Dynamic Flow Control Experiments for Innovative High-Lift Configurations in IHK / M-FLY Programs


1 Technische Universität Braunschweig, D-38106 Braunschweig, Germany
2 Technische Universität Berlin, D-10587 Berlin, Germany
3 Universität der Bundeswehr München, Werner-Heisenberg-Weg 39, D-85577 Neubiberg, Germany
4 Universität Stuttgart, Pfaffenwaldring 21, D-70550 Stuttgart, Germany
5 DLR, Institute of Aerodynamics and Flow Technology, D-38108 Braunschweig, Germany
6 Airbus Deutschland GmbH, Airbus-Allee 1, D-28199 Bremen, Germany.

Summary

Meaningful analysis of the performance potentials of dynamic flow actuators for increasing the lift is presently not possible without detailed wind-tunnel experiments on realistic airfoil shapes. The approach of the present work consists of combining advanced flow actuation approaches to delay flow separation on both the high-lift flap and the leading edge of the main wing of a state-of-the-art, two-element airfoil section and performing high-quality flow measurements at chord Reynolds numbers between 2 and 3 Million. The project objective is to demonstrate technology potentials to increase the maximum lift coefficient as well as the maximum angle of attack, and to identify possible interactions between the different flow actuation approaches along with guidelines for future aerodynamic design improvements and needs for further testing.

1 Introduction

Dynamic 3D actuators for the control of turbulent shear layers at high-lift configurations aim at improved lift coefficients. This can be exploited to simplify the high-lift system or to increase its aerodynamic performance which in turn could improve aircraft performance, reduce noise sources and possibly reduce aircraft cost. Furthermore, dynamic flow control may be viewed as a development towards the laminar-flow wing since it may be used to avoid slotted leading-edge high-lift devices and their distortions to the clean wing flow.

While significant basic research on the understanding of dynamic flow actuators has been accumulated over recent years, meaningful analysis of the performance potentials of such systems, installed on a transport aircraft configuration, is not possible without detailed wind-tunnel experiments on realistic airfoil shapes. The innovation of the present work consists of combining advanced flow actuation approaches to delay flow separation on both the high-lift flap and the leading edge of the main wing of a state-of-the-art, two-element airfoil section and performing high-quality flow measurements at chord Reynolds numbers between 2 and 3 million. The project objective was to demonstrate technology potentials to increase maximum lift coefficient as well as the maximum angle of attack, and to identify possible interactions between the different flow actuation approaches along with guidelines for future aerodynamic design improvements.

The work content covered by the present paper has been performed in the German Aeronautics programs IHK (“Innovative Hochauftriebskonfiguration”) and M-FLY (“Multidisziplinäre Flugphysikalische Optimierung”), in which co-ordination and co-operation with Airbus have taken place [1]. The contributions of the IHK program focused on the understanding of mechanisms for effective boundary-layer actuation and on the design and qualification of actuator devices for affecting the leading edge flow and the flow over the high-lift flap. The airfoil wind tunnel model named DLR-F15 was also designed and manufactured and it was equipped with the actuation devices. After two wind tunnel entries performed within the program IHK
extended research into the parameter space of efficient flow actuation was performed within M-FLY and this effort is still being continued.

In the frame of these efforts, universities combined their knowledge and technologies in the control and delay of different flow separation processes of high-lift airfoils. Technische Universität Berlin introduced pulsed operation of a suited blowing system on the slotted high-lift flap. The approach is based on the observation that the shear layer of the slot flow over the flap is very receptive to two-dimensional forcing and hence, dynamic blowing from spanwise, segmented slots in the forward part of the flap is an effective means to enhance momentum transfer within the shear layer and delay flow separation [2]-[5].

Technische Universität Braunschweig contributed pneumatic vortex generators designed to delay boundary layer separation at the leading edge [6], which was expected for large flap deflection angles. Axial vortices can be generated by normal blowing from yawed slots or by using oblique-direction blowing from circular holes. The large parameter space of these devices had been experimentally explored for flows over flat plates and single-element airfoils [7], [8]. In parallel Universität Stuttgart performed numerical simulations in order to better understand flow phenomena of pneumatic vortex generators [9].

DLR lead the effort to design and manufacture a 0.6m chord wind tunnel model to be tested in DNW-NWB wind tunnel. While the baseline model provided options for testing two-element and three-element high lift configurations, the dynamic flow control systems defined by Technische Universität Berlin and Technische Universität Braunschweig were integrated into the two-element airfoil. Following detailed testing of the reference configurations without flow control [10] the partners jointly performed tests of the DLR-F15 airfoil model during several tunnel entries. The present paper describes the complex wind tunnel model DLR-F15 equipped with the different actuator systems. These systems proved their function throughout the testing. Aerodynamic results were obtained for several flap settings and actuation system parameters. Ranges of efficient flow control operation and significant increases of maximum lift and corresponding angles of attack could be obtained.

