CEAS Aeronaut J (2014) 5:239–251
DOI 10.1007/s13272-014-0103-6

ORIGINAL PAPER

SFB 880: fundamentals of high lift for future commercial aircraft

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Received: 17 December 2013 / Revised: 25 February 2014 / Accepted: 26 February 2014 / Published online: 19 March 2014

Abstract The recently founded Collaborative Research Centre SFB 880 of the Technische Universität Braunschweig, “Fundamentals of High-Lift for Future Commercial Aircraft”, develops new knowledge in aircraft noise, advanced approaches towards active high lift, and in the dynamics of flight with active high lift during short takeoff and landing operations. The research centre has therefore devised a range of research projects that aim at integrated aeroacoustic and aerodynamic design capabilities for drastic noise reductions and the generation of active high lift with an extremely high efficiency of the used onboard power. Flight dynamics of commercial aircraft with increased lift capabilities for takeoff and landing by means of active control and including the effects of aeroelasticity and engine failure modes are also investigated. The research centre has developed a joint strategy for technology assessment using high-quality conceptual design data of a reference aircraft that represents the state of the art in CO_2 reductions, low noise, and short takeoff and landing for point-to-point air connections within Europe. The paper describes the overall strategy of the coordinated research work and gives examples of recent results.

Keywords Acoustics · High-lift aerodynamics · Active high lift · Flight dynamics

1 Introduction

The mobility needs of industrialized countries have resulted in continuous growth rates of air transportation that bring our aviation system close to its capacity limits and add significantly to CO_2 emissions, perceived noise and land usage. These issues are strongly reflected in the recently published “Vision Flightpath 2050—Strategic Research and Innovation Agenda” [1]. According to these long-term industrial objectives of the major European aviation stakeholders, new technological approaches can only be successful if they address simultaneously environment protection, drastic energy savings, improved flight safety, and reductions in door-to-door travel times as the enabler for continuous growth in European aircraft manufacture and aviation operations.

A more detailed view on technologies for future commercial transport reveals the large role that the high lift system of the aircraft has on the aircraft operating cost, the usage of natural resources and aircraft emissions, as well as flight safety. The multi-element high lift systems used on current aircraft have a multitude of effects on aircraft performance. While their manufacture and maintenance directly affect aircraft operation cost, the lift generation capabilities of these systems allow overall wing design for optimum cruise efficiency and enable aircraft service to a prescribed class of airport infrastructures. However, the current high lift systems exhibit very limited flexibility to extend their performance once wing sizing and the integration of the leading edge and trailing edge devices for high lift have taken place. This leaves very little room to

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This paper is based on a presentation at the German Aerospace Congress, September 10–12, 2013, Stuttgart, Germany.

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adapt takeoff and landing performance to a growing aircraft weight or to configuration changes such as the installation of an engine with a larger diameter, during the lifespan of an existing aircraft family. Further, the need for conventional leading edge devices is a severe difficulty in the introduction of laminar flow on the wing, as envisaged for significant cruise drag reductions. Finally, conventional slats and high lift flaps represent a major source of airframe noise on current aircraft. Note that the performance of the high lift system directly affects the air speed at takeoff and approach conditions and hence all sources of airframe noise, as these sources scale with the 5th to 6th power of flow speed.

The recently founded Collaborative Research Centre SFB 880 located in Braunschweig, Germany, combines the competencies of Technische Universität Braunschweig, Universität Hannover and the German Aerospace Center, DLR, for fundamental and applied research in high lift of future commercial aircraft. The overall working hypothesis of the Research Centre SFB 880 states that active high lift systems with high levels of aerodynamic efficiency will add significant value to future civil transport. These active systems will provide much higher flexibility in the generation of high lift for aircraft families and aircraft upgrades, allow significant reductions of airframe noise emissions, and provide a viable path towards short take off and landing (STOL) capabilities. The latter route of research aims at a new transport aircraft segment for operation on airports with shorter runway length presently not considered in commercial air transport [2]. The new class of aircraft would be equipped with advanced technologies for drastic airframe and engine noise reduction. It would represent a community-friendly aircraft (labelled "Bürgernahes Flugzeug" in German language) designed for operations much closer to the home of its passengers than possible today.

The Research Centre SFB 880 has therefore devised a range of technology projects that aim at drastic noise reductions and at the generation of efficient and flexible high lift. The research also addresses flight dynamics of aircraft at takeoff and landing.

Research Area A "Fundamentals of Aeroacoustics" develops an integrated aeroacoustic and aerodynamic design methodology. The research area aims at reductions of airframe noise sources by using aircraft surfaces capable of reducing the generation of aerodynamic noise combined with new configuration approaches. Newly developed computational capabilities will be applied to explore the reduction of airframe noise sources by surface materials with tailored porosities. Similar significant reductions of the aircraft noise related to propulsion appear possible by using close integration of the propulsor with the wing. This calls for understanding the physics related to propulsive efficiency, propeller noise generation and shielding. Close integration of propeller and wing flow leads to the risk of increased acoustically induced structural vibrations and corresponding larger cabin noise levels. Modeling the related transmission paths is therefore addressed by the research as well.

Flexibility in the performance of high lift systems beyond the current multi-element mechanical solutions can be only obtained by employing the high flow turning offered by active flow control. A powerful control means is obtained by tangential blowing over carefully designed flow turning surfaces, hence making use of the Coanda effect. Research Area B "Efficient High Lift" focuses on active high lift flaps with Coanda-type blowing with the aim of obtaining drastic reductions of the needed blowing power. The research area brings together design advances in aerodynamics, new flow sensors and flow actuators, new adaptive wing structures and advanced compressor technology.

Research Area C "Flight Dynamics" aims at extending the rather limited knowledge base on the flight dynamics of commercial aircraft that use means of active control for increased lift capability at low-speed flight. Flow simulation of aircraft configurations are used to characterize transient behaviors of flow control and to provide an aerodynamic database. The database is used in flight simulations which also take the wing aeroelastic degrees of freedom into account. These flight simulations identify suited control approaches and provide control requirements to cope with atmospheric disturbances and engine failure modes.

Technology assessment plays an integrated part in coordinating the Research Centre SFB 880. For this purpose a reference aircraft configuration is developed as a fully iterated preliminary aircraft design. The reference configuration represents the state of the art in CO_2 reductions, low noise, and STOL for point-to-point air connections within Europe. The design is used to assess the individual impact that the various research projects on aeroacoustics, aerodynamics, advanced wing materials and structures, and aircraft flight mechanics have. As the research work in the three Research Areas, A, B, C, need a reference aircraft configuration for guiding method development, simulations and analysis, the operation scenario and aircraft design are presented in the following section.

