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LOW SPEED FLOW CONTROL

OVERVIEW OF R&T ACTIVITIES IN LUFO AND EUROPEAN PROJECTS

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Abstract

Flow control technology is of immense importance in modern aerodynamics. For example high-lift systems of modern transport aircraft are almost designed to their limits in that they are kept as simple as possible but produce the required lift for take-off and landing. Further optimisation of an already highly optimized low speed configuration is very challenging and the improvement gains via pure shape design might not justify the required effort. One major limiting factor, especially for single-flap systems (slotted or not) is the flow separation that occurs at rather high flap deflection angles.

However, active separation control by means of dynamic wall jets has in recent years proven to be a very effective and robust tool to delay separation or to reattach an already separated flow. This will enable the design of more efficient high lift configurations and enhanced efficiency of further low speed relevant components (e.g. control surfaces). In addition, due to the flow control on demand capability, active flow control is a perfect candidate to improve the flow at off design conditions. For instance in case of engine failure at take off an extreme and immediate rudder deflection has to be realized, active flow control ahead of the rudder might improve the rudder efficiency drastically.

This paper highlights some recent findings in national and European R&T projects. Examples from ongoing studies illustrate how active flow control can improve the high lift performance. In European projects major design and validation work is ongoing, whereas numerical tools to prepare flow control as a design parameter are in the focus of national projects.

Key words: flow control; low speed

1. INTRODUCTION

Active flow control plays an ever-growing part in aerodynamic research. As the conventional aerodynamic designs are pushed to their limits, active flow control seems to be one possibility to overcome certain aerodynamic limitations, e.g. flow separation.

The low speed performance is a principle design objective of any civil transport aircraft for economical and ecological reasons.

Recent research has proven, that active flow control is a promising concept to realize high lift performance beyond the performance achievable by pure shape design [1].

Conventional high lift systems (no flow control applied) are limited in performance by separation effects, which might occur at large deflection angles due to decelerated flow. Hence, separation delay via active flow control is a key concept to overcome such limitations. Fig 1 is a simple sketch of a dynamic jet actuator installed at the flap operated at high lift conditions.

The technological objectives related to flow control application at low speed regime are therefore:

- Support drag reduction technology via simplification of high lift devices and enabling drag reducing technologies (laminar technology)
- Improved performance of high lift and other devices at low speed regime
- Indirect benefits due to reduction of unsteady flow phenomena (reduction of airframe noise)

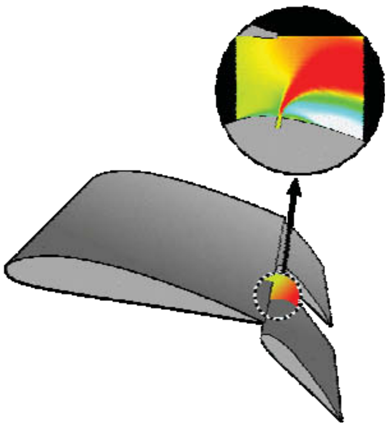


BILD 1. Active flow control via unsteady dynamic jet vortex generators installed at the flap

(sketch provided by TU Berlin)

2. TECHNICAL APPROACH

The low speed performance is a principle design objective of any civil transport aircraft for economical and ecological reasons.

Airbus has set up a long term strategy (in line with strategic papers prepared with significant influence from industry, [2-6]), which contains experimental and numerical studies to develop flow control technologies for all Airbus products. These Flight Physics guided investigations are complemented by extensive flow control hardware developments (actuators, sensors, control units), which are done in close collaboration in between several disciplines, aiming to ensure an overall aircraft benefit. Within EADS group EADS-IW has key competences on actuator technologies, but these hardware aspects are outside of the focus of this paper.
The major items to be tackled are:

- Identify how an aircraft benefit can be obtained by flow control
- Understand the flow mechanisms, which need to be controlled
- Define flow control technology targets linked to various application challenges (this paper focuses on low speed aircraft configurations)
- Derive from these targets technical objectives in all involved disciplines
- Develop and validate flow control capabilities (experimental, numerical, etc.) and apply these to applications of systematically increasing complexity (typical R&T approach to be done in close collaboration with institutes)
- Assess the overall aircraft benefits at appropriate stages of the technology developments

