ACTIVE CONTROL OF SEPARATION ON TWO AND THREE DIMENSIONAL HIGH-LIFT CONFIGURATIONS

Ralf Petz, Wolfgang Nitsche
Berlin University of Technology
Institute of Aeronautics and Astronautics
Marchstr. 12, Sek. F2, 10587 Berlin, Germany

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Abstract

The purpose of this paper is to address several questions concerning active separation control in order to improve the aerodynamic performance of conventional high-lift systems. Pulsed blowing from the shoulder of the trailing edge flap is used to delay boundary layer separation and thus increase lift and reduce drag in the post-stall region. Experimental results of two specific wind tunnel models are presented, i.e. a two-dimensional generic set-up and a three-element half model with a finite swept-back wing. Special attention is paid to some of the excitation parameters and the resulting problems when making a transition from one basic test case to a more sophisticated set-up. Although a lot of investigations have already been conducted, some aspects in active flow control experiments are hard to predict and are based on experience and intuition rather than on knowledge.

The results presented in this paper show that pulsed blowing enhances the lift-to-drag ratio in the post-stall region by increasing lift and reducing drag. However, it is almost impossible to find optimal excitation parameters with manual tuning of excitation frequency and amplitude. The generic set-up was therefore used to investigate a closed-loop separation control, which yielded even better results than the open-loop test. Transferring the experience to a more complex and sophisticated three-dimensional set-up is quite a challenging task mostly because of the finite wing span and wing sweep. However, pulsed blowing is able to improve lift and drag in the 3D case as well, but excitation parameters differ from those used in the generic test case.

1 Nomenclature

α, AoA	angle of attack
δ_f	flap deflection angle
c_{main}	chord length main airfoil (2-D model) chord length clean configuration (3-D model)
c_{flap}	flap chord length flap
F^+	nondimensional forcing frequency
c_μ	nondimensional oscillatory blowing momentum coefficient
Re_c	chord Reynolds number
c_L	lift coefficient
c_D	drag coefficient

2 General Introduction

Trailing edge devices on modern passenger aircraft have become simpler, lighter and more efficient compared to 1960, ‘70, and ‘80 where mechanically complex double- and even triple-slotted fowler flaps have been used [1, 2]. These systems produce a very high maximum lift c_{Lmax} but carry a weight penalty in cruise condition [3]. Modern wind tunnel testing techniques and the use of CFD-codes made it possible to reduce prediction errors and to design high-lift systems to meet the design requirements. Single-slotted fowler flaps seem to be the choice of most modern passenger aircraft. In order to achieve the required lift with single flaps special attention is paid to the spanwise arrangement (e.g. thrust gate, high-speed aileron, all-speed aileron) and more fowler motion is required because the flap deflection is limited by flow separation. Large fowler motion in turn requires heavier and more complex flap tracks. Further significant improvements in single-flap systems seems to be hard to achieve with conventional methods. One possibility to improve existing high-lift systems by preventing flow separation on the flap may be active flow control by means of periodic excitation. Taking into consideration system weight, actuator power consumption, actuator weight, system complexity etc., it follows that by using periodic excitation, smaller flap chords or lighter flap tracks with reduced fairings may be used resulting in a cruise drag reduction of 2-3% [4].

One part of active flow control experiments especially focuses on high-lift flows in order to delay flow separation and improve the effectiveness of simple fowler flaps. Besides the trailing edge some experiments actively suppress flow separation on the leading edge of single airfoils [5] and on high-lift configurations with the intention of replacing a slat system. Few experiments consider both locations simultaneously and their interaction [6]. Most investigations are aimed at studying the impact of different excitation parameters, i.e. reduced frequency F^+ and oscillatory blowing momentum coefficient c_μ [7]. Often generic set-ups are used because they can handle some important flow conditions more easily, such as a turbulent boundary layer upstream of the separation location and the installation of actuators. More sophisticated investigations are carried out on wing sections in order to test high Reynolds numbers, sweep or compressibility effects [8, 9, 10]. Up to now active separation control has been used mainly under laboratory conditions and although a lot of effects and parameters have been investigated and trends seem to be forming it is still difficult to draw conclusions and predict results without extensive testing.

Even though a lot of information is available, conducting active flow control experiments is still a very challenging task. This paper intends to present two very different test cases, which are investigated experimentally in order to prove the effectiveness of periodic excitation on slotted trailing edge flaps. Both experiments are aimed at suppressing flow separation and allowing higher flap deflection angles and thus higher lift. An experimental investigation on active flow control by periodic excitation is a multi-parameter problem, which makes it impossible for the experimenter to analyze every single parameter combination. Usually some of the parameters are set to fixed values in order to reduce the amount of variable parameters, taking into account that false or incorrect conclusions may be drawn. The set-up of such an experiment is either dominated by extensive preliminary testing or based on experience but less on flow physics as there are no prediction tools (except validated CFD) available yet, e.g. for best excitation location, jet direction or amplitude. Hence, this paper focuses on problems concerning some of the excitation parameters, especially coming from a very well investigated but generic test case, and tries to transfer this knowledge to a more complex set-up but without the opportunity of preliminary testing.

