AERODYNAMIC BENEFITS OF PULSED BLOWING APPLIED TO HIGH-LIFT AIRFOILS

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1 NOMENCLATURE

f	=	excitation frequency
l_a	=	distance from the actuator position to the trailing edge of the flap
u_∞	=	free stream velocity
Re_c	=	chord Reynolds number
c_{main}	=	main airfoil chord
c_{flap}	=	flap chord
c_{clean}	=	cruise condition chord
b	=	span
H	=	excitation slot width
St	=	Strouhal number nondimensional excitation frequency, $f \cdot l_a/u_\infty$
c_μ	=	nondimensional momentum coefficient, $2H/c_{flap} \cdot (u'_{jet}/u_\infty)^2$
c_L	=	lift coefficient
c_D	=	drag coefficient
α	=	angle of attack
δ_f	=	flap deflection angle

2 ABSTRACT

This work describes experimental investigations aiming at the delay of flow separation by means of pulsed blowing. High-lift airfoils with simple slotted flap systems are the choice of interest, because they suffer from massive flow separation at medium to high flap deflections. In order to improve the aerodynamic performance, periodic forcing, i.e. in this case pulsed blowing, is introduced at the flap shoulder through a narrow spanwise oriented slot in the model surface. The results show that pulsed blowing is able to delay flow separation on the flap or to reattach an already separated flow if frequency and amplitude of the wall jet are in the correct domain. Optimizing these parameters, e.g. frequency, jet velocity, duty cycle, spanwise location, 2D or 3D excitation modes, manually is often not possible simply because the number of parameters is too large and they influence themselves mutually. Hence, first concepts of closed-loop control are presented.
Two different wind tunnel models are investigated, a generic two dimensional model and a realistic half model with a sweptback wing of constant chord and finite wing span. The wind tunnel tests were carried out in a chord based Reynolds number regime of $Re_c = 0.3 \cdot 10^6$ to $Re_c = 10^6$. Forces and moments were measured using a six-component balance system allowing a fast and reproducible comparison of forced and unforced test cases.

3 INTRODUCTION

Active flow control by means of alternating suction/blowing or pulsed blowing has been investigated by a growing number of researchers in recent years [1, 2]. The effectiveness of active flow control concepts in order to control massive flow separations has been tested on bluff bodies [3, 4], single airfoils [5] and high-lift configurations [6, 7]. Particularly high-lift systems with simple flaps, vented or sealed, can benefit from active separation control by suppressing flow separation on the flap or by reattaching an already separated flow. In most cases, periodic excitation is introduced into the flow locally by small wall jets emerging from narrow slots in the model surface. If larger models are investigated, e.g. wings with a high aspect ratio, the spanwise oriented slot is usually made up of several smaller segments in order to achieve a spanwise homogeneous jet velocity distribution. Segmented actuator systems are also used in order to generate rolling moments by using spanwise distributed excitation.
Whether alternating suction and blowing or pulsed blowing is used, periodic excitation outper-

forms steady blowing in most of the investigated test cases in terms of aerodynamic benefit and energy required for flow excitation [8]. In recent experiments steady suction, periodic suction and superposition of zero-net-mass blowing and steady suction are investigated as well [9].

Care has to be taken comparing different flow control methods because they often require a very sensitive parameter tuning. For instance, it is often not feasible to compare the effectiveness of steady blowing and pulsed blowing even if a single actuator design is used, e.g. compressed air and fast-switching valves. Slot direction and slot width have to be taken into account and optimized for each case. Effective steady blowing requires an almost tangential wall jet that energizes the weakened boundary layer, whereas periodic forcing requires a different wall jet direction in order to be as effective as possible.

The forcing mode, periodic blowing, alternating suction and blowing or even periodic suction, depends heavily on the excitation mechanism which in turn is constrained by the model size. The free stream velocity, respectively the Reynolds number, determines the excitation frequency and the momentum coefficient. To design a single actuator that is capable of achieving different excitation modes is helpful but slot positions and wall jet direction should be adapted for each test case. Hence, custom-built actuators are developed for specific test models and test cases. Often externally compressed air, fast switching valves and a tubing system are used in order to produce a pulsed wall jet that is easily adjustable in frequency and amplitude. High frequencies (>500 Hz) are not possible due to performance limitations of the valves. Nevertheless, this set-up is fairly simple, cheap, robust and reliable.

