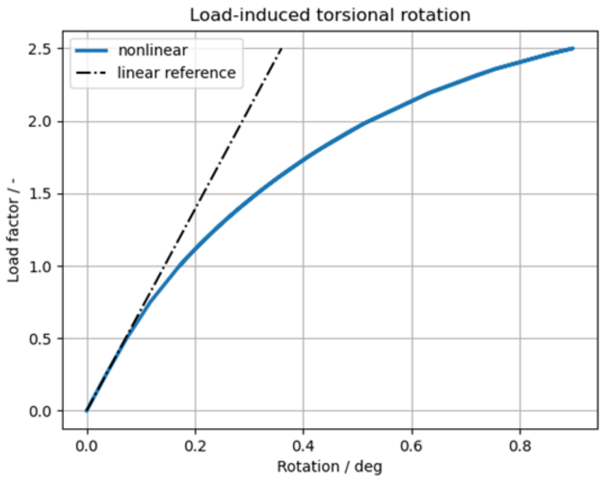


FIGURE 23. Load displacement curve for the rotation of the wing-box in FIGURE 22

4.2. Active Load Alleviation

The SE²A Cluster promotes fundamental research in active load control techniques that include the synthesis of control systems and the definition of sensor and actuation subsystems.

The approach integrates the components and technologies developed in other Cluster projects into a single model of fairly low order which comprises several hundred to a few thousand states. Depending on the various combinations of technologies selected (e.g. on the sensors and actuators), various models will be created. These models include the structure, the aerodynamics (including unsteady effects), and the actuation and sensor systems, as well as a simulation of the flight control computers with various functions, such as basic flight control laws, autopilot modes, and active load alleviation.

The design of active load alleviation functions for the different combinations of sensors and actuators is one of the main tasks of this research project. This task also involves many interactions with the groups designing the system components, starting from specifying the needs and requirements for the load alleviation functions, then developing low-order models of the system components for integration in the overall model, and finally assessing the control technologies. The assessment of the full system, including load alleviation functions, also provides valuable insight as to whether the initial requirements were correct, or whether they should be adjusted. For instance, the tuning of the load alleviation functions for best overall performance could favour significantly lower actuation speeds as initially specified. This would allow for relaxing the initial specification, and hence, avoid unnecessarily heavy subsystems.

The design of the load alleviation functions is therefore a task that must be repeatedly performed, as a range of combinations of sensors and actuators will be considered, because several design loops may be required for each combination, and because the overall aircraft design itself, through evolution of the assumed technologies, will also evolve over time. As the mid-range reference aircraft is the initial focus of load alleviation, the research project on active load control systems plays an important role in the overall design of this reference configuration of the SE²A Cluster.

The techniques and methodologies used for the design of the active load alleviation functions represent a major part of the research work. This Cluster research comprises two main approaches in this respect: an adaptive control approach and a robust control approach.

The behaviour of the flexible aircraft depends on the precise mass distribution of the payload, the amount of fuel in the wings, and even on slight differences between individual aircraft, among many other parameters. The robust control approach considers only parameters that can be reliably known, measured, or estimated as scheduling variables. These typically include a small set of characteristics of the actual operating point such as Mach number, dynamic pressure, and mass. All other effects are uncertainties against which the load alleviation functions must be robust. Consequently, it is expected that the robust control approach, compared to the adaptive approach, will provide controllers that sacrifice some performance in favour of robustness and easier certification. The difference in load alleviation performance between these two approaches will hence be investigated: depending on how large this difference is, the additional complexity of the adaptive approach (especially for certification) might be justified or not. Prior work on both approaches can be found in Refs. [29], [30] and references therein.

The Cluster research also addresses questions related to innovative sensor configurations. For instance, by fusing measurements from sensors distributed throughout the airframe, the current state of the airplane, including its flexible modes, can be better estimated. Another promising sensor technology is the use of a Doppler lidar sensor to detect/measure the gust a short distance ahead of the aircraft (typically 50-150 m). As demonstrated in previous investigations (see e.g. [31]), a short anticipation time of about 0.2-0.3 s already permits significant improvement of the gust load alleviation performance by e.g. enabling the use of small pitch manoeuvres to partly compensate the gust-induced angle of attack variations. The definition of precise lidar sensor requirements is expected to be a challenging task. This investigation will likely be performed in a similar manner as the work presented in [32] for the detection and alleviation of wake vortices.

Finally, the research on active load control systems also includes sound uncertainty quantification (UQ) investigations aimed at assessing the uncertainty levels of the final results, as well as permitting the efficient characterization of complex relationships between e.g. some of the lidar sensor parameters and the precision of the lidar-based wind estimation, or even the global load alleviation performance.

