ACTIVE SEPARATION CONTROL ON A HIGH-LIFT CONFIGURATION BY A PERIODICALLY PULSATING JET

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Abstract

This paper describes experimental results on controlling flow separation by periodic excitation on the flap of a generic high-lift configuration. The slotted flap of the 2D test model is equipped with a newly designed actuator that meets the desired requirements of frequency and amplitude range but is still fairly small, very robust and reliable. It consists of fast switching solenoid valves connected to compressed air which produce a periodically pulsating jet at the flapt's leading edge. This actuator mechanism enables the control of the separated flow on the flap in terms of lift gain an drag reduction resulting in a lift/drag ratio enhancement of 20-25%. Because of the actuator assembly with individually controllable segments the separation can be forced to attach only on certain parts of the flap. This can be utilized to generate a roll moment without the need of a mechanical aileron.

1 Nomenclature

α	angle of attack
η	flap deflection angle
c_{main}	chord length main airfoil
c_{flap}	chord length flap
F^+	nondimensional forcing frequency
c_μ	nondimensional momentum coefficient
Re	chord Reynolds number
c_L	lift coefficient
c_D	drag coefficient
c_p	pressure coefficient
c_L/c_{L0}	lift coefficient with excitation versus unexcited lift coefficient
$\frac{x}{c}$	nondimensional length

2 General Introduction

Flow control technology is of immense importance in modern aerodynamics [1]. The present experimental investigations were carried out with the aim to enhance the lift of a two dimensional generic high-lift model by periodic excitation. The intention was to locally actuate the flow at the leading edge of the slotted flap to suppress turbulent flow separation or to get the already separated flow to reattach and regain the full lifting force. This can be especially useful for minimizing the complexity of high-lift systems of modern passenger aircraft concerning multiple trailing edge devices. If the aerodynamic performance can be significantly improved by a small amount of energy for active flow control, the landing distances of large aircraft could be reduced due to slower approach speeds which would also result in a quieter approach. As will be shown in this paper the local excitation has a global effect on the complete flow field around the high-lift configuration.

It has been demonstrated in a number of experiments that oscillatory flow control is an effective tool to delay boundary layer separation. These experiments show that it is possible to control the flow in a variety of ways (regarding flow separation) mostly on single element airfoils [2]

[3] or generic test models [4] [5] from low to flight Reynolds number [6]. The authors mostly use alternating blowing and suction through a spanwise oriented small slot to enhance shear layer mixing and transfer high momentum fluid from the shear layer to the wall an thus prevents boundary layer separation. A first application of flow control by local periodic excitation has been demonstrated by [7] and [8] who successfully performed tests to eliminate separation at the wings of a tilt-rotor aircraft.

Principle tests on a high-lift configuration at low Reynolds number regarding active flow control with periodic excitation have shown that the flow can be effectively controlled in terms of lift enhancement [9]. The new experiments presented here describe a way to enhance not only lift but to control drag and roll moment behavior with a newly developed segmented actuator that fits into the flapt's interior.

The results show a significant influence of the flow due to excitation. The jet that is formed by by the flap gap and the main airfoils trailing edge is inherently very receptive to perturbations often called jet flapping. Since the flapping motion is excitable, a pulsating jet is used to get the separated jet to attach to the flapt's upper surface. This paper does not go into the physical details of why this excitation works so well but describes the aerodynamic benefits of active flow control and its application to a high-lift configuration in terms of global lift gain and drag reduction.

3 Experimental setup

All experiments were performed in a closed-loop wind-tunnel with a low degree of turbulence of 0.3%. The wind-tunnel setup used for this investigation allows wind speeds reaching up to $30\frac{m}{s}$. Most results presented here were gathered at Reynolds numbers around $0.5 \cdot 10^6$ but test withs higher Reynolds numbers up to $1 \cdot 10^6$ were conducted.

