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Active Separation Control on the Flap of a Two-Dimensional Generic High-Lift Configuration

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The paper describes experimental results of controlling flow separation by periodic excitation on the flap of a generic high-lift configuration. The single slotted flap of the two-dimensional test model is equipped with a robust and reliable actuator system that fits inside the flap. The flow is excited using a pulsed wall jet that emanates from the upper surface near the flap's leading edge through a small spanwise-oriented slot. By preventing the flow from separating or by reattaching the separated flow, lift and drag are substantially improved, resulting in a lift-to-drag ratio enhancement of 20–25%. Because of the actuator assembly with spanwise individually addressable segments, the separated flow can be forced to attach only to certain parts of the flap. Local spanwise excitation is thus used to generate a rolling moment without the need to deflect an aileron.

Nomenclature

c_D	=	drag coefficient
c_{flap}	=	flap chord
c_{main}	=	main profile chord
c_L	=	lift coefficient
c_l	=	rolling moment coefficient
c_p	=	pressure coefficient
c_μ	=	nondimensional momentum coefficient $2(h/c_{\text{main}})(u'/u_\infty)^2$
F^+	=	nondimensional forcing frequency fl_a/u_∞
h	=	excitation slot width
L/D	=	lift-to-drag ratio
l_a	=	length from actuator position to the trailing edge of the flap
Re_c	=	chord Reynolds number
t	=	time, s
u_j	=	velocity at excitation slot exit
u'	=	phase-locked rms amplitude of the velocity close to the excitation slot (still air)
x	=	coordinate
x/c	=	nondimensional length
y	=	coordinate
α	=	angle of attack
Δc_L	=	percentage lift gain due to excitation
$\Delta L/D$	=	percentage lift-to-drag ratio gain due to excitation
δ_f	=	flap deflection angle

I. Introduction

FLOW control technology is of immense importance in modern aerodynamics as the conventional designs are pushed to their limits [1]. Starting out with the initial aim of delaying boundary layer separation, i.e., on a wing, as it is presented in this paper, flow control is also put to the test for jet vectoring [2,3], engine improvement [4,5], or wing tip/flap side edge vortex breakdown [6]. Not only aerodynamics is investigated but a lot of interest is paid to actuator technology used in flow control experiments, which is nearly as important as the aerodynamics [7,8].

It has been demonstrated in a number of experiments that oscillatory flow control is an effective tool to delay boundary layer separation [9]. These experiments show that it is possible to control the flow in a variety of ways (regarding flow separation) mostly on single-element airfoils [10] or generic test models [11,12] from low to flight Reynolds number [13]. The authors mostly use alternating blowing and suction through a spanwise-oriented small slot to enhance shear layer mixing in order to transfer high-momentum fluid from the shear layer to the wall, thus preventing boundary layer separation due to the severe adverse pressure gradient. Regarding flow reattachment the excitation is most effective if the excitation frequency is in the range of natural instability frequency of the separated shear layer. There still seems to be an unresolved debate concerning the wall-jet direction, which is in most cases tangential or perpendicular to the surface. A first application of flow control by local periodic excitation to a real-size aircraft has been demonstrated on the wings of a tilt-rotor aircraft, which were equipped with actuators to prevent flow separation to improve the hover capability significantly [14,15].

Modern transport aircraft use slotted trailing-edge devices to prevent flow separation on the flap by transferring high-momentum fluid from the main wing's lower surface to the weakened flap's boundary layer. The additional momentum delays separation on the flap up to a certain flap deflection angle and thus allows higher lift coefficients. This passive method of flow control has its limits and can only be further improved by double- or triple-slotted flaps that have a weight penalty in cruise conditions. Active separation control is on the one hand very useful for minimizing the mechanical complexity of modern high-lift systems with multiple trailing-edge devices. On the other hand, it could be used to improve the aerodynamic performance of simple high-lift systems with single-slotted flaps by simplifying the flap track geometry or reducing the flap chord. If the aerodynamic performance can be significantly enhanced by a small amount of energy necessary 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. The downside of active flow control is the necessary sensor–actuator system that has to be simple, robust, reliable, and low-energy-consuming, no more complex or heavier than the original mechanical flap system. Active separation control will only be applied to real-size aircraft if the amount of energy necessary to prevent separation is low and the aerodynamic benefit is high, resulting in a high figure of merit. To minimize the energy consumption of the actuators it is very important to look for

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inherently occurring flow instabilities in the separated flow, which, if properly excited by periodic excitation, can dramatically improve the actuator efficiency [16].

High-lift configurations with slotted flaps, as presented in this paper, develop a very complex flow flied with congruent boundary layers in the flap region. The jet flow produced by the gap between flap and main airfoil is inherently very receptive to perturbations, often called jet flapping. Because the flapping motion is excitable, a pulsating jet is used to reattach the separated jet to the flap's upper surface. Because of the complex flowfield with different shear layers in the vicinity of the excitation location (main wing wake, separated shear layer, planar jet flow), it is very difficult to detect instabilities or to differentiate distinct mechanisms experimentally. Figure 1 shows two particle image velocimetry (PIV)-images of the flowfield with and without forcing to give an insight view on how periodic forcing acts on reattaching the separated flow. The flowfield on the left-hand side is dominated by the large separation region on the flap. Regions with high vorticity (highlighted by grayed areas) are found within the separated shear layer and the flow separating from the trailing edge of the flap. The arrows, indicating the local velocity vector, clearly show vortices in the separated shear layer. By introducing periodic blowing these structures are excited and mixing between the separated region, and the shear layer is enhanced resulting in an attached jet flow (right-hand-side picture). Hence, the vortices produced by the excitation now follow the surface of the flap and are of smaller magnitude as in the separated case. Amplification of coherent structures in the separated shear layer is the primary mechanism for flow reattachment. But reattachment process is also affected by surface curvature and the inherently occurring flapping motion of the separated jet. Principal tests on a generic high-lift configuration with periodic excitation at low Reynolds numbers ($Re_c = 1.5 \times 10^5$) revealed that the flow can be effectively controlled in terms of lift improvement [17]. The experimental investigations presented in the following paper were carried out with the aim of enhancing the aerodynamic performance (lift and drag) of a two-dimensional generic high-lift configuration by pulsed blowing [18,19]. The intention was to locally excite the flow near the leading edge of the slotted flap to suppress turbulent flow separation or to get the already separated flow to reattach to the surface of the flap. As will be shown in this paper, local excitation has a global effect on the complete flowfield around the high-lift configuration and has a substantial impact on lift, drag, and the pitching and rolling moment. Active flow control was successfully investigated up to Reynolds numbers of 1×10^6.