The first experiment was conducted on two-dimensional generic high-lift configurations in order to gain some knowledge on important excitation parameters, e.g. frequency, amplitude, jet direction and location up to Reynolds numbers of 10^6 [11]. After extensive open-loop testing a closed-loop system with actuator, sensor and controller was applied and successfully tested [12, 13]. By controlling only one excitation parameter (duty cycle) the results of the closed-loop case even improved on the open-loop results. However, the generic set-up does not provide realistic flow conditions that are encountered on a typical aircraft wing, e.g. flap cove, wing sweep, finite wing span, realistic airfoil shapes or wing-fuselage fillet. A second experiment is conducted in order to test and examine the effectiveness of pulsed blowing on a complex half

model, which provides some of the above mentioned restrictions[14]. It consists of the fuselage and a three-element wing containing slat, main wing and flap, modern airfoil shapes, a sweep angle of 30° and a finite wing span. The investigations show a substantial improvement in lift and drag resulting in a lift-to-drag ratio enhancement of about 20% to 25% in the 2D-case and about 15% in th 3D-case.
However, the results demonstrate that some of the excitation parameters used successfully in the two-dimensional case cannot be transferred to the three-dimensional set-up. A prediction from generic test case to realistic configurations still seems to be very difficult and in some cases almost impossible. Once the excitation parameters are tuned to fit the three-dimensional flow conditions the aerodynamic benefits of the 3D set-up seem to be slightly lower than in th 2D set-up.

3 Experimental set-up

The two wind tunnel models used in this investigation have complex set-ups that are described below only briefly. The wind tunnel allows velocities of up to 40m/s at a low degree of turbulence. Both models are designed to be fitted to a six-component wind tunnel balance (placed underneath the test section) that enables simultaneous acquisition of all three forces (lift, drag, side force) and all three moments (pitch, yaw and roll), allowing direct comparison of unexcited and excited flow results. A pulsating jet, adjustable in frequency, amplitude and duty cycle, emanating from the flap shoulder is used to excite the flow. In order to produce the pulsing of the jet fast switching solenoid valves are utilised that are connected to compressed air. Although additional plumbing is required for this type of excitation system compared to zero-net-mass-flux actuators that require only electrical wiring, it is ideal for testing small to medium size wind tunnel models because steady blowing, pulsed blowing, steady suction or pulsed suction are possible with on actuator set-up. An effort is made to implement the necessary actuators inside the flap in order to reduce pressure losses inside the actuator system. However, the implementation of the actuators differs in each model because of different wing shapes and sizes.

Two-Dimensional Generic Set-Up:
The generic test model consists of a NACA 4412 main wing and a NACA 4415 shape flap. Flap gap and overlap are fixed and no fowler motion is possible while the flap is deflected. In order to obtain a turbulent boundary layer trip wires are placed on the leading edge of the flap. The actuator is placed inside the flap and segmented in spanwise direction making it a total of elven independently controllable segments which share a common pressure supply. Figure 1 displays the set-up and the actuator assembly. More information concerning the test model and the actuator performance is given in [11].

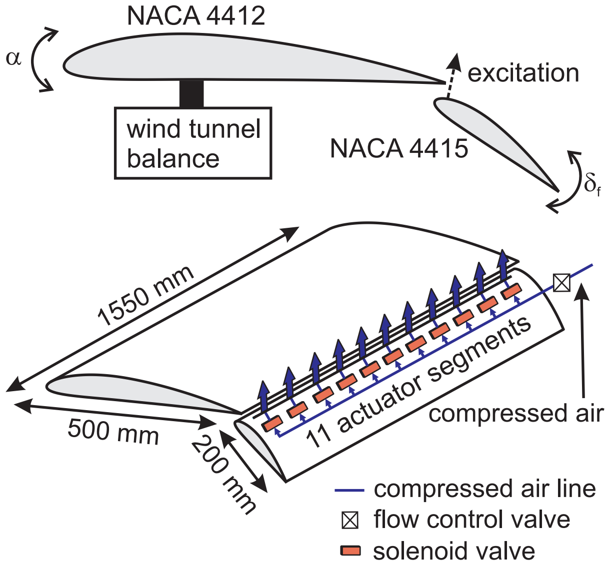

Fig. 1 Two-dimensional wind tunnel model and actuator assembly.

Angle of attack α and flap deflection angle δ_f are adjusted automatically by a stepper motor allowing a fast and precise angle sweep either for the complete configuration or just the flap. The pulsed jet emanates perpendicular to the surface of the flap through a very narrow slot, which is placed at 3.5% x/c_{flap} and extends along 80% of the flap span. The frequency is easily adjusted by changing the frequency of the valves while the jet velocity can be controlled by a flow control valve that changes the supply pressure. The direction of the jet in respect of the surrounding flow changes with the deflection angle because the actuator is installed inside the flap. This must be kept in mind when analysing the results because it may have an impact on excitation frequency and amplitude, which has not yet been investigated. Figure 2 shows the correlation between flap deflection angle and jet exit direction.