2 Reference configuration and technology assessment

The Collaborative Research Centre SFB 880 investigates a broad range of aircraft technologies where the importance and benefits of the individual approaches can only be assessed by taking the complex interactions in transport aircraft design into account. The research centre therefore operates a central project on preliminary aircraft design with the objective of identifying and quantifying those interactions. The aircraft design project has the task of

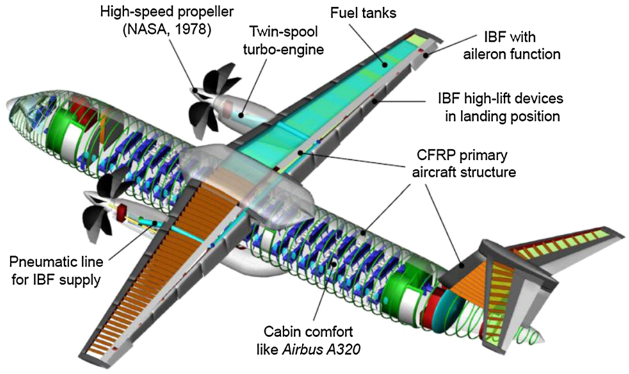

Fig. 1 SFB 880 reference configuration

supplying aircraft requirements and design data to the cooperating research projects, which enables them to perform useful and consistent simulations, experiments and analysis of the results. The design project, on the other hand, uses technology data obtained from the various research projects, such as geometrical descriptions, aerodynamic and weight data to compute the technology impact on STOL performance, fuel burn, noise impact, direct operating cost (DOC), and other relevant quantities. For this purpose a well-established preliminary aircraft design simulation method is employed and refined as necessary.

As part of the research strategy of the SFB 880, at least two virtual aircraft configurations are needed to assess the technological progress of the centre:

- The long-term vision of a new segment of cruise-efficient low-noise transport aircraft with STOL capabilities is projected into the SFB 880 Reference Configuration. The reference configuration for around 100 passengers with a range of 2,000 km features advanced turboprop propulsion along with internally blown high lift flaps (IBF), displayed in Fig. 1.
  The design employs present state-of-the-art technologies available for operation in the year 2025. The present concept of the reference configuration is viewed as a technologically sound starting point for fundamental research work.
- Broad mid-term application areas of the collaborative research are addressed by defining a suitable SFB 880 Transfer Configuration. The transfer configuration is used to assess technology values in conventional transport aircraft. This configuration is modeled as a modern fan engine aircraft of the Airbus 320 class.

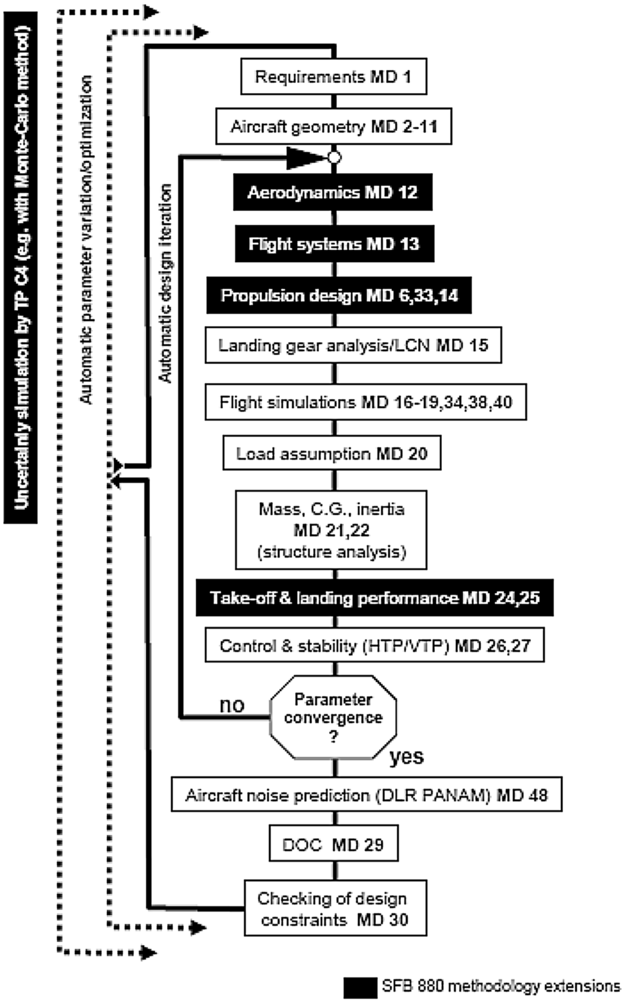

Fig. 2 Schematic of preliminary aircraft design with PrADO and design modules (MD)

2.1 Preliminary aircraft design method

For overall design analysis and optimization of transport aircraft configurations, the Preliminary Aircraft Design and Optimization tool PrADO [3] of Technische Universität Braunschweig is used. PrADO has a modular structure and simulates the iterative overall design process for any desired aircraft concept, according to Fig. 2. The core consists of a set of design modules (MD), each of which fulfills a subtask in the design sequence. To provide a wide range of applications, the modules largely use physics-based models that are not bounded by statistics or specific aircraft configurations. These modules communicate with each other through a data management system, which offers flexibility to adapt PrADO to new design problems. The design core is enclosed by additional loops which allow an automatic variation or optimization of design variables describing the aircraft configuration and the propulsion system.

The analysis of an aircraft with active high lift system requires several methodology extensions. To calculate the aerodynamic characteristics of the STOL aircraft, a multiple lifting line method with modeling of IBF using 2D RANS airfoil data is used [4]. During the present, initial stage of the project, propeller slipstream effects are neglected for the calculation of the aerodynamic characteristics. The system aspects of the active flaps are included in PrADO by an aircraft system model from Koeppen [5] which has been supplemented by a pneumatic line for compressed air supply [4]. The systems design module calculates the masses and center of gravity positions of the pipes, valves, and distribution elements including the necessary flow properties (flow mass rate, temperature and total pressure) at the engine bleed port. These data are used for engine sizing and the calculation of the engine off-design behavior with or without operation of the internally blown flap system. For engine design and analysis, a thermodynamic engine model based on Mattingly [6] is available. Further necessary data for engine design, including the propeller size and mass, gear box mass, and propeller efficiency factor, are taken from detailed NASA studies [7]. Note that the documented propeller of Reference [7] has its highest efficiency factors in the Mach regime between 0.7 and 0.8 and is well suited for a 100 seater.

2.2 SFB 880 reference configuration

The SFB 880 Reference Configuration shown in Fig. 1 has a high wing arrangement with turboprop engines mounted in front of the wing. The efficient propulsion system in combination with a carbon-fiber reinforced plastics (CFRP) primary structure leads to a reduced takeoff and landing weight which helps to achieve the given STOL requirements. The pivotal element is however the IBF system that enables large flow turning and hence 50 % larger lift coefficients compared to conventional multi-element solutions. The extraction of compressed air takes place behind the low-pressure compressor (LPC) of the engine to allow for a safe IBF operation in all low-speed flight phases. The necessary LPC pressure ratio is 2.7 including one-engine-inoperative (OEI) conditions.

