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Recent Onera Flow Control Research on High-Lift Configurations

This paper concerns the recent and most representative work performed at Onera on the application of flow control technologies to high-lift systems of aircraft wings. Two different objectives are considered. First, keeping present architecture, flow control could either enhance the aerodynamic performance (mainly mean and stall lift coefficients) or simplify the mechanisms (flap gap or size). Secondly, a drastic geometry simplification, very attractive for aircraft manufacturers, like slot or even slat suppression, leads to a strong depletion of aerodynamic performance. In that case, the objective of flow control is to retrieve as much as possible the reference airfoil performance. Various flow control devices, from simple mechanical or fluidic vortex generators to pulsed blowing, are considered. Combined numerical and experimental studies are presented and the efficiency of the control is discussed.

Introduction

Aircraft high-lift systems are essential in low speed conditions for take-off and landing phases to reach the necessary high-lift coefficients (flap efficiency) and delay stalling (slat efficiency), as presented in figure 1. To do so, such complex mechanisms have been optimized throughout the aviation history, leading mostly to a single extended slat and one or more extended flap(s). Nonetheless, these optimized extended elements are still complex, heavy and expensive to manufacture. To overcome these issues, the coupling of flow control technologies and high-lift systems allows either an enhancement of actual high-lift device efficiency, or a simplification of the high-lift mechanisms. Hence, applying flow control directly at the design phase of the aircraft could lead to simpler and less expensive systems (from the manufacturing and maintenance point of view). Furthermore, some reduction of drag and acoustic emissions could be expected too.

The interest in flow control for high-lift elements is rather old, as presented in 1961 in an interesting book [11] that summarizes worldwide research on that topic. More recently, in a 1999 NASA/Boeing report from McLean et al. [12], a full integration study of flow control, both with steady or unsteady technologies, was carried out for the full aircraft development, including manufacturing, systems, costs and maintenance. Among all of the aircraft elements, high-lift systems were identified for flow control as the most promising in terms of potential and benefits. It was also highlighted that an accurate aerodynamic performance study of the flow control efficiency was the first mandatory input to perform the accurate full design.

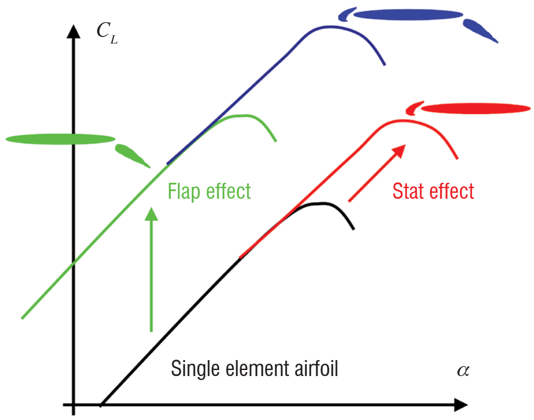

Figure 1 - High-lift slat and flap effects on the lift polar

To simplify high-lift systems of wings using the flow control application, two main separate topics can be considered. The first concerns the flap efficiency. Some studies evaluated its improvement based on present architecture, while others were aimed at eliminating the flap slot. The second topic concerns the leading edge region. Basically, it is aimed at delaying stall directly on a retracted slat configuration, which is difficult because of the very high suction peak in that region. Some people consider that such a configuration is too difficult to be controlled (see [12]) and prefer working on a droop nose configuration [16].

Many means of control exist; from simple passive mechanical vortex generators, to active fluidic, pulsed or synthetic actuators. Many studies in the literature (See [7], [12], [17], [21] and [23] among many) demonstrate the efficiency of these control devices and the potential of fluidic pulsed/synthetic technologies to reach affordable mass flow and/or energy provided by the aircraft systems. Indeed, pulsed or synthetic blowing allows for almost the same specific conditions and flow control characteristics and even better maximum lift coefficient to be achieved with a limited injected energy. In 2000, Greenblatt and Wygnanski [8] published a reference review of flow control by periodic excitation. Most of the efficiency parameters for unsteady flow control are presented for two-dimensional configurations and the results presented in this paper confirm its conclusions.