II. Experimental Setup

All experiments were performed in a closed-loop wind tunnel with a low degree of freestream turbulence of 0.3% up to a freestream velocity of 30 m/s. Most results presented here were gathered at Reynolds numbers of 0.55×10^6. Tests with higher Reynolds numbers up to 1×10^6 were successfully conducted as well.

A. Wind-Tunnel Model

The test model (Fig. 2) consists of a NACA 4412 main airfoil with a single-slotted NACA 4415 shape flap, which has a chord length of $0.4c_{\mathrm{main}}$. The setup is completely two-dimensional, resulting in an aspect ratio for the main wing of 3.1 and for flap of 7.75. The configuration was chosen because it was investigated previously, both numerically [20] (without flow control) and experimentally [21] (with flow control, $Re_c = 1.5 \times 10^5$), and a small set of data for the base flow is available by way of comparison. The large flap chord helps integrating the excitation mechanism inside the flap, although realistic flap chords are between 20 and 30% of the main chord. The position of the flap, given by overlap and gap, is fixed in respect of the trailing edge of the main wing. The angle of attack and the flap deflection angle may be adjusted independently and automatically, allowing tests at many different settings within a short period of time. Both angles are operated by a computer connected to stepper motors inside (flap adjustment) and outside (angle of attack adjustment) of the model to allow a fast yet precise change of parameters. Main profile and flap are equipped with trip wires at the leading edges to fix the transition and guarantee a turbulent separation. The pulsed jet

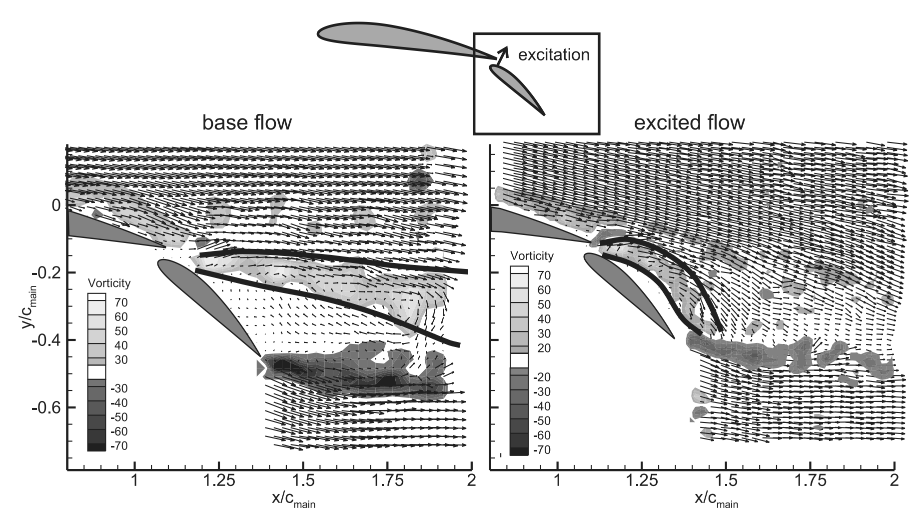

Fig. 1 Snapshots of PIV data for an unexcited and excited flow (water tunnel, $Re_c = 0.16 \times 10^5$).

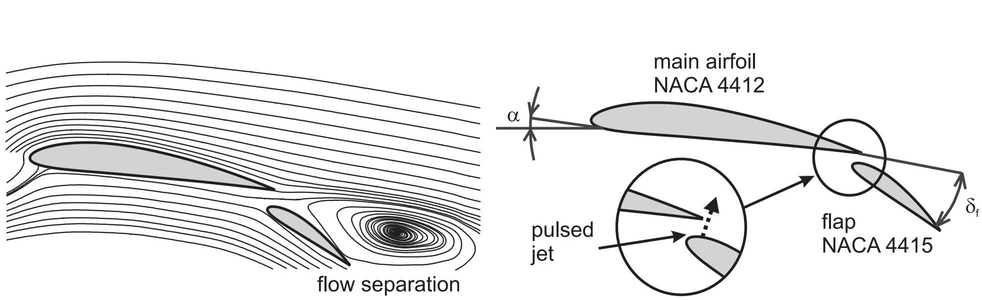

Fig. 2 Left: streamlines highlighting the separation on the flap. Right: high-lift setup.

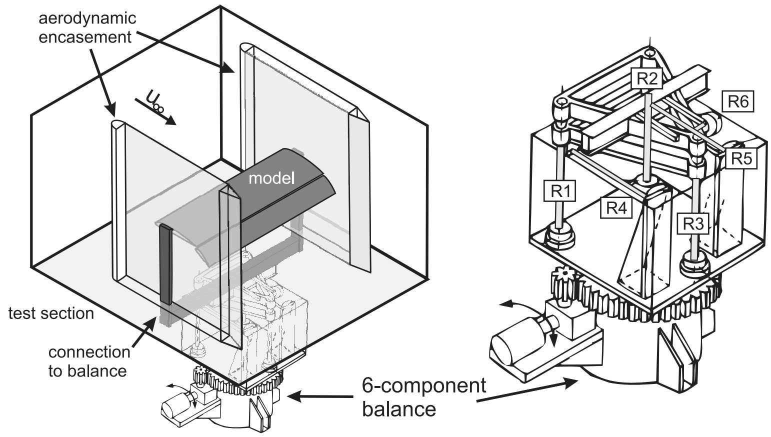

Fig. 3 Sketch of the experimental setup and the balance system.

blows through a spanwise continuous thin slot that is located at the flap's upper surface at $3.5\% x/c_{\mathrm{flap}}$ (Fig. 2).

The test model is placed inside a test section (2000 × 1400 mm) and mounted on a six-component balance installed beneath the test section (Fig. 3). Forces and moments are transferred into the balance via a very stiff metal frame construction as shown in the figure. The two upward-directed beams reaching into the test section are aerodynamically encased. To minimize measurement errors the gap between the encasing and the test model is reduced to 0.1 mm but still assures contact-free motion of the model. Because of the balance, the actuator and most of the measurement equipment is placed inside the model and connected to a minimum of cables leading out of the test section. The main airfoil is equipped with 42 pressure orifices at midspan on the upper and lower side to measure the static pressure distribution using a scanivalve system. Additional miniature pressure transducers are installed inside the flap, of which 25 measure the unsteady pressure distribution on the flap at midspan (upper and lower surface). The remaining 11 transducers are connected to the 11 actuator segments to monitor the excitation amplitude and phase (see Sec. II.B). Two stepping motors for flap angle adjustment, various power supplies, a microcontroller for actuator frequency control, and two pressure regulator valves complete the setup of the main airfoil.