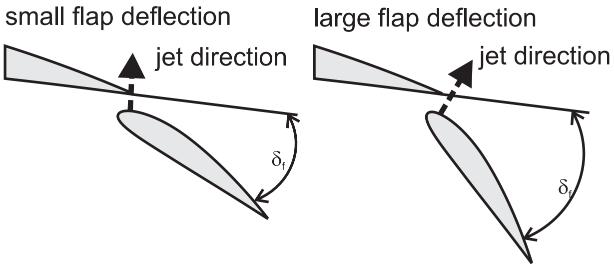

Fig. 2 Jet direction changes with flap deflection.

Swept Constant Chord Half Model:
The generic set-up lacks some important aspects that real configurations have to deal with, e.g. modern airfoil shapes, slat, sweep, flap cove, finite wing span to name just a few. In order to implement these aspects and to get closer to real aircraft wings, a half model is used in the second test case. The test model is mounted to the six-component balance system allowing fast and precise measurement of all forces and moments acting on the model. The model and the balance system are connected to a turntable enabling fast and automatic adjustment of the angle of attack. The single-slotted flap is connected to the main wing by four flap tracks allowing manual adjustment of flap gap and overlap in order to test off-design conditions. The flap deflection is controlled by four small linear actuators allowing a fast change of flap settings (no fowler motion). Figure 3 shows the model and the actuator system which consists of fast switching solenoid valves and compressed air as described for the generic set-up.

One major difficulty results from the small flap, which, although it is made out of glass fibre-reinforced composites, leaves room for an actuator of about 7 to 8mm in height. Because of insufficient room inside the flap the solenoid valves are placed inside the fuselage and connected to the excitation slots by compressed air lines. This assembly represents a compromise to the small interior of the flap and thus faces some disadvantages, e.g. pressure losses and reduction of excitation frequency due to the longer tubes and deterioration of the excitation jet time-dependent velocity profile. As the flap is deflected the excitation direction changes as described for the 2D set-up. The Reynolds number, based on the clean configuration chord length, is set to $0.32 \cdot 10^6$ in this first test series. In further investigations the Reynolds number will be increased to 10^6.

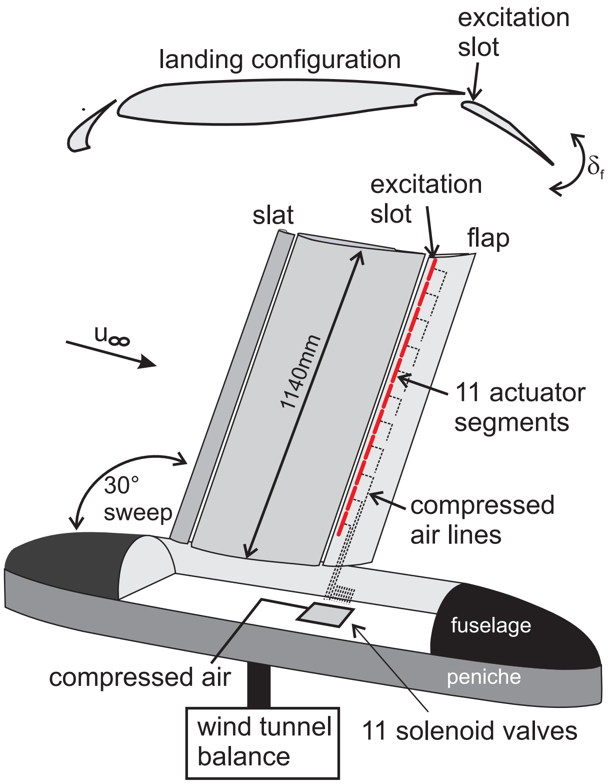

Fig. 3 3D half model with a constant chord sweptback wing ($chord_{clean} = 450mm$).

4 Results

Experiments that deal with active separation control by some form of periodic excitation encounter a multi-parameter problem. Since not all parameter changes can be addressed in this investigation (e.g. excitation frequency or excitation amplitude) special emphasis is placed on the excitation location and jet direction when transferring knowledge from one experiment to another. At first the separation behaviour of both configurations is analyzed in order to determine the dominant flow features. Figure 4 shows the large flow separation on the upper surface of the flap of the 2D test case. The upper picture is taken from PIV data and shows calculated streamlines coloured with the local static pressure. The contour plot below displays the local velocity of the flow around the trailing edge flap measured by a moveable single hot wire.

