An Active Flow Control Strategy for High-Lift Flaps

F. Haucke\textsuperscript{1}, M. Bauer\textsuperscript{1}, T. Grund\textsuperscript{1}, W. Nitsche\textsuperscript{1}, B. Gölling\textsuperscript{2}

\textsuperscript{1} Technische Universität Berlin, Institut für Luft- und Raumfahrt
Marchstraße 12, 10587 Berlin, Germany
Frank.Haucke@ilr.tu-berlin.de

\textsuperscript{2} AIRBUS, High-Lift Devices, Flight Physics
Airbus-Allee 1, 28199 Bremen, Germany

The present paper describes an approach for active flow control by means of pulsed blowing from the flap shoulder in order to delay turbulent flow separation. Current investigations of TUB are mainly focused on three different types of wing models. The first experimental setup is a two-dimensional high-lift configuration consisting of a main element and a single slotted trailing edge flap at a Reynolds Number of \( R_{e_c} = 1 \cdot 10^6 \). It has a transonic body shape in clean configuration. The next step was to extend these AFC investigations to realistic models such as a three-dimensional half model with a three element high lift configuration of finite span at Reynolds Numbers of up to \( R_{e_c} = 1.6 \cdot 10^6 \) and Mach Numbers of up to \( M_a = 0.2 \). Another project at TUB deals with the application of AFC on the plain flap of the sailplane “Stemme S10”. The single slotted trailing edge flaps or plain flap respectively of the different models are equipped with a specially designed excitation mechanism that is capable of producing a pulsed wall jet with high jet velocities using compressed air and fast switching solenoid valves. The results include measurements from a six-component wind tunnel balance and miniature pressure sensors. For each case, this paper will show the effectiveness using this kind of AFC in more detail. For selected configurations, significant enhancements in lift coefficients were achieved, while drag forces were reduced.

1 Nomenclature

<table>
<thead>
<tr>
<th>symbol</th>
<th>unit</th>
<th>description</th>
<th>symbol</th>
<th>unit</th>
<th>description</th>
</tr>
</thead>
<tbody>
<tr>
<td>( b )</td>
<td>[mm]</td>
<td>span</td>
<td>( \alpha, \alpha_{AoA} )</td>
<td>[(^\circ)]</td>
<td>angle of attack</td>
</tr>
<tr>
<td>( c_{flap} )</td>
<td>[mm]</td>
<td>flap chord length</td>
<td>( \beta )</td>
<td>[(^\circ)]</td>
<td>blowing angle</td>
</tr>
<tr>
<td>( c_{ref} )</td>
<td>[mm]</td>
<td>reference chord length</td>
<td>( \delta_f )</td>
<td>[(^\circ)]</td>
<td>flap deflection angle</td>
</tr>
<tr>
<td>( c_p )</td>
<td>[-]</td>
<td>pressure coefficient</td>
<td>AFC</td>
<td>active flow control</td>
<td></td>
</tr>
<tr>
<td>( C_D )</td>
<td>[-]</td>
<td>drag coefficient</td>
<td>TUB</td>
<td>Technische Universität Berlin</td>
<td></td>
</tr>
<tr>
<td>( C_L )</td>
<td>[-]</td>
<td>lift coefficient</td>
<td>BIT</td>
<td>Berlin Institute of Technology = TUB</td>
<td></td>
</tr>
<tr>
<td>( D_{Ce} )</td>
<td>[-]</td>
<td>duty cycle of excitation</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>( f_e )</td>
<td>[Hz]</td>
<td>frequency of excitation</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>( F_{re} )</td>
<td>[-]</td>
<td>reduced frequency of excitation</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>( m_{jet} )</td>
<td>[kg sin]</td>
<td>mass flow of pulsed jet</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>( p_d )</td>
<td>[bar]</td>
<td>pressure in the duct</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>( Re_c )</td>
<td>[-]</td>
<td>chord Reynolds number</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>( S_{ref} )</td>
<td>[m(^2)]</td>
<td>reference area</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>( t )</td>
<td>[s]</td>
<td>time</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>( T )</td>
<td>[s]</td>
<td>periodic time</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>( u )</td>
<td>[m/s]</td>
<td>velocity</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>( u_{jet} )</td>
<td>[m/s]</td>
<td>velocity of pulsed jet</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>( w_{in} )</td>
<td>[m/s]</td>
<td>incident velocity</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>( V_N )</td>
<td>[m/s]</td>
<td>normalized volume flow rate</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>( x, y, z )</td>
<td>[m]</td>
<td>cartesian coordinates</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

