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DLR's morphing wing activities within the European network

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Abstract

Smart Structures technology called Adaptronics in Germany covers the entire field of making the elastomechanical behaviour of structures adaptable. The main objectives are vibration control, noise reduction and shape control. The latter is directly related to morphing of airframes, thus being a focus of DLR's aeronautical research program. DLR initiated the national morphing wing activities in the mid-nineties with research projects on morphing wing trailing egdes. The lessons learned where exploited continuously in different national and international projects up today. The research covers the most relevant application scenarios of morphing like smart trailing egde, smart winglet, or smart leading egde including the smart slat. Presently the gapless droop nose for laminar wings of future civil transport aircrafts is in the focus of the investigations at DLR in collaboration with European partners. This paper gives a survey of the related national and international activities where DLR has been involved in since the mid-nineties and elaborates the challenge of designing morphing wing structures, i.e. to provide flexibility for the deformation and stiffness for carrying high loads at the same time.

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Keywords: morphing wing, smart droop nose, smart trailing egde, smart slat, smart winglet

1. Introduction

The need for morphing aeronautical structures has gained during the past years due to the increasing demands on civil aeronautics to both positively influence global climate change and to improve local noise and air quality. The present IPCC report [1] illustrates the human caused climate changes and

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recommends significantly reducing greenhouse gases from all anthropogenic sources. Similar conclusions the ACARE group has made and recommends the civil aircraft industry to reduce their emissions per passenger kilometer (CO_2 < 50%, NO_x < 80%, noise < 50%) until 2020 [2]. Air traffic is presently increasing by 5% per year, about doubling the global economics growth of 2.6%. This means the air traffic will double within the next 20 years. Presuming that kerosene will stay the main fuel in use the specific fuel consumption must be reduced by 50% only in order to keep the emission level constant to today. The World Health Organization (WHO) describes that prolonged or excessive exposure to noise, whether in the community or at work, can cause permanent medical conditions [3]. Morphing structures in civil aircraft industry are able to contribute to these goals.

Intensive research has been performed within the field of morphing airframes over the last 20 years. Typical technology drivers have been micro air vehicles, missile control, unmanned air vehicles, helicopters, combat aircraft, and transport aircraft. Due to the extreme large bandwidth of application scenarios there is not only one morphing solution that applies to all. Large load and large scale applications like transport aircraft naturally require quite different approaches than micro air vehicles with small dimensions and low load requirements. Scaling of concepts from large to small and vice versa is hardly possible. DLR is mainly involved in civil transport aircraft. Consequently this paper focusses on large scale, high load morphing.

Figure 1 depicts DLR's roadmap for morphing wing surfaces. These are in particular the adaptive leading egde including smart slats, the smart trailing edge, and the smart winglet.

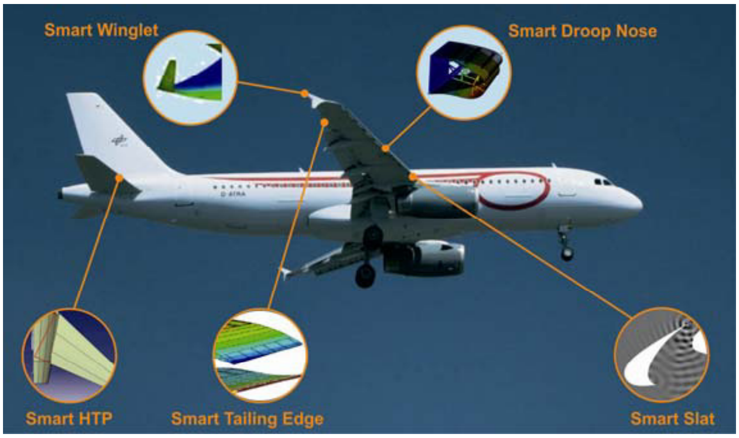

Fig. 1. Research roadmap of adaptive wing technologies

Significant progress has been made large scale morphing. However, it has not yet been realized compatible to low mass and low energy requirements until today. Typical technological challenges in realizing a morphing aeronautical structure are to be seen as follows:

(1) Highly elastic skin capable to withstand air loads;
(2) Appropriate compliant mechanism or kinematics to deform skin;
(3) Connection of compliant mechanism or kinematics to elastic skin;
(4) Actuator integration, both discrete and distributed.

Of course system requirements like durability and reparability are demanding tasks for all of the technological challenged described above. The overview of the development of morphing wing structures at DLR points out that comprehensive and continuous effort is needed to meet these challenges.