So called synthetic jets, better named zero-net-mass flux actuators, have to be designed very accurately (cavity size, operating frequency of the piezo membrane) in order to achieve high jet velocities. For a piezo membrane/cavity set-up, this is only possible if the mechanical resonance frequency or the Helmholtz frequency is met. Depending on the piezo used and the cavity size, these frequencies are often orders of magnitude higher than the relevant frequencies used for effective flow control. Amplitude modulation (pure sine or pulse) are needed to excite the flow with lower, effective frequencies [10]. The small size of these devices gives a big advantage, but robustness and reliability do not match that of industrial manufactured valves. If an overall figure of merit has to be determined, piezo actuators offer a very easy way to measure the power consumption and compare it to the lift and drag benefits [11].

Despite the fact that actuator design is difficult but important, periodic forcing offers great aerodynamic possibilities. Applied to high-lift configurations flap systems, vented or sealed, benefit the most from separation delay by periodic forcing [6, 7]. Once the flow is already separated it can by reattached to the flap's surface as well. Periodic perturbations are usually introduced at the flap shoulder in the vicinity of the time averaged separation location. A major problem is the finding of optimal excitation parameters for each test case. Separation delay and reattachment require different forcing frequencies and excitation magnitudes. Hence, for efficient flow control each flap deflection angle has its own set of optimal parameters. This does not only apply for frequency and amplitude but for slot location and wall jet direction as well. Despite the fact that these optima will probably never be found by a manual tuning, periodic forcing works robust and reliable even in off design cases. Lift improvements of 10% to 15% are possible in two and three dimensional test cases. 2D wing configurations show an additional decrease in drag due to the fact that the large separation region above the flap is suppressed by flow excitation. However, wings with finite span show a different behaviour because once lift is increased the induced drag will rise as well. But there is a chance that the strength of the wing tip vortex may be affected by periodic forcing as well, offering the chance to have an impact on the total drag [12, 13]. The control of the rolling motion is possible by spanwise distributed forcing, using a spanwise segmented actuator made from small individual addressable segments.

In order to optimize such a multi-parameter problem, closed-loop systems have to be investigated. These systems are able to sense the flow state fast and reliablly and feed this information to a controller. The controller itself runs a certain strategy that is able to interpret the sensor signals in real time and controls actuator parameters like frequency and amplitude [14].

Low weight, small, robust, reliable and effective actuators for small to medium wind tunnel models are required for high Reynolds number tests with realistic configurations in order to scale actuator performance and power consumption to real size airplanes. Fluidic oscillators are gaining more and more attention because they do not require fast oscillating mechanical components if an internal feedback loop is used [15, 16].

The following sections describe two experiments that use pulsed blowing to enhance the aerodynamic performance of simple slotted flaps. These experiments were conducted within the framework of the Collaborative Research Center 557 control of complex, turbulent shear flows at Berlin University of Technology.

4 EXPERIMENTAL SET-UP

Two different test models have been equipped with an excitation mechanism and investigated in a closed-loop wind tunnel with a test section cross section of 2000 mm x 1400 mm. Experiments started on a generic two dimensional high-lift configuration consisting of a main airfoil and a single slotted flap (figure 1). Reynolds numbers ranging up to $Re_c = 10^6$ have been investigated, however the results presented in this paper were gathered at a Reynolds number of $Re_c = 0.55 \cdot 10^6$. This set-up was used as a principal test bed to investigate pulsed blowing and different closed-loop strategies. The large flap (chord length of 200 mm) allows an easier installation of actuators inside the flap. Although the configuration is generic, it generates a typical high-lift flow field with confluent boundary layers and a jet above the slotted flap [17].

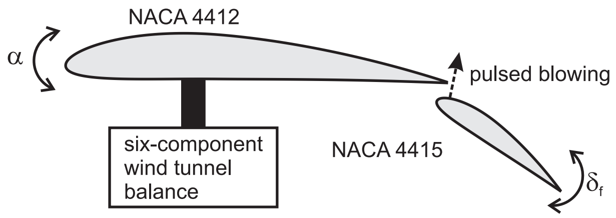

Figure 1 2D high-lift model with periodic forcing introduced at the shoulder of the single slotted flap