A very large amount of studies on this topic exist in the literature, both from the experimental and numerical points of view. Due to the appropriate field of flow control presented in this paper, it is rather difficult to present and make reference to the most representative studies performed worldwide. Hence, some authors cited in the references performed rather complete reviews of some of the most representative studies. Some of them were performed at an academic level, mostly on two dimensional configurations at rather small Reynolds numbers ($< 10^6$). In these cases (see [8] and [21] for example), accurate studies are performed in almost incompressible flows and the fluidic response of the flow to an unsteady excitation is significant. At more realistic Reynolds numbers ($> 10^6$) and Mach number ($M = 0.2$), the control efficiency is generally strongly reduced, but still promising (See [6], [18] and [24] as examples). Hence, to help aircraft manufacturers to apply flow control technologies to their airplanes under low speed conditions, Onera has carried out most of its studies on this topic at Reynolds numbers higher than 1 million, with Mach numbers most of time equal to 0.2.

The objective of flow control applied to the high-lift flap system could be either to improve current high-lift system performance, or simplify the high-lift mechanism. First, the most important dimensionless parameters used in the flow control community are presented. Then, the second section of this paper is dedicated to flow control applied to the flap system; the third is aimed at delaying stall using flow control near the leading edge.

Definition of dimensionless parameters

In the flow control community, some classical dimensionless variables are used to define the control parameters. Among these, the most important ones for this paper are the following:

- The velocity ratio (VR) defines the ratio between the jet exit velocity and the local flow velocity in the vicinity of the actuator.
- The momentum coefficient (C_μ) defines the fluidic momentum injected versus a "global" reference effort on the studied configuration.

  - for steady blowing:

$$C_\mu = \frac{q_m . U_j}{Q_{\inf} . S_{ref}} \tag{1}$$

  - for pulsed blowing (squared signal):

$$C_\mu = \frac{\rho_j S_j < U_j^2 >_t}{Q_{\inf} . S_{ref}} = \frac{1}{DC} . \frac{< q_m >_t . < U_j >_t}{Q_{\inf} . S_{ref}} \tag{2}$$

For a squared signal: $< U_j^2 >_t = DC \times U_{peak}^2$ and $< U_j >_t = DC \times U_{peak}$, where U_{peak} is the amplitude of the squared signal, ρ_j is the jet density, S_j is the blowing orifice area, $< q_m >_t = \rho_j S_j < U_j >_t$ is the time-averaged mass flow rate, $< U_j >_t$ is the time-averaged output velocity, DC is the duty cycle and S_{ref} is the reference surface (flap or entire wing). Since there is a factor $1/DC$ in the pulsed blowing definition, it can be noted that to obtain the same C_μ coefficient between steady and unsteady blowing, the mean mass flow rate $< q_m >_t$ in the unsteady blowing case must be decreased by a factor $\sqrt{DC}$, which means a $1 - \sqrt{DC} \approx 30\%$ mean mass flow rate reduction for $DC = 0.5$.

F^+ is the reduced frequency for unsteady blowing:

$F^+ = \frac{F_{injection} . x_{te}}{V_\infty}$, where $F_{injection}$ is the forcing frequency and x_{te} is the distance between the actuator and the trailing edge.

Flow Control on the Flap

According to McLean et al. [12], flow control applied to the flap system is of major interest. Two different strategies can be considered. First, keeping the same architecture, the flow control could lead to a higher performance or to a limited simplification of mechanisms (reduce flap size and/or gap). Some experimental studies were successful [17] in this objective, as well as detailed numerical work [9][10]. A more "aggressive" strategy is to strongly modify present architecture. Thus, the flap slot suppression leads to a strong separation and thus to a significant loss of lift. Applying flow control in the shoulder region of the flap could lead to an efficiently controlled flap, as presented by Seifert et al. [21].

"Classical" flap architecture

A well-known application of flow control to the flap consists in using mechanical vortex generators in its leading edge region, in order to delay the separation that may occur in the landing phase. This strategy, used nowadays on some commercial aircraft, is very attractive since these actuators, whose height is almost the same as the local boundary layer thickness, are hidden under cruising conditions. Accurate numerical restitutions of these actuators in a 2.5D configuration on the flap were carried out at Onera during the AWIATOR [2], [4] program and successfully compared to experiments. Despite this accurate numerical study, it appears that this expensive strategy was not feasible for complex three dimensional configurations and in a design process. Indeed, the actuators were fully meshed, leading to a prohibitive grid size on more realistic configurations and each actuator characteristic (location, sizes, orientation, etc.) leads to a dedicated grid. An example of this simulation is presented in figure 2, showing the vortices generated on the upper flap side. Optimal parameters where defined for the mechanical vortex generators and they were located upstream of the separation. The advected vortices increase the mixing between the boundary layer and the outer flow and consequently increase the boundary layer momentum, leading to a boundary layer that is more resistant to the adverse pressure gradient, thereby delaying the separation close to the flap trailing edge.