B. Excitation System

Designing actuators for active flow control experiments is probably the most critical factor. Models with reduced size for basic low-speed wind-tunnel tests require miniature flow control actuators that will probably never be used in any real application. But they still have to be low-energy-consuming and capable of producing high frequencies and high amplitudes to justify the concept. The main difficulty in these kinds of experiments is the large number of parameters, some of which have to be set before testing, e.g., actuator location and jet direction. In this case, the jet emanates perpendicular from the upper surface of the flap. The excitation slot is located near the leading edge, slightly upstream of the time-averaged separation point. At this location the flap has sufficient space to house an actuator that is about 15 mm high. Once the flap is deflected downwards the jet direction changes in relation to the freestream direction. Jet direction definitely has an impact on controlling separation and is one topic of the ongoing investigation. However, up to this point the effect has not been resolved. One critical actuator parameter is the excitation amplitude because if it is too low there is no impact on the flow at all, making the experiment entirely worthless and drawing false conclusions. As a result of preliminary tests, compressed air is used in combination with fast-switching solenoid valves to produce a pulsed wall jet (no suction phase) with velocities of 30 m/s maximum. The excitation slot reaches across 81% (1255 mm) of the entire wing span and is only interrupted by two flap hinges and the deflection angle adjustment at each flap end (Fig. 4). To fulfil the requirements of a constant velocity distribution along the span, the excitation system is divided into 11 spanwise aligned segments. Each actuator segment consists of a solenoid valve connected to a small and specially designed aluminum block containing four additional pressure chambers (see Fig. 5). This block spreads the pulsed air, exiting the valve, to a rectangular cross section ending in a narrow slot (span 114 mm) at the flap's surface. The velocity profile of each actuator segment is optimized to be as homogeneous along the actuator span as possible. The solenoid valves may be addressed individually but share a common air supply. This makes it possible to reach not only two-dimensional but also three-dimensional excitation modes or local spanwise excitation aiming at roll moment control. The solenoid valves allow excitation frequencies in the range of $F^+ = 0 \ldots F^+ = 2$ based on the flap chord length. An example of the time-related velocity very close to the slot is shown in Fig. 5 together with details of the actuator buildup. Because the solenoid valves are completely either open or closed the resulting velocity profile looks similar to a square signal. In opposition to other flow control investigations, only the blowing phase is realized here. The effect of the suction phase, which can be implemented principally, has not been investigated and remains open. The excitation amplitude is controlled by two flow control valves placed in the main wing. By adjusting the pressure in the actuator system the jet velocity is altered. The amplitude of each

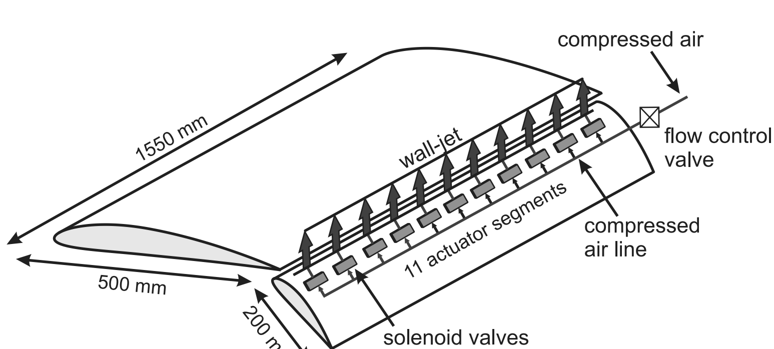

Fig. 4 Integration of the actuator system into the flap.

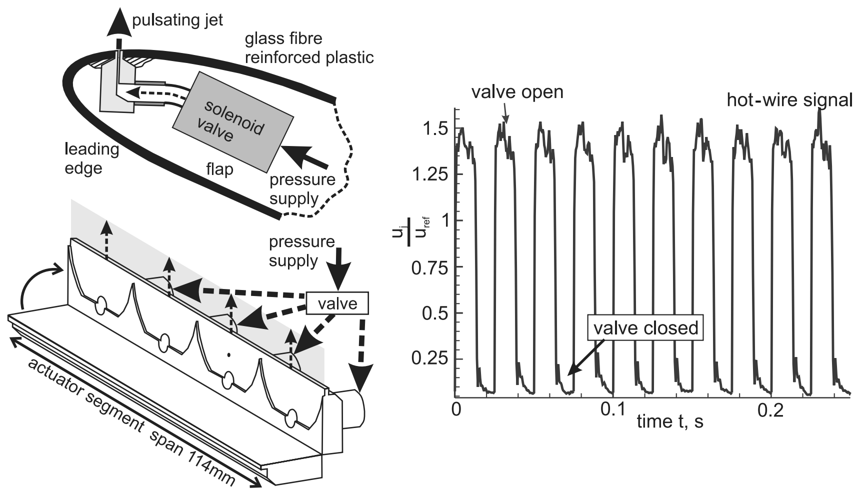

Fig. 5 Left: sketch of the actuator buildup. Right: velocity close to the actuator slot.

actuator segment is controlled by a single pressure transducer. It monitors the periodic change of pressure in the actuator cavity and provides additional information on the excitation phase. A calibration of excitation velocity, cavity pressure, and nondimensional momentum coefficient c_μ was performed for each actuator segment before the wind-tunnel tests (see next section). The use of compressed air that is externally generated has one advantage over zero-net-mass-flux actuators that produce a sinusoidal alternating suction and blowing jet, especially in model testing: it allows detailed comparison of steady and periodic blowing as well as steady and periodic suction. Applying additional pressure lines alternating suction/blowing is possible as well. The disadvantage of such a system is the necessary plumbing accompanied by pressure losses and more space required for the valves. This actuator assembly is not intended for real applications but is very useful for wind-tunnel experiments as it is very robust and reliable and allows fast and easy changes in frequency, amplitude, duty cycle, active actuators segments, and 2-D and 3-D excitation modes.

III. Experimental Uncertainty

The experimental uncertainty in the determination of forces and moments using the balance system was estimated by 0.1% for lift, drag, side force, and yaw moment, and 0.3% for the rolling and pitching moment. The gap between the model and the side walls was narrowed to 0.1 mm to minimize leakage effects and pressure equalization from the upper and lower wing surface. However, the error cannot be quantified because no exact data are available for comparison. The obtained forces and moments are corrected using a standard two-dimensional wind-tunnel wall correction method [22].