3.1 Wind Tunnel Model

The test model (Figure 1) consists of a NACA 4412 main airfoil with a single slotted NACA 4415 shape flap. The flap has a chord length of $0.4 \cdot c_{main}$ by an aspect ration of 3.1. The setup is completely two dimensional.

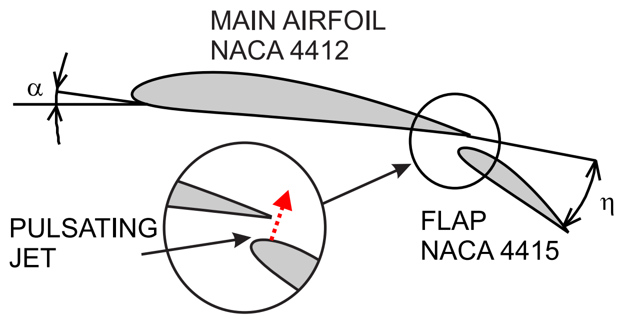

Fig. 1 Wind tunnel test model.

Angle of attack α and flap deflection angle η can be varied automatically and independently for testing a wide range of different geometric configurations. Flap overlap and flap gap are fixed so that in terms of the flap only a rotational degree of freedom remains. Both main profile and flap are equipped with trip wires at the leading edges to fix the transition and guarantee a turbulent separation.

The test model is placed inside a test section (2000 mm x 1400 mm, w x h) and mounted on a 6-component balance installed underneath the test section (see figure 2). Forces and moments are transferred into the balance via a very stiff beam construction as shown in the figure. The two upward directed beams reaching into the test section are aerodynamically encased by two sidewalls. To minimize measurement errors the gap between the sidewalls and the test model is reduced to $0.1mm$ but still assures contact-free motion of the model. Forces and moments presented here are corrected by a standard wind tunnel wall correction method [10]. Because of the balance the complete measurement equipment and the actuator is placed inside the model and connected to a minimum of cables that have to be lead through the model and out of the test section.

The main profile is equipped with 42 pressure

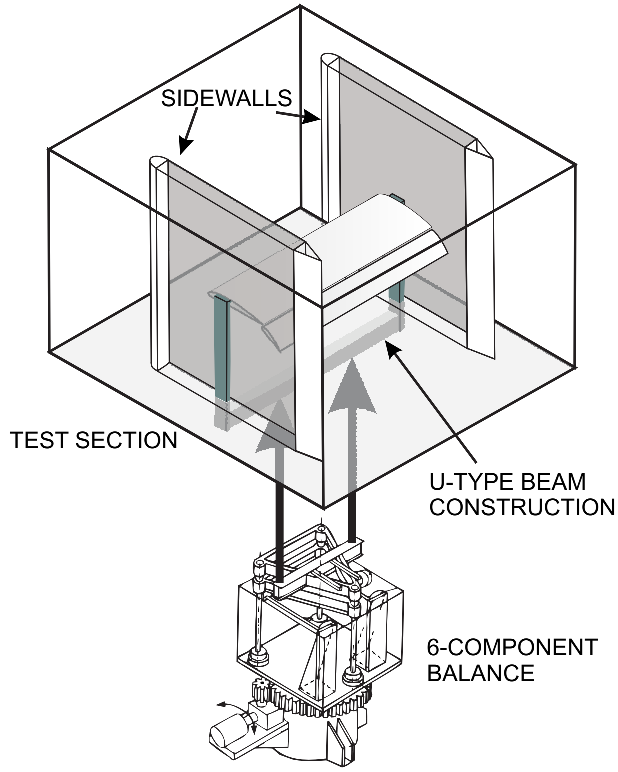

Fig. 2 Test model and test section.

orifices at the upper and lower side of the airfoil to measure the static pressure distribution. 36 pressure transducers are installed inside the flap of which 25 measure the unsteady pressure distribution on the flap. The remaining 11 transducers monitor the actual excitation amplitude and phase of each actuator segment (see following section). Two stepping motors for the flap angle adjustment and divers power supplies complete the setup of the main airfoil.

