ACTIVE SEPARATION CONTROL ON A SLATLESS 2D HIGH-LIFT WING SECTION

F. Haucke , I. Peltzer , W. Nitsche
Chair for Aerodynamics
Department of Aeronautics and Astronautics
Berlin Institute of Technology
Marchstr. 12–14, 10587 Berlin, Germany
Tel.: +49 30 314 24426 Fax.:+49 30 314 22955
Email: Frank.Haucke@ilr.tu-berlin.de

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Abstract

In the present paper, active separation control by means of pulsed blowing from the flap shoulder in order to delay turbulent flow separation is investigated. Experiments are carried out on a two-dimensional high-lift configuration consisting of a main element and a single slotted flap for a Reynolds number of about $Re_c = 1 \cdot 10^6$. The trailing edge flap is equipped with a specially designed excitation mechanism that is capable of producing a pulsed wall jet with high jet velocities. Compressed air and fast switching solenoid valves are used to excite the flow at different locations. The direction of the pulsed jet is also varied for the measurements. Furthermore, the effect of flap gap and flap overlap on excitation location sensitivity is investigated. The results include measurements from a six- component wind tunnel balance and miniature pressure sensors. For selected configurations enhancements in lift coefficients of up to 25% are possible, while the drag forces are reduced.

1 Nomenclature

symbol	unit	description
b	$[mm]$	span width
c_f	$[mm]$	flap chord length
c_m	$[mm]$	mean chord length
c_μ	$[-]$	momentum coefficient
c_p	$[-]$	pressure coefficient
C_D	$[-]$	drag coefficient
C_L	$[-]$	lift coefficient
DC_e	$[\%]$	duty cycle of excitation
f_e	$[Hz]$	frequency of excitation
$F_e^+ = \frac{f_e \cdot c_f}{u_\infty}$	$[-]$	reduced frequency of excitation
Re_c	$[-]$	chord Reynolds number
u	$[\frac{m}{s}]$	velocity
u_∞	$[\frac{m}{s}]$	incident velocity
p_d	$[bar]$	pressure in the duct
t	$[s]$	time
T	$[s]$	periodic time
$\dot{V}_N$	$[\frac{l_N}{min}]$	normalized volume flow rate
α	$[^\circ]$	angle of attack
β	$[^\circ]$	blowing angle
δ_f	$[^\circ]$	flap deflection angle

2 Introduction

Effective but simple high lift devices become more important for cases of high take-off weights and steep approach trajectories. In general 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 demonstrated experimentally that periodic excitation on single airfoils [1, 2] is effective. Different mechanisms for active flow control are possible. 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 enhanced by up to 25% for selected configurations. They [5] also conducted experiments with a more realistic model, like 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 effect on the effectiveness of the separation suppression. Due to the large number of parameters which can be varied, it is very expensive to investigate every combination manually. Therefore, by using a closed loop separation control [6] excitation parameters, such as frequency and duty cycle, could be optimized to achieve faster maximum improvements in lift and drag. The investigations described in this paper are similar to the experiments of [4]. But instead of a generic model without a cove at the main element and with a fixed flap position, a more realistic slatless two- dimensional high- lift configuration of a transonic wing section at higher Reynolds number is used for active flow control with pulsed jets. In this case some additional parameters, such as flap gap and flap overlap, are also taken into consideration. Active flow control using periodic pulsed jets is an other promising way to improve high-lift configurations of real aircrafts. If sufficient enhancements in aerodynamic performance could be achieved in an efficient way then the complexity, weight and dimensions of flap systems could be reduced thereby lowering in the direct operating costs (DOC).

3 Experimental Setup

All experiments 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 $1 \cdot 10^6$. This Reynolds number might be too low to assure a fully developed turbulent flow around the model for each variation of angle of attack, flap deflection angle, flap gap or flap overlap. Therefore small tapes, placed at suitable positions near the leading edges of the main element and of the flap, were used to force the laminar to turbulent transition process along the span wise direction. One tape setting was found that was capable of generating a turbulent flow and preventing a laminar leading edge separation for all tested configurations. Further measurements of the presented model are planned with higher flow velocities in a larger test section to investigate the influence of Reynolds number on active flow control.