A possible scenario for low speed flow control application would then be:

- Separation control for enhanced high lift performance (including slat less wing as laminar wing enabler)
- Separation control for empennage control surfaces
- Undercarriage flow separation control, noise control
- Full benefit can only be achieved if the aircraft is designed right from the start including these technologies

Major expected benefits might be summarized as follows:

- Simplification of movables
- Increased Clmax results in increased pay load for given approach speed or reduced approach speed for given aircraft
- Increase aero performance of trailing edge high lift supports laminar wing designs
- Load benefits via e.g. spanwise flow control adjustments
- Lift increase could enable shorter landing gear, enable longer fuselage
- Noise benefits via reduction of flow unsteadiness
- Increased L/D results in increased payload and / or range
- Separation control is an additional design parameter, thus enlarges the design space

In order to realize the desired flow control technical objective, it is necessary to develop actuation systems (actuators, sensors, control units) with sufficient flow control authority but also with minimum possible weight, energy and space requirements.
As described above, to realize the step change in low speed performance it is necessary to better understand the phenomena of flows close to separation and to investigate thoroughly phenomena of controlled flows.
In national programmes (LuFo, DFG) some focus was put onto enhancements of numerical and experimental capabilities and validation of flow control predictions and technology concepts at well defined wind tunnel models of increasing complexity.
Since active flow control is an innovative area with a lot of open issues, a German flow control network was established during LuFo3 IHK programme. To ramp up technology developments in this field, network activities were increased within LuFo 4 (M-Fly).
The German Flow Control Network (in nationally funded projects) was established between DLR and three universities, namely the Institutes of Technology in Berlin, Braunschweig and Stuttgart. DLR is responsible for providing a large scale experimental test bed and access to the wind tunnel facility. The Berlin Institute of Technology investigates separation control actuation at the flap. The Braunschweig Institute of Technology focuses on separation control actuation at the leading edge. Additionally the Stuttgart Institute of Technology participates for a more detailed theoretical insight by providing direct numerical simulation of fluidic actuators.
Before LuFo4 most experimental tests were done on simple two-dimensional profiles or at constant chord swept wing models and flow control hardware (including flow control algorithm hardware and software) was developed for the purpose of a proof of concept level. All these activities were performed at institutes and the success of these multi-annual studies allowed industry to perform the next step of technology validation. A high lift active flow control wind tunnel test with a three-dimensional swept wing industrial model was done in an industrial facility at Airbus. The complete flow control hardware (including flow control electronic units) were developed and provided by TU Berlin, whereas numerical prediction for flow control configurations were done by DLR. Airbus provided the wind tunnel infrastructure and modified the wind tunnel model.
In parallel to experimental and flow control system work, numerical prediction capabilities were significantly enhanced in M-Fly. There are several options to numerically model flow control. It is generally accepted, that one should distinguish in between the following models:

- **Flow control devices fully resolved**
  passive device: actuator geometry resolved
  active device: device resolved in mesh and boundary condition adapted to flow control
- **Flow control device partly resolved**
  device not present in mesh, modelling of flow control effects via source terms in momentum

equations

- **Flow control device fully modelled**:
  flow control device and impact of device on flow modelled via source terms in RANS equations and turbulence model locally adjusted to flow control effects

The overall goal within LuFo4 project M-Fly was to qualify the Navier-Stokes code TAU (DLR). This was supported by complementary studies of several institutes tackling flow control predictions with other simulation models (DNS, DES). The above mentioned fully resolved approach was implemented in terms of special boundary conditions reflecting the close to digital signal of the actuator valves and comparisons were made against wind tunnel data. Complementarily, the above mentioned fully modelled approach was incorporated for passive flow control devices into Navier-Stokes code TAU within LuFo4 project ComFliTe.