The second configuration is a more realistic wing-body combination. The half model consists of a generic fuselage section and a constant chord wing of c_{clean}=450 mm in clean cruise condition with a sweep angle of 30°. Retractable high-lift devices, i.e. slat and single-slotted flap, are mounted to the leading and trailing edge completing the three-element high-lift configuration. All tests presented in this paper were performed in a landing configuration with a slat angle of δ_s=26° and a constant slat gap and overlap. The single-slotted flap is set to fixed gap and overlap values as well (figure 2). Reynolds numbers for this test case reached up to $0.8 \cdot 10^6$ [12]. Due to the wing sweep, the finite wing span and the constant chord, a complex flow field evolves with very different flow characteristics in the inboard and outboard section of the flap. In both cases angle of attack and flap

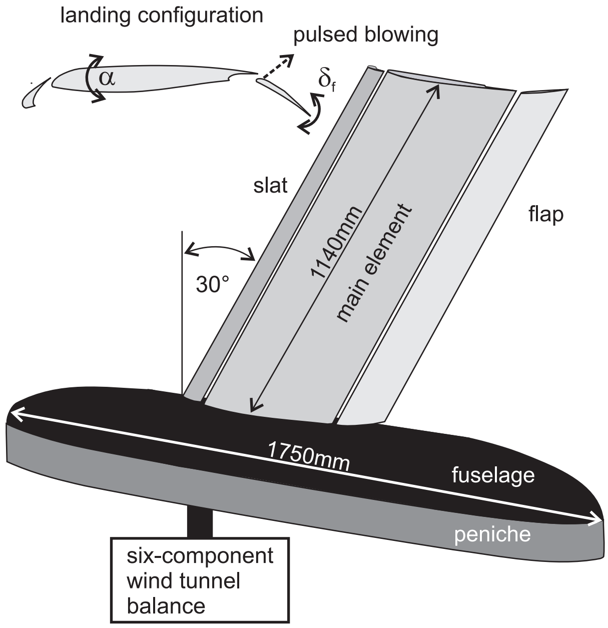

Figure 2 Swept constant chord half model with pulsed blowing at the shoulder of the single slotted flap

deflection angle may be adjusted independently and automatically, allowing tests at many different settings within a short period of time. Main profile, slat and flap are equipped with trip wires at the leading edges to fix the transition and guarantee a turbulent separation. Both test models are mounted on a six-component balance installed beneath the test section, allowing a simultaneous acquisition of all forces and moments acting on the models.

4.1 EXCITATION MECHANISM

Selecting an appropriate excitation mechanism for a specific test case needs a thorough investigation in order to determine operating frequency range, jet velocities, excitation mode and, if closed-loop experiments are planned, the response time. Once these boundary conditions are set, a proper excitation mechanism has to be designed. Most experimenters have to develop their own model specific actuators which have certain limitations either in frequency range or jet velocity. Often used piezo electric actuators based on a small cavity and a fast oscillating piezo membrane seem to be the choice in most experiments. They produce an alternating suction and blowing jet, which is ideal for energizing a weakened boundary layer. In the suction phase, fluid with a low kinetic energy is sucked into the cavity end energized during the blowing phase which produces additional strong vortices and enhances mixing of low and high momentum fluid in order to prevent separation. Although these kinds of actuators are very small and need only electrical wiring, they need a very accurate design, particularly in terms of piezo clamping and cavity size. Because piezo material is able to oscillate within μm only, the jet velocities leaving the excitation slot are very small unless the Helmholtz-frequency of the cavity or the resonance frequency of the piezo ceramic is met. These frequencies are usually too high for direct separation control. Changing the operating frequency of the piezo membrane results in a dramatic loss of jet velocity. Hence, the piezo is driven in one of the resonance frequencies and lower frequencies are achieved by amplitude modulation.

For the two test models piezo driven actuators were considered but not implemented because of the small flap size of the 3D model and comparison of steady blowing and pulsed blowing was desired (regardless of slot location and jet direction) with the option of testing periodic suction and alternating suction and blowing in later tests. In order to achieve all of the mentioned excitation modes, small fast switching solenoid valves are used in both experiments which are connected to a compressor providing compressed air at 5 bar max.. The compressor is placed outside of the test section making, compressed air lines necessary. In order to achieve a spanwise homogeneous excitation jet velocity, eleven (2D case) and twelve (3D) actuator segments are placed along side each other. One segment consists of an individually addressable valve connected to a specifically designed cavity that spreads the air along one actuator span. A major disadvantage of this kind of actuator assembly is the space required for tubing. For the 2D model the complete assembly of eleven actuator segments is placed inside the flap (figure 3).