3.1 Model

For the experimental investigations, a two dimensional high lift configuration consting of a main element and a single slotted trailing edge flap is used. In clean cruise conditions the model has a transonic body shape and a profile depth of $c_m = 600mm$ (see fig. 1).

A very stiff beam construction connects the model with a six- component balance that is placed underneath the test section. To reduce the influence of the wind tunnel walls' boundary layer, the span width of the model measures only b=1550mm, while the cross section amounts to 2000mm x 1400mm (w x h) (see fig. 2). The vertical beams of the wing's mounting are encased aerodynamically by side walls, which are not shown in the picture. To avoid lateral pressurization between the wing's lower and upper side

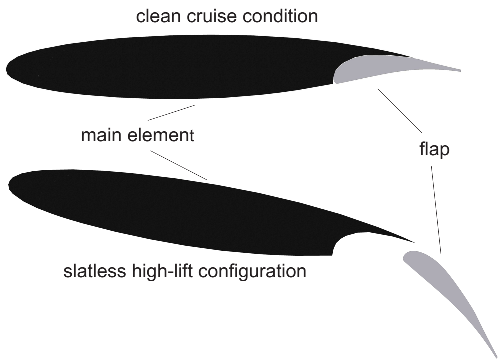

Fig. 1 Wind tunnel test model

the distances between the ends of the model and the side walls are very small ($\approx 0.1mm$) but it is ensured that the rotatory motion is still contactless.

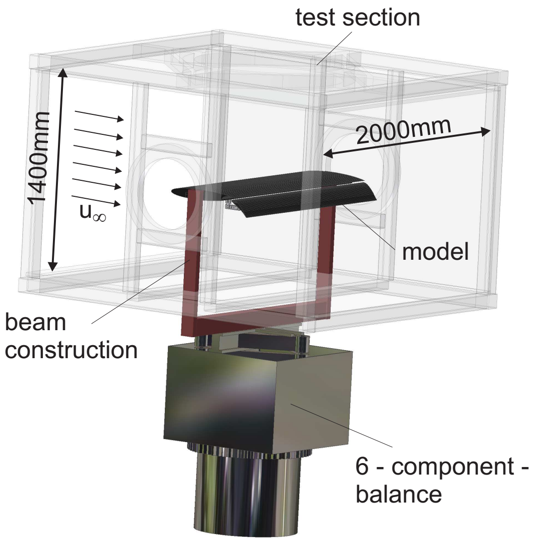

Fig. 2 Experimental set-up

All forces and moments are measured directly from the balance system. The pressure distribution in the mid section of the wing is acquired by miniature pressure sensors. Most of the measurement equipment is integrated within the main element to reduce the supply and data lines which have to be led through the mounting, along the beam construction, out of the test section. Angle of attack and flap deflection angle can be changed by computer controlled stepping motors. In order to setup flap gap and flap overlap, special flap holders are used to set up the desired values.

3.2 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. 3).

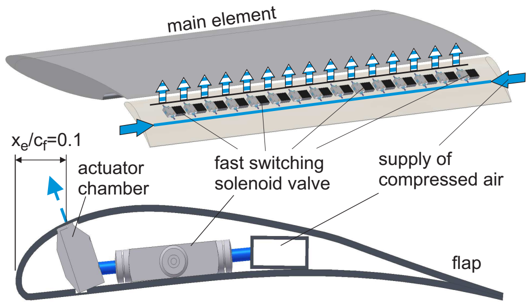

Fig. 3 Principal of actuator system and actuator set-up A

Due to a square wave supply voltage (see fig. 5), 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 flow exit geometry. The local and temporal uniformity of the jet along the slot is also desired. The amplitude of the pulsed jets is set by the pressure within the compressed air duct which is controlled by electronic proportional pressure regulators outside of the test section. In addition an electronic volume flow rate meter is used in order to determine the consumption of compressed air. The maximum normalized volume flow rate per valve amounts $\dot{V}_{N,valve,max} = 100\frac{l_N}{min}$. For these measurements all actuators operate with the same frequency, duty cycle and pipe pressure. Two settings were used to investigate flow excitation.