In European funded projects (e.g. Smart Fixed Wing Aircraft (SFWA) programme within Joint Technology Initiative JTI) CFD codes were applied and the focus is on demonstration activities aiming to realize a technology readiness, which might open the door to do a flight test for selected low speed flow control concepts.

Within the so-called fluidic control surfaces technology stream the following sub-streams are currently under investigation:

- Passive flow control, new kinematics, smart surfaces for application at high lift devices
- Leading edge active flow control for slatless wing
- Trailing edge active flow control applied at flaps
- Active flow control to support load control functions

The main goal of SFWA is technology development and demonstration, the capability development is not within the scope of SFWA, since it is regarded as major European demonstrator platform to validate ACARE2020 required technology targets.

3. RESULTS FROM NATIONALY FUNDED R&T PROJECTS

Parallel to the development of new boundary conditions for the TAU code, basic experiments with high resolution measurement techniques were initiated and performed, in order to validate the new flow control features in TAU. In order to do this in a systematic fashion and to identify any mis-matches between experiments and prediction, several test were done with increasing complexity:

- Flat plate, single actuator
- High-lift airfoil (FNG)
- Industrial near 2.5D high-lift airfoil (FNG)

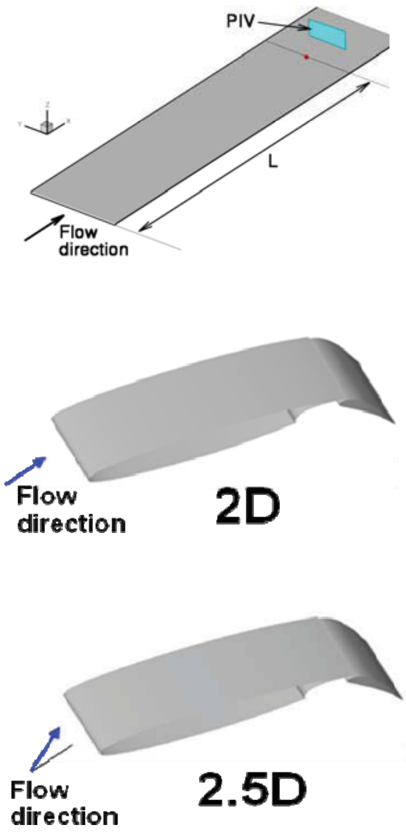
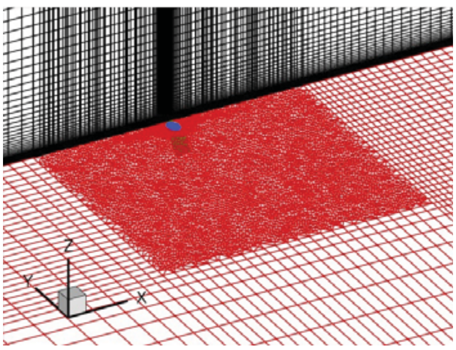


BILD 2. Series of basic experiments for code validation [7]

Mesh generators were updated and several grids were constructed in order to resolve also tiny flow control features in the vicinity and downstream of the actuation device.



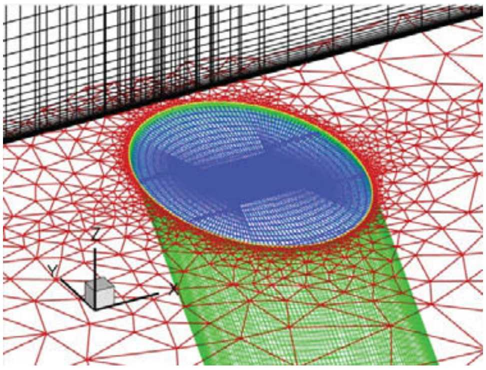
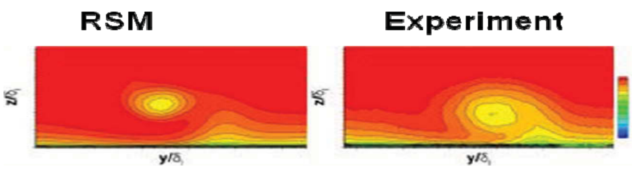