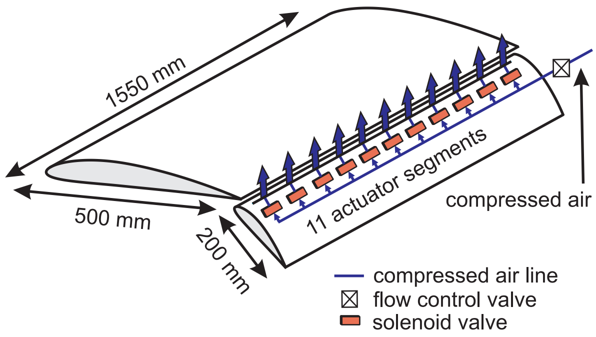

Figure 3 Actuator assembly of the 2D test model

Unfortunately, this was not possible for the 3D model, because the flap has a chord length of 112 mm and a maximum thickness of 9 mm only. For that reason the valves had to be placed inside the fuselage and were connected to the cavities inside the flap via long air lines (figure 4). The long tubes decrease the maximum frequency and amplitude. Despite these disadvantages, the setup can be used to produce a steady blowing jet (all valves are open), a pulsed jet with a max. frequency of about 250 Hz (less in the 3D case due to the long tubes). Exchanging the compressor with a vacuum pump, steady suction and pulsed suction can be investigated using the exact same actuators. Since the valves have two input ports and only one exhaust port, high pressure and low pressure of different magnitudes can by applied to

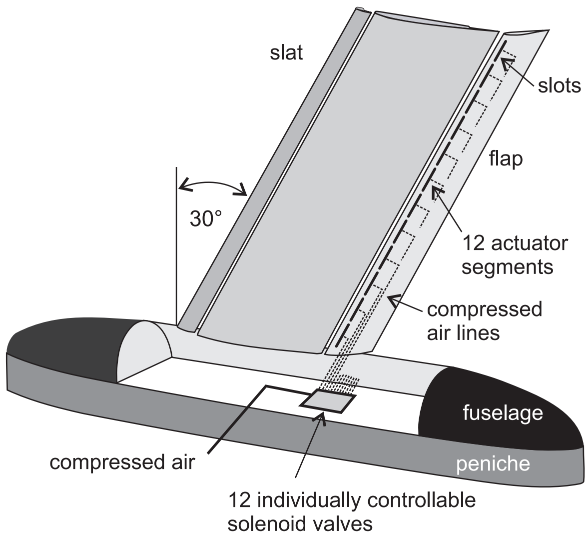

Figure 4 Actuator assembly of the 3D test model

the input ports in a way that alternating suction and blowing can be investigated. This set-up requires additional tubing that is only possible in the 2D case. Despite the fact that a lot of excitation modes are possible with this set-up, one has to remember that each of these modes requires an optimised slot location and jet direction in order to have meaningfully results to compare. For closed-loop control the actuators have to be segmented in spanwise direction giving the controller the change to individually address each segment and control the flow efficiently. In order to reduce the response time for the controller, frequency and amplitude have to be adaptable within tens of a second or faster.

5 RESULTS OF OPEN-LOOP TEST CASES

The results for both test cases show that pulsed blowing is a suitable way to control the separation on the flap [18, 12, 17]. In the 2D case, lift improvements of 12% to 15% compared to the baseline case without flow control are possible. By measuring lift for a wide range of angles of attack and flap deflection angles configurations, the resulting maximum lift of this specific flap gap and overlap setting is obtained. Figure 5 and figure 6 show contour plots representing the lift coefficient as a function of α and δ_f for the baseline case without flow control and with pulsed blowing.