The pressure sensor used for sensing the pressure distribution on the main wing has an accuracy of 0.5%. The transducers used for the excitation system and the pressure distribution on the flap have a resolution of less then 0.5 Pa and are able to measure pressure fluctuations of up to 1 kHz. Because of the installation of the transducers, which are connected to short pressure lines, the cutoff frequency is reduced to 0.5 kHz (experimentally determined).

The angle of attack is adjusted by a stepper motor with a gear transmission ratio of 820:1. The repeatability lies well within 0.1 deg. The flap deflection angle is adjusted by two stepper motors placed inside the main wing, each having a transmission ratio of 40:1. The rotating motion is transferred to the flap via a V-ribbed belt. To account for the angle uncertainty a tilt sensor is installed inside the flap, which has a resolution of 0.1%.

The actuator is calibrated in still air using a traversable hot wire. The hot wire is placed as close to the excitation slot as possible to measure the correct jet velocity. This is a crucial part for the calculation of the nondimensional momentum coefficient. The complete frequency and amplitude ranges are measured to calculate the corresponding c_μ. Because of the length of the actuator slot of 1254 mm, the calibration was carried out only at discrete locations of each actuator segment. The cited c_μ values are therefore within $\pm 15\%$ of the quoted values.

IV. Results

The effect of periodic forcing on the flowfield around the model is demonstrated by lift and drag measurements. Periodic excitation was successfully tested at different Reynolds numbers reaching from 0.2×10^6 to 1×10^6. Most data were collected at a Reynolds number of 0.55×10^6. The angle of attack sweep as well as the flap deflection angle variation are always conducted by first raising the angle in one-degree steps and, once the maximum angle is reached, lowering it again. This procedure makes it possible to clearly identify the angles at which active separation control is effective or not and to detect possible hysteresis effects (for clarity reasons, decreasing angles are not shown in the diagrams).

A. Unexcited Flow

The base flow without excitation was thoroughly investigated to document the separation behavior on the flap and on the main wing for different α and δ_f settings. The tests also included measurements of identical configurations to check for repeatability. The left-hand side diagram of Fig. 6 shows the lift coefficient vs the angle of attack for selected flap deflection angles. For a given deflection the lift rises linear with increasing α. Once the angle of attack is set beyond $c_{L\max}$ the flow separates due to the severe adverse pressure gradient. By deflecting the flap downwards the effective camber of the configuration is increased, causing a shift upwards and to the left of the lift values. However, it can generally not be observed whether the flow separates from the flap or from the main wing because the balance system measures only integral values of the complete configuration. By looking at the data in more detail one can see that at high deflection angles ($\delta_f > 25$ deg) the lift values are only slightly increased compared to the next-lower δ_f. This is an indication that the flow on the flap is partially or fully separated while it is still attached to the main wing. Additional measurements of flap deflection angle sweeps and surface pressure measurements were conducted to clarify the separation behavior. The diagram on the right of Fig. 6 displays the drag curves for the same set of flap deflections. The results are in very good agreement with the lift curves, indicating flow separation at exactly the same angles of attack.

B. Excited Flow

The large number of variable parameters affecting active flow control experiments makes it impossible to investigate each and every aspect related to unsteady excitation. The governing parameters in this case are in random order: some of these parameters have to be set before the wind-tunnel test while the model

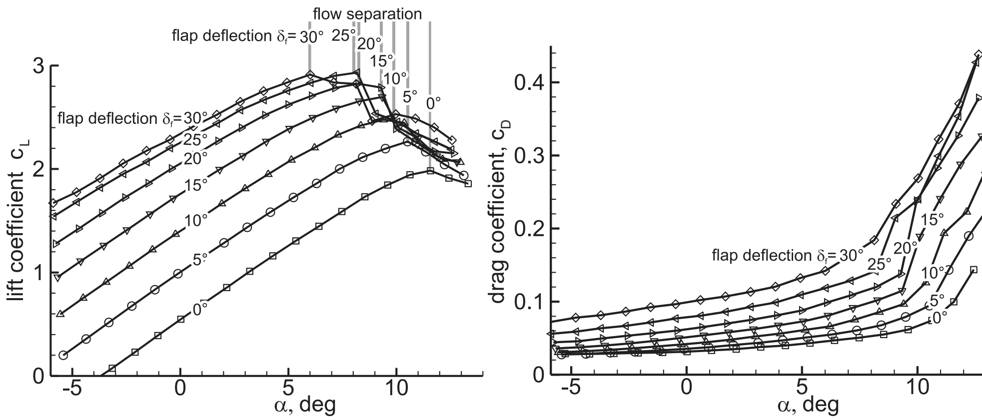

Fig. 6 Lift and drag distribution at different flap deflections without excitation.

is still being made. This is one of the crucial moments because if, for instance, the excitation location is not correctly chosen, periodic forcing does not have the desired effect on the flow. If these fixed parameters, which are emphasized in Table 1, are disregarded, 8 of the 12 parameters remain that have to be taken into account during the experiments. To conduct the experiments in a limited amount of time the number of variable parameters has to be reduced. One has to keep in mind that by setting some parameters to constant values, incorrect conclusions may be drawn because most of the parameters depend on each other.

Various tests were performed to determine applicable excitation parameters that yield lift enhancement and drag reduction. Unfortunately, there is not a single frequency that gives optimum results, but rather a frequency range that seems to be sensitive to the flow condition, i.e., whether the flow is already separated and reattachment is provoked or flow separation is delayed [11,23]. Because most of the tests were conducted sweeping either the angle of attack or the flap deflection angle from low to very high and back to low angles, both cases are occurring within one test case.