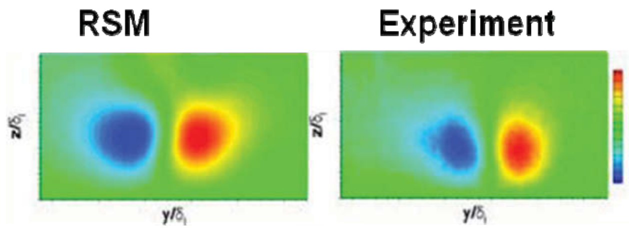
BILD 3. Sketch of meshes for flow control purposes [7]

By doing detailed PIV measurements and extensive numerical runs DLR succeeded to predict the main features of the flow control jet (round orifice as shown above) downstream of the orifice. These DLR studies were complemented and supported by extensive numerical investigations of University partners within German flow control network (Ref. 8, 9, 10 and 11).

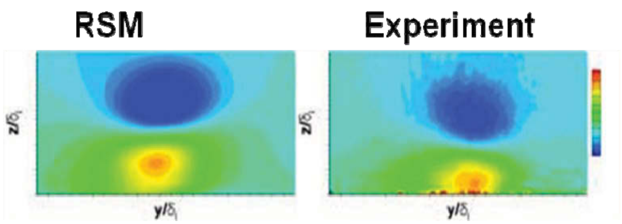
The following figure shows this comparison for the flat plate test case at randomly selected location downstream of the orifice for various velocity directions.



Stream wise velocity component (x/c=0.2m; flat plate)



Wall normal velocity component (x/c=0.2m; flat plate)



Span wise velocity component (x/c=0.2m; flat plate)

BILD 4. Single jet actuator: TAU prediction vs flat plate experiment [7]

The main outcome was that the RANS simulations can reasonably well predict the mean flow quantities for the steady (constant) vortex generators jets. This enables the transposition of the approach towards complex configurations, industrial applications. A more challenging investigation included steady vortex generators jets for stall delay. The RANS predictions and the experimental findings differed when it comes to the enhancement of maximum lift and corresponding maximum angle of attack. It is not surprising that with common turbulence models the prediction of maximum lift is still a challenge. Instead, with the AFC application, the flow complexity was increased. Although a steady blowing application was addressed, it is believed that a time-dependent simulation (URANS or high order modelling) is recommended for capturing the complex flowfield and predicting the stall behaviour.

In order to demonstrate the potential of high lift flow control at an industrial wing a proof of concept experiment was done at an industrial wind tunnel using a swept wing (Bild 5).

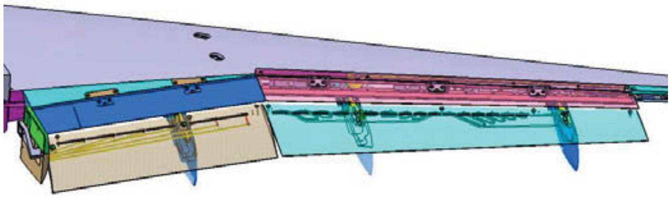


BILD 5. Sketch of swept wing with flow control equipped flaps. (LuFo / DFG-SFB557 investigated configuration at Airbus Bremen wind tunnel)

This was a joint collaboration of industry (Airbus), which provided the wind tunnel infrastructure and the model, and TU Berlin, which developed the complete flow control system hardware (as an essential part of DFG funded transfer projects: T4, T5 and T6 within SFB557; Ref. 11, 12, 13). The flow control concept is shown in BILD 6.

This final application of flow control within M-Fly was possible, since detailed and extensive studies for several disciplines were done at TU Berlin within DFG-SFB557 prior to the above mentioned transfer projects. These findings prepared the necessary know-how for an application at an industrial wing. This paper cannot describe the outcome of these institute investigations, the reader is referred to publications at the active flow control 2 conference (Berlin, 2010; King, R. Editor) mentioned in the references.