2 Experimental Setup and Results

The airfoil wind tunnel model DLR-F15 is designed in a modular setup as shown in Fig. 1. The model has several rows of pressure tabs to evaluate sectional normal forces. The design allows for rather efficient changes of the configuration during the tests. The two-element model configuration was used in the present work. Fig. 2 displays the model mounted in the atmospheric wind tunnel DNW-NWB along with the wake rake used to measure airfoil drag. Several different model setting configurations were investigated to assess flow control potentials, four of them have been identified for more detailed analysis according to Fig.3. The configuration fs#1 maximizes lift coefficients without severe flap separation using moderate flap angles, see Fig.4. The aerodynamic flap loading was then increased by somewhat larger flap angles and increased gap in fs#2, and by increasing flap angles to a larger extent in fs#3. Configuration fs#4 combined both strategies, leading to rather large flow separations on the flap. Effects of transition from laminar to turbulent were carefully monitored during initial testing and transition strips using tape and pneumatic turbulators were used on the leading edges of the main wing and the flap to avoid premature stall and lift hysteresis associated with these moderate Reynolds numbers (Fig.5). Sidewall boundary layer effects on the stalling behavior were also analyzed by varying the configuration close to the wind tunnel sideline. It was found that the 3D flow close to the side wall tends to stall early, thereby causing some nonlinearity of the lift curves close to maximum lift [10].

Fundamental aerodynamic mechanisms of axial vortex generators were investigated by direct numerical simulations [9] and comparisons to flow field measurements [7] for simpler geometries as shown in Figs. 6-8. Regions of blockage by the actuation device and momentum increase close to the wall were identified and this helped the selection of actuators for the high-lift airfoil. Fig. 9 sketches the leading edge actuation scheme finally used. Locating the actuation orifices at the lower leading edge surface keeps blockage areas away from adverse pressure gradients and takes advantage of lower blowing velocities required. Note that the definition of momentum coefficient given in Fig.9 is used throughout this paper. Fig.10-11 display the results of leading-edge flow control on case fs#3, for which leading edge stall could be successfully
suppressed and trailing edge stall eventually took over. Gains obtained by leading-edge flow actuation for numerous cases are finally displayed in Fig. 12. Areas of effective flow actuation with significant gains on maximum lift and the corresponding angles of attack are observed.

The setup introduced by Technische Universität Berlin for active control of slotted-flap flow separation is displayed in Fig. 13. This system was integrated into the CFRP flap structure along the full span of the configuration. Figs. 14-15 display efficient lift enhancement and drag reduction obtained for configuration fs#4. The actuation forces the flow to re-attach up to the tailing edge as seen from the pressure distributions in Fig.16. The amount of lift augmentation by using the active flap therefore depends on the amount of flow separation present on the flap without actuation. Finally, Fig.17 displays test data where both leading edge and flap actuation were employed. To this point we find that the effects may be regarded as additive, i.e. no disadvantageous interactions of dynamic actuation schemes were observed.

3 Conclusions

The results of the present work demonstrate successful qualification and operations of advanced dynamical flow actuation systems on a medium size high-lift airfoil wind tunnel model. These systems proved effective at flow conditions for which flow separations were present at suited locations along the airfoil. The results point to the need to develop and verify aerodynamic design rules and methods that anticipate the possible use of flow control early in design. Next research steps in flow control for high-lift systems will also address delay of trailing edge separations on the main wing, since it is felt that geometries optimized for maximum lift applications exhibit trailing edge stall in many instances. Ranges of efficient flow actuation should be extended by employing staggered flow actuation and suitable control laws should be explored to further reduce the power needed for actuation. Finally, wind tunnel testing at higher Reynolds numbers and on 3D wing sections should be pursued.

Acknowledgements

This work was funded by the German Government within the frames of the 3rd and 4th Aerospace Research Programs (LuFo III and LuFo IV).