The IBF system is designed for maximum aircraft lift coefficients of 3.5 during takeoff and approach and for values of 4.5 during the final phase of the landing. This determines the necessary mass flow rates of 14.4 kg/s during takeoff with moderate flap angles of 43° and of 17.2 kg/s during the landing with flap angles of around 65°. Each of the two engines is designed to deliver the full IBF flow rates for the whole high lift system as necessary in an OEI situation.

Table 1 Selected design data of SFB 880 reference configuration

	Conventional aircraft	SFB 880 reference configuration
Max payload	12,000 kg/100 PAX	12,000 kg/100 PAX
Range (km)	2,000	2,000
High lift system	Slat and Fowler	IBF
Propulsion	Fan engine	Turboprop engine
MTOW (kg)	42,664	41,922
Cruise Mach number	0.78	0.74
Wing loading (kg/m^2)	533	456
Thrust/weight	0.41	0.53
L/D (cruise)	14.63	14.55
T/O field length (m)	1,456	800
Landing field (m)	1,803	782
SFC at cruise (kg/N h)	0.0642	0.0478
DOC ($/seat km)	0.081	0.076

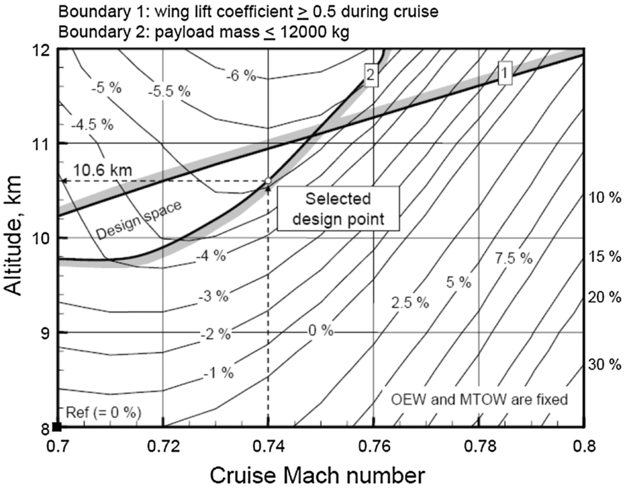

Fig. 3 Effect of Mach number and altitude on DOC

The wing has a simple tapered planform with a low leading edge sweep of 10° to reduce wing weight and manufacturing cost. In addition, the reduced sweep improves the usable maximum lift coefficient, which is approximately 11 % higher compared to a wing with 28° sweep. The empennage is arranged as a classical T-tail to move the horizontal stabilizer out of the propeller slipstream.

Top-level aircraft design requirements are shown in Table 1. The optimal cruise condition for the reference configuration is found at Mach 0.74 and 10.6 km altitude with the parameter variation mode of PrADO, as displayed in Fig. 3. The objective is here to minimize DOC without exceeding the cruise lift coefficient of 0.5. The optimal Mach number depends on the propeller characteristics, while the cruise altitude results from the constraint on lift coefficient at this operating point.

The wing loading and planform of the SFB 880 Reference Configuration were also optimized. The starting point was a wing layout based on the Fairchild-Dornier 728/928 project. This aircraft was redesigned with PrADO

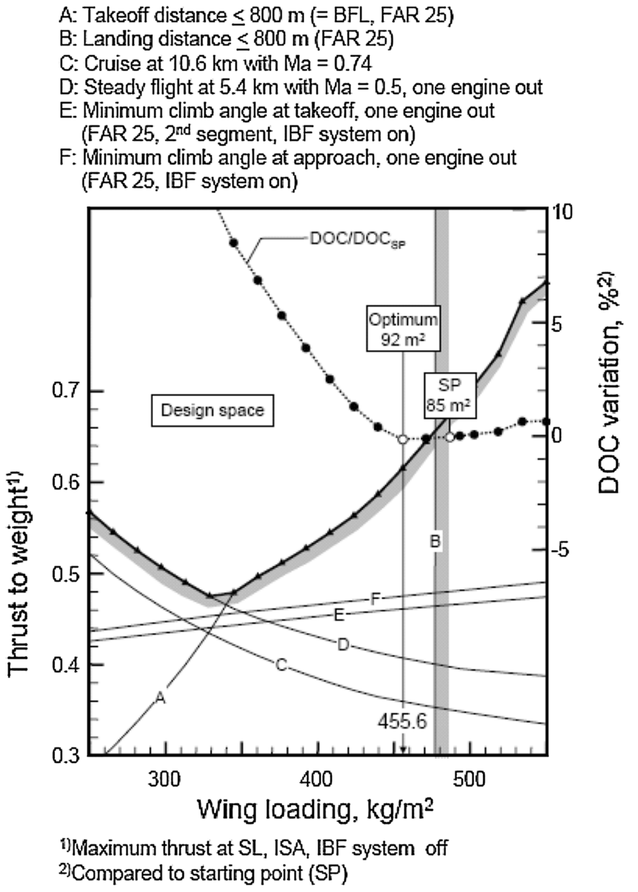

Fig. 4 Variation of thrust-to-weight ratio and DOC over wing loading

assuming a CFRP primary structure and a 100-seat 2,000 km mission with conventional high lift devices (slat and Fowler flap). This design is denoted as conventional aircraft in the following.

Figure 4 shows the wing loading as a function of the thrust-to-weight ratio for the SFB 880 design requirements. As the landing distance requirement of 800 m determines the wing area, the IBF approach shows its clear advantage. With active high lift, a wing loading of about 456 kg/m^2 is achieved which makes the STOL aircraft competitive to conventional aircraft in cruise. The corresponding lift-to-drag ratio is almost identical to the conventional aircraft; see Table 1. On the other hand, the aircraft thrust is driven by the takeoff requirement of 800 m FAR 25 runway length. The STOL aircraft needs approximately 28 % more maximum takeoff thrust which includes the power for the air extraction from the engine.

The optimization of other wing planform parameters, as seen in Fig. 5 for wing aspect ratio and wing taper, is dominated by their effects on the wing structural loads leading to a lighter wing and therefore a cheaper aircraft.