Since the design of such mechanism is too expensive to be fully performed in a wind tunnel or flight tests because of the multiplicity of physical scales involved (actuator sizes << flap length), dedicated methods were developed to numerically perform this optimization at a rather low cost, especially concerning the grid generation and size. To do so, Bender et al. [1] introduced a very simple source model based on the lifting line theory, which is called the BAY model. The effect of the vortex generator is directly introduced into the flow and thus a single grid can be used for the entire design process of the actuator. This model was successfully used by Jirasek [10] on a high-lift airfoil and Brunet et al. [4] on a flat plate and an airfoil under transonic flow conditions.

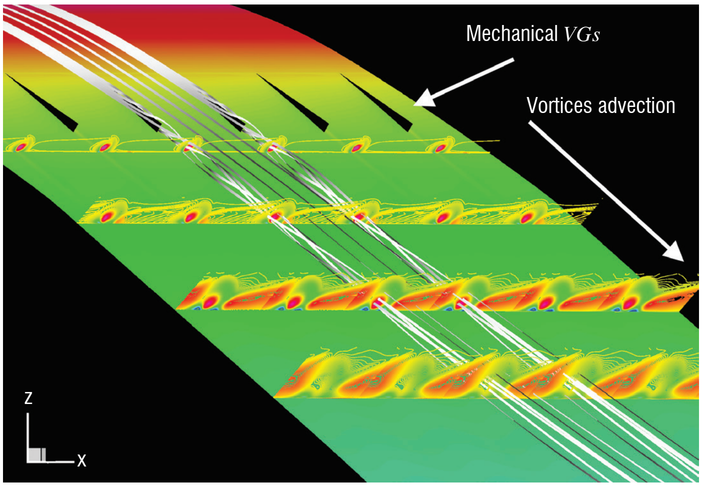

Figure 2 - Mechanical vortex generators on the flap (See [4])

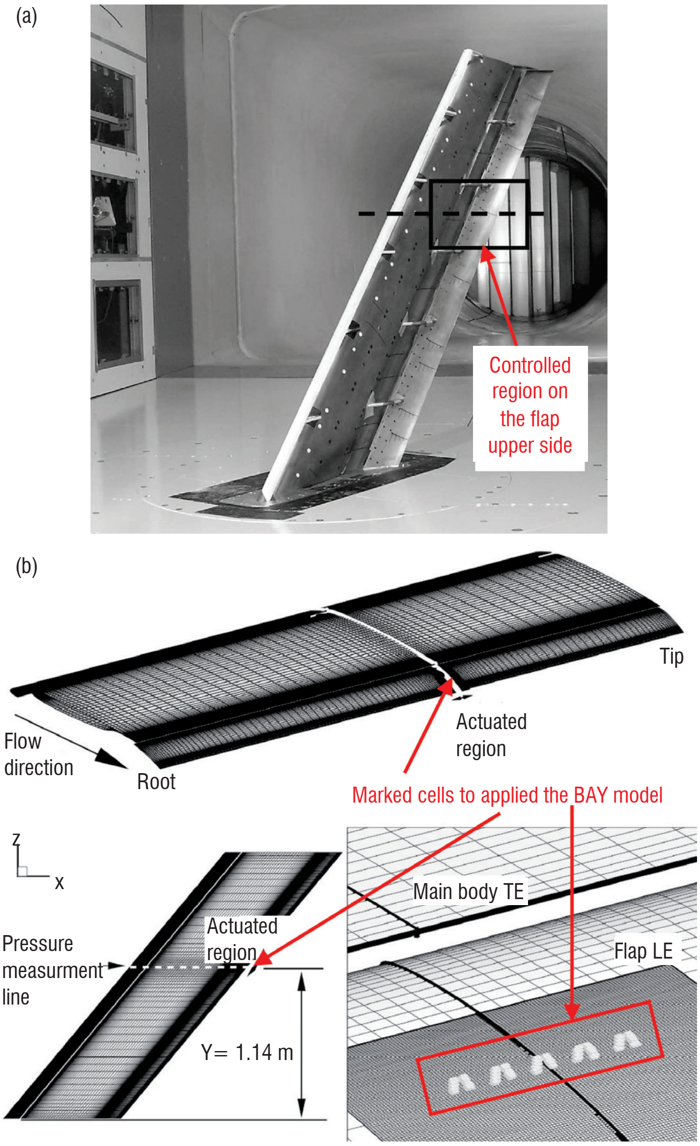

Figure 3 - Model installed in the F1 test section (a) – Skin grid of the AFV wing with cells marked to apply the BAY model (Bender et al. [1]) (b)