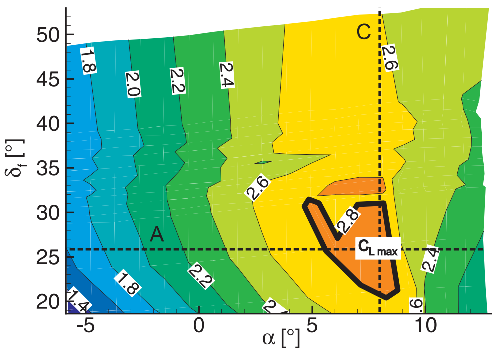

Figure 5 Lift coefficient depending on angle of attack and flap deflection angle for the baseline case

Extracting a set of angle of attack and flap deflection angle sweeps from the above shown diagrams makes a direct comparison of the maximum lift coefficient for both cases possible. Figure 7 shows these polar diagrams for the baseline and the ex-

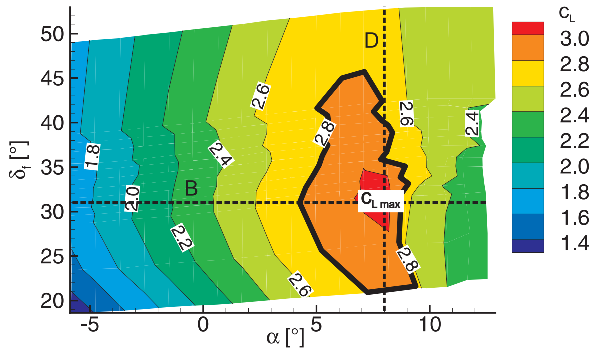

Figure 6 Lift coefficient depending on angle of attack and flap deflection angle for the controlled case

cited case. Due to the pulsed blowing, separation on the flap is delayed and maximum lift is improved by 4% caused by a flap deflection angle increase of 6°. During the angle sweeps the excitation parameters are kept constant. A nondimensional frequency of St=0.9 and a nondimenional momentum coefficient of $c_\mu = 0.08\%$ were used. An optimization for each configuration may result in even better improvements. Different excitation parameters are also necessary for separation delay and flow reattachment. In the 2D case the lift improvement due to the separation delay is accompanied by a drag reduction resulting in a lift-to-drag ratio enhancement of up to 25%.

Due to the finite wing span in the 3D case, the impact of pulsed blowing is somewhat different. Despite sweep and finite span, a lift improvement of 10% is still possible if baseline and controlled case are compared. A Strouhal number of St=0.72 and a c_μ=0.11% yielded good lift improvements. The elimination of the separation on the flap does not result in a drag reduction compared to the same case without flow control. As can be seen in the diagram, the total drag in the forced case is equal to the baseline case for low angles of attack. At higher angles the total drag of the configuration with excitation is even higher than in the baseline case. The lift gain in the controlled case increases the induced drag component, compensating the drag reduction due to the elimination of the separation on the flap. Hence, L/D improvement is less than in the 2D case (figure 8). However, a spanwise distributed forcing with different intensities has shown that drag can be influenced as well if a high amplitude pulsed blowing with the outboard wing tip segments is introduced. For such a three dimensional flow field even different forcing

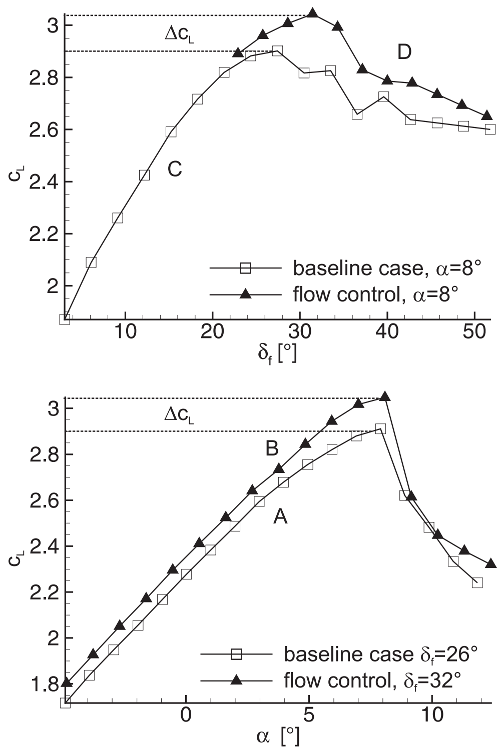

Figure 7 Increase of maximum lift due to a larger flap deflection angle with active flow control ($Re_c = 0.55 \cdot 10^6$)