2. Overview of DLR's morphing wing projects

DLR's Institute of Composite Structures and Adaptive Systems has been active on the field of morphing wing structures since 1995. The development started with internal DLR projects, followed by collaborative projects funded within the German Aeronautics Research Program (LuFo) and large scale European projects within the 6th and 7th Framework Program (Fig. 2): Smart structures for wings (ADIF, DLR project), Adaptive Wing Technology (AWiTech, DLR project), Adaptive gap control (Pro-HMS, LuFo project), Smart Winglets (IHK, LuFo project), Smart Leading Edge Device (SmartLED, LuFo project), Smart High Lift Devices for Next Generation Wings (SADE, EU-FP7 project), Smart Intelligent Aircraft Structures (SARISTU) and Smart Fixed Wing Aircraft (JTI-SFWA, EU Project).

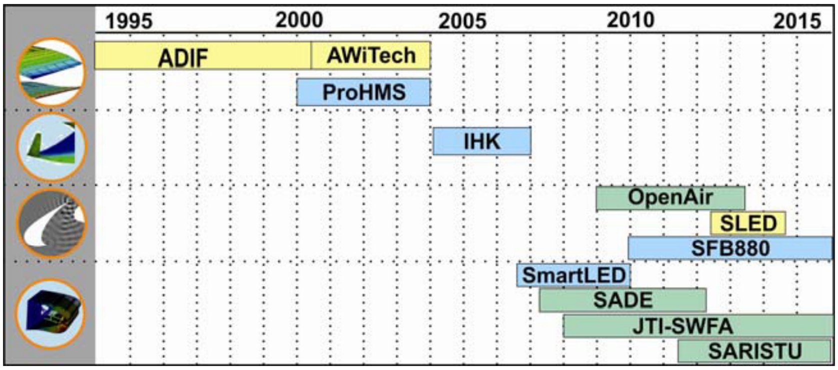

Fig. 2. DLR's Research of adaptive wing technologies within the European context, yellow: DLR funded, blue: National research funds, green: EU-FP7 funded

2.1. DLR's early morphing wing projects in the nineties – smart trailing egde and local profile bump

The ADIF project marks the beginning of morphing wing research at DLR in 1995. The main goal of this project was to adapt the wing shape of civil transport aircraft continuously during cruise flight. Background and motivation to this project was that the fixed wing of an aircraft is designed optimally only for one flight condition, whereas an optimized performance at the design point leads to a worse off-design performance. To compensate for this disadvantage, a morphing wing for optimal adaptation and variation of the profile geometry with concepts for a variable camber and a local spoiler bump was investigated within ADIF (Fig. 3).

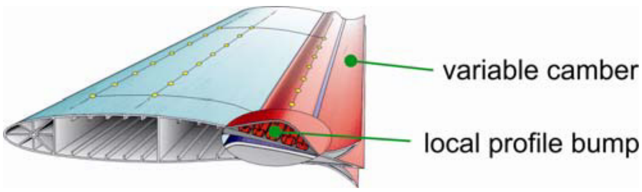

Fig. 3. DLR's morphing wing concepts in ADIF

The objective of the research of a flexible trailing edge was to achieve a chordwise and spanwise differential camber variation with the same structural system providing a smooth contour with no additional gaps. The camber variation concentrated on the trailing edge, since this region has the highest efficiency under aerodynamic as well as under structural aspects. On civil transport aircraft flaps and ailerons are positioned in this region. For camber variation two different concepts were investigated, the finger concept and the belt rib concept.

The finger concept substitutes the inflexible ribs of a conventional flap by ribs of a flexible design. These flexible ribs are realized by combining separate plate like elements with revolute joints [5]. In order to avoid the actuation of each rib a transmission beam is designed to cluster ribs so that two actuators drove five ribs reducing the actuator amount significantly. As a result it is possible to achieve a deformed shape like an arc or like the elastic line of a beam [6]. The concept was realized as a functional 1:1 demonstrator.

In the second concept a closed belt transfers the actuator stroke into a camber variation of the airfoil. The upper and lower parts of the belt are connected by spokes. The contour of the trailing edge is changed by alteration of the angle of the spokes in the undeformed rib. This enables a variable, but span wise constant cambering. An experimental feasibility study demonstrated the concept on a 1:2 scaled model of a 500 mm wide flap section with two belt ribs [7, 8].