3.2 Actuator

The actuator is placed inside the flap which has a maximum thickness of 30*mm* (see figure 3). The slit where the pulsating jet is emitted is placed at the leading edge of the flap at $\frac{x}{c_{flap}} = 3.5\%$ and reaches across 81% of the entire wing span due to the installations of the flap deflection angle mechanism at both sides. The jet direction is not adjustable and always perpendicular to the flaps upper surface so that jet direction changes with varying flap deflection angle.

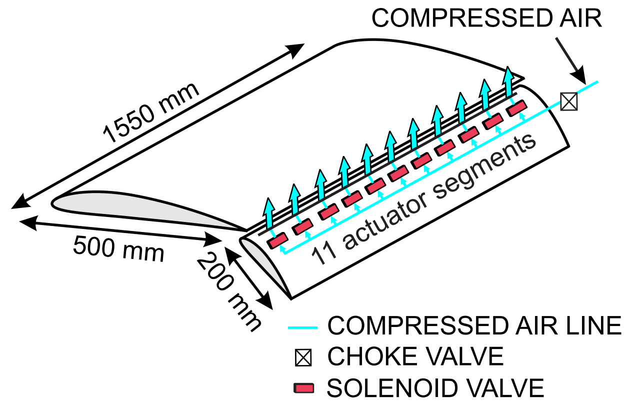

Fig. 3 Integration of the actuator into the flap.

The actuator itself consists of 11 segments. Each segment is made out of a fast switching small solenoid valve connected to a small aluminium block. This block converts the compressed air attached to the valve from a circular outlet of the valve to the narrow slit. The velocity profile is optimized to be very homogenous along the actuator span. One segment is $15-20mm$ high, 114*mm* wide and 115*mm* long. 11 of these segments are placed along the span to form the complete actuator mechanism. The solenoid valves have only two states which are open or closed. This produces a blowing pulsating jet with a velocity profile at the slit that looks like square signal (see figure 4).

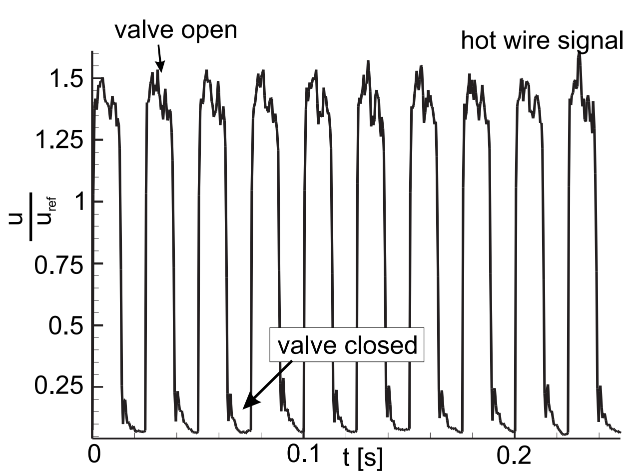

Fig. 4 Pulsating jet generated by the actuator mechanism.

The use of compressed air that is externally generated removes the demand of the actuator to produce high amplitudes itself. This in turn enables the building of a compact and very robust actuator that has been 100% reliable during the investigations. Actuator segmentation has an additional advantage because every valve can be individually controlled in terms of frequency. This is done by a fast programmable micro controller which controls the valves open and close times and enables a fast and easy change of parameters via a normal PC. At this stage all actuator segments share a common amplitude that is controllable by a choke valve placed inside the main airfoil. This will be changed in future works so that each segment is independently adjustable in frequency and amplitude. Spanwise segmentation allows a two dimensional actuation (all valves open and close at the same time) as well as a three dimensional actuation where the valves open and close at different times along the span with a freely adjustable phase offset. This type of actuation generates not only a two dimensional spanwise vortex but also streamwise vortices at the ends of each segment. The majority of investigations concerning active flow control use a blowing suction type of actuation. A suction phase can easily be integrated and separately adjusted compared to the blowing phase. This will also be done in future works.