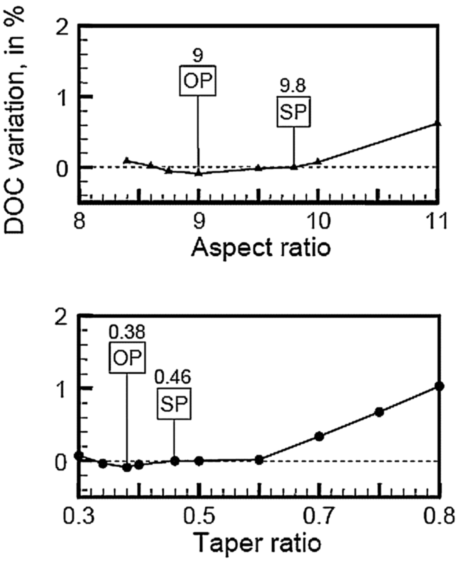

Fig. 5 Optimization of wing planform parameters (*SP* starting point, *OP* selection for SFB 880 reference configuration)

Note that due to the rather low range of the selected aircraft class and despite assuming a 50 % higher than present oil price for the year 2025, the fuel costs are only 23 % of the DOC.

Finally, Table 1 compares the important aircraft performance parameters of the SFB 880 Reference Configuration to the conventional aircraft with fan engines and passive high lift devices. In spite of a 15 % higher wing area and 28 % more (installed) static thrust, the reference configuration with the IBF system shows about 6 % less DOC, while the takeoff and landing distances are about 50 % smaller. This is due to the combined effects of active flow control and turboprop engine characteristics.

2.3 Design uncertainty assessment

The overall objective of the reference configuration is to function as a virtual application reference based on sound design and technology data. Further, any incremental design result for the reference configuration should represent the progress in technology achieved by SFB 880 research work in a smooth and reliable way. This calls for a robust aircraft configuration.

The design of the SFB 880 Reference Configuration is based on design data with significant uncertainty. The assumed maximum lift coefficient of overall aircraft with the active high lift system, for example, depends on the uncertainty with respect to the flow simulation method and this affects landing field length, while the assumed CFRP material data come with an uncertainty that affects aircraft empty weight.

Table 2 Selected uncertainty bands for Monte-Carlo design simulation

Uncertain parameter	Uncertainty band (%)
Aerodynamics	
Lift coefficient	−5 to 5
Induced drag	−5 to 5
Zero lift drag	−5 to 5
Structure	
Wing mass	−5 to 5
Fuselage mass	−5 to 5
Propulsion	
Compressor efficiency	−3 to 3
High-pressure turbine efficiency	−3 to 3
Low-pressure turbine efficiency	−3 to 3
Fuel burn factor	−3 to 0
Total pressure ratio	−3 to 3
Maximum turbine entry temperature	−3 to 3
Engine mass	−5 to 5
Internal blowing system	
Mass	−50 to 100
Needed mass flux	−5 to 5

As the reference configuration represents an aircraft that is quite different from commercial aircraft in the present service there is no statistical data that could be used for a conclusive verification of the computed design. This situation motivates an analysis of the effects of data uncertainties on the design of this novel aircraft configuration. The uncertainty analysis is performed to identify design parameters where the associated uncertainties have large effects on aircraft size, performance and cost and to identify the critical growth of aircraft components.

The uncertainty analysis of the SFB 880 Reference Configuration is here based on Monte-Carlo simulations with the design method PrADO. For this purpose, uncertainty bands were defined for a selected number of design input data as shown in Table 2. The sizes of these uncertainty bands were estimated based on expert knowledge. The stochastic values within these bands were always equally distributed. This procedure resulted in totally 12,191 full design runs of PrADO.

Each of these individual design runs required several hours of computing time on a state-of-the-art processor. Therefore the computations were parallelized on 24 processors. The Monte-Carlo simulations were then evaluated to yield probability distributions on the resulting design. The effects of parameter uncertainties on the design are evaluated by monitoring technical aircraft parameters, i.e., engine shaft power, aircraft empty weight, cruise *L*/*D*, fuel mass, FAR25 landing field length and DOC, while the takeoff field length of 800 m was kept constant as a constraint. The individual designs represent the sensitivities of the design to the uncertainties of design parameters as displayed in Fig. 6, for the example of the landing field length. It turns out that the landing field length depends somewhat on the fuselage mass, but very little on changes of the required IBF mass flux. There is a clear effect of the lift coefficient on field length, as expected, but the sensitivity is moderate. In general, the SFB 880 Reference Configuration appears as a robust aircraft design. Adverse variations of lift, weight and propulsive efficiency result in engine growth needed to fulfill the 800 m takeoff field constraint. This growth, however, is moderate as seen in Fig. 7. The uncertainty analysis shows that 90 % of all parameter variations can be covered with an increase of engine shaft power by 7 %. Note that the maximum increase of DOC for these samples was only 2.5 %. The present results indicate that the design objectives of the SFB 880 Reference Configurations are met.

3 SFB 880 research areas

The collaborative research of the SFB 880 aims at drastic reductions of aircraft noise, at a new level of flexibility in the achievable lift coefficient for high lift systems, and at a fundamental knowledge base on the dynamics of commercial aircraft with STOL capabilities. These basic research directions are strongly interrelated. For example, the aircraft flow noise depends largely on configuration and performance of the high lift system, whereas the aerodynamic approach to achieve high lift coefficients has to comply with certain constraints set by flight mechanical analysis of the overall aircraft. The logic of the three research areas of the Research Centre SFB 880 and their current status will be briefly described in the following. The reader is referred to References [8–10], for more details on the individual research areas.

3.1 Fundamentals of aeroacoustics

Active high lift systems are employed to enable much improved short takeoff and landing capabilities for future commercial aircraft, while reductions of airframe noise due to reduced flight speed appear generally possible. However, the new high lift approaches also bear the risk of new noise sources. These are noise from the interaction of locally high-speed turbulent flows with configuration edges and noise from the interaction of the propulsor with the airframe. The research approach of the research centre for drastic noise reductions employs therefore the combination of using the potentials of noise source reducing and noise absorbing aircraft surfaces and also configurational measures to exploit the acoustic synergies offered by integration of propulsion and airframe.

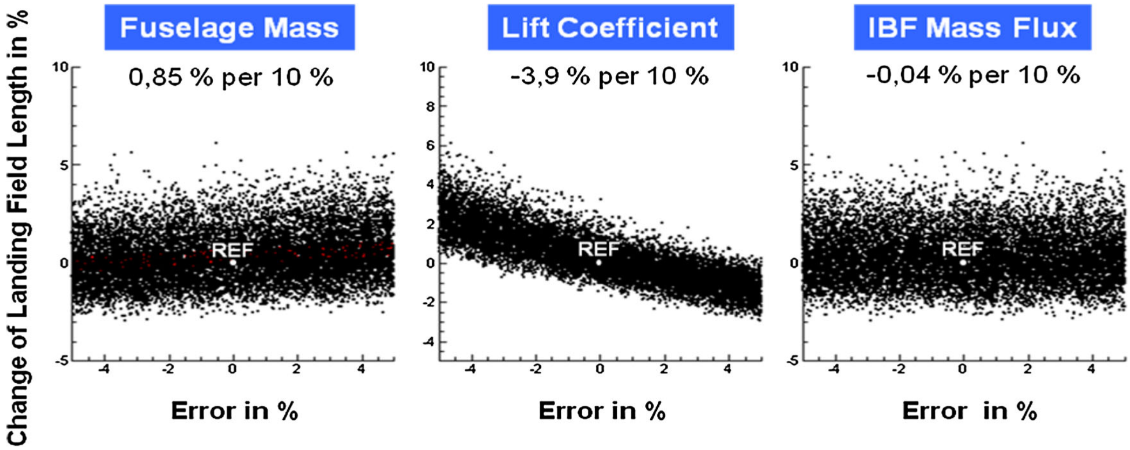

Fig. 6 Effects of fuselage mass, lift and blowing mass flux errors on landing field length