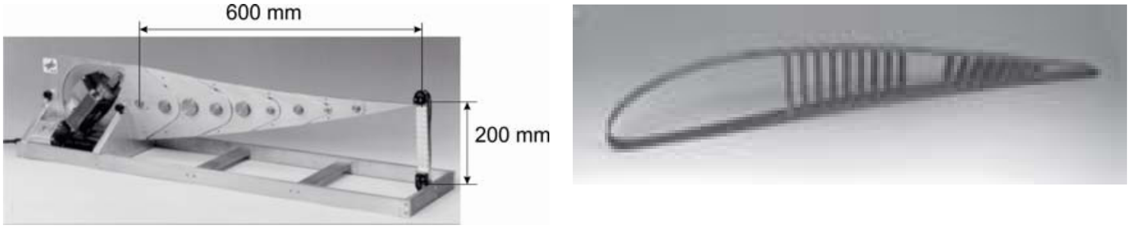

Fig. 4. Morphing trailing edge: Finger concept (left) and belt rib concept (right)

The realization of an adaptive spoiler bump is motivated by the need to control the transonic shock for improvement of the aerodynamic efficiency of future large civil transport aircrafts by reducing the wave drag. Beside passive ventilation an active approach is the structural thickening of the profile underneath the transonic shock, the bump. In contrast to the ventilation the isentropic compression waves are generated by thickening of the profile. The concept of the local profile bump consists of three layers. The bottom layer is the load-carrying structure where a second layer of actuators is integrated. The top layer is the actual deformable structure consisting of a chord wise flexible skin. Since the volume of the spoiler is strictly limited, the actuators has to be very compact, has to have a high translation ratio and has to provide a significant stiffness in both, chord wise and span wise direction. The actuator is a CFRP spring tube with two symmetrical hollows. The two hollows can be pressurized. Again feasibility of the concept was shown in a technical demonstrator [9].

2.2. Active gap control

The lessons learned from the investigation of the smart trailing edge led to the question of improving the high lift behavior of transport aircraft by adaptation of the elastic line of the flap with the wing's elastic line. The first step was the determination of the optimal track positions for two tracks. With these positions it was possible to calculate the best stiffness distribution of the passive structure made of carbon fiber. Aligning the fibers in a certain angle to the span wise direction leads to a bending-torsion-coupling in the flap that is necessary to follow the twisted contour of the wing. The small difference in the required stiffness of the flap for the considered load cases is provided by a structurally integrated actuator system. It was decided to build a demonstrator of an adaptive fowler flap with this kind of actuation. The demonstrator consists of 16 SMA wires with 2 mm diameter, integrated into the spar in form of a double-T. The spar itself is made of glass- and carbon fibers and has the dimensions $l \times b \times h = 1\,000$ mm $\times$ 66 mm $\times$ 38 mm. The laminate thickness is constantly 3.5 mm. This demonstrator shows that this kind of actuation is suitable for deformation of the spar and that the results of the analytical and numerical calculations fit quite well with the experimental results [10]. After activating the wires 3.5 mm deformation was measured. Extrapolated to a typical Fowler flap this would mean 30 mm active deformation. For heating the wires 5 V and 60 A were required when starting from 20°C room temperature.

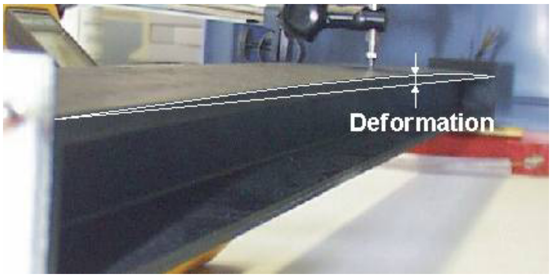

Fig. 5. Active deformation of a spar with integrated SMA wires

The experiences with the active gap control at the leading edge are now utilized in the smart slat research. The challenge of the adaptive slat technology is to address active and adaptive structure technologies to reduce the slat noise. Complementary experimental and numerical tests were executed at NASA in order to isolate slat noise sources and the underlying noise generation mechanisms [11]. DLR-studies ([13, 14]) show that a reduction of radiated noise is achievable through an active gap control. It is expected to define a lightweight morphing slat concept with minimal impact on performances, certification requirements, weight and reliability.

Active gap control on slats is investigated in the OPENAIR project which is still running. The concept chosen for further development is based on the actuating of the elastic outer skin with a conventional actuator/kinematic system located inside of the slat shape. Figure 6 depicts the selected concept which is currently under investigation. The design variables are defined by the lay-up of composite skin layers, the position and construction of the force application point, and the direction of the actuating force. Electro-mechanical actuators are preferred. Calculated requirements can be fulfilled by several actuating systems e.g. rotatory actuation using strain wave gearing or linear actuation using ball screw gearing. The required space inside of the slat shape of today's civil aircraft is mainly occupied by a bleed-air-based anti-icing system. A possible solution may be the substitution of the bleed system with one of the existing alternatives, e.g. electro-thermal de-icing.