The actuator amplitude is controlled by 11 fast pressure transducer of which each is connected to one actuator segment. The periodic change of pressure allows a calibration and gives additional information of the excitation phases of each segment.

4 Results

The results shown here mainly represent the global effect of the actuation in terms of lift and drag forces using a two dimensional actuation. First of all the unexcited flow was investigated in a wide parameter range concerning both angles α and η to document the separation behavior. Afterwards the same configurations were tested under the influence of actuation with different excitation frequencies and amplitudes. The force balance measurements were always conducted in the same way by first increasing α or η from a minimum to a maximum value and afterwards decreased it again to detect possible hysteresis effects. The influence of Reynolds number variation was investigated as well but is not presented here.

4.1 Unexcited Flow

Figure 5 shows lift (upper diagram) and drag (lower diagram) coefficient versus angle of attack for exemplary flap deflection angles. As the angle of attack increases the lift rises linear until flow separation on the main airfoil occurs. At low flap deflection angles the lift drop is fairly smooth but with increasing η the loss of lift becomes more and more sudden. The maximum lift increases as well but with the penalty of an earlier separation.

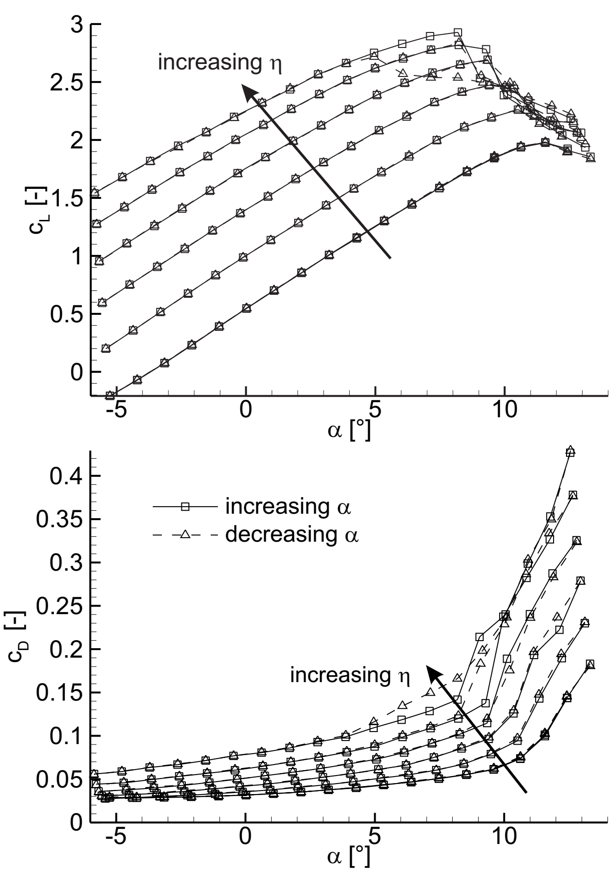

Fig. 5 Lift and drag distribution without excitation.

The diagram also demonstrates the accuracy of α adjustments while it is increased and decreased again. The decreasing angle of attack curves are only visibly if a lift hysteresis is present. The lower diagram shows drag polar plots for the same configurations. The accuracy observed in the upper diagram applies also to the drag measurement. The increase in drag due to flow separation is clearly visible and occurs at the same angles of attacks as the lift drop earlier.

4.2 Excited Flow

The next figures display some exemplary results of force balance measurements with actuation. In the course of this investigation not only geometric parameters were varied but also excitation parameters like frequency, amplitude, number of active actuator segments and three dimensional actuation. Best excitation frequency and amplitude were determined in a set of preliminary tests. The most successful frequency in terms lift enhancement is found at a reduced frequency of about $F^+ = 1$ as is shown in figure 6 for two different excitation amplitudes at fixed angles. The dependency of the excitation frequency is not very strong. The by far more important parameter is the excitation amplitude which has to exceed a certain level to have a measurable influence on the flow.