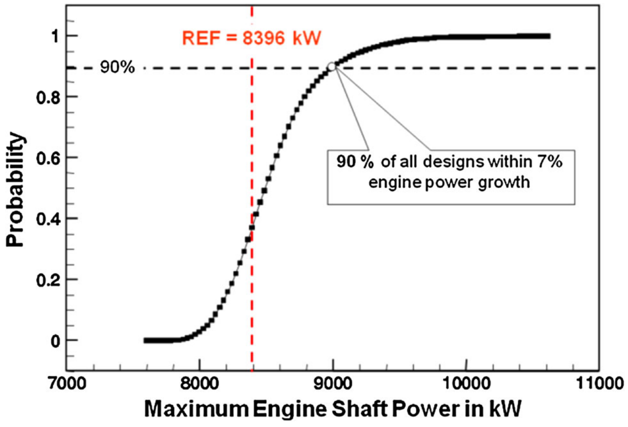

Fig. 7 Engine growth over all design samples

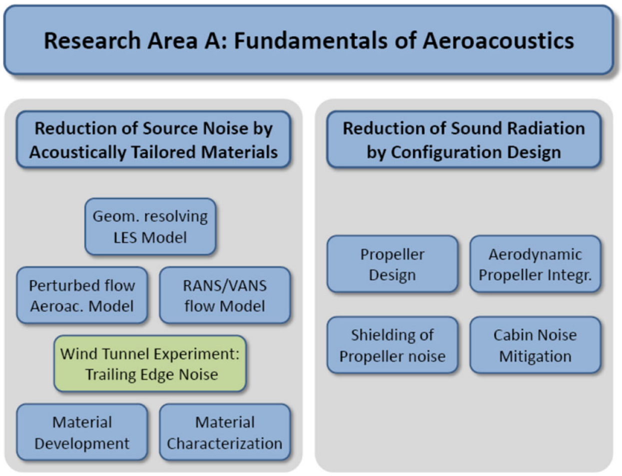

Fig. 8 Schematics of research in aeroacoustics

The schematic of fundamental research in aeroacoustics is displayed in Fig. 8. The use of tailored materials for airframe noise reduction needs an integrated set of simulation models for predicting the acoustic and aerodynamic effects of porous surface materials at high Reynolds numbers. The corresponding CAA and CFD models use volume averaging of the porous surface and advanced representations of turbulence [11]. They are validated by dedicated geometry resolving large eddy simulations [12] and aeroacoustic wind tunnel experiments.

The computational methods and experiments are used to provide fundamental knowledge on the physical mechanisms of noise source attenuation and noise absorption by porous surfaces. Computational results on the noise generation by vortex advection over an airfoil trailing edge are displayed in Fig. 9. It could be demonstrated by careful setup of computations that noise mitigation offered by micro slits at the trailing edge is dominated by modification

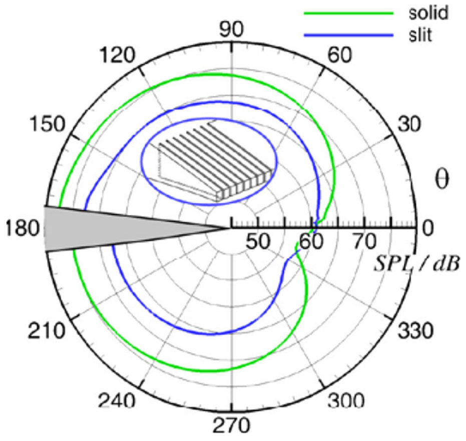

Fig. 9 Computed measure of trailing edge noise emissions for solid and slit edges

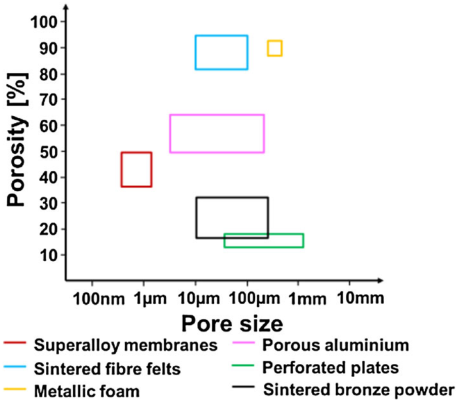

Fig. 10 Overview of the investigated surface materials

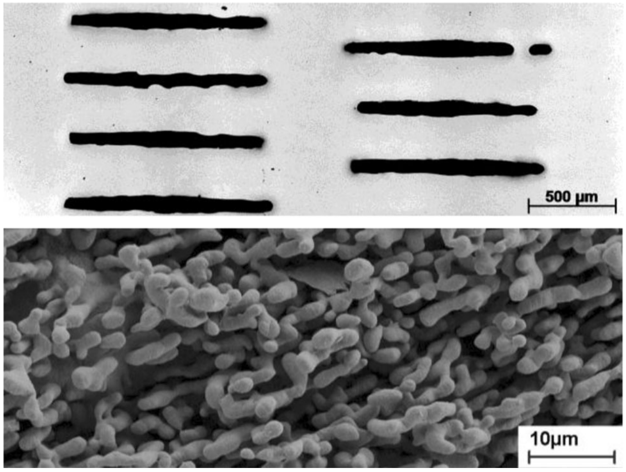

Fig. 11 Surface materials with nonisotropic permeability

of the source near the field through a perfusion flow between the two trailing edge sides. The effects of slits on turbulence can be neglected [13].

The research area extends these results to a range of existing and new surface materials as displayed in Fig. 10. These materials are superalloy membranes, sintered fiber felts, sintered powders, metallic foams, and perforated plates, covering a pore size range from 500 nm to 1 mm, and a porosity range from 15 to 95 %. The materials are thoroughly characterized with respect to their geometrical, mechanical, acoustics and flow-through properties. Special attention is on materials with non-isotropic porosities, as flow over a surface with isotropic porosity is a known source of noise by itself. Figure 11 presents the microscopic views on two non-isotropic plate materials used. Commercially available laser perforated plates (upper part) exhibit a slit width of around 100 μm. The research centre also develops new Ni-based superalloy membranes that exhibit smoothly distributed and directed pores in the 1–10 μm range [14, 15], as displayed in the lower part of Fig. 11.