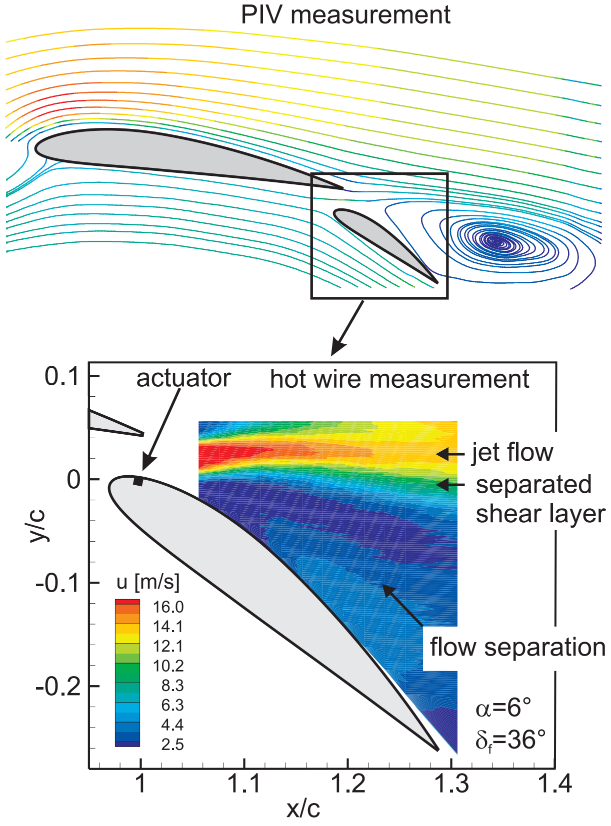

Fig. 4 PIV data and hot wire measurement showing a massive flow separation on the flap.

The data very clearly shows the formation of a separated jet that is formed by the flap gap resulting in high velocities (red) inside the jet and low velocities (blue) in the separated region (negative velocities cannot be measured by a single hot wire). Between these two flow regions a separated shear layer is formed (green) containing high-velocity fluctuations. Although these are averaged data, instantaneous PIV data show that the separation is dominated mainly by two-dimensional structures. Moving downstream of the separation point the flow becomes more and more three-dimensional due to small pressure differences along the span. The flow separates on the flap due to the severe adverse pressure gradient $\delta p/\delta x$ that grows with increased flap deflection.

The half model has a very different aerodynamic set-up as it is equipped with leading edge and trailing edge high-lift devices with modern airfoil shapes. The constant chord wing has a finite span of 1120mm and a sweep angle of 30°. The leading edge of the flap is much more curved than the NACA shape of the 2D set-up and is already optimised in order to prevent flow separation by passive means. As the flap is deflected downwards and separation is encountered the streamlines on the flap bend towards the wing tip due to the finite span and sweep (fig. 5). As the flap angle approaches its maximum deflection the flow is unable to overcome the adverse pressure gradient and the streamlines bend even more towards the wing tip until the flow completely separates. Wing tip vortex, sweep and pressure gradient play a major role in the separation process. This differs significantly from the 2D test case where the separation is mainly caused by one parameter only, i.e. the pressure gradient.

The constant chord of the wing produces a very strong unrealistic wing tip vortex, which interacts heavily with the flow around the outer part of the flap. The low pressure inside the vortex enhances the cross flow resulting in an almost parallel flow to the trailing edge of the flap at the onset of separation. The inboard section of the flap is slightly affected by the wing-fuselage fillet where a local flow separation occurs at high deflection angles. Predictably, the flow is very different from the two-dimensional test case and shows mainly local and three-dimensional flow phenomena, which have yet to be investigated in detail.

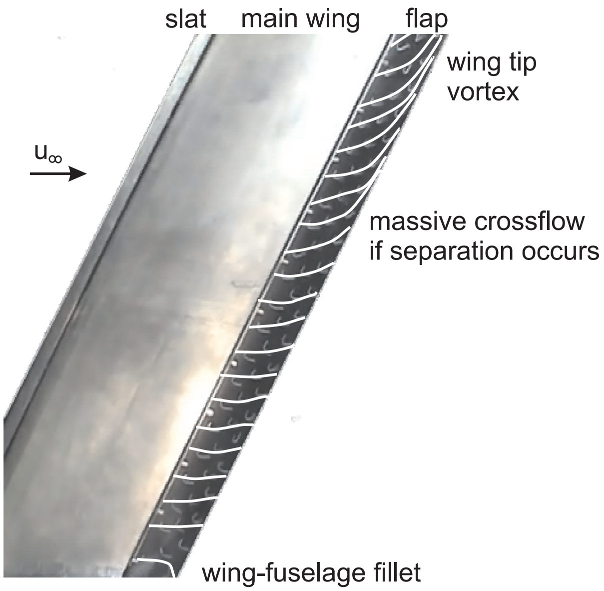

Fig. 5 Wool tuft visualisation on the flap near the onset of separation (flow directions are highlighted by white lines for better visibility).