In the course of this investigation the best frequency and amplitude of the excitation apparatus in terms of lift enhancement and drag reduction by reattaching the flow were obtained for a fixed configuration ($\alpha = 6$ deg, $\delta_f = 36$ deg). Figure 7 shows the percentage lift gain against the excitation frequency for different excitation amplitudes. Measuring the frequency receptivity is difficult because the amplitude has to be very low. If it is too high the flow separation is prevented by brute force and not by effectively using flow instabilities. If the amplitude is too low the flow is not completely reattached, gaining only around 5% in lift. Once the amplitude exceeds a certain amount, the highest lift gains are obtained around reduced frequencies of approximatgely $F^+ = 1$. Previous investigations show a similar behavior of a weak frequency dependence in the domain around $F^+ = 1$. The right-hand-side diagram shows the impact of frequency and amplitude on drag. It appears that frequencies above $F^+ = 0.5$ reduce the drag significantly. At very low amplitudes, higher frequencies seem to improve the drag as well, which was not investigated any further. The second test case to determine a set of good excitation parameters was performed by sweeping the flap deflection angle from low to high and back to low angles. At first the onset of separation is delayed by keeping the flow attached to the surface. As very high angles are

Table 1 Governing parameters for the high-lift test case with active separation control

Configuration	Excitation apparatus
1. Angle of attack	6. Excitation frequency
2. Flap deflection angle	7. Excitation amplitude
3. Reynolds number	8. Number of active actuator segments
4. *Flap Gap (fixed)*	9. Duty cycle
5. *Flap Overlap (fixed)*	10. Excitation mode (2-D or 3-D)
——	11. *Excitation location (fixed)*
——	12. *Excitation direction (fixed)*

approached the flow separates despite active forcing, and once the angle is lowered again periodic forcing is used to reattach the separated flow again. The results are plotted in Fig. 8, showing the delay of separation in the left-hand-side diagram and the reattachment in the right-hand-side diagram. Both diagrams show the benefit in lift-to-drag ratio compared to the unexcited flow. All results were obtained with a fixed c_μ of 6×10^{-4}. To keep the flow attached, higher frequencies seem to perform better than the lower frequencies, especially at very high deflection angles. Higher excitation frequencies than $F^+ = 2$ could not be investigated because of actuator limitations. Using a high excitation frequency for reattaching the flow (right-hand-side plot) is not as effective as a reduced frequency of about $F^+ = 1$. Flow reattachment and delay of separation seem to be more effected by excitation amplitude than by excitation frequency. This has to be further investigated because lift and drag might be effected differently.

One has to keep in mind that as the flap is deflected the excitation direction relative to the surrounding flow is changed as well. This might have an additional effect on both excitation frequency and amplitude, which is not taken into account. To reduce the number of parameters the excitation frequency and the amplitude were set at the fixed values, $F^+ = 0.9$, $c_\mu = 6 \times 10^4$, during the flowing measurements of α and δ_f sweeps. This simplification has to be kept in mind when evaluating the results. It is most likely that by optimizing both parameters for every combination of α and δ_f, one would get probably even better results as presented in the following section.

The Reynolds number is set at 0.55×10^6, but higher Reynolds numbers up to 10^6 were tested successfully. The results presented next were obtained using a two-dimensional excitation mode using all 11 actuator segments working in phase with a duty cycle of 50%. The two remaining parameters are the angle of attack and the flap deflection angle.

Figure 9 displays the effect of separation delay due to excitation while sweeping the flap deflection angle δ_f (α is fixed at 7 deg). As the flap is deflected downwards, lift increases until the flow separates from the flap at $\delta_f = 30$ deg. The drag curve (diagram on the right-hand side) shows a sudden increase at the same deflection angle as the loss of lift is noticed. The same configuration is then tested again with the influence of periodic excitation. The lift curve with excitation shows no difference compared to the base flow, as long as the base flow is attached to the surface of the flap. Once the flow separates due to the severe adverse pressure gradient, periodic excitation keeps the flow attached up to a deflection angle of 39 deg. The reason for this is the enhanced mixing caused by periodic excitation while strengthening the boundary layer to sustain the adverse pressure gradient. This improves the deflection angle by 9 deg. By avoiding the large separation region the drag is lowered as can be seen in the diagram on the right-hand side. As the deflection is increased beyond $\delta_f = 39$ deg excitation reaches its limits and is not able to keep the flow attached. Nevertheless the separation is not very sudden, indicating that even in the post-stall region excitation can improve the course of separation. Two conclusions may be drawn from this early result:

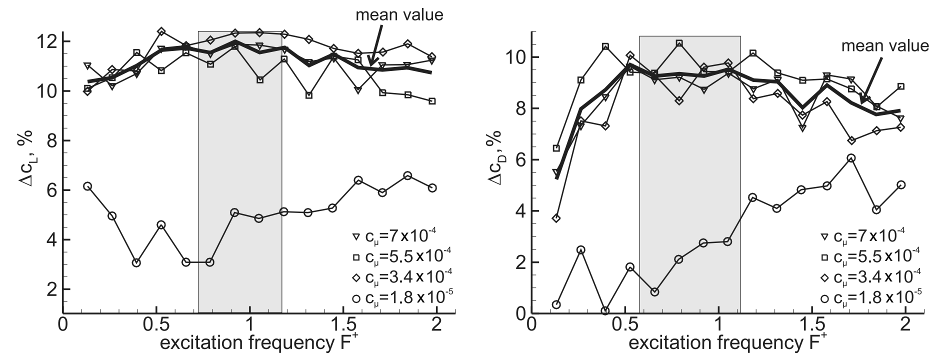

Fig. 7 Impact of forcing frequency and amplitude on lift and drag ($\alpha = 6$ deg, $\delta_f = 36$ deg).

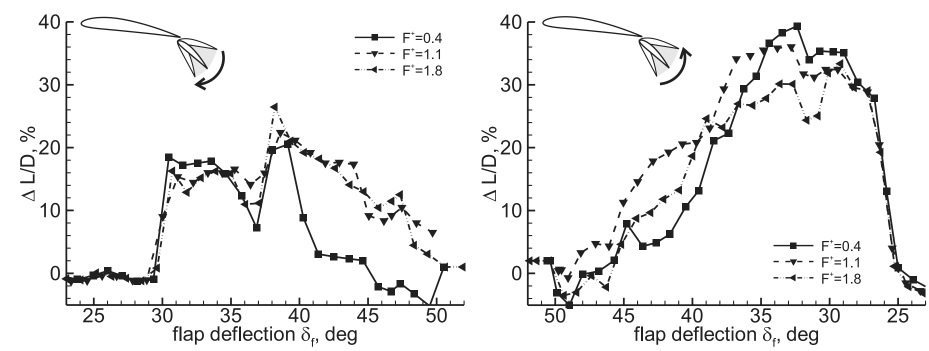

Fig. 8 Lift-to-drag ratio benefit for delay of separation and flow reattachment.