2 Introduction

Effective but simple high lift devices become more important for cases of high take-off weights, steep approach trajectories and short take off and landing distances. The limits of high lift systems are set by the poor properties of highly decelerated flows, which are caused by high deflection angles. The aim is to avoid turbulent flow separation using local periodic excitation. In the past many investigations regarding active flow control on different models were carried out. It was
AFC on High-Lift Configurations

demonstrated experimentally that periodic excitation on single airfoils [1, 2] is effective. Different mechanisms for active flow control are being employed. Melton et al. [3] used a piezoelectric actuator for zero-net-mass-flux excitation on the flap shoulder of a supercritical airfoil. Petz et al. [4] investigated active separation control on the trailing edge flap of a generic two-dimensional high lift configuration, which consisted of two different NACA airfoils. The lift to drag ratio was increased by up to 25% for selected configurations. The same authors [5] also conducted experiments with a more realistic model, a three-dimensional constant chord sweptback wing. In both cases, periodic pulsed jets were used successfully to control turbulent flow separation on the trailing edge flap. An externally compressed air supply, fast switching solenoid valves and specially designed actuator chambers are the three main components of the described actuator system. These experiments indicated that both, the location and direction of the jets have a significant influence on the effectiveness of separation control. Due to the large number of variable parameters, it is expensive and time consuming to investigate every combination manually. Therefore closed loop control was used to optimize parameters like frequency and duty cycle to speed up the maximization of lift and drag improvements. Currently three different types of wing models are being used at TUB for active flow control investigations on trailing edge flaps. One model is a two-dimensional wing in high-lift configuration consisting of a main element and a single slotted trailing edge flap at a Reynolds Number of $Re_c = 1 \cdot 10^6$. In clean configuration this model has a transonic body shape. For selected test cases enhancements in lift of up to 25% were achieved, while drag forces were reduced [6]. Further research is also directed to the actuator performance such as optimizing actuator chamber design and positioning on the flap while using the advantages of closed loop separation control. Following the work of Petz et al. [5], a more realistic three dimensional half model is currently used for investigations regarding active flow control using pulsed jets from the flap shoulder. TUB is also working on another project, which deals with the application of AFC on the plain flap of the sailplane “Stemme S10”. Active flow control using periodic pulsed jets is a promising way to improve high-lift performance of real aircrafts. If sufficient enhancement in aerodynamic performance can be achieved in an efficient way, the complexity, weight and dimensions of flap systems could be reduced and thereby lower the direct operating costs (DOC).

3 Actuator System

One actuator segment consists of three main components; a supply of compressed air, a fast switching solenoid valve and a chamber (see fig. 1).

![Fig. 1 Schematic Assembling of Actuator System](image)

With a square wave supply voltage (see fig. 1), which is controlled by a computer, each fast switching solenoid valve is opened and closed cyclically with the desired frequency and duty cycle. This generates an oscillating flow within the connecting pipe to the actuator chamber. The purpose of the chamber is to transform the pulsed flow, originating from the valve, into an oscillating jet with the desired jet geometry. Thereby the local and temporal distribution of the jet along the slot depends on the internal geometry of the actuator chamber. The amplitude, or momentum coefficient $c_p$ respectively, of the pulsed jets is determined by the pressure within the compressed air duct which is controlled by electronic proportional pressure regulators outside the test section. In addition, an electronic mass flow rate meter is used in order to determine the consumption and the momentum coefficient of compressed air. For the measurements it is possible to control the actuator segments in frequency and duty cycle independently from each other.