Besides the experimental findings, this high-lift wing-body configuration was also the subject of numerical investigations. The time-depended simulations conducted by DLR gave us for the first time a detailed view of the unsteady flow structures (see BILD 7).

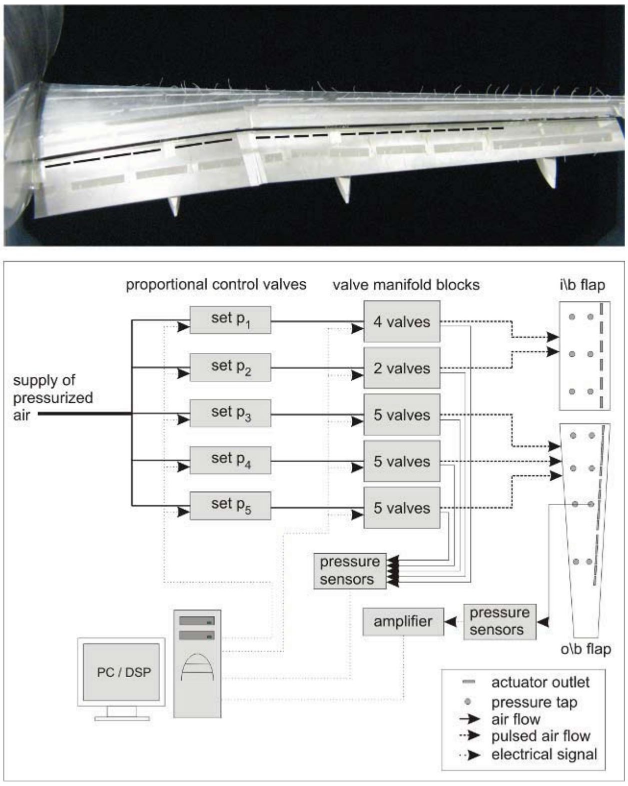


BILD 6. High lift flow control technology developed by TU Berlin (DFG-SFB557 [12])

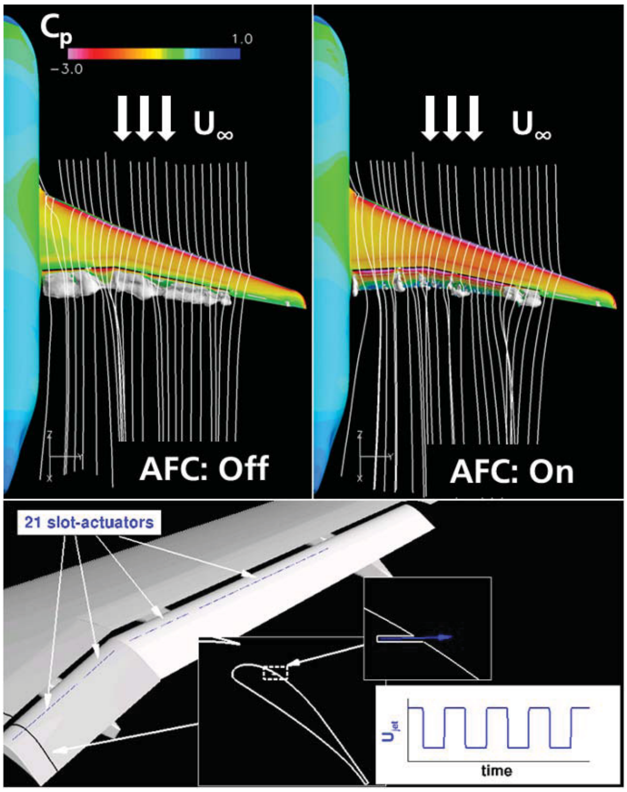


BILD 7. Time-dependent numerical simulation with Active Flow Control on the trailing edge flap of a transport aircraft configuration by DLR [14]

4. RESULTS FROM EUROPEAN FUNDED R&T PROJECTS

As explained above, the main goal of the European Joint Technology Initiative (SFWA is an essential part of it) is to further develop technologies following the ACARE goals.