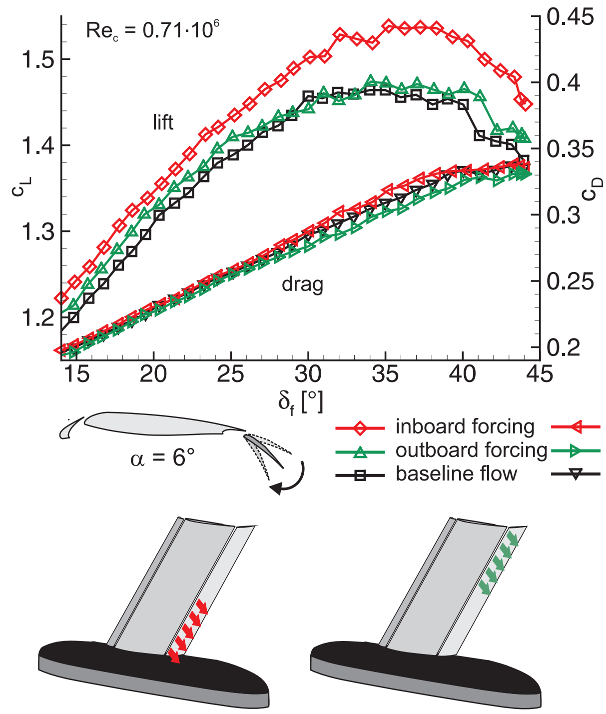

Figure 9 Impact on lift and drag due to spanwise distributed excitation ($Re_c = 0.5 \cdot 10^6$)

frequencies may be needed in order to influence spanwise different flow phenomena (figure 9).

6 PROBLEMS OF APPLYING CLOSED-LOOP FLOW CONTROL

In further investigations both test cases were equipped with a closed-loop separation control system. The basic control system is made up of three essential parts: fast responding actuators, a suitable control strategy and sensors. Determining the location of flow separation requires an array of streamwise positioned sensors. In both cases this is not necessary because the excitation location is fixed. Hence, the challenge in these cases is to differentiate between attached flow and separated flow in a fast and reproducible manner with a minimum number of sensors. The sensors had to be surface mounted and integrated into the models as they would be in a real environment. As a result of preliminary testing, the pressure difference of two distinct positions in streamwise direction on the flap yielded very good results of detecting the flow state on the flap. Separated flow gives a low pressure difference and an attached flow a high pressure difference. This easy method enables a very fast determination of the flow state on the flap and needs less computation time to be interpreted by the controller. In order to give the controller a detailed view of the spanwise flow conditions on the flap, additional pressure transducers are placed downstream of each excitation slot. Although it would have been desired to have a controller for each sensor-actuator system, hardware limitations on the digital signal processor side made combination of segments into three independently working controllers necessary (figure 10). In both cases an extremum seeking

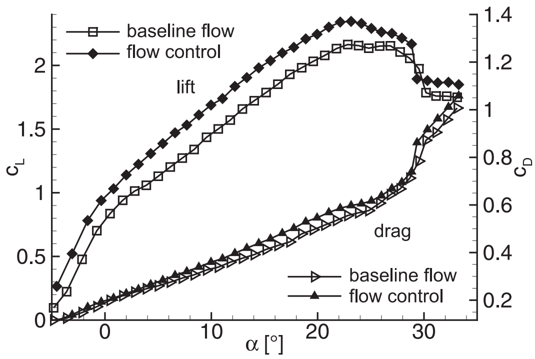

Figure 8 Lift and drag for baseline and controlled case ($Re_c = 0.5 \cdot 10^6$)

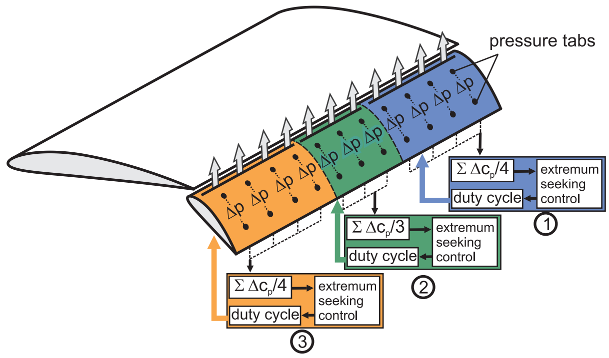

Figure 10 Closed-loop set-up of the 2D model with three independently working controllers