This BAY model was introduced into the Onera *elsA* software [4] and used to simulate the same 3D set-up as that tested during the AEROMEMS II project [15],[23] in the F1 wind tunnel of Onera. The simulated case, including the refined area to capture the vortex generator effects, is presented in figure 3 and more details can be found in [15]. As presented, only a very limited region was controlled on the swept AFV wing, using these actuators located at x/c_{flap} = 25 %, which were counter-rotating vortex generators, their height being roughly equal to the boundary layer thickness. The flap angle was increased from 32.4° at its original setting to 40°, in order to reinforce the flap separation to be controlled and thus the flap gap was reduced, because of the flap rotation.

Tests were conducted in the F1 wind tunnel of Onera at a freestream Mach number equal to 0.22 and a Reynolds number of $Re_C = 6.27\,10^6$. Among all the tested angles of attack, the one equal to 12° is selected in this paper to compare simulations with experiments. Hence, pressure coefficient distributions, with or without the vanes, are presented in figure 4 for an equipped pressure chordline located in the vicinity of the actuators, as presented in figure 3. It appears that the simulation performed with the Spalart-Allmaras turbulence model, without control, does not agree well with measurements close to the trailing edge of the flap, because of a massive separation that extends over a large part of the flap. This modeling error is well known for such simulations. On the other hand, both simulations and experiments with vortex generators present a higher suction peak of the flap leading edge and a monotone pressure recovery at the trailing edge, showing only a limited separation. The beneficial control effect is not visible on all other parts of the airfoil, except at the trailing edge of the main element. Nevertheless, this rather limited global effect is mostly caused by the very limited spanwise extension of the controlled region. To enhance this effect, it is necessary to apply flow control to the entire flap. In the end, as presented in the details in [16], counter-rotating mechanical vortex generators, which are optimum for 2D flows, are not suitable for the 3D flows on a swept wing, since only one vane on each pair creates a vortex, the other being aligned with local streamlines.

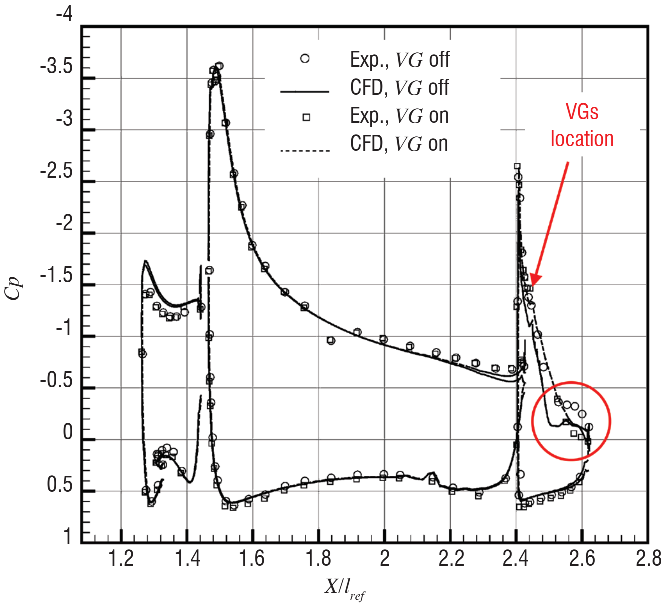

Figure 4 - Pressure distribution, with or without *VGs* on the flap

As presented above, flap efficiency can be increased using mechanical vortex generators installed near its leading edge, allowing a higher lift or different flap installation characteristics. The drawback to this mechanism is its passive, permanent effect, even in flight domains like take-off, where it is useless. To solve this problem, adaptable and/or on-off vortices can be created using Air-Jet Vortex Generators (*AJVGs*). Many parametric studies exist for these *AJVGs* (For example, there is an interesting review on 2D cases by Greenblatt and Wygnanski [8] and a wing/body study by Crowther [7]) and they allow more or less the same effects as classical mechanical ones to be obtained. The same configuration as that previously presented in this paper has been studied with such *AJVGs*, both by experimental and numerical means. Conclusions are identical to those obtained for the mechanical vanes and the grid difficulties and sizes are also the same. Such grid complexity and size problems for numerical studies can be partially solved using a source term model, like the BAY model presented previously, or by using a chimera approach, as presented in the following sections.

Slotless flap installation

One major way to simplify this flap deployment is to completely suppress the flap slot, resulting in a "simple" hinged slotless flap, as presented in figure 5 (see [13