References

triple segmented main wing for adaptation of leading and trailing edge devices
side adapters for variable span for different tunnel cross sections
continuously adjustable brackets in all degrees of freedom
chord length $= 0.6$m

Figure 1: Layout of Wind Tunnel Model DLR-F15

- DLR F15-model in DNW/NWB:
  - wall-to-wall 2D high-lift model
  - $2.8 \times 3.2$m closed test section
  - normal forces from pressure integration, drag from wake probing
  - force data uncorrected for tunnel wall interference
  - typical flow conditions:
    - $Ma = 0.15 \sim 0.2$
    - $Re = 2.0 \times 10^5 \sim 3.0 \times 10^6$

Figure 2: Experimental Setup
- fs#1  "optimal setting"
  - optimized with numerical methods to give maximum $c_{\text{drag,\text{max}}}$ in two-element configuration
  - $\phi_e=40.1^\circ; \, g=0.8 \%, \, \phi=2.3 \%$
- fs#2  "increased gap"
  - increased gap $\Delta g/c = 2.0\%$
  - slightly increased flap angle
  - $\phi_e=45.0^\circ; \, g=2.7 \%, \, \phi=0.5 \%$
- fs#3  "increased angle"
  - increased angle $\phi_e=49.0^\circ$
  - $\phi_e=49.1^\circ; \, g=0.9 \%, \, \phi=2.3 \%$
- fs#4  "increased gap & angle"
  - mixture of fs#2 and fs#3
  - $\phi_e=49.0^\circ; \, g=2.7 \%, \, \phi=0.5 \%$

Figure 3: Configurations for Flow Control Research (Not to Scale)

Increasing flap circulation leads to stalling from the L/E

Figure 4: Configurations for Flow Control Research

Tesa-film, $d = 50 \mu m$

$b = 2 \, mm$

$x=4.5mm$  $x=0mm$

Figure 5: Sample Result of Transition Fixing Investigations
• Supplement experiments by numerical simulation
• Provide theoretical background / support
• More insight into unsteady flow-field details
• Mechanisms for generation of longitudinal vortices

*Figure 6: DNS of Jet Vortex Actuators on Flat Plate by Uni Stuttgart*

**Simulation A**

**Simulation B**
• reduced distance
• higher $c_\mu$

*Figure 7: Streamwise Momentum Coefficient at $y = 0.25$ mm*

**Experiment**

**Simulation B**

30 mm behind slot center

*Figure 8: Slot actuator: Streamwise Velocity Difference (controlled – uncontrolled flow)*
Actuator orifices: circular holes, $\alpha=30^\circ$, $\beta=90^\circ$, diverging/converging orientation

Momentum coefficient:
$$c_m = \frac{\dot{m}_j \Delta v_j}{\rho/2 V_c^2 A_{wing}}$$

**Figure 9**: Flow Actuation at Leading Edge: Assembly of Actuator Device by TU Braunschweig

**Figure 10**: L/E Separation Delay by Boundary Layer Actuation ($fs\#3$ $Re = 2.0 \times 10^6$)

**Figure 11**: L/E Separation Delay by Boundary Layer Actuation ($fs\#3$ $Re = 2.0 \times 10^6$)
• $\Delta \alpha_{\text{max}}$ correlates well with $c_p$ (for a given flap setting)
• $\Delta \alpha_{\text{max}}$ scatters (T/E-stall, attaching flap flow)
• weak Re-sensitivity (fs#2)

**Figure 12:** Efficiency of L/E Separation Delay

Maximum excitation frequency, $f_{x, \text{max}} = 330 \text{Hz}$
Maximum duct pressure, $\rho_{d, \text{max}} = 8 \text{bar}$
Location of excitation, $x_{c}/c_t = 20\%$
Blowing angle, $\beta = 30^\circ$

**Figure 13:** Flow Actuation of High Lift Flap: Assembly of Actuator Device by TU Berlin

Effect of AFC on lift curve

$\delta = 49^\circ$, gap=2.7%, overlap=0.5%

$f = 300 \text{Hz}$, $St_i = 1.0$, $\Delta = 50\%$

**Figure 14:** Active Flow Control on High-Lift Flap (fs#4, $Re = 2.0 \cdot 10^6$)
Effect of AFC on drag polar

$\delta_r = 49^\circ$, gap=2.7%, overlap=0.5%

$f=300$Hz, $St_r = 1.0$, $\Delta = 50\%$

![Graph showing effect of AFC on drag polar](image)

Figure 15: Active Flow Control on High-Lift Flap ($f=300$Hz, $Re = 2.0 \cdot 10^6$)

Effect of AFC on cp-distributions

$\delta_r = 49^\circ$, gap=2.7%, ovl=0.5%

$f=300$Hz, $St_r = 1.0$, $\Delta = 50\%$

![Graph showing effect of AFC on cp-distributions](image)

Figure 16: Active Flow Control on High-Lift Flap ($f=300$Hz, $Re = 2.0 \cdot 10^6$)

- flap setting $\delta_r = 45^\circ$, gap=2.65%, ovl=0.55%
- Effects of L/E- and Flap-Actuation are mostly independent of each other
- Effects are additive
- Disadvantageous interactions of the dynamics have not been discovered

![Graph showing effects of actuation](image)

Figure 17: Combined Actuation L/E & High-Lift Flap ($f=300$, $Re = 2.0 \cdot 10^6$)