Actuator set-up A: From previous investigations the following details were used for this setting: The position of excitation on the flap's upper side is located at $x_e/c_f = 0.1$. The jet direction is normal ($\beta = 90°$) to the surface (see fig. 3). 15 actuator segments each with a slot width of 0.3mm and slot length of 90mm are integrated in span wise direction within the trailing edge flap.

Actuator set-up B: An important component of this investigation is determining the relationship between the locations and directions of the jets and their effectiveness in preventing turbulent flow separation. In this case the actuator slot is located at $x_e/c_f = 0.2$ and the geometrical blowing angle is $\beta = 30°$. 13 actuator segments, each with a slot width of 0.4mm and a slot length of 50mm, are integrated in the same way as described above (see fig. 4). For each setting a new flap was built using glass-fibre reinforced plastic.

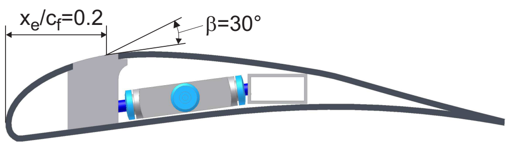

Fig. 4 Actuator set-up B

Parameter range: The number of parameters for investigating active flow control is very large. In the present investigation the location and direction of excitation is fixed for each flap. Flap gap and flap overlap can be set-up manually during the experiments. Angle of attack, flap deflection angle and excitation parameters, such as frequency, duty cycle and supplied air pressure are changed by computer controlled devices (see fig.5).

4 Results

All results presented in this paper were obtained for a chord Reynolds number of about $Re_c = 1 \cdot 10^6$. First, some results for actuator set-up A will be presented and discussed. After that the

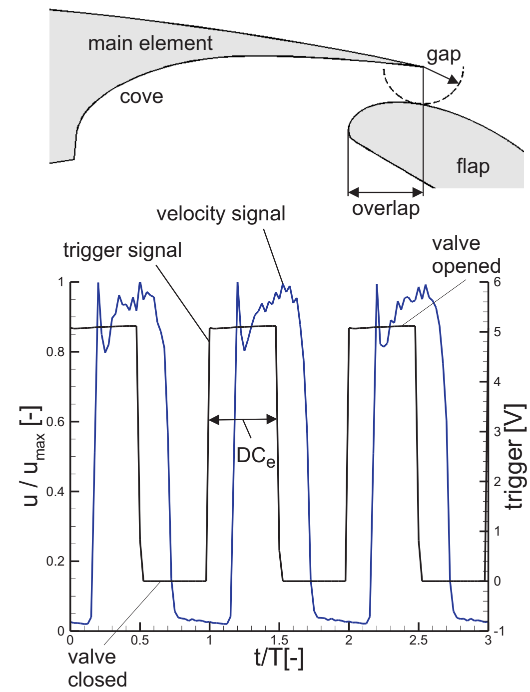

Fig. 5 Parameters for Excitation top: definition of flap gap and flap overlap bottom: square wave excitation signal (trigger) vs. time resolved velocity profile in the center of the jet exit without cross flow measured with hot wire

second actuator configuration will be analyzed. The forces and moments measured by the six-component balance are corrected by a standard wind tunnel correction method [7].

4.1 Results for actuator set-up A:

Pulsed blowing could generate large scaled flow structures. It is assumed that for each geometrical configuration the frequency and momentum of the pulsed jets have a different influence on lift enhancement.

Figure 6 shows some exemplary results for variations in frequency and momentum. Here, the blowing momentum is expressed by the pressure in the duct of compressed air p_d. For the given gap and overlap values the greatest improvement in lift coefficients can be achieved for frequencies between 75Hz and 100Hz and a duct pressure of $p_d = 6bar$. The corresponding Strouhal numbers are between 0.5 and 0.66.