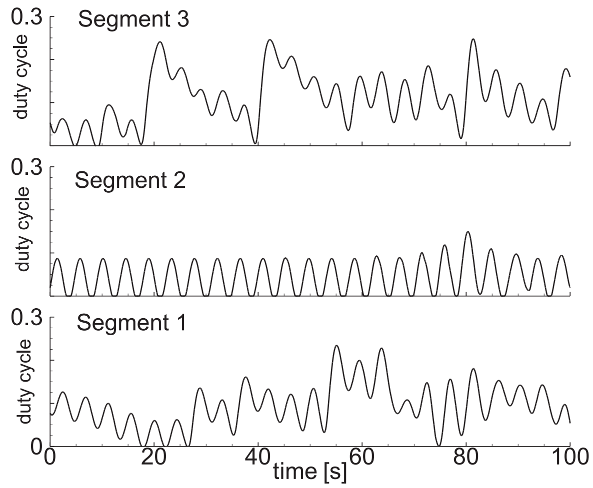

Figure 11 Results of closed-loop performance in the 2D case with the corresponding controller outputs

controller was implemented because it is robust and does not need a detailed description of the plant [14]. However, it is not considered to be very fast but still enables response times of less than a second deepening of the control parameters. In this first attempt only the duty cycle of the valves is controlled, because this is the only parameter that has a very short response time, is addressable for each valve independently and has sufficient control authority.

During an automatic lift polar measurement, this system is able to detect the flow state on the flap and keeps the valves closed as long as the flow is inherently attached to the flap. Once a separation is detected on a spanwise location of the flap the controller excites the flow on that part. The other actuators are kept closed in order to save energy and are not opened until the flow separates completely. Figure 11 shows the controller outputs (duty cycle) for the three controllers. It can be seen that the duty cycle is constantly adjusted to the flow on the two outside segments and less in the middle part of the flap. The 3D case is much more complicated to control because the flow field around the finite wing changes from the inboard to the outboard section, which is dominated by a large wing tip vortex. In order to capture the separation on the flap, twelve pressure sensors are used in the same way as in the 2D case. However, at the onset of separation, the flow on the flap is affected by massive cross flow due to the sweep angle and the wing tip vortex in a way that the flow is almost parallel to the trailing edge of the flap. In this case, the pressure difference is not as robust and clear for separation detection as in the 2D case making it more difficult for the controller to calculate appropriate output signals. In addition, the flow around flap tracks and fairings produces an even more complex flow field with local separation regions due to flap gap blockage. Six independently working controllers were implemented in order to close the control loop and to effectively control the flow (figure 12). One major difficulty

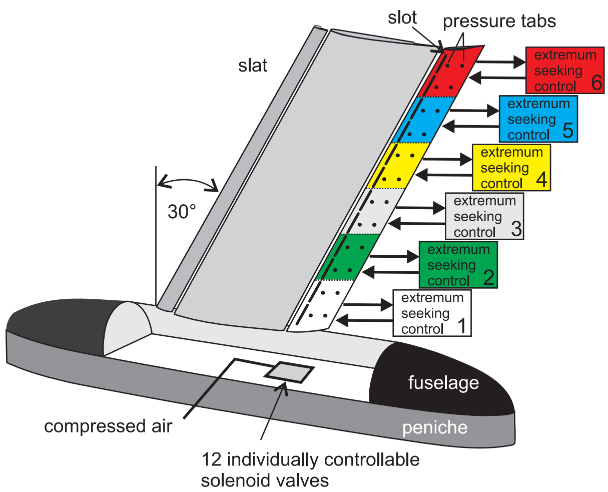

Figure 12 Closed-loop set-up of the 3D model with six independently working controllers

for the controller in this case is to identify the effect of the actuator on the downstream located sensors. Because this system is not coupled in a way that information of neighbouring sensors are used to calculate the output signals of one control segment, the lift improvements are less than in the 2D case. However, despite the complexity of the flow and the restrictions of the control system set-up not being coupled, the controllers are able to improve the results of the open-loop case (figure 13). Figure 14 shows the six controlled

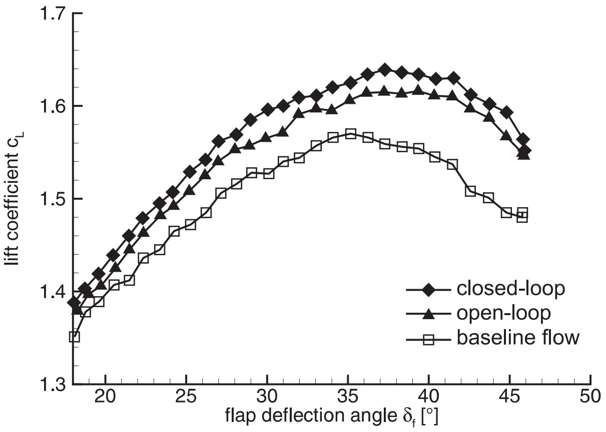

Figure 13 Closed-loop result of the 3D model (flap deflection angle sweep)