4 Wind Tunnel Model A

Parallel to the national project M-Fly which is funded by the government within the “Luftfahrtforschungs- und Technologieprogramm” of the Federal Republic of Germany a two dimensional high lift configuration consisting of a main
element and a single slotted trailing edge flap is used for experimental investigations regarding AFC. In clean configuration this model has a transonic body shape and a profile depth of $c_{ref} = 600\text{ mm}$ (see fig. 2). This configuration is of simple geometry but the usage of a modern profile is a step to further AFC applications on more realistic models.

4.1 Model A - Experimental Setup

All experiments for wing model A were carried out in a closed-loop wind tunnel. For these measurements maximum flow velocities of up to 30m/s were used. The corresponding Reynolds numbers reached values of about $1 \cdot 10^6$. Transition fixing was employed to ensure a fully developed turbulent flow for each configuration. Therefore small tape strips were applied in span-wise direction near the leading edges of the main element and the flap. One fixing was found that was capable of generating a turbulent flow and preventing a laminar leading edge separation for all tested configurations.

4.2 Model A - Actuator Setup

In this case the actuator slots are located at $x_e/c_{flap} = 0.2$ and the geometrical blowing angle is $\beta = 30^\circ$ with respect to the flap’s upper surface. 13 actuator segments, each with a slot width of 0.4mm and a slot length of 50mm, are integrated side by side in span wise direction within the flap, see fig. 3.

A large number of parameters can be varied for the AFC experiments. The location and direction of excitation is fixed for the flap. Flap gap and flap overlap (see fig.3) can be changed manually during the experiments. Angle of attack,
flap deflection angle and excitation parameters (see fig.1), such as frequency, duty cycle and momentum coefficient are changed by computer controlled devices.

4.3 Model A - Results

All results presented for wind tunnel model A were obtained for a chord Reynolds number of about \(\text{Re}_c = 1 \cdot 10^6\). The forces and moments measured by the six-component balance are corrected by a standard wind tunnel correction method [7]. Figure 4 shows lift and drag versus angle of attack for a flap deflection angle of \(\delta_f = 40^\circ\). While the gap is set to \(\text{gap} = 2.1\%\), the overlap value is set to \(\text{overlap} = 0.55\%\). The maximum angle of attack is about \(\alpha_{\text{C}_\text{L, max}} = 8^\circ\) for the unexcited base flow. For higher AoA lift decreases and drag increases drastically due to turbulent flow separation on the main wing.

Pulsed blowing using this actuator setting results in significantly enhanced lift. An increasing momentum coefficient leads to increased lift forces, while the drag is slightly decreased in the linear regime of the lift polar. At the same time the maximum angle of attack is slightly reduced. In addition, figure 4 shows the actuation efficiency, which is the ratio of lift enhancement and momentum coefficient, vs. momentum coefficient. In the present example for each AoA between \(\alpha = 0^\circ\) and \(\alpha = 8^\circ\) the highest values for actuation efficiency were obtained for the smallest investigated momentum coefficients of about \(c_\mu \approx 0.12\%\). For increasing momentum coefficients or increasing AoA the actuation efficiency is reduced. Obviously there has to be a maximum in actuation efficiency in a \(c_\mu\)-range of \(0 < c_\mu < 0.12\%\) for this actuator setup if this correlation is a continuous function and the point of origin is included as well. For higher AoA (\(\alpha > 8^\circ\)) turbulent flow separation on the main element occurs and causes a drastic reduction in lift. In this region there is no benefit generated by AFC. The corresponding distribution of pressure coefficients for \(\alpha = 5^\circ\) is shown in figure 5. The flow separation on the flap occurs between \(x_e/c_{flap} = 0.2\) and \(x_e/c_{flap} = 0.3\), which is expressed by the constant pressure level further downstream. Due to excitation, the pressure on the flap’s upper surface is lowered significantly at this span wise location and separation is suppressed. The whole pressure level of the main element’s upper surface is lowered significantly as well, which is the main reason for the global lift increase. The more the momentum coefficient is increased, the lower the pressure levels are on the element’s upper sides, while the pressure on the lower surfaces of main wing and flap is only slightly changed.