The SFB 880 Reference Configuration employs propeller propulsion which is well suited for achieving high takeoff thrust values along with low fuel burn in cruise. Acoustically, jet noise is practically eliminated by design. However, propeller sound radiation to the ground and the interactions of blade wakes with the wing call for mitigation. This is addressed by combined aerodynamic/acoustic design studies for propeller/airframe integration, maximizing noise shielding to the ground. Over-the-wing propeller arrangements have been therefore computationally analyzed. The aerodynamic results at takeoff conditions display a positive interference effect on induced drag for over-the-wing propellers compared to classical tractors that would eventually improve aircraft climb angles by 2–3 %. Acoustic shielding analysis with the DLR fast multipole method, on the other hand, shows a potential of 6 dB propeller noise reduction for over-the-wing configurations [16]. Unfortunately, the propulsive efficiency of over-the-wing propellers at cruise conditions is significantly less than with tractors. This limits possible propeller positions as well as the cruise Mach number. It turns out that over-the-wing propellers cannot be used efficiently at Mach numbers beyond 0.6 [17].

To describe a reduction of a potentially increased vibration excitation of the aircraft structure by partial lining of shielding surfaces with porous material, respective modeling and simulation of structure-borne sound are developed [18, 19].

3.2 Efficient high lift

A drastic increase of flexibility in high lift performance beyond the capabilities of classical mechanical multielement solutions can only be achieved by employing active flow control. Employing active flow control on commercial transport aircraft, however, bears the risk that the systems used for power supply to the active high lift devices and the mechanical power consumption itself introduce high costs on the overall aircraft level and render active high lift uncompetitive.

Research Area B therefore focuses on technologies that reduce the mechanical power needed for active lift and on the means for drastic reductions of weight and cost of the associated systems. Figure 12 displays the schematic of the research efforts. The choice of the aerodynamic approach for active flow control is crucial. It is well known that powerful control authority for flow turning is obtained by internal blowing over carefully designed blowing surfaces, hence making use of the Coanda effect [20].

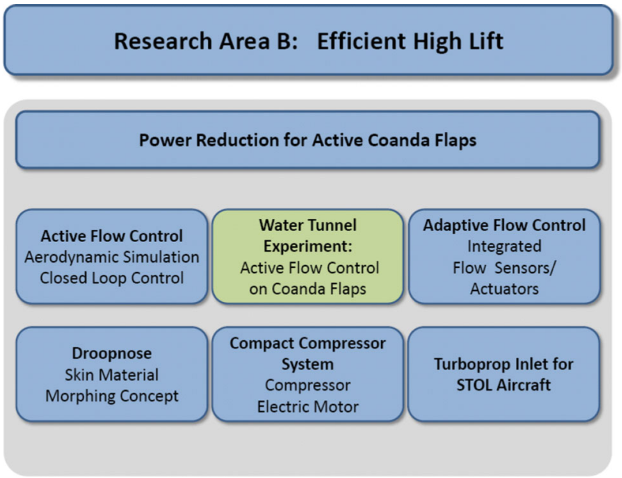

Fig. 12 Schematic of research in efficient active high-lift

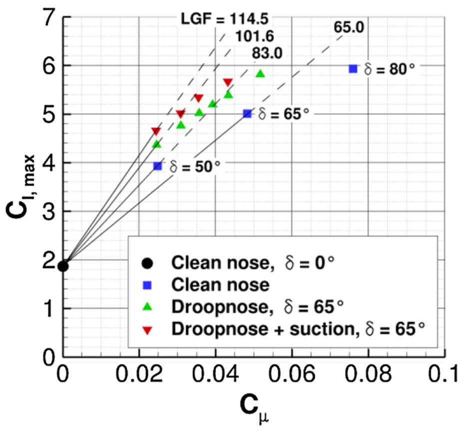

Fig. 13 Lift gains versus blowing momentum obtained by droopnose and combined suction and blowing approaches (δ—deflection angle of flap)

A suitable measure of active-lift efficiency is the lift gain factor, LGF, that relates the lift increase to the momentum coefficient of blowing, c_μ:

$$\mathrm{LGF} = (c_{L_{\max}} - c_{L_{\max,\mathrm{reference}}})/c_\mu.$$

While preliminary research on the design of a suitable wall jet thickness and the Coanda surface shape [21] had achieved LGFs of around 83 for $c_L = 4$ and 65 for $c_L = 5$ (see blue data in Fig. 13), the current interdisciplinary work of the SFB 880 explores four routes towards further improved exploitation of the blowing momentum:

- Reduce boundary layer losses upstream of the Coanda flap by a morphing droopnose.
- Use the benefits of boundary layer suction offered by installing distributed compressors along the wing span.

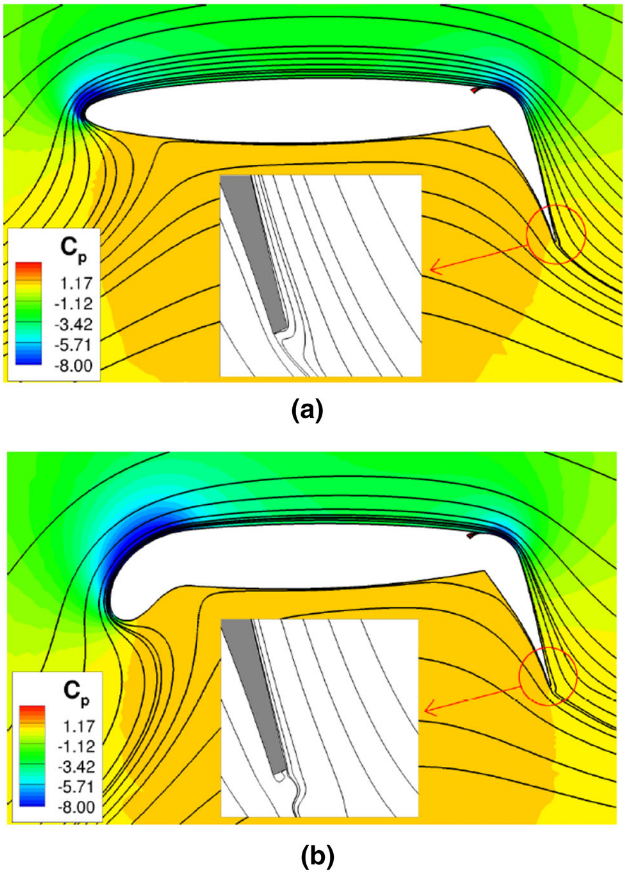

Fig. 14 Flow around active high-lift airfoil with morphing droop nose at $c_\mu = 0.035$. **a** Clean nose, $\alpha_{\mathrm{stall}} = 3.0°$, $c_L = 4.456$ and **b** clean nose, $\alpha_{\mathrm{stall}} = 12.3°$, $c_L = 5.02$

- Improve blowing efficiency by pulsed blowing.
- Explore the benefits offered by closed loop control of wall-jet blowing.