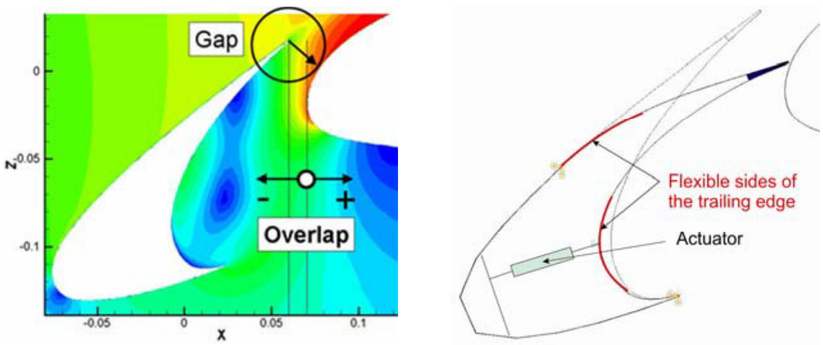

Fig. 6. Smart slat concept

2.3. Active winglet

The active shape adaption of winglets is of interest for load reduction, performance driven control of airflow, low noise drag creation without lift decrease, and destabilization of wake vortex. Three different approaches for composite winglet design have been investigated and compared

(1) Passive composite winglet with tailoring for load control
(2) Winglet with conventional tab
(3) Smart winglet

Different laminate stacking sequences have been investigated for dimensioning the aeroelastic tailored winglet. For the both sides of the skin the tailoring angle has been varied. The dimensioning and optimization of the layers was done so that the laminate remains symmetrical. 18 configurations for the winglet were investigated for an iso-loaded winglet. In comparison to reference aluminum winglet a 8% lighter winglet design was achieved which additionally has a higher torsional stiffness.

The aerodynamic performance of a composite winglet with conventional tab weighs after optimization about 4% more than the reference aluminum winglet. Additionally, for certain tab angles between −5° and 5° a drag reduction was discovered.

The combination of structural tailoring with smart structures technologies leads to so-called smart tailoring. Smart tailoring primary aims at the skins. Tailored anisotropic skin materials show different potential for activation by integrated smart materials, e.g. shape memory alloys. Less deformation are possible in load carrying direction where the fibers are aligned naturally than in the matrix dominated vertical direction to the load path. This means, whenever the sizing loads lead to pure up bend of the winglet, anisotropic design will precisely restrict this up bending deflection. Active camber can be introduced efficiently while active bending is constricted by the passive structure. In order to dimension the winglet a compromise between bending stiffness and deformability has to be found. The study revealed that the weight of the adaptive winglet is positioned between the reference aluminum winglet (4% lighter) and the tailored winglet (4% heavier).

2.4. Smart leading edge

New wing concepts like high aspect ratio low sweep (HARLS) for future aircrafts have been suggested and investigated within the 6th European Framework Program. The concepts are characterized by slim, high aspect ratio wing profiles in order achieve laminar flow for drag reduction. In this context the high lift systems at the leading edge are of particular importance. Conventional high lift systems like slats cause gaps and steps in the contour which hinders the realization of a laminar airflow. Moreover, the gaps represent a significant source of noise during landing. These findings lead to the concept of a gapless droop nose at the leading edge as the only alternative.

The European and national projects smart high lift devices for next generation wings (SADE) and smart leading edge device (SmartLED) as well as part of the European funded “Joint Technology Initiative” Clean Sky smart fixed wing aircraft (SFWA) are aiming for a major step forward in the development and evaluation of the potential of morphing airframe technologies. A smart leading edge is developed and tested in 1:1 ground test in the SmartLED project.

3. Smart droop nose

Numerous patents and concepts starting from the early 20 s deal with mechanics and kinematics for the deformation of parts of the airfoil or the complete airfoil. The majority of these patents considers the inner mechanism for the deformation of the airfoil as key issue and assumes a flexible skin not specified otherwise. However, the skin play a decisive role in the design of morphing structures of today’s transportation aircrafts bearing high surface loading on the wing. A suitable skin has to provide flexibility for the deformation and stiffness for carrying high loads at the same time. In consequence, the skin design plays a central role in the design of morphing wing technologies.