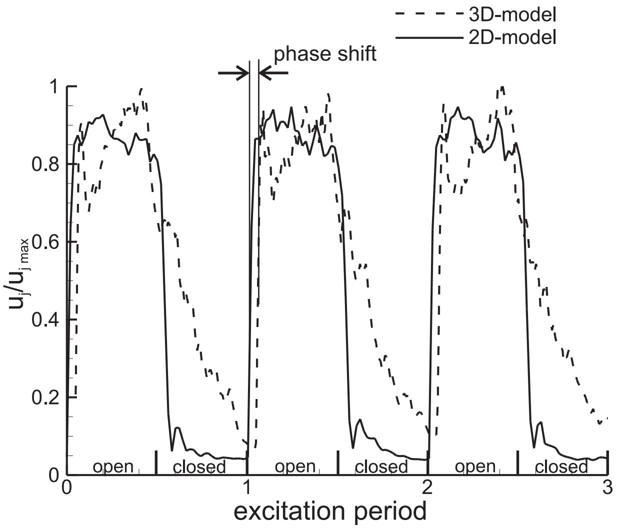

Fig. 6 Time-dependent excitation jet velocity for both actuator systems (100Hz).

In both cases the flow is excited using a pulsating jet without any suction phase. This differs from most experiments previously described, which use alternating suction and blowing resulting in a sinusoidal excitation. The lack of a suction phase is a result of the actuator layout, which uses compressed air and fast switching valves. Further tests will be conducted to clarify this point as the valves are capable of handling a vacuum. Figure 6 shows the time-dependent velocity fluctuations very close to the excitation slot for the 2D and the 3D test case.

The discrete pulses can be observed in both actuator assemblies but the longer tubes necessary for the half model corrupt the signal quality. Due to the longer tubes a phase shift between the valve opening and the velocity exiting the slot is noted as well. In the 2D-test case the valves are installed inside the flap leaving only a very short tube between the actual slot and the valve. The signal clearly has a better quality and shows very discrete pulses.

By dividing the actuator into smaller segments that are aligned in spanwise direction and the ability to control each segment (valve) independently, various modes of operation become possible. In the basic operation mode (mode 1) all valves work in phase, i.e. they open and close at the exact same time and with the same frequency. Working in second mode the valves open and close at different times along the span (phase delay) producing not only spanwise but also longitudinal vortices. In the third mode each valve is operated at different frequencies, which can be combined with the first and second mode. The fourth mode regulates the duty cycle of each valve, which can be set from 0% (valve closed) to 100% (continuous blowing), which can be combined with mode 1-3. Mode 4 enables local spanwise actuation while an arbitrary number of valves is closed and does not take part in the flow excitation. The excitation amplitude for all actuator segments is controlled and monitored by a single pressure control valve. In order to reduce the number of parameters the results presented in this paper are obtained with all valves working in phase with the same frequency and a duty cycle of 50%. Using solenoid valves -which can be controlled with extremely high precision - may not be the first choice for a practical application but has some advantages in model testing as it allows different excitation modes with a single but fixed set-up.

4.1 Results

In both test cases various geometric settings are tested with and without unsteady excitation. Only a few exemplary results are presented in this section with the focus on lift and drag. All data shown is corrected for wind tunnel interferences [15]. Because of the balance system used, it is possible to compare the results of unforced and forced flow instantly. Figure 7 shows lift versus drag for an angle of attack of $\alpha = 7^\circ$ while the flap deflection angle is varied from 0° to 50° (2D model). Plotted below is the unexcited case and one case with excitation.

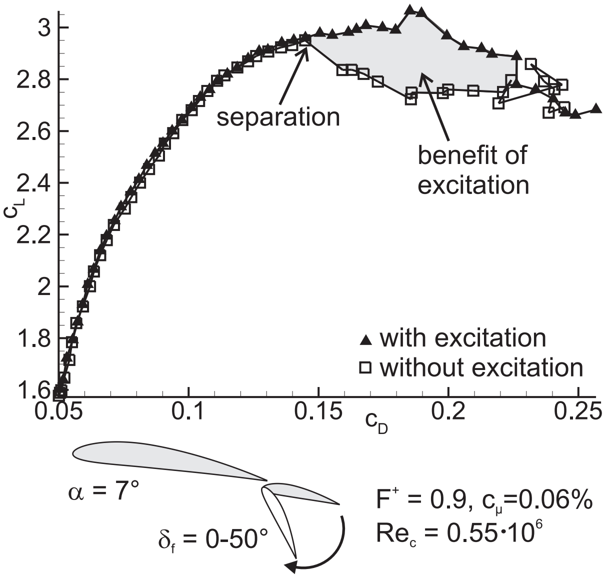

Fig. 7 Lift versus drag for unexcited and excited case showing improvement in the post-stall region (2D model).

Periodic excitation with a non-dimensional forcing frequency (based on the length from the actuator position to the trailing edge of the flap) of $F^+ = 0.9$ is able to suppress flow separation and increases the maximum flap deflection angle by 9°. Although it is known that there is a difference in excitation frequency between flow reattachment and delay of separation, a non-dimensional frequency of around $F^+ = 1$ seems to work well in this case. However, higher frequencies than $F^+ = 2$ are not possible due to the limited frequency of the solenoid valves.