In the SFWA two major large transport aircraft technologies shall be matured and validated, the all new low drag “smart wing”, and the integration of the most advanced engine concepts. In line with the concept of the CleanSky program, it is the explicit target to prove both technologies to a status close to a potential application through major dedicated large scale ground and flight demonstrations. The first key technology is the all new “smart wing”, which features a substantially reduced aerodynamic drag through a step changing laminar wing design. The second key technology is the integration of advanced propulsion system with special focus on the Contra Rotating Open Rotor (CROR), which has the potential for a uniquely large reduction in the specific fuel burn.
Additional technologies, supplementing in particular the development and validation of the smart wing, are being prepared, ground and flight tested in dedicated work packages. Low speed flow control technologies play a prominent role in these areas, since low speed flow control serves also as an enabler of laminar wing technologies.

The technical objective treated by a European consortium is to develop, design and test low speed flow control technology concepts in several wind tunnels accompanied by numerical predictions. The complexity of the configuration and size (thus Reynolds number) of these models are increased in a systematic fashion, in order to reach technology readiness levels in well defined steps.

Recently passive flow control testes were successful undertaken in a midsize wind tunnel at a swept wing, which is a vital step before testing active flow control concepts at swept wing configurations.

Previous EC funded projects (e.g. AVERT) indicated that active flow control applied to the flap will significantly increase the flap performance, this is in line with findings from national projects. This is very relevant for SFWA, since SFWA can extend and build upon this know-how.

The following figure sketches the two-dimensional configuration from AVERT project and the impact of increased actuator mass flow of dynamic jet actuators positioned at the flap leading edge.

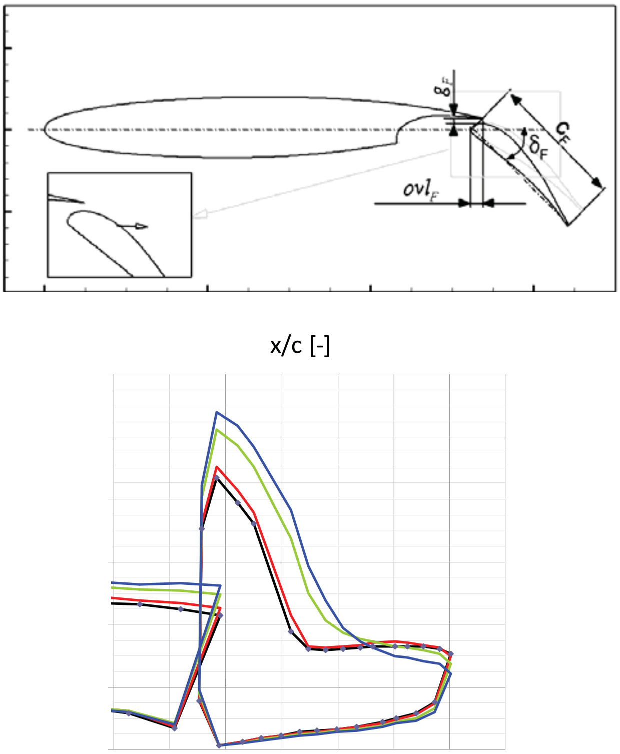


BILD 8. Flap configuration with high potential for lift enhancements via flow control [15]

In order to maximize the benefit of flow control it is essential, that the flow control concept is incorporated into the component design. DLR did extensive studies to design a flap, for which flow control concepts are taken into account right from the beginning of the design loop. The figure shows the flow control "receptive" shape of such a flap after various design cycles.