In addition, figure 5 shows an oil flow visualisation for the unexcited base flow and for the flow with AFC for slightly changed flap configuration. Without AFC, large separation areas occur in the mid section and the outer regions of the flap which is caused by the strong deceleration of the flow. Due to excitation, the pressure on the flap’s upper surface is lowered significantly at this span wise location and separation is suppressed. The whole pressure level of the main element’s upper surface is lowered significantly as well, which is the main reason for the global lift increase. The more the momentum coefficient is increased, the lower the pressure levels are on the element’s upper sides, while the pressure on the lower surfaces of main wing and flap is only slightly changed.

In addition, figure 5 shows an oil flow visualisation for the unexcited base flow and for the flow with AFC for slightly changed flap configuration. Without AFC, large separation areas occur in the mid section and the outer regions of the flap which is caused by the strong deceleration of the flow. Although a two-dimensional wing configuration is used, the separation areas are interrupted by flow which is attached for a longer distance. This 3D separation scenario is caused by the flap holders that are used to fix the flap. Activating AFC causes the flow to attach directly downstream of the excitation locations. The flow between two actuator slots is attached for a longer distance and only small separation areas occur further downstream.
4.4 Model A - Conclusion

Active flow control on a slatless two-dimensional high-lift configuration was investigated. Pulsed jets from the flap’s shoulder were used to suppress turbulent flow separation. Compared to the base flow without excitation, pulsed blowing is able to keep the flow attached. Hence, the trailing edge pressure of the main wing is significantly reduced. As the excitation affects the stagnation pressure location of the main element as well, the pressure on the upper surface is lowered, resulting in lift coefficient improvement. Drag forces can also be reduced using periodic blowing. The improvement in lift coefficients depends on the configuration and reached values of about 25%. Further investigations on this topic will focus on analyzing the physics of the high-lift flow field by using time-resolved miniature pressure sensors and particle image velocimetry in order to find an optimal way of excitation, while including the advantages of a closed-loop separation control. The influence of Reynolds number on active flow control is another important point that will be focused on as well.

5 Wind Tunnel Model B

In cooperation with Airbus, active separation control experiments were conducted on a three element wind tunnel model in high-lift configuration with a slat and a single slotted flap. The designated model’s wing is swept, tapered and finite; therefore the flow over the wing is highly three-dimensional. The immediate aim of the experiment is to eliminate flow separation on the model’s trailing edge flaps by means of pulsed blowing at the flap shoulder. To achieve that, the model was equipped with actuators which allowed generating unsteady jets exiting the flaps through rectangular slots at defined positions.

5.1 Model B - Experimental Setup

A combination of proportional and fast switching valves allowed for setting the amplitude and frequency of the excitation independently for each of the 21 actuators integrated in the flaps. For details of the actuation system, see figure 6 and 1. During the test, different deflection angles of the flaps, as well as different settings for gap and overlap are investigated.

A 6-component balance is used for measuring the forces and moments on the model, from which the aerodynamic coefficients can be calculated. These coefficients are employed to assess the quality of the AFC attempts for different flow control parameters and different high-lift configuration settings.

The tests were conducted at a Mach number of $M = 0.2$ and a Reynolds number of $Re = 1.6 \cdot 10^6$ at the Airbus Low Speed Wind Tunnel facility in Bremen, which provides a test section of 2.1m x 2.1m.