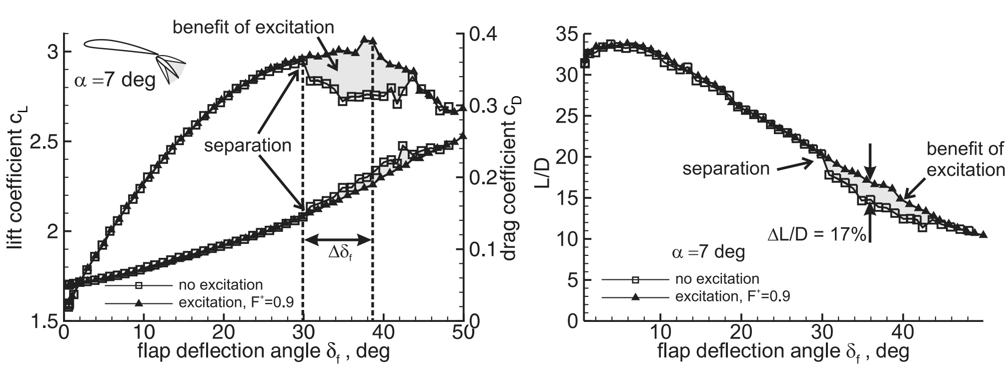

Fig. 9 Example of polar diagram with and without excitation.

1) Periodic excitation can prevent separation at large deflection angles.

2) Periodic excitation does not cause additional drag as long as the flow is attached in the first case.

The question that remains open up to now is why periodic excitation loses its impact on the flow once the deflection angle is above 40 deg. One reason could be the excitation amplitude that has to be increased to account for the stronger pressure gradient. The second reason could be the direction of the excitation jet that is moved in a possibly unfavorable position as the flap is deflected. The benefit of periodic excitation is even more obvious if the aerodynamic quality, the lift-to-drag ratio, is considered (right-hand side of Fig. 9). Even a small gain in lift and a small reduction in drag improves the aerodynamic performance and results in a significant increase in the lift-to-drag ratio. The gain in L/D ratio in this case provides a substantial improvement of the performance of 17% compared to the base flow. An angle of attack sweep with a fixed flap deflection is an even more interesting case. This resembles a wing in takeoff or landing condition. Figure 10 displays lift and drag against angle of attack for the excited and unexcited case. Flap deflection is set to 32 deg, which is near the onset of separation. The unexcited lift distribution shows a significant loss of lift at $\alpha = 2$ deg. This results from a sudden separation on the flap while the flow on the main wing is still attached. The lift then rises still further until the flow on the main wing separates as well at $\alpha = 7$ deg. Excitation keeps the flow fully attached to the flap and regains lift and 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 the lift-to-drag ratio by up to 20–25% over a wide range of angles of attack as shown in Fig. 11. The diagram on the right-hand side demonstrates the same effect for a different flap deflection angle of $\delta_f = 38$ deg. Because of the higher deflection of the flap the flow is already separated even at very low angles of attack. However, excitation is able to suppress the flow separation and increases the lift-to-drag ratio at almost all angles by 10–12%. A complete series of α and δ_f sweeps were measured to document the impact of separation control on the overall $c_{L\,\max}$ and at off-design conditions. Figure 12 shows the lift coefficient for a series of angle of attack and flap deflection combinations. The combinations were measured without flow control (illustration on the left) and with flow control (illustration on the right). The excitation parameters were kept constant throughout the complete measurement procedure. Consequently, this result does not represent an optimum but rather a first demonstration of what is possible with active separation control. The maximum lift in the uncontrolled case is around $c_L = 2.9$ at $\alpha = 7$ deg and $\delta_f = 31$ deg. The separation angles are clearly seen at angles of attack in excess of 8 deg and above deflections of 31–33 deg. The excited case gives a smoother picture without sudden lift

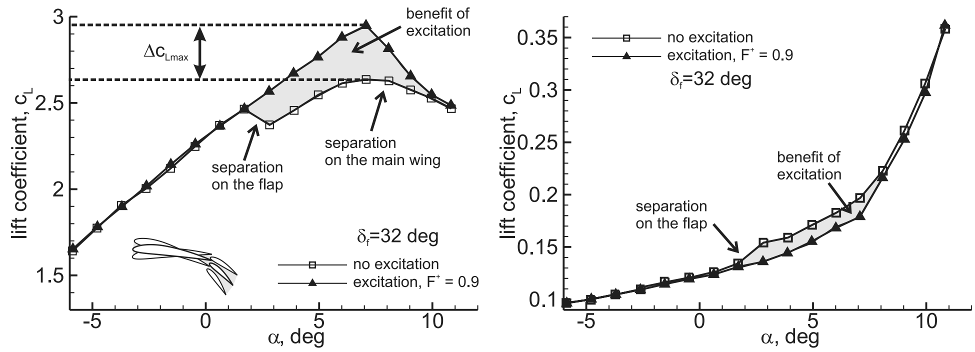

Fig. 10 Lift and drag vs angle of attack with and without excitation.

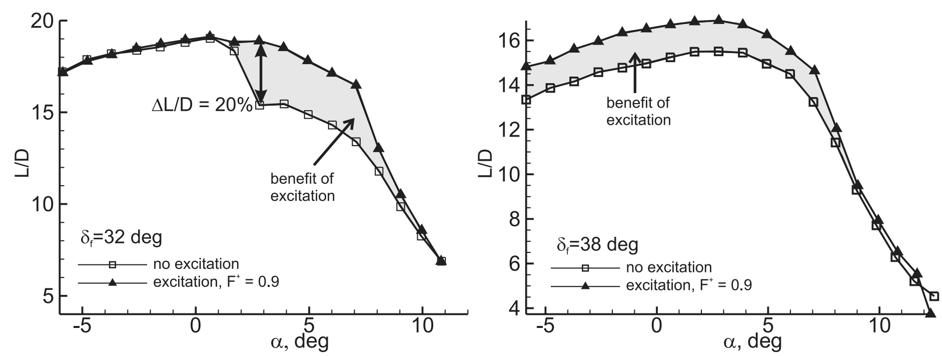

Fig. 11 Lift-to-drag ratio for two different flap settings with and without excitation.