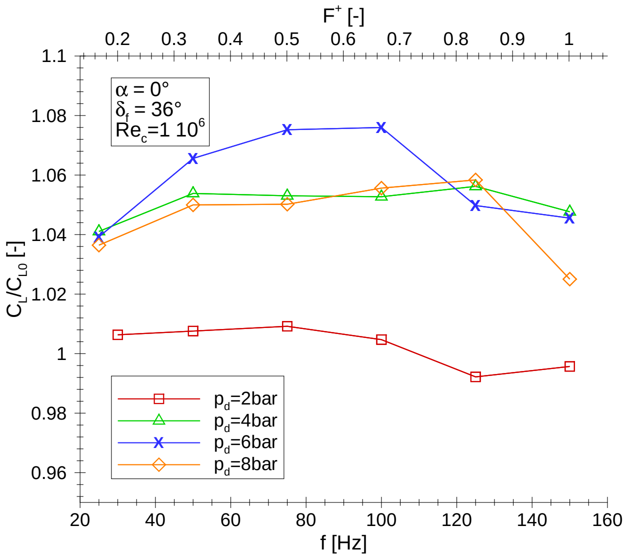

Fig. 6 Actuator set-up A: Variation of frequency and duct pressure

These values can be changed for different values of gap, overlap, angle of attack or flap deflection angle.

Figure 7 shows lift and drag plotted against angle of attack for special gap, overlap and flap deflection angle values. The frequency was set to $f_e = 75Hz$. Due to the excitation the lift coefficients are shifted upwards by about $\Delta C_L \approx 0.18$. In this case the drag coefficient is increased, too. The angle of attack for the maximum lift coefficient is about $\alpha \approx 9.5^{\circ}$. For higher α- values the lift coefficients decrease and the drag coefficients increase drastically, which is caused by turbulent flow separation on the main element. The improvements in lift coefficients can be explained by the local pressure distribution, for example at $\alpha = 2^{\circ}$ and $\delta_f = 40^{\circ}$, as shown in figure 8. In the unexcited case flow separation on the trailing edge flap occurs at $x_e/c_f \approx 0.2$, which is indicated by the constant level of pressure values further downstream. Due to excitation on the trailing edge flap, the surge tip is shifted a little bit downstream, the values for local pressure coefficients are decreased and the local separation on the flap is suppressed. Furthermore, excitation on the flap reduces the local pressure on the main element's trailing edge and top surface. The pressure levels on the bottom of the main element and the flap are shifted to slightly higher cp- values. Altogether the enhancement of the pressure distribution improves lift.