3.1. Design

A comprehensive description of a suitable design process for a continuous flexible gap and step less smart droop nose is given in [15, 18]. The resulting smart leading edge design developed at DLR consists of a monolithic, flexible glass fiber skin with tailored stiffness in chord direction and omega shaped stringers in span direction. The actuator forces for deformation of the skin are transferred into the skin by a kinematical chain which is compatible to the desired structural deformation. The stringers act in this configuration as stiffeners in span direction and simultaneously as interface between the skin and the kinematics.

Figure 7 (right) depicts the Finite Element (FE) model of the final design. The optimization step of the design process leads to a variable skin thickness distribution in circumferential direction of the smart leading edge. The skin thickness varies between 1 mm and 5 mm as shown in Fig. 7 (left).

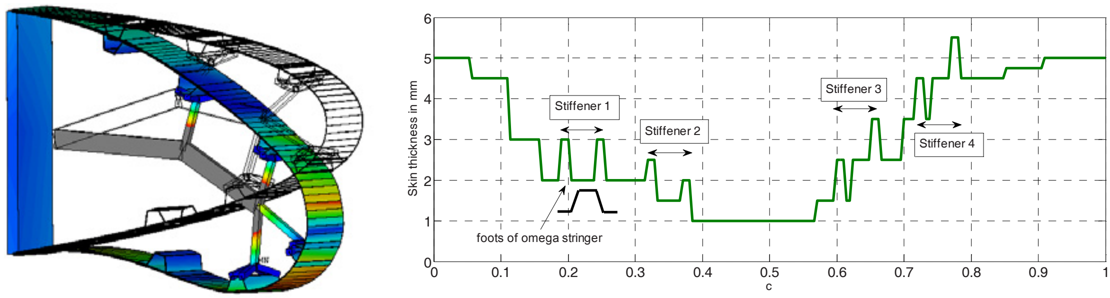

Fig. 7. Continuous flexible gap and step less smart droop nose (left: FE model, right: skin thickness distribution and location of omega stringers for load introduction

Glass fiber prepreg composite is chosen as skin material being well known from its application in rotor blades. The material provides a good compromise concerning stiffness and large strain capability which is important for the stiffness under aerodynamic loading and the static strength for drooping of the leading edge. The fiber layup and stacking sequence is chosen according to the maximum strains in the outer fibers of the elastic skin. The most critical material parameter is the tensile strength of the laminates matrix. Therefore, the outer fiber layers are aligned in circumferential i.e. 0° direction of the skin. Providing stiffness in span direction and torsional stiffness layers of ±45° and 90° are used in layers which are nearer to the neutral fiber of the laminate.

The design on the one hand provides the desired morphing capability of the leading edge of about 20° droop angle and on the other hand sufficient support for the aerodynamic loads in high lift and cruise configuration.

3.2. Ground test of a composite smart droop nose

A full scale segment of a smart leading edge structure was manufactured in order to demonstrate the morphing capability of the smart leading edge of a transportation aircraft with conventional flight certified materials. The wings plan form and design is similar to a medium range single aisle aircraft like the Airbus A320. The ground test on the two meter span section taken from the inner part of the outer wing near the kink was built for ground tests persues two main goals. The first goal is the validation of the leading edge morphing into the desired position without aerodynamic loads. The second one is the investigation of the deformation behavior under relevant wing bending derived from 1.15 g and 2.0 g loads [20]. Figure 8 shows the test setup for the ground tests. The test rig consists of a front spar carrying the smart leading egde structure and drives for bending the whole structure.

High resolution measuring cameras and specially developed optics are utilized for precise measurements of the deformed and undeformed shape. The finite element mesh of the FE model is imported into the inspection software for comparison and verification of the design. The measurement system provides the possibility to compare directly the surface meshes of the finite element model and the measured surfaces. The comparison of the undeformed structure and the design matches very good.

Reasons for minor deviations are caused by manufacturing and assembly tolerances. A larger deviation of the meshes distance is expected in the deformed state due to the discrete character of the finite element modeling and the fact that the inner mechanism is considered to be perfectly rigid in the simulation.