5.2 Model B - Results

On the configuration of interest, natural separation occurs on the flap if no AFC is applied. By variation of the flow control parameters, their influence on the lift gain is ascertained. The efficiency of the AFC system is of special interest in this industrial measurement campaign. Figure 7 gives an overview over the results obtained during the campaign.
The upper left graph presents a comparison of different lift polars to visualize the lift gain achieved by AFC. As there is no separation on the flap for the optimized configuration in the linear regime, the gap is increased to force separation. For this modified configuration, a lift gain of about $\Delta c_L \approx 0.3$ is achieved in the linear regime of the polar. For high AoAs, the flow separates on the flap even on the optimized configuration. Therefore a $\Delta c_L$ of approximately 0.12 can be gained compared to optimized configuration in the non-linear region of the polar, although the camber of the configuration is reduced due to the modified configuration. Another virtue of AFC is presented in the top right plot, where the optimized configuration is compared to a configuration with increased flap deflection angle. Without AFC the flow is fully separated on the flap at a deflection angle of $\delta_f = 50^\circ$. This separation is prevented with the use of AFC and therefore allows a higher camber for the high-lift configuration. The combination of increased flap deflection angle and AFC therefore increases the lift in the linear and non-linear regime of the polar compared to the optimized passive configuration.

Lift gain or loss for different AoA as a function of $c_\mu$ is displayed in the bottom left plot of figure 7. At low AoA, actuation with small amplitudes leads to a reduction of lift, while for AoA greater than about 3°, any actuation increases the lift. The largest gain in lift is achieved with the maximum $c_\mu$ available of about $c_\mu = 0.85\%$. There, $c_L$ can be increased by approximately 25 to 30 lift counts. The bottom right plot shows the efficiency of the actuation for different angles of attack as a function of $c_\mu$. The efficiency is here defined as: efficiency $\approx \frac{\Delta c_L}{c_\mu}$. As mentioned above, actuation at low AoA with low intensity leads to a loss in lift. Therefore the efficiency is negative in these cases. At low values for $c_\mu$, small variations of the lift gain for different AoA have a tremendous influence on the efficiency. For $c_\mu$ higher than about 0.3%, the efficiency differs only about $\pm 20\%$ and with maximum excitation the variation is down to about $\pm 1\%$.

5.3 Model B - Conclusion

The experiments verified the concept of pulsed blowing as a suitable tool for separation control on a complex model at landing Mach number and reasonable Reynolds number. Lift was increased significantly over a broad range of angles of attack with only moderate energy input necessary.
AFC on High- Lift Configurations

Fig. 7 Results of the campaign: Top Left: Lift polars for optimized passive configuration, AFC reference configuration and for the case of AFC on (all $\delta_f = 45^\circ$); Top Right: Lift polars for optimized passive configuration ($\delta_f = 45^\circ$) and for the case of AFC on ($\delta_f = 50^\circ$); Bottom Left: Actuation Efficiency at different AoA as a function actuation amplitude; Bottom Right: Comparison of actuation with pulsed blowing and continuous blowing

6 Wind Tunnel Model C

This part of the paper presents first experimental results regarding AFC that were obtained with a real wing section of the “Stemme S10” glider, the HQ41-airfoil. The reference chord length is 0.83m and the wing’s span is 1.55m. This laminar airfoil has a 14.5% chord plain flap and a low taper ratio. These investigations are carried out in the context of the “Sonderforschungsbereich SFB 557 - Control of complex turbulent shear flows” - in preparation for In-flight demonstration tests for AFC applications.

6.1 Model C - Experimental Setup

All investigations were conducted in a closed-loop wind tunnel with a low degree of turbulence of 0.3% with the same test section as used for model A. With a Reynolds number of up to $Re_c = 1.75 \cdot 10^6$, incident velocities of a real glider are covered. While angle of attack $\alpha$ can be varied automatically, flap deflection angle has to be adjusted manually. The experiments are carried out with a flap deflection angle of $\delta_f = 16^\circ$, which is relevant for In-flight experiments. Forces and moments are measured with a six-component balance (see fig. 2) and are corrected using a standard wind tunnel wall correction method [7]. In order to assess the local flow field, the static pressure at the mid section $y/b=0.5$ is measured using pressure transducers that are installed inside the wing.
6.2 Model C: Actuator Setup

The actuator chambers were produced using stereo lithography method. The application of this method allows complex inner contours of the actuator chambers. As described in chapter 3 14 actuator segments were integrated in the plain flap in span wise direction. One segment is 27mm high, 17mm wide and 80mm long, see fig. 9(left). The actuators are located at $x_e/c_{flap} = 15\%$ of the flap’s chord length with a slot width of 0.3mm and an blowing angle of $35^\circ$ with respect to the flap’s surface.