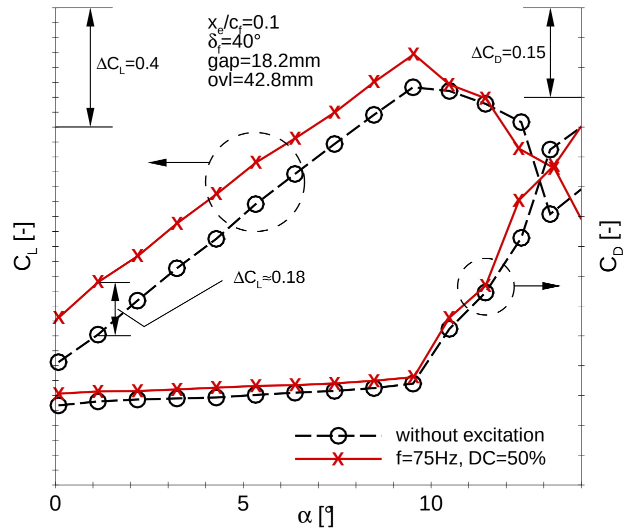

Fig. 7 Actuator set-up A: example for lift & drag polar

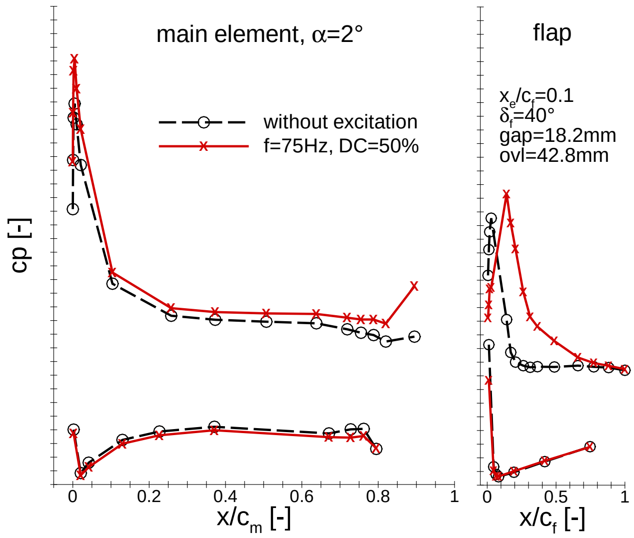

Fig. 8 Actuator set-up A: example for cp distribution

Figure 9 displays lift coefficients and the relative change in lift coefficients depending on overlap and gap of the flap for an angle of attack of $\alpha = 5^\circ$ and a flap deflection angle of $\delta_f = 40^\circ$. For smaller overlap values combined with smaller gap values the lift increases up to an optimum in the case of unexcited base flow for the plotted range.

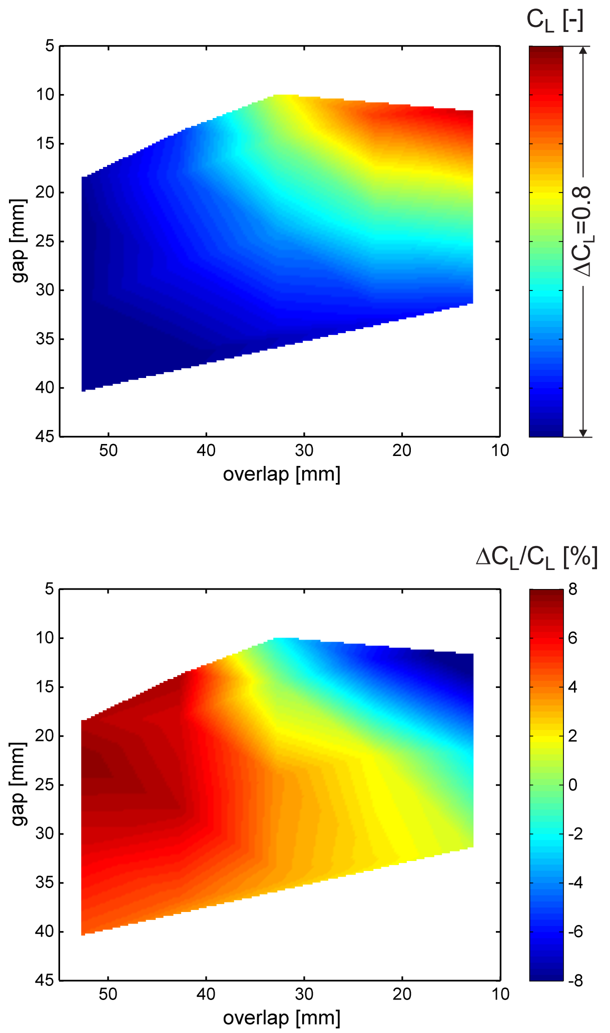

Fig. 9 Actuator set-up A: $\alpha = 5^\circ$, $\delta_f = 40^\circ$ top: lift coefficient bottom: relative change in lift coefficient due to excitation with $f_e = 75Hz$, $DC_e = 50\%$

The bottom picture of figure 9 shows the resulting relative change in lift coefficients for the excitation parameters $f_e = 75Hz$ and $DC_e = 50\%$. In this case the lift can be enhanced by up to 8% for higher overlap and smaller gap values.

4.2 Results for actuator set-up B:

The second setting for excitation was used in order to increase the effect of active flow control. Compared with actuator set-up A, the position of excitation is located further downstream at $x_e/c_f = 0.2$, which was closer to the time averaged separation line for the selected configurations. The blowing angle was set to $\beta = 30^\circ$ in order to control a wider range of the downstream flow field in a more effective way. Figure 10 shows lift and drag versus angle of attack for a flap deflection angle of $\delta_f = 40^\circ$. While the gap is set to $gap = 12.6mm$ the overlap value amounts to $overlap = 3.3mm$. The maximum angle of attack is about $\alpha_{C_{L,max}} = 8^\circ$ for the unexcited base flow. For higher α- values the lift decreases and drag increases drastically due to turbulent flow separation on the main wing.