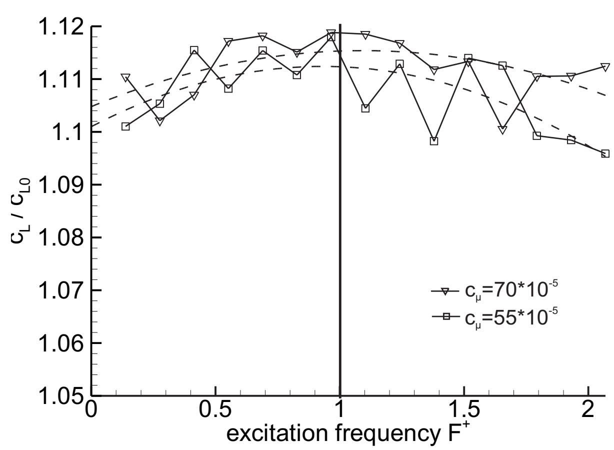

Fig. 6 Variation of forcing frequency at a fixed configuration.

Following the investigations of excitation parameters were measurements concerning the documentation of lift enhancement by subsequently changing the angle of attack and flap deflection angle in different variations.

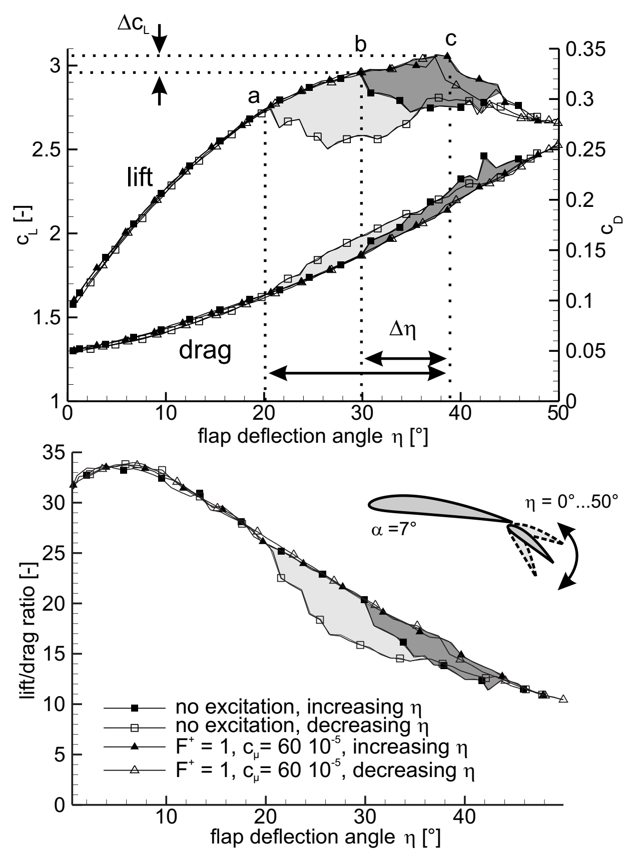

Fig. 7 Example of flap polar diagrams with and without excitation.

The first set of diagrams (figure 7) display the effect of a pulsating actuation by a variation of flap deflection angle η while α is fixed at 7°. Lift increases as the flap is moved downwards in one degree steps. Without excitation the separation occurs at $\eta = 30°$ (marked with *b*). By decreasing the angle again a large hysteresis is visible and reattachment of the flow does not occur until $\eta = 20°$ (marked with *a*). The complete polar is then measured again but this time with periodic excitation. This actuation keeps the flow attached to the flap and therefore delays flow separation by up to 9° (marked with *c*). Then the flow separates but if η is decreased again the hysteresis effect that was noticed in the unexcited case vanishes almost completely.