6.3 Model C - Results

The presented results show a summary of the previous measurements with actuation. In the first attempts all actuators were driven by the same signal. A variation of mass flow rate and of frequency was carried out for a flap deflection angle of $16^\circ$.

Figure 10 shows lift (left diagram) and drag (right diagram) coefficients versus angle of attack. A comparison of the unexcited and the actuated flow is given for different mass flow rates at a fixed actuation frequency. A gain in lift is
recognizable in the linear regime of the lift polar for pulse d excitation. With increasing momentum coefficient $c_\mu$ (increase of the mass flow rate) lift is increased further. A reduction of drag is found for negative angles of attack as shown in the right diagram of figure 10. For $\alpha > 3^\circ$ and a momentum coefficient $> 0.05\%$, drag is increased slightly.

![Figure 11: Model C: example of actuator efficiency](image1)

In figure 11 the actuation efficiency versus momentum coefficient for angles of attack between $\alpha = -4^\circ$ and $\alpha = 4^\circ$ is displayed. The highest efficiency of actuation is obtained for an AoA of $\alpha = 2^\circ$ whereas it is reduced significantly for $\alpha = 4^\circ$. The reason for this is the reduction of $\Delta C_L$ from an AoA of approximately 3 degrees on, see fig. 10.

Figure 12 shows the pressure distribution of the wing section for an angle of attack of $\alpha = 2^\circ$ with and without excitation for two different frequencies. Due to excitation on the flap at the static pressure on the main wing is reduced which leads to an increase in lift. In addition, the actuated flow reattaches and therefore drag is reduced.

The benefit of the pulsed excitation can be represented by the improvement of aerodynamic quality of the wing. An example for this lift to drag ratio is displayed in figure 12 (right). The increase in lift as well as the reduction of drag lead to a benefit of up to 20% in the lift to drag ratio for the relevant flight application case.

![Figure 12: Model C: examples for static pressure distribution (left) and a lift to drag ratio (right) with/without excitation](image2)

### 6.4 Model C - Conclusion

Active flow control on a real glider wing section was investigated. In these tests mass flow rate and actuation frequency were varied to assess their influence an AFC. The results show a gain of lift and a reduction of drag in the angle of attack range relevant for In-flight tests. An improvement of the lift to drag ratio of up to 20% was achieved.
7 Conclusion

Flow control experiments have been carried out on three different models: a two element 2D high-lift configuration, a three element 3D high lift-configuration and a glider wing section with a plain flap. An actuator system was developed that allowed the generation on a pulsed jet exiting from the flap shoulder, which intensifies turbulent structures and therefore delays separation on the flap.

The presented experiments demonstrate that TUB’s actuation system provides sufficient control authority to keep a decelerated flow over a flap attached or to enforce reattachment of a separated flow. The required energy input is moderate with a required $c_p$ of less than 1%. The actuation concept was transferred from generic studies to increasingly complex geometries such as the 2D two element airfoils or the 3D high-lift configuration presented in this paper. The capabilities of the actuation system in In-flight experiments will be investigated on the “Stemme S10” sailplane.

The results obtained so far show a significant increase in lift of up to 50 lift counts, depending on the configuration. Through optimization of excitation parameters as well as of excitation location and other geometrical parameters, further improvement of AFC efficiency and lift gain may be achieved. Especially the combination of AFC and closed loop control may open up new fields of AFC applications and lead to enhanced overall performance of an aircraft.

Acknowledgments

This work is being supported in the national projects “Multidisziplinäre Flugphysikalische Optimierung M-Fly”, “Sonderforschungsbereich SFB557” and “Transferbereich SFB557-TFB”, funded by the government within the “Luftfahrtforschungs- und Technologietechnologieprogramm” of the Federal Republic of Germany, the “Deutsche Forschungsgemeinschaft DFG” or AIRBUS respectively.

Literatur