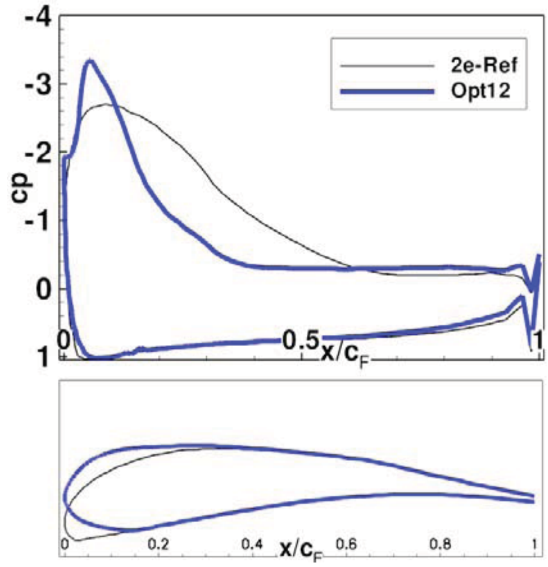


BILD 9. Flap design suitable for flow control. Black: starting condition (reference), Blue: result of shape optimization for flow control.

Similar design efforts and technology developments are currently ongoing for other components as well (e.g. leading edge flow control for slat less wing) but this paper can just highlight a few examples of SFWA.

In SFWA such developments at specific components are studied in work package 1 "Technology Development". Within WP1 flow control concepts are picked up at typical "laboratory levels" TRL 2 or TRL 3, to be advanced to a TRL 4. In work package 2 "New Configuration" the integration of the smart wing, respectively the innovative power plants as major components takes place, including the preparatory R&T to integrate the major parts into the overall aircraft concept. Work package 3 "Flight Demonstration" accommodates the flight demonstration activities to validate and demonstrate the SFWA target technologies under real operational condition in an aircraft environment at large or even full size. These demonstrators are providing the key information to advance the SFWA-technologies from TRL5 to TRL6. A specific "Low Speed smart Wing Flight Demonstrator" has been defined to further mature low speed flow control technologies.

For the purpose of an overview paper, one can just highlight a few examples from EC projects. In SFWA, all work packages are active, currently the focus for low speed flow control is still on work package 1 "Technology Development", and this focus will gradually shift towards work package 2 and 3 in the near future.

5. CONCLUSIONS

Within national projects (LuFo, DFG) major achievements were reached: These are vital steps towards larger scale demonstrations, which are core activities of R&T at European level.

The most relevant low speed flow control results within the scope of this paper are:

- Successful industrial high lift test in B-LSWT with flow control at flap indicate aerodynamic potential of high lift performance improvement
- Aerodynamic work on high lift flow control complemented system and FPO studies
- Detailed experimental studies with strakes and blowing to improve rear fuselage stall behaviour performed and recommendations for future flow control device settings formulated, however, this paper had to focus on high lift flow control results
- Grid and turbulence model studies successfully completed
- Predictions (TAU in RANS modus) in agreement with experimental trends
- Implementation of improved delayed DES in TAU completed
- DNS studies on pressure gradient impacts more challenging than expected, efforts within remaining project time redirected towards sweep angle effects
- CFD parameter studies, how control parameters influence jet formations performed

Within European project SFWA major results were achieved building upon the know-how of previous EC funded projects (e.g. AVERT) for passive and active low speed flow control items:

- An important wind tunnel test program to validate technology concepts for passive flow control devices has been performed and is now in analysis phase
- In addition and to support this aerodynamic proof of concept, structural and kinematic designs studies were performed. The goal is to derive an overall multidisciplinary concept for advanced passive flow control technologies for high lift devices.
- For active flow control numerical studies on the DLR F15 benchmark took place without and with flow control. The results are promising
- Investigations on structures items for flow control:
  - structural design for low speed high lift structural integration
  - analysis of general requirements for the structural incorporation of flow control

6. OUTLOOK

The following activities are essential elements of a systematic multi-annual approach:

- Further development of flow control techniques towards industrial needs (e.g. performance, energy needs, integration, maintenance and flight certification issues.)
- Proof of flow control concepts towards higher maturity, multidisciplinary studies
- Industrialization of actuator hardware including proof of robustness, efficiency
- Continuation of low speed flow control work in EC, nationally funded projects
- CFD enhancements: validation unsteady configurations, high quality experiments, supported by higher fidelity codes at R&T partnership
- Updates of industrial design processes to include flow control as a design parameter (to be based on proven tools).

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