4.3. Flow Physics of Load Reduction

New technologies of fluidic or micro-mechanical flow actuators have the potential to provide fast, efficient, and adjustable lift redistribution, as an enabler for alleviation of gust- and manoeuvre-induced wing loads. The SE²A Cluster therefore aims to identify and characterize potential candidate actuators for future load alleviation systems using flow simulations and wind tunnel tests. Based on an extensive literature review, a range of flow actuation schemes were compared in a preliminary RANS simulation study [33] to generate a comprehensive database for comparison of dynamic lift reduction concepts on a 2D airfoil representative of a modern transport aircraft. These concepts are sketched in FIGURE 24. Apart from a classical trailing edge flap, micro-tabs, bumps, wall-normal jets, a jet flap, and a Coanda-type trailing edge jet were investigated over a range of operating conditions from sub-scale wind tunnel conditions up to a full-scale aircraft at transonic cruise conditions.

FIGURE 25 depicts a cross-comparison of the performance of different load reduction schemes to compensate a lift increase of $\Delta C_L = 0.358$. This value is determined by simulating a 400 ft vertical 1-cosine gust encountered at cruise flight conditions for M = 0.78. The graph features corresponding changes in sectional drag ΔC_D and pitching moment coefficient ΔC_{My} that the actuators produce while countering the gust-induced lift, as well as the required flap deflection δ, actuator height h_a or momentum coefficient C_μ, for the respective load reduction scheme. The results show that the fluidic actuation methods, especially Coanda-type trailing edge blowng and wall-normal jet actuators, exhibit performance comparable to conventional trailing edge flap, without complex mechanical designs. Due to their comparably low mass flow requirements in terms of C_μ and fast reaction time (as observed with unsteady RANS simulations and a wind tunnel test [34]), the Coanda and wall-normal blowing actuators were selected for further investigation in the following project phases.

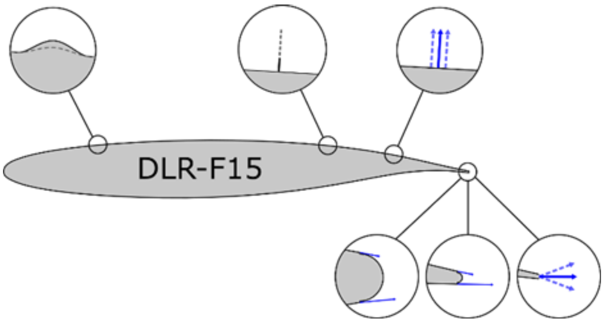


FIGURE 24. Overview of candidate flow acuation schemes, after [33]

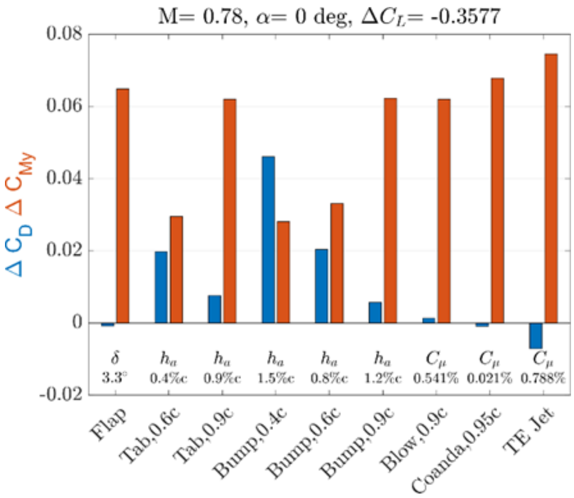


FIGURE 25. Drag and pitching moment changes for different methods at same ΔC_L, after [33]

The selected fluidic actuators are presently optimized for high load control authority (ΔC_L), minimal side effects (ΔC_D, ΔC_{My}), and optimal baseline airfoil performance without blowing. This research employs a more detailed CFD examination of actuator interactions for a range of different gusts, temporal actuator behaviour in terms of step-response, and pulsed blowing for mass flow reduction. Actuator performance on swept wing sections will also be investigated, as well as applications on a 3D wing at representative flight conditions.

A range of wind tunnel investigations will be conducted for validation of the numerical results and characterization of underlying flow physics like jet-freestream interactions, flow separation effects, and unsteady actuator behaviour. Initial demonstrators have already been employed to test early versions of wall-normal and Coanda blowing on 2D airfoils. These will be followed by comprehensive tests on 2D and 3D wings in subsonic wind tunnels. Based on the combined numerical and experimental dataset, a reduced order model will be derived that considers steady and time-dependent effects of fluidic actuators on integral wing loads. This model will be used for the development of the full gust and manoeuver load alleviation control system, as explained in Section 4.2, and the data will serve the needs of preliminary reference aircraft design within the SE²A Cluster of Excellence.

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