Although the separation is successfully de-

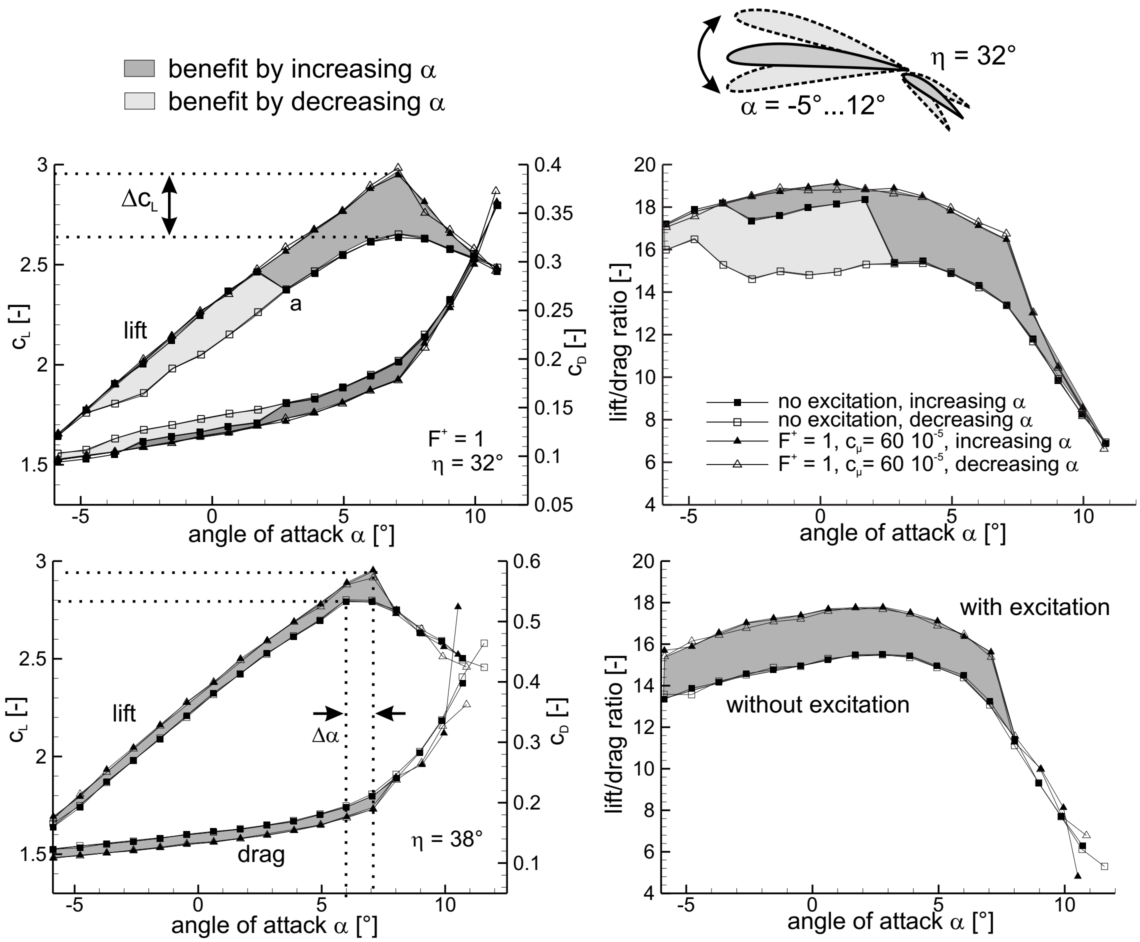

Fig. 8 Lift and drag distribution with/without excitation.

layed only a small gain in maximum lift is noticeable. The drag distribution shows the same behavior. As the angle is increased the drag rises. As long as the flow is attached to the flapt's upper surface no differences between unexcited and excited flow is observed. The increase in drag is consistent with the loss of lift without excitation. The additional drag due to the large separation region is avoided when actuating by keeping the flow attached. The gray colored areas indicate the increase in terms of lift and the decrease in terms of drag due to excitation.