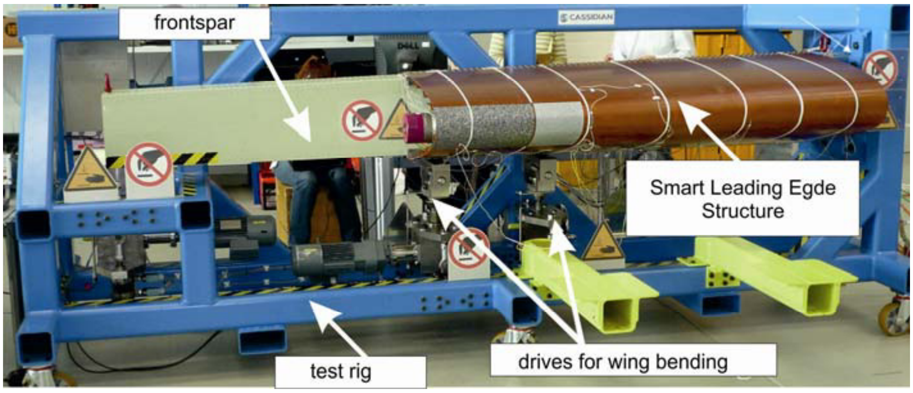

Fig. 8. Test setup with test-rig, test (front) spar and smart leading edge structure

The measurements indicate a major deviation of the meshes at the lower side of the larger cross-section in the deformed state (Fig. 9). In the rest of the leading edge section the meshes are in good agreement except areas at the leading edge tip. A comparison of the 2D measurements of the initial assessment with the 3D measurements in Fig. 9 indicates a good agreement of the deviation of the shapes in the larger cross-section of the leading edge segment. Local deviations from simulation results can be assigned to insufficient measurement accuracy during the tests, manufacturing tolerances and tolerance problems during assembly. In combination with a bending load the wing skin showed beginning shear buckling of the sidewalls in the experimental testing under the 2.0 g loading and clearly formation shear buckling in 2.5 g loading of the structure. No stability problems of the smart leading edge structure were observed.

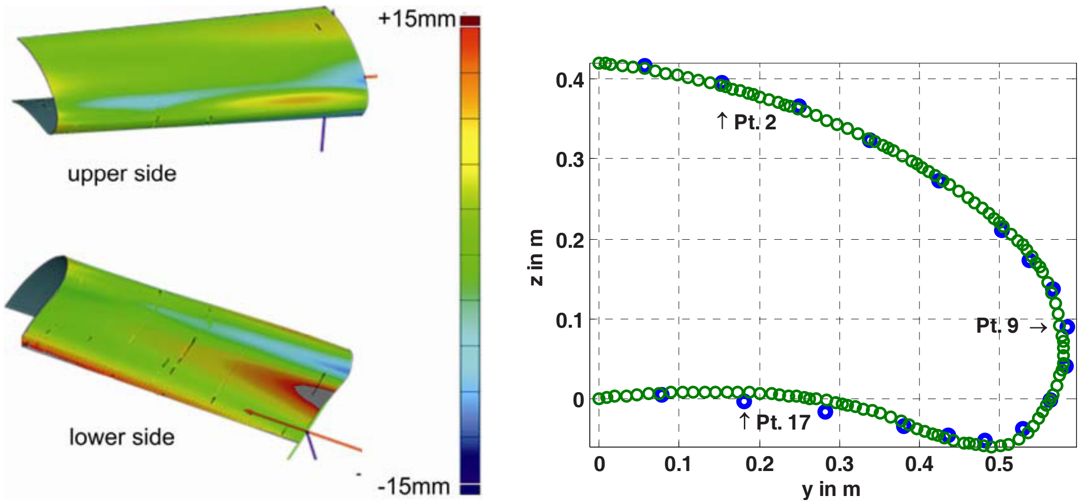

Fig. 9. Analysis of distance of finite element model and deflection measurements of upper and lower side of the leading edge segment in deformed position, 18° deployed: (left: difference between design an measurement, right: detailed view at x = 161 mm (measured points in blue and finite element nodes in green)

3.3. Future work on the smart droop nose

The SADE project started within the 7th European Framework Programme in May 2008, coordinated by DLR. It comprises 13 partners from 9 European nations. Versatile adaptability based on "morphing" or "smart structures" concepts are addressed. Morphing high lift devices "smart leading edge" and "smart single slotted flap" are to be developed and investigated. The technological realisation and optimisation of these concepts towards the special requirements of full scale systems is the most essential challenge for morphing today. Hence, a realistic full scale section of a morphing wing is manufactured and will be tested in the TsAGI T101 wind tunnel for an investigation these effects in autumn 2012. The setup of the planned wind tunnel test is sketched in Fig. 10. The model will have 6 m span and 3 m chord of which the mid 2 m will comprise gapless high lift devices.