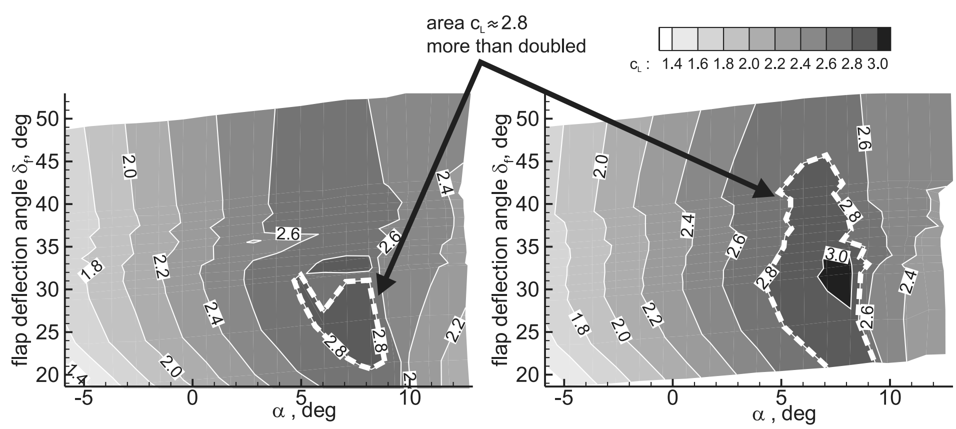

Fig. 12 Contour plot of lift coefficients with and without flow control.

drops. The maximum lift is shifted to slightly higher deflection angles of 33–34 deg. Overall maximum lift is improved by about 5%, but there is still room for improvement by optimizing the excitation parameter. Another important aspect is the possibility to achieve certain lift coefficients by using very different configurations. In the unexcited case, e.g., a c_L of 2.8 or higher, this may only be achieved with any combination of αs between 6 and 8.5 deg and flap settings between 24 and 29 deg. The same lift with active flow control can be achieved with a combination of α between 5 and 9 deg and δ_f between 20 and 45 deg, which clearly proves the benefit of active flow control. Transferring these results to real applications, although this is only applicable in an abstract sense because real configurations are highly optimized, high-lift coefficients are possible with low-flap deflections for takeoff. For landing, large flap settings with high lift and high drag but an improved L/D ratio are possible.

C. Pressure Distributions

Although the periodic perturbations are introduced to the flow locally by a very narrow slot, the impact on the flow is global. The attached flow on the flap and the altered pressure distribution are not the only reasons why the lift is so dramatically increased. A large amount of lift enhancement is produced by the altered flowfield around the complete configuration up to the stagnation point of the main wing. Pressure distributions of the main wing and the flap illustrate how the increase in lift due to local excitation is generated. Figure 13 shows the differences in local static pressure at midspan at a fixed flap deflection angle with and without excitation (left-hand side). The benefit of the excitation is clearly seen by the attached flow on the flap and the lower static pressure and thus higher velocities around the main 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 as seen in the diagram the right-hand side. The excitation is barely able to keep the flow attached to the flap, but this does not influence the flow on the main wing. It was also noted that trailing-edge separation on the main wing can be slightly delayed by 1 deg due to forcing on the leading edge of the flap if the separation is near to the trailing edge of the main wing.

D. Rolling Moment

Another interesting point on controlling the flow with a spanwise segmented actuator with individually addressable segments

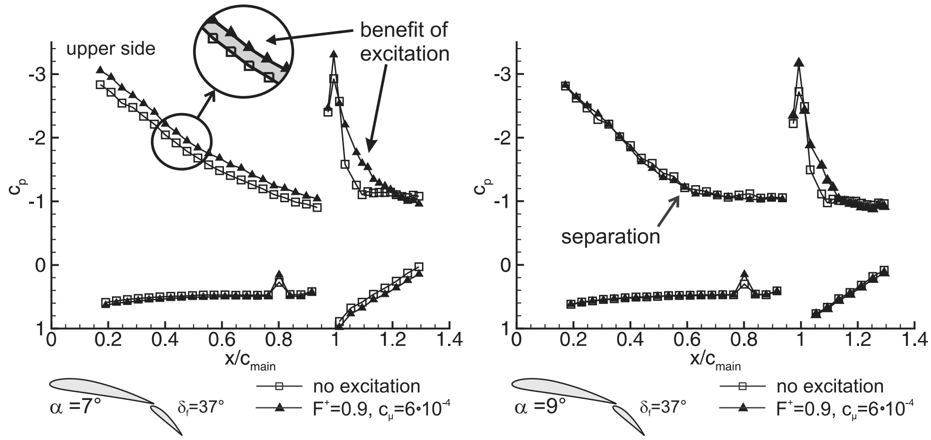

Fig. 13 Static pressure distribution for $\alpha = 7$ deg and $\alpha = 9$ deg with and without excitation.

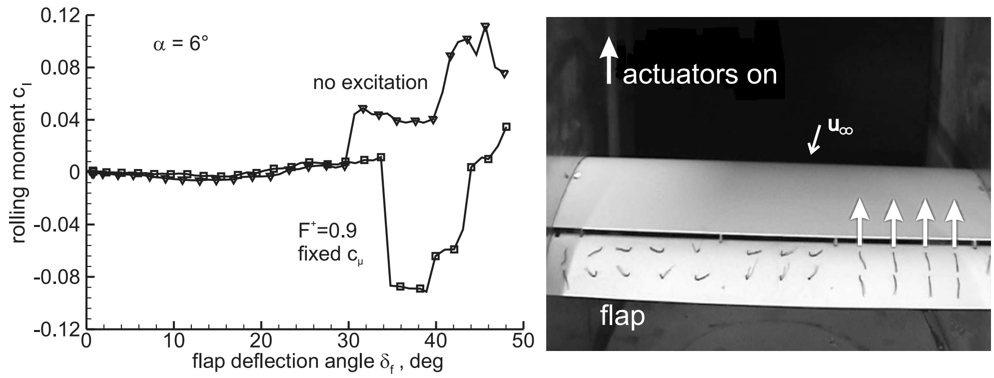

Fig. 14 Left: rolling moment with local spanwise forcing. Right: wool tuft visualization.