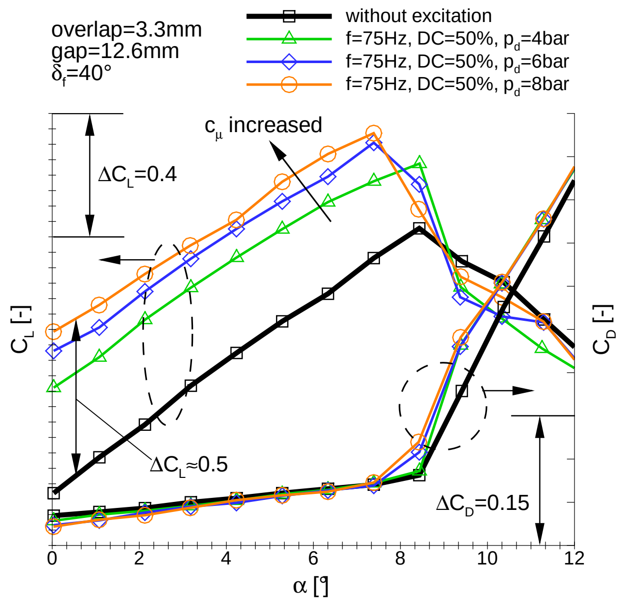

Fig. 10 Actuator set-up B: example for lift & drag polar

Pulsed blowing with this actuator setting results in significantly enhanced lift. Increasing the duct pressure or the momentum coefficient respectively leads to increased lift forces while the drag is slightly decreased in the linear range of the lift function. Furthermore, at the same time the maximum angle of attack is slightly reduced. In addition to figure 10, the corresponding distribution of pressure coefficients for $\alpha = 5^\circ$ is shown in figure 11. The flow separation on the flap occurs between $x_e/c_f = 0.2$ and $x_e/c_f = 0.3$, which is expressed by the constant pressure level further downstream. Due to excitation, the pressure distribution on the flap's upper surface is lowered significantly at this span wise location and separation is suppressed. The whole pressure level of the wing's upper surface is lowered significantly as well, which is the main reason for the global lift enhancements. The pressure values of the lower surfaces of main wing and flap are only slightly changed.

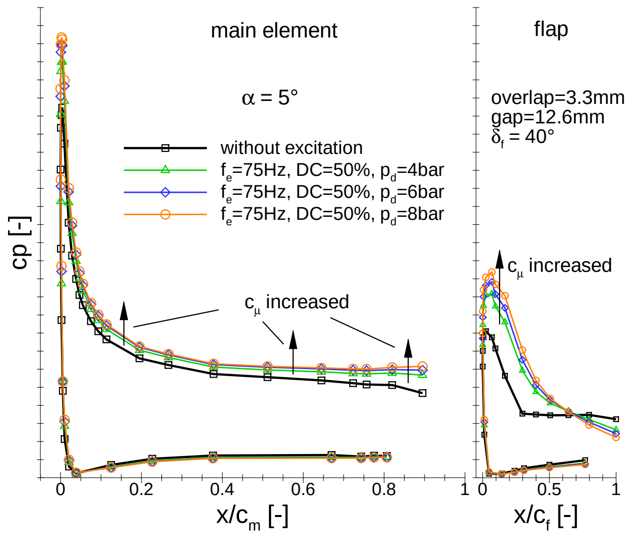

Fig. 11 Actuator set-up B: example for cp distribution

5 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. Because the excitation effects the stagnation pressure location of the main element as well, the pressure on the upper surface is lowered, resulting in lift coefficient improvements. Drag forces can also be reduced due to periodic blowing. Two actuator settings were the essential part of the experiments. Flow excitation with a wall jet perpendicular to the flap's upper surface resulted in lift enhancements of up to 8% for higher overlap values. Pulsed blowing at a position further downstream closer to the time averaged separation line with an inclined periodic wall jet was more effective than normal blowing. The improvements in lift coefficients depended on each configuration and reached values of about 25%. Further investigations in this topic will focus on analyzing the physics of the high-lift flow field by using timeresolved miniature pressure sensors and particle image velocimetry in order to find an optimal way for excitation, while including the advantages of a closed-loop separation control. The influence of Reynolds number on active flow control is an other important point that will be focused on as well.

Acknowledgments

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