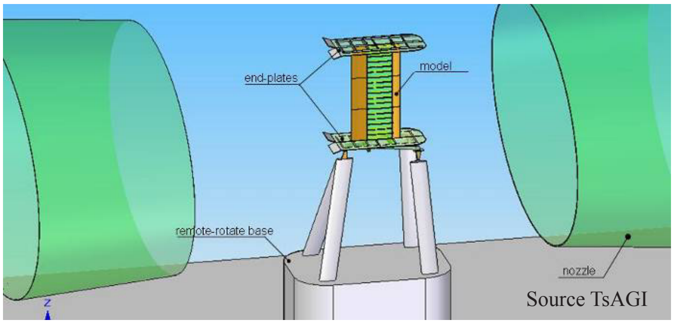

Fig. 10. Wind tunnel test setup

The developed two prototypes for ground tests and wind tunnel tests will mature the technology through the consideration of industrial requirements like bird strike, maintenance, and fatigue. These topics are addressed in the SARISTU project which started last year. Though present results are very promising and these demonstrators will be a big step forward to increase the technology readiness level, it still is a long way until such structures come into service.

4. Adaptive systems for flow sensing and control

Morphing wing technologies aim for an optimal flow for all different flight conditions. An alternative or even complementary approach to influence the flow conditions is blowing out pressurized air. A novel technology for improving the efficiency of high-lift systems is to influence the boundary-layer of airfoils with highly deflected flaps using the Coanda-effect. It is characterized by very high lift coefficients, which permit steep and therefore quiet approaches and departures. The high-lift coefficient results from the delay of flow separation on the flap by a highly energized jet of compressed air, the Coanda-jet. While most studies use valves to control the mass flow, an approach being under investigation in the Collaborative Research Center "Fundamentals of High Lift for Future Civil Aircraft – SFB 880" uses an actuated lip, forming one side of the jet nozzle, to influence the jet. Thus, morphing technology is combined with active flow control. The combination of MEMS based flow sensors and piezoelectric actuators build an adaptive Actuator-Sensor-System as shown in Fig. 11.

The experimental part of this research includes design, manufacturing and testing a water tunnel model with the actuated lip. The research is supposed to bring new insight on the increased efficiency of pulsed blowing. The lip's deformation will be achieved by piezo-ceramic actuators embedded carbon fiber substrate. Finally the actuated lip in combination with a closed-loop controller is expected to show further progress in efficiency. Information on pressure and shear stress will be fed back into the controller by embedded micro sensor arrays. Initial practical tests will be carried out in a large water tunnel, which allows higher Reynolds-numbers than achievable in the wind tunnel and therefore much easier time resolved measurements and closed-loop control. Therefore, a prototype of the slot-lip is built from high-performance stack actuators imbedded a metal lip structure (Fig. 12).

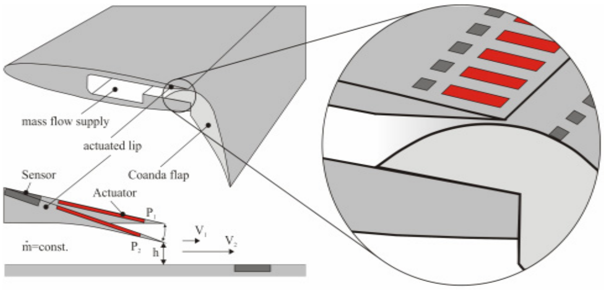

Fig. 11. Actuated lip of the blowout slot with embedded Sensor-Actuator-System

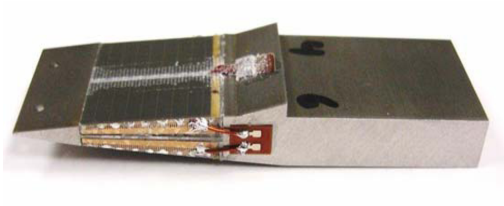

Fig. 12. Prototype of the actuated slot-lip with embedded multilayer piezo actuators

The actuated slot lip for the water tunnel model is encountering high loads of approx. 6 bars. Therefore an advanced, powerful and robust actuator, being able to withstand water environment, is needed. Within this research project advanced multilayer piezo-ceramic actuators, utilizing the d_{33}-effect at a low operating voltage level of app. 120 volts are being used and further refined. Due to the small build envelope of the model for the water tunnel tests, a compact bending actuator configuration was chosen to perform a slot opening of 0.2 mm oscillating at 30 Hz.

Another focus is the merging of actuators and sensors to a compact but flexible system, enabling the integration into a laminate. Here the interactions of actuator control signals and sensor measurement signals as well as the joint production process and the interactions with the laminate are being investigated.