concerns the rolling moment. Once the flow on the flap separates it is possible to reattach the flow as shown earlier. By merely using a selected number of actuators on one side of the flap, a rolling moment is generated by attaching the separated flow locally on that side. A snapshot on the right-hand side of Fig. 14 demonstrates this ability very clearly. Wool tufts on the flap show a completely separated flow on the nonactuated side, whereas the flow on the right is attached due to local forcing. The measured rolling moment (figure on the left) quantifies the behavior observed. As long as the flow is attached to the flap the rolling moment is gradually zero as it should be in a two-dimensional test case. Without any excitation the flow separates at a deflection angle of 30 deg, generating a positive rolling moment. The rolling moment depends on the separation behavior (α, δ_f) and is to some extent unpredictable. The same configuration with four active actuator segments on the right-hand side of the flap (indicated by the arrows in the chart) shows a completely different behavior. The onset of separation is delayed by 4 deg and as soon as the separation occurs on the rest of the flap's span, a strong negative rolling moment is generated. Excitation keeps the rolling moment upright from 34 deg to almost 42 deg until the flow separates despite active forcing. Figure 15 demonstrates the capability to control the rolling motion by using different actuator arrangements in a time-depended way. The rolling moment coefficient is plotted vs time starting with a separated flow and no rolling moment at $t = 0$. After 1 s four actuators on the left flap side are turned on, showing an almost immediate response resulting in a positive rolling moment. After 3 s the actuators are turned off, stopping the rolling motion. A sudden separation with immediate reattachment of the flow is noted within this period, resulting probably from a very high flap deflection where active forcing starts to lose its impact. However, after 4 s two actuator segments on the inner right side are active, showing a lower rolling moment in the opposite direction. Shutting down all segments stops the motion. As a result not only the rolling direction can be controlled but also the strength by using different actuator segments along the span. Generation of a rolling moment by local excitation is one more

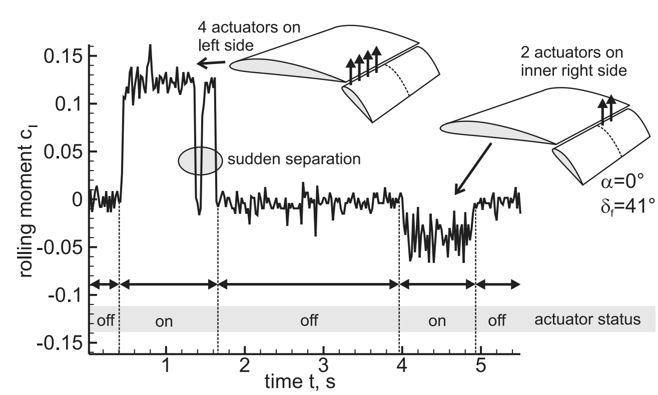

Fig. 15 Fast control of the rolling moment using different actuator segments.

aspect of active separation control. This in turn requires a spanwise segmented and individually addressable actuator assembly.

V. Benefits of Applying Separation Control to High-Lift Systems

Although this is a very fundamental investigation, some comments are made regarding the application of separation control techniques to existing high-lift configurations. If brought to application, unsteady separation control has to be a self-sustaining, autonomously working system. The well-defined conditions of a laboratory wind-tunnel environment are not applicable to real configurations with deflected spoilers, deployed landing gears, or gusty winds. Only a closed-loop system is able to compensate for disturbances by sensing the flow state and adapting the excitation parameters. One reason this simplified high-lift configuration was chosen is the ability to implement a closed-loop system in a well-defined but not too complicated flow environment [24,25]. This setup helps to identify adequate control strategies to gain knowledge for more complex and realistic test cases with swept and tapered wings of finite span.

However, the results obtained in this fundamental research can help to identify possible benefits by applying these flow control techniques to existing trailing-edge devices (e.g., larger flap deflection). It is known that a major aspect in real application is the induced drag component due to the finite wing span, which is nearly 70% at takeoff, approach, and landing. Hence, the presented lift-to-drag ratio improvements due to unsteady forcing will be slightly lower if finite wing span is considered [26].

A feasibility study conducted by NASA [27] for the use of active flow control techniques on a realistic transport aircraft configuration showed that simplification of current trailing-edge devices is one possible application for active separation control. The weight reduction due to simple flap systems is equivalent to reducing the cruise drag by 1.9%. Because of smaller flap track fairings, an additional 1.3% of cruise drag could be saved.

Improving a highly optimized trailing-edge device with flow control techniques is still difficult and is only useful if a sufficiently large separation is present. The largest benefit of separation control on trailing-edge devices could be realized if active flow control is integrated in the high-lift design process. The weight of a trailing-edge system breaks up into 30% for the flap panels, 34% for support and mechanism, 25% for actuation, and 11% for fairings [28]. Relieving some of the constraints, e.g., in gap and overlap, which have tight requirements especially on single-slotted flap systems, could save a lot of weight on actuators and support and mechanisms. Larger flap deflections of 40 or 50 deg lead to a reduction of fowler motion, which could save some additional weight.

In this multidisciplinary design environment active flow control could be used to build lighter, less complex, maintenance-friendly (excitation system depended), and system-oriented trailing-edge devices that match the aerodynamic performance of current single- or double-slotted flap systems, provided a reliable and robust yet compact and lightweight actuator exists.

VI. Conclusions

Experimental investigations on a two-dimensional high-lift configuration with active flow control were carried out to demonstrate the ability to control flow separation on a single-slotted flap. The aim was to enhance the aerodynamic quality of the complete configuration by suppressing the flow separation on the flap that is caused by the severe adverse pressure gradient. To do so a suitable actuator had to be developed that is capable of producing the desired excitation frequencies and amplitudes and is still reliable and robust in operation. A specific solution to the problem was found by using externally generated compressed air in combination with fast-switching solenoid valves. By choosing a spanwise segmented assembly local excitation on parts of the flap is possible as well as three-dimensional excitation modes. Local periodic excitation has a severe impact on the flow around the complete configuration once the excitation parameters are in a correct domain. The massive flow separation at large deflection angles is prevented, increasing the flap deflection angle by up to 10 deg. The lift is increased by up to 12%, whereas the drag is reduced by the same amount. This in turn enhances the lift-to-drag ratio by 20–25%. The overall maximum lift is improved by as much as 5%. Besides the benefits in lift and drag, a rolling moment is generated by attaching the flow only on one part of the flap. This is possible because the actuator arrangement is segmented in spanwise direction and each segment is individually addressable. This results in the following conclusions.

Local periodic forcing is a very suitable technique to improve existing high-lift systems. It has a global effect on the flow around the configuration. In addition to improving most of the aerodynamic coefficients, the advantage of such a system consists most of all in the extended field of application. High-lift coefficients can be achieved with a number of very different angles of attack and flap deflection settings. Bearing in mind that the excitation parameters (slot location, jet direction) are not optimized there is probably more room for improvement. The large number of variable parameters makes it very difficult to find optimal excitation parameters for every combination of angle of attack and flap deflection. To bring active flow control to application closed-loop system have to be implemented, which can also be used to optimize excitation parameters more quickly in wind-tunnel experiments. Further investigations have to be conducted to clearly identify the mechanism of periodic forcing on slotted flaps and to work out the governing parameters. Up to now no prediction tools are available to transfer this kind of knowledge to different experiments.

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