A second example is plotted in figure 8 where the flap is set to an unfavourably high deflection and the angle of attack is swept. The result shows an improvement at all angles of attack due to the suppression of the separation on the flap. Taking into account all the results, a maximum improvement of 10-12% in lift and drag is possible.

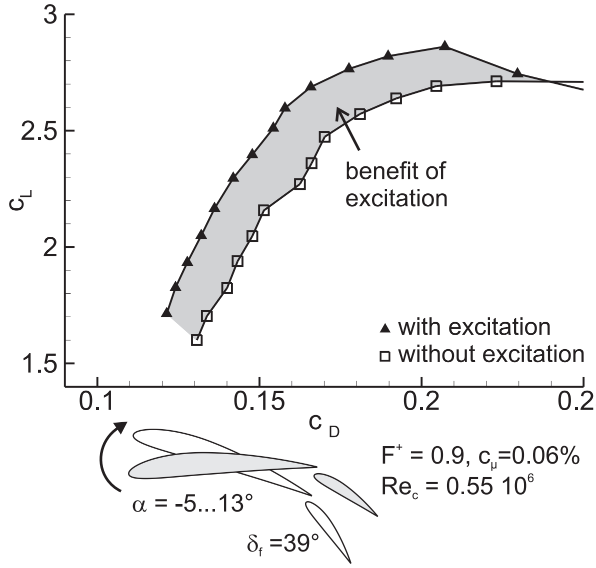

Fig. 8 Lift versus drag for unexcited and excited case during an angle of attack sweep (2D model).

The reason for the effectiveness of unsteady excitation in the two-dimensional test case is the amplification of coherent structures in the separated shear layer. The jet passing through the flap gap gets excited and starts to move up and down. If the amplification is high enough it touches the surface of the flap and remains attached. Although these results, only an exemplary part of which is included here, demonstrate the effectiveness of unsteady excitation some questions still remain to be answered. Above flap deflection angles of 40° to 45° the excitation seems to lose its impact on the flow and even an increase in excitation amplitude does not alter this situation. In addition to its frequency and amplitude, which may be easily varied in most experiments, the location and direction of the excitation in combination with the local curvature of the flap has a very strong impact as well. However, when conducting experiments with wind tunnel models, it is almost impossible to change the excitation location during a test run. The most applicable way to achieve this is to incorporate several streamwise cascaded excitation slots, which can only be realized in larger models or with miniature flow control actuators.

Transferring the knowledge of frequency, amplitude, location and direction of the excitation to the complex half model does not seem to be too complicated at first glance. Figure 9 displays both trailing edge flaps (drawn to scale) and excitation locations. As the curvature of the flap is very different, especially in the leading edge region, it seems that the location applicable for the 2D case is too far upstream for the 3D case due to the flap curvature.

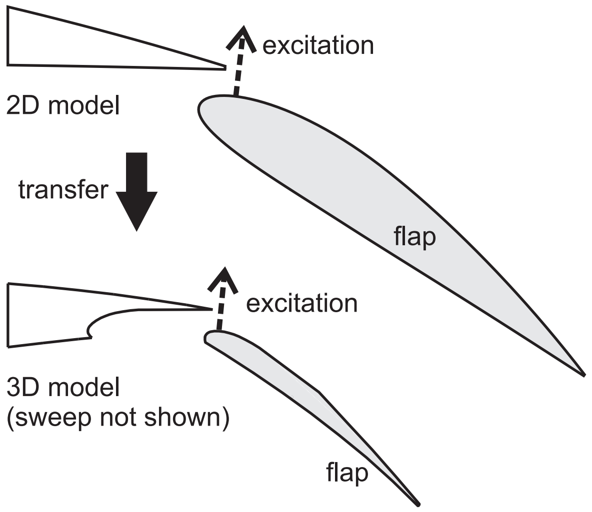

Fig. 9 Excitation locations and jet directions for the 2D and 3D test case.

The separation process in the 3D case highlighted in the previous chapter is rather a different one due to sweep effects and a finite wing span. Although no detailed flow field measurements have been conducted up to this point, it would appear that (proceeding from oil flow visualization) longitudinal vortices are generated in addition to streamwise vortices.

In order to test the sensitivity of periodic excitation to the flow two different excitation locations and directions were investigated. Figure 10 shows the results for a similar arrangement of excitation location and direction as used in the 2D case, i.e. the excitation slot is located far upstream and the jet emanates almost perpendicular to the surface. The plot displays the unexcited case and cases with pulsed blowing at different forcing frequency ranging from $F^+ = 02$ to $F^+ = 1.2$ at a constant blowing coefficient $c\mu$. It is noticeable that forcing with any of the frequencies does not enhance lift or drag but rather triggers separation earlier than in the unexcited case. This negative effect seems to be stronger if the excitation amplitude is increased. However, these constitute merely the first few tests, which have yet to be verified because the complex three-dimensional flow field may have additional impact on the excitation. As a first conclusion it is, however, possible to deduce that the excitation location and/or the excitation direction depends very much on the flap geometry and the local flow phenomena.