The first concept has already resulted in largely reduced blowing powers shown in Fig. 13, as nose geometry deformations were used to alleviate the nose suction peak for reduced boundary layer losses [22]. The resulting airfoil shape is displayed in Fig. 14. The droopnose also brings about a significantly larger angle of attack at maximum lift. This effect is critically needed for aircraft flight during landing; see Sect. 3.3. The aerodynamic characteristics of the droopnose configuration will be verified using water tunnel tests in the near future.

Morphing droopnose geometries as shown in Fig. 14 can be only accomplished by new structural technologies that combine highly deformable skins with suited attachments and new solutions for internal deformation mechanisms. A hybrid skin structure consisting of compliant elastomer combined with discrete fiber-reinforced stiff laminate bundles was developed and modeled [23] where the global bending strain is mainly conducted by the

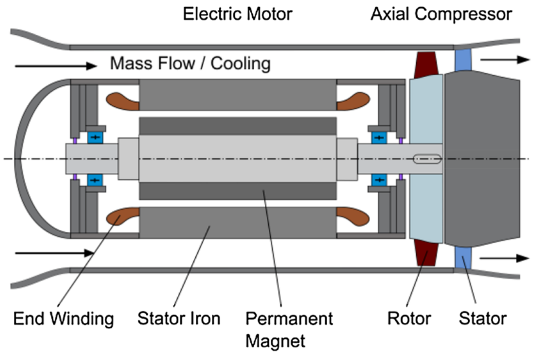

Fig. 15 Motor integration in compressor concept

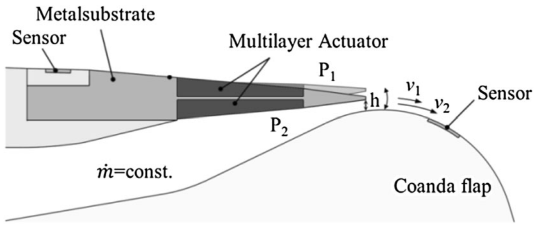

Fig. 16 Concept sketch of integrated flow actuator and sensors for pulsed blowing and closed-loop control

elastomer in the outer skin regions. Current manufactured configurations consisting of glass-fiber/epoxy and thermoplastic polyurethane show an outstanding ratio of spanwise to chordwise bending stiffness of around 15. A two-stage optimization framework for the droopnose with large deformations was also developed. The first step optimizes the flexible skin and saves its stiffness parameters for the second step, which performs the topology optimization of interior kinematics with nonlinear structural behaviors [24].

Using the benefits of boundary layer suction in combination with wall jet blowing relies on the concept that the pressurized air for blowing is generated by distributed compressors along the wing span. Figure 13 indicates that LGF improvements of around 15 % may be expected from this approach. Mapping the compressor requirements in a Cordier diagram reveals that single-stage axial compressors are best suited. The requirements for low-weight efficient compressors with the needed range of operation call for compressor optimization. A two-stage optimization process is currently being developed and tested. During the preliminary design stage a large number of design variables are determined using simplified physical models and empirical correlations [25], whereas detailed design optimization is used to define profile and blade shapes.

The challenge in the electric motor of the compressor lies in the high output power at high rotational speeds of up to 60,000 rpm. A synthesis of design constraints on rotor diameter, weight and efficiency has resulted in choosing a permanent magnet synchronous machine that is air-cooled using the air flow from the suction slot to the compressor [26], according to Fig. 15. The strong interactions found between compressor, electric motor and power electronics motivate a joint design with an integrated optimization framework in future.

Pulsed blowing and closed-loop flow control make fast actuation devices and flow sensors necessary. Piezo ceramic multilayer actuators are therefore embedded in a metal substrate to allow slot control in flow experiments, as sketched in Fig. 16. Specific design challenges result from the planned tests in a water tunnel. FEM analysis and load testing on a functional demonstrator indicate that the challenges from the high loads in water can be met. Also, suited coatings for waterproofing the actuators were developed. Flow sensing is performed with a combination of MEMS based pressure sensors to identify the unsteady flow turning and extremely thin hotfilms to measure the near-wall boundary layer flow. The actuation and sensing systems will be employed in future water tunnel tests for investigations of pulsed blowing and closed-loop control.

The requirements to provide pressurized air in active high lift aircraft represent a significant challenge to the design of the core engine and its inlet. Preliminary design of a two-spool axial compressor turboprop addressed two variants: (i) generation of pressurized air by bleed flow from the LPC and (ii) providing additional shaft power to an electric generator used to power distributed compressor systems along the wing span. These variants differ largely in turboprop engine size and the inlet mass flow. Detailed inlet designs and comparisons with reference inlets will identify the critical engine design trades involved here.

3.3 Flight dynamics

Low-speed flight of cruise efficient commercial aircraft with short takeoff and landing capabilities means flying at a much higher lift coefficient as commonly used in aircraft flight, and with the blowing rate as a new aircraft control parameter. This presents a number of research questions addressed by Research Area C. The elements of current research are seen in Fig. 17. The wing stalling behavior is addressed by high-fidelity simulations of the full reference configuration [27]. Initial results for Coanda flaps without leading edge device as displayed in Fig. 18 reveal stall at low angles of attack, $\alpha = 3°$, which would exclude a useful landing operation. Wings with large flow turning by active means generate a large negative pitching moment that is important for trim. Besides static effects the active lift system also contributes unknown behaviors of the dynamic