5. Conclusions

DLR's experience in the field of large scale morphing wing structures capable to handle high loads for civil transport aircraft has evolved within the past 15 years from initial internal projects over nationally funded collaborations to European interdisciplinary teams. On this route different approaches for morphing have been investigated leading to a comprehensive knowledge base. The research covers the most relevant application scenarios of morphing like smart trailing edge, smart winglet, or smart leading egde. The experience of the past shows clearly that the challenges of developing morphing wing structures can only be tackled in interdisciplinary teams comprising experts from materials research, structural mechanics, aerodynamics, aeroelasticity, flight mechanics, and systems engineering. Within Europe such groups have been formed with members from academia, research establishments, and aircraft manufacturers allowing for a justified optimism that the challenges can be overcome. Finally, smart morphing structures for civil transport aircraft may become reality.

References

[1] Bernstein L, Bosch P, Canziani O, Chen ZL, Christ R, Davidson O, et al., Climate Change 2007, Synthesis Report, http://www.ipcc.ch/pdf/assessment-report/ar4/syr/ar4_syr.pdf.

[2] Advisory Council for Aeronautics Research in Europe (ACARE), 2008 Addendum to the Strategic Research Agenda*,* http://www.acare4europe.com/sites/acare4europe.org/files/document/ACARE_2008_Addendum.pdf.

[3] World Health Organization, Occupational and community noise, http://www.who.int/peh/Occupational_health/OCHweb/OSHpages/OSHDocuments/Factsheets/noise.pdf.

[4] Queen Mary University of London, Children's reading and memory affected by exposure to aircraft noise, http://www.qmul.ac.uk/qmul/news/newsrelease.php?news_id=133.

[5] Monner HP. Realization of an optimzed camber by using formvariable flap structures. *Aerospace Science and Technology* 2001; **5**: 445–455.

[6] Hilbig H, Wagner H. Variable wing camber control for civil transport aircraft. ICAS Procedings, ICAS-84-5.2.1, 1984.

[7] Campanile LF, Sachau D. the belt-rib concept: A structronic approach to variable camber. *Journal of Intelligent Material Systems and Structu*res 2000; **11**: 215–224.

[8] Campanile LF. lightweighht shape-adaptable airfoils: A new challenge for an old dream. In: Wagg D, Bond I, Weaver P, Friswell M, editors. *Adaptive Structures – Engineering Applications*, Wiley&Sond Ltd.; 2007.

[9] Monner HP, Bein Th, Hanselka H, Breitbach E. Design aspects of the adaptive wing – the elastic trailing edge and the local spoiler bump. *The Aeronautical Journal of the Royal Aeronautical Society*, February 2000.

[10] Nagel B, Anhalt C, Monner HP, Breitbach E. Adaptive spaltkontrolle an hochauftriebsklappen, nachbar flughafen – technologien und verfahren zum fliegen im flughafennahbereich, DGLR, Bremen, Oktober 25–26, 2004.

[11] Khorrami MR. Understanding slat noise sources, EUROMECH 449, Chamonix, France, 2003.

[12] Choudhari MM, Khorrami MR. Slat cove unsteadiness: Effect of 3D flow structures, AIAA 2006-0211, 2006.

[13] Caro S, Pott-Pollenske M. An integrated design appraoch to reduce slat noise. *J of Sound and Vibration* 2007; **304**: 421–449.

[14] Dobrzynski W, Ewert R, Pott-Pollenske M, Herr M, Delfs J. Research at DLR towards airframe noise prediction and reduction. *Aerospace Science and Technology* 2007; **12**: 80–90.

[15] Kintscher M, Wiedemann M. Design of a smart leading edge device. In: Wiedemann M, Sinapius M, editors. *Adaptive, Tolerant, and Efficient Composite Structures*, Springer; 2012.

[16] Kintscher M. Method for the pre-design of a smart droop nose using a simplex optimization scheme. SAE Technical Paper 2009-01-3113, 2009.

[17] Monner HP, Kintscher M, Lorkowski Th, Storm S. Design of a smart droop nose as leading edge high lift system for transportation aircraft, AIAA 5.5. – 7.5., 2009.

[18] Kintscher M, Heintze O, Monner HP. Structural design of a smart leading edge device for seamless and gapless high lift systems, 1st EASN Association Workshop on Aerostructures, Paris, France, Oct 7–8, 2010.

[19] Kintscher M, Monner HP, Riemenschneider J, Wiedemann M. First results of the groundtest of a fibre reinforced continuous flexible gap and stepless smart droop nose for high lift applications, DLRK, Bremen, 2011.

[20] Monner HP, Kintscher M, Riemenschneider J. Groundtest of a Composite Smart Droop Nose, AIAA 2012-1580, 2012.