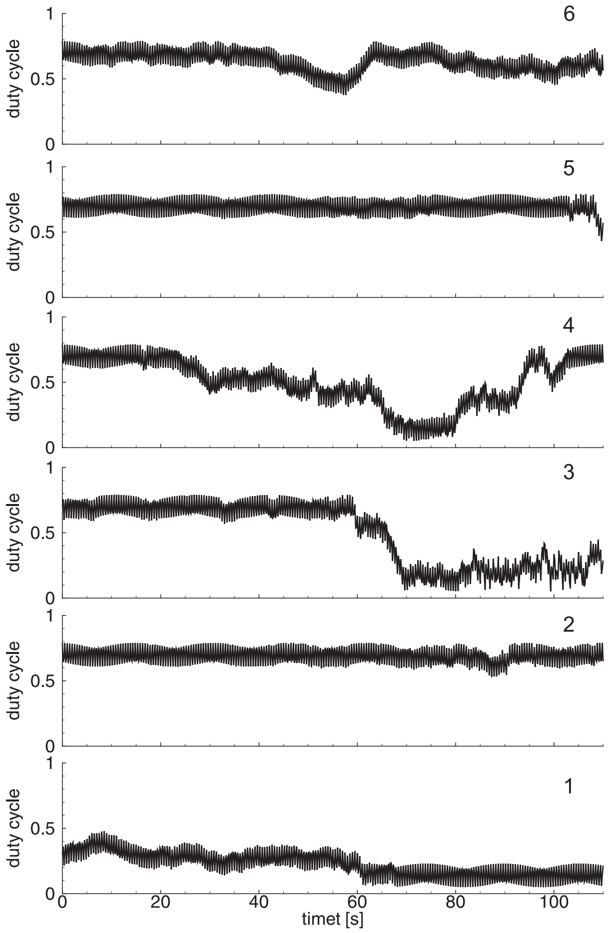

Figure 14 Controller outputs showing a very different excitation on inboard and outboard flap segments

duty cycles. The inboard segment (1) is the least amplified, whereas the outboard segments are amplified the most. Some sensors are located behind flap track fairings (e.g. segment 2) signaling the controller a separation even at low flap deflections.

7 CONCLUSION

Applying active flow control to high-lift airfoils can significantly improve the aerodynamic performance in terms of lift enhancement. Slotted flaps in particular can benefit from a local periodic forcing that is able to change the complete flow field around the high-lift configuration with a low amount of excitation energy. The influence on the total drag very much depends on whether infinite two-dimensional or finite wings with sweep and taper are investigated. The drag reductions measured in the 2D test case could not be achieved with the 3D model because the induced drag component plays an important part in the total drag. Although the excitation parameters are not optimized for each test case, pulsed blowing is very effective in terms of separation delay or reattachment of separated flows. Nevertheless, closed-loop systems with a suitable and very fast control strategy have to be developed not only for application but for a fast optimization of excitation parameters for small scale wind tunnel tests as well. Furthermore, this automatic tuning is very helpful to save actuator energy because delay of separation and flow reattachment need different excitation parameters. For instance, during an angle sweep starting at low angles the flow is inherently attached. Once the critical angle is reached flow control is able to delay separation applying a certain frequency and amplitude. Increasing the angle even further, the flow separates despite the forcing. If the angle is then reduced, different excitation parameters are needed in order to reattach the flow with a minimum of energy. Once the flow is fully attached to the surface, different frequencies and less jet momentum is necessary to keep the flow attached. If effective and efficient separation control is needed outside of a clean laboratory environment, fast closed-loop systems are required.
The effectiveness of periodic forcing over steady blowing is often times proven, but the efficiency of the total system including the power to drive the actuators and their weight is often neglected. In order to be able to scale the results of wind tunnel experiments with active flow control, the aerodynamic benefits and the power required have to be measured. One problem still exists so that

this task will remain difficult in the future. Small models require very small actuators operating in different frequency and amplitude ranges than a real application would need. Scaling of actuator performance is and will be difficult unless a verified database resulting from flight tests is available.

8 ACKNOWLEDGMENT

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