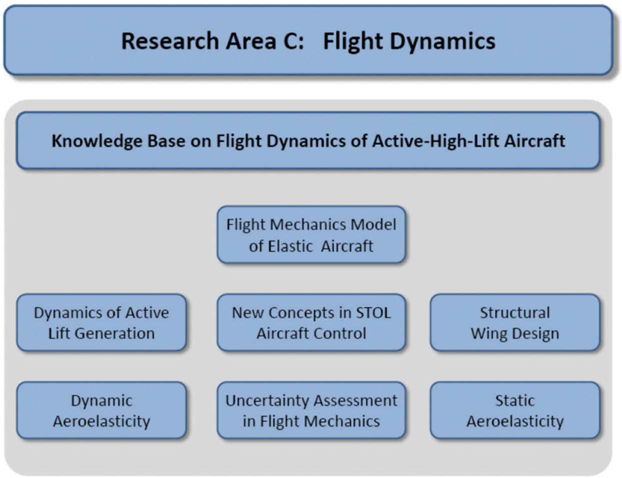

Fig. 17 Schematics of research in flight dynamics

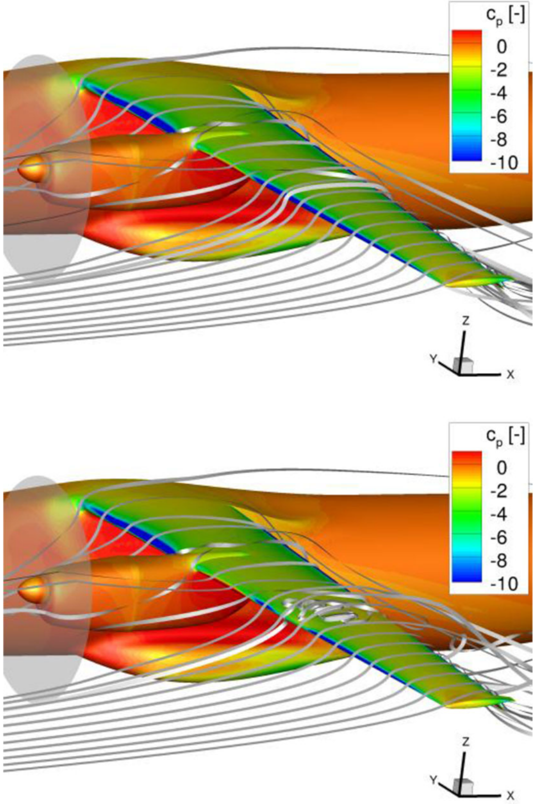

Fig. 18 RANS simulation of wing stall of complete reference configuration with Coanda flaps at $\delta = 65°$ and $c_\mu = 0.033$ on wing: $\alpha = 2°$ below stall (*upper part*) and $\alpha = 3°$ beyond stall (*lower part*)

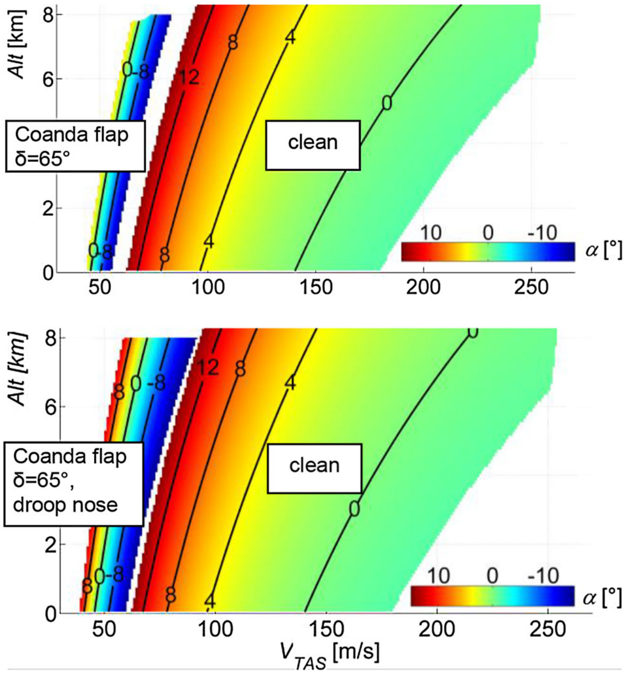

Fig. 19 Trimmed flight envelopes for reference configuration with and without high-lift setting: fixed nose (*upper part*) and morphing droopnose (*lower part*)

derivatives relevant for longitudinal and lateral aircraft motions. Moment coefficients and derivatives must be known for unsymmetrical engine failure cases, and they are obtained by a number of numerical flow computations. The aerodynamic data is used to define the flight mechanics model. This model is used for static and dynamic flight simulations which take into account the atmospheric gust flow environment close to airports.

The model has delivered the trim envelopes of the reference configuration shown in Fig. 19 [28]. While the configuration without leading edge device has a much too small incidence range of flight, the reference configuration with droopnose as of Fig. 14 exhibits a larger trim envelope that would allow usual landing approaches. Future flight simulations will address flight control behaviors at the low dynamical pressure of the reference configuration and the specific stability problem of flying far on the backside of the power curve.

There exists little published knowledge about the aeroelastic phenomena of wings with active high lift. These are elastic behaviors of the slots used for flow control, static torsion divergence, control reversals, and low speed flutter. Therefore work is performed to investigate elastic effects by employing structural and aerodynamic models of varying fidelity. These models are based on a fully stressed wing structure along with detailed packaging of the needed systems [29]. This model is used for deformation analysis of slots and the global wing [30]. Also reduced models for flutter analysis are derived by using modal analysis of the detailed model. The flutter analysis employs wing bending and torsion degrees of freedom [31]. An unsteady aerodynamic model that takes the nonlinear lifting behavior of Coanda flaps into account was defined using a data base of

Navier–Stokes simulations. First results indicate that low-speed bending flutter may exist because of vanishing aerodynamic damping observed close to maximum wing lift, and depending of the blowing momentum. The reduced aeroelastic flutter model is also integrated with the flight mechanical model, to study interactions of flight mechanics and aeroelasticity.

The flight simulations of the reference configuration with active high lift exhibit many uncertainties that have their origin in the computational approaches for aerodynamics and structures, in the reduction process for flutter computations, and further in assuming a model of the atmosphere. As the reference configuration is rather far away from the range of existing knowledge it is felt that a well-founded analysis of uncertainty on the flight dynamics is a useful area of research investigations. While classical Monte-Carlo simulations can be used to address the effects of uncertain input data, this is generally not practical if many parameters are uncertain. The research centre develops therefore a range of modern stochastic methods. The stochastic collocation method does not need any changes of the original flight mechanical computation code (nonintrusive uncertainty approach). This method was shown around two orders of magnitude more efficient than direct Monte-Carlo integration [32]. It will be used in future studies to assess robustness in flight mechanical behaviors.

4 Conclusions

The Collaborative Research Centre SFB 880 combines the competencies of Technische Universität Braunschweig, Universität Hannover and the German Aerospace Center, DLR, for fundamental and applied research in high lift of future commercial aircraft. Based on a thorough analysis of long term requirements for sustained growth in aviation the centre focused its research on the fundamentals in aeroacoustics and on efficient and viable approaches towards active high lift. The research activities combine the disciplines of aerodynamics, aeroacoustics, materials, structures, adaptronics, turbomachinery and flight mechanics. The centre is now in its third year of research, and the results obtained so far are significant and promising. Future work will aim at combining more of the disciplinary models and technologies in order to cope with the multidisciplinary aspects of the design problems and to exploit synergies as well. The centre welcomes opportunities for new cooperations with other researchers in the field.

Acknowledgments The funding of the Coordinated Research Centre SFB 880 by the German Research Foundation, DFG, is thankfully acknowledged.

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