The benefit of periodic excitation is best seen in the lower diagram displaying the aerodynamic quality, the lift to drag ratio. The gain in lift and the reduction in drag add to a substantial performance benefit of 20-25% in the lift to drag ratio.

The local excitation on the flapt's leading edge changes not only the local flow field around the trailing edge device but influences the complete flow around the wing. This is shown in figure 8 where the angle of attack is varied with a fixed flap deflection angle. These four diagrams demonstrate the benefit of periodic excitation in comparison to the unexcited flow as displayed in the last figure.

Once again the gray colored areas indicate an increase in terms of lift and a decrease in terms of drag due to excitation. The unexcited lift distribution in the upper left diagram shows a significant loss of lift at $\alpha = 2^\circ$ (marked with *a*) while η is fixed to a moderate angle of 32°. This results from a sudden separation on the flap while the flow on the main profile is still attached. The lift then rises still further until the flow on the main profile separates as well. A large hysteresis is noticed during the decrease of α with a very late reattachment at low angles of attack. Excitation in turn keeps the flow fully attached to the flap and regains maximum lift and minimum drag compared to the unexcited flow. The lift increases by up to 12% while the drag at the same time decreases by up to 12%. This behavior again results in a dramatic gain of lift to drag ration by up to 25% over a wide range of angle of attack shown in the right diagram.

The same positive effects are measurable at different flap deflection angles as displayed exemplary in the lower two diagrams which again show lift and drag polare plots on the left and lift/drag ratio on the right. This time η is set 5° further to 38° where the flow on the flap is fully separated even at negative angles of attack. Because of the actuation separation on the flap is prevented until the separation on the main airfoil occurs. The lift distribution with excitation shows a higher c_L during the complete polar plot until the flow separates on the main airfoil which is even delayed slightly due to the attached flow on the flap. The lift to drag ratio demonstrates again the benefit of actuation over the complete range of α.

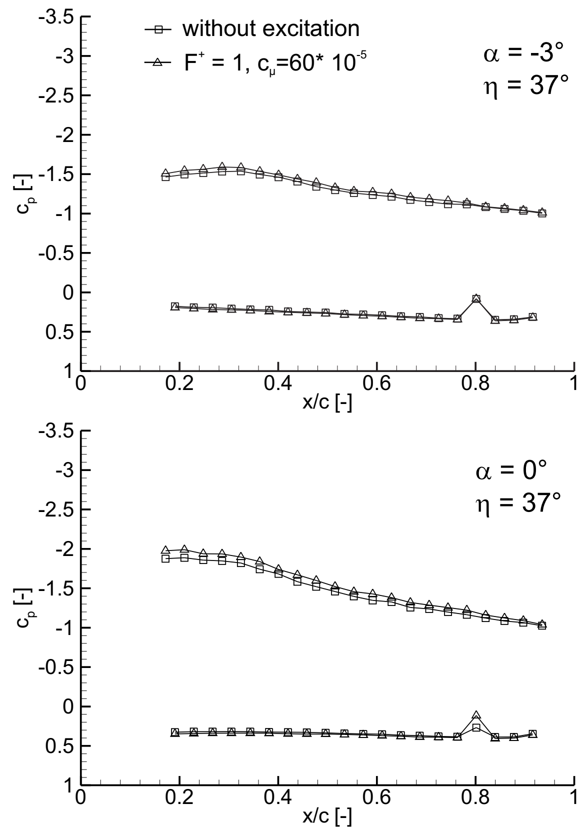

Fig. 9 Static pressure distribution $\alpha = -3°$ and $\alpha = 0°$ (main airfoil).

4.3 Pressure Distributions

The pressure distribution of the main airfoil illustrates how the increase in lift due to local excitation at the flaps leading edge is generated. Increase in lift due to local periodic excitation is not exclusively produced because of the regained lifting force at the flap. By far the larger amount of lift is generated by the changed flow around the main airfoil. Diagrams in figure 9 and 10 show the differences of local static pressure on the main profile at a fixed flap deflection angle with and without excitation.