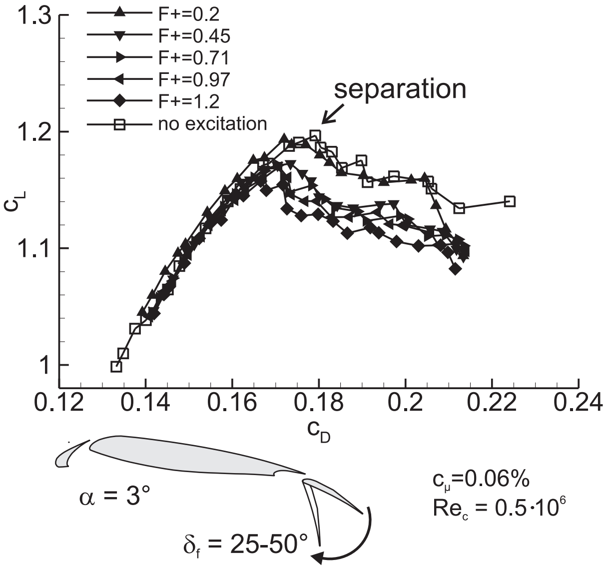

Fig. 10 Lift versus drag for unexcited and excited flow during an angle of attack sweep (3D model).

Allowing for the surface curvature of the flap, the excitation slot is moved downstream only a fraction of the flap chord and tilted in the direction of the flow. Due to the small size of the flap the two slot positions are situated only within a few millimetres of each other. The exact same configuration (α, δ_f, Re_c, F^+, c_μ) as displayed in figure 10 is measured again with a changed slot location and jet direction. The results are plotted in figure 11 for a flap deflection sweep.

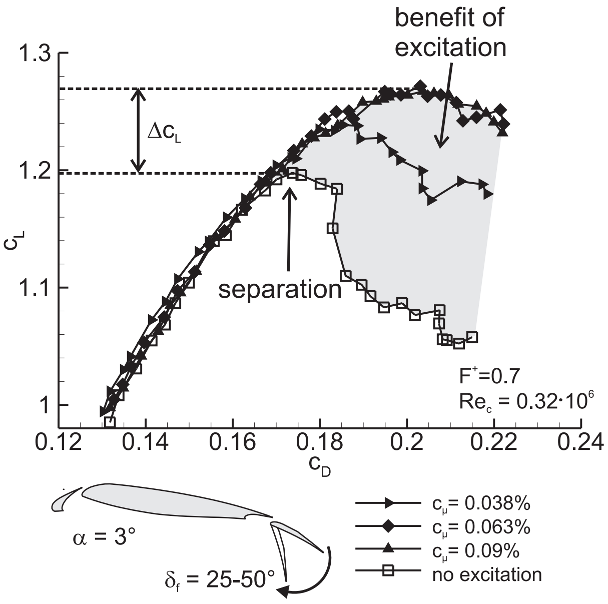

Fig. 11 Lift versus drag for the unexcited and excited case during an angle of attack sweep (3D model).

The unexcited flow encounters a separation at a deflection angle of $\delta_f = 36^\circ$. Exciting the flow with a low amplitude results in a slight increase in lift by keeping the flow attached and shows different post-stall behaviour. By increasing the amplitude separation is almost completely suppressed resulting in a very mild stall increasing the maximum flap angle from 36° to 44°. There seems to be a saturation in the excitation amplitude because increasing the amplitude even further does not improve either lift or drag. However, the excitation location and its direction were altered only on a very small scale which seems to improve the results dramatically. Which one of these two parameters, i.e. excitation slot position or jet direction, has a bigger impact on the flow has yet to be determined.

In order to compare the results to the two-dimensional test case, the angle of attack is swept with and without unsteady forcing. Figure 12 display the results for a fixed flap deflection angle of $\delta_F = 45^\circ$. Due to the large flap deflection the flow is separated even at low angles of attack. The excitation forces the flow to reattach resulting in a higher lift. In this case, there is almost no reduction in drag as demonstrated in the two-dimensional case. This is probably due to the finite wing span because once the separation is suppressed and the lift is increased the induced drag by the wing tip vortex is increased as well. The balance system permits only the collection of integral values (e.g. lift and drag) and does not allow any differentiation between the individual drag portions. However, this effect is still under investigation.

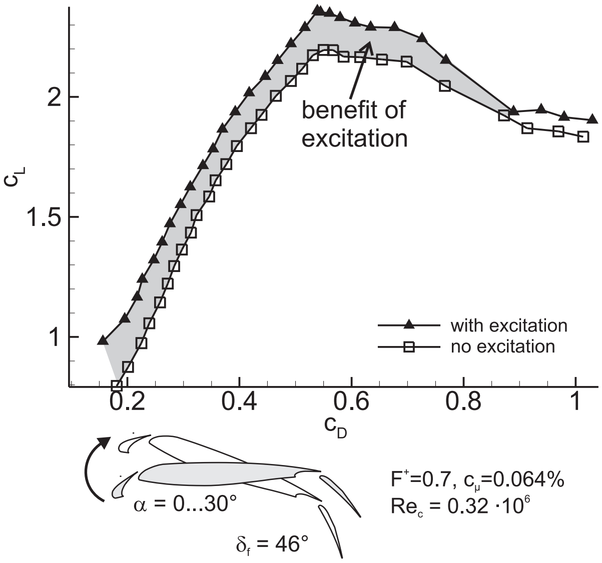

Fig. 12 Lift versus drag for the unexcited and excited case during an angle of attack sweep (3D model).