As can bee seen in the upper diagram of figure 9 there is almost no difference in static pressure visible at a negative angle of attack. As the angle of attack increases (lower diagram) the curve with excitation shows a lower static pressure on the upper side which explains the lift increase. This behavior is most effective at the point where the separation occurs on the trailing edge of the main profile (see upper diagram in figure 10). Here the benefit of the excitation is clearly seen by the lower static pressure and thus higher velocities around the airfoil. The gain in lift due to actuation on the flap has its limits when the separation on the main airfoil is starting to grow and the point of separation moves to the leading edge. Hence the effect of excitation is marginal.

5 Conclusion

Experimental investigations on a 2D high-lift configuration with active flow control were carried out to demonstrate the ability to control the flow on the flap. The aim was to develop a suitable actuator that is capable of producing the desired frequencies and amplitudes and is still reliable and robust in operation. The system should

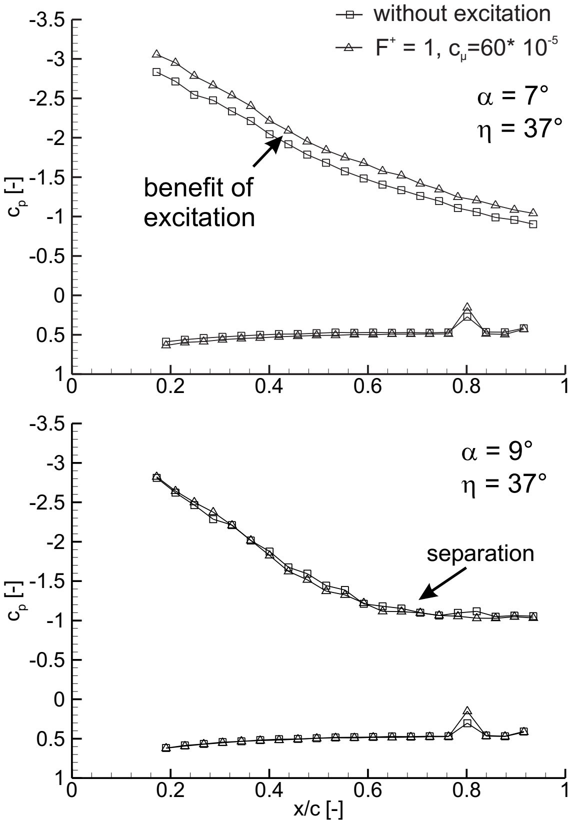

Fig. 10 Static pressure distribution $\alpha = 7°$ and $\alpha = 9°$ (main airfoil).

fit inside the flap as it must in a real application. A solution was found by using externally generated compressed air in conjunction with fast switching solenoid valves. This excitation mechanism is capable of producing high amplitudes at desired forcing frequencies. By choosing a segmented assembly local excitation on parts of the flap are possible as well as three dimensional actuation.

Flow separation on the flap tends to decrease the camber of the complete configuration by changing the direction of downwash at the trailing edge. Therefore the total circulation decreases resulting in a loss of lift. The circulation is regained by reattaching the flow on the flap due to periodic excitation. This demonstrates that local excitation has a global effect influencing even the stagnation point of the main profile. Periodic excitation has the following effects observed during the tests:

1. Separated flow can be reattached and the full lifting force is regained.
2. Flow separation is successfully delayed and higher flap deflection angles are possible.
3. Lift and drag are substantially improved so that the overall aerodynamic performance (lift/drag ratio) is massively improved by 20-25%.
4. Hysteresis effects are almost completely suppressed.
5. The use of a segmented actuator enables the generation of roll moments by local excitation which only locally attaches the flow to the flap (results are not presented here).
6. No additional drag is produced by excitation while the flow is still attached.

This demonstrates the ability of flow control to enhance the performance of high-lift configurations.

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