5 Conclusion

The intention of this paper is to show some aspects of active separation control by means of pulsed blowing from the flap shoulder of two different high-lift configurations. The main focus is placed on the location and direction of the excitation when moving from a generic and two-dimensional test case to a more complex and three-dimensional wind tunnel model. The influence of excitation frequency and amplitude are not within the scope of this paper.

In both test cases the lift can be increased significantly in the post-stall region by either delaying flow separation or reattaching an already separated flow (no data shown). By choosing unfavourable excitation parameters in terms of location on the flap and/or excitation direction unsteady forcing triggers early flow separation. As the models used are of medium size a change of the slot position in the millimetre range has a severe impact on the results. Since the complex half model incorporates modern airfoil shapes the leading edge of the flap is highly curved which probably plays an equally important part as the position and direction. A further aspect arises due to the finite wing span, which generates a wing tip vortex. Investigations on drag reduction by periodic forcing in combination with finite wings have yet to be conducted.

The results show that pulsed blowing provides the opportunity of enhancing the performance of realistic three-element high-lift configurations, encountering wing sweep, finite span, flap cove and modern airfoil shapes. Further investigations on the three-dimensional half model will be conducted at higher Reynolds numbers of up to 10^6 and detailed flow field measurements are required to work out some of the flow phenomena in the separated flow on the flap.

References

[1] Reckzeh, D.: *Aerodynmaic Design of Airbus High-Lift Wings in a Multidisciplinary Enviroment*. In: CEAS/KATnet Conference Bremen. (2005)

[2] Rudolph, P.K.C.: *Mechanical Design of High Lift Systems for High Aspect Ratio Swept Wings*. NASA/CR - 196709 (1998) 1–118

[3] Rudolph, P.K.C.: *High-Lift Systems on Commercial Subsonic Airliners*. NASA-CR 4746 (1996)

[4] McLean, J.D., Crouch, J.D., Stoner, R.C., Sakurai, S., Seidel, G.E., Feifel, W.M., Rush, H.M.: *Study of the Application of Separation Control by Unsteady Excitation to Civil Transport Aircraft*. Technical Report CR-1999-209338, NASA (1999)

[5] Huang, L., LeBeau, R.P., Huang, P., Hauser, T.: *Optimizition of Blowing and Suction Control on NACA 0012 Airfoil using Genetic Algorithm*. AIAA 2004-0225 (2004) pdf.

[6] Melton, L.P., Yao, C.S., Seifert, A.: *Active Control of Separation from the Flap of a Supercritical Airfoil*. AIAA Journal **Vol. 44** (2006) pp. 34–41

[7] Nishri, A., Wygnanski, I.: *Effects of Periodic Excitation on Turbulent Flow Separation from a Flap*. AIAA Journal **Vol. 36** (1998) pp. 547–556

[8] Seifert, A., Pack, L.G.: *Dynamics of Active Separation Control at High Reynoldsnumbers*. AIAA-Paper 0409 (2000)

[9] Seifert, A., Pack, L.G.: *Compressibility and Excitation Location Effects on High Reynolds Numbers Active Separation Control*. Journal of Aircraft **Vol. 40** (2003) pp. 110–126

[10] Seifert, A., Pack., L.G.: *Effects of Sweep an Active Separation Control at High Reynolds Numbers*. Journal of Aircraft **Vol. 40** (2003) pp. 120–126

[11] Petz, R., Nitsche, W.: *Active Separation Control on a High-Lift Configuration by A Periodically Pulsating Jet*. ICAS 2004-118 (2004)

[12] Petz, R., Nitsche, W., Becker, R., King, R.: *Lift, Drag and Moment Control on a High-Lift Configuration by Means of Active Flow Control*. In: CEAS/KATnet Conference on Key Aerodynamic Technologies. (2005)

[13] Becker, R., King, R., Petz, R., Nitsche, W.: *Adaptive closed-loop separation control on a high-lift configuration using extremum seeking*. 3rd AIAA Flow Control Conference, to be published (2006)

[14] Petz, R., Nitsche, W.: *Active Control of Flow Separation on a Swept Consant Chord Half-Model in High-Lift Configuration*. 3rd AIAA Flow Control Conference, to be published (2006)

[15] Barlow, J.B., Rae, W.H., Pope, A.: Low Speed Wind Tunnel Testing. 3rd edn. John Wiley &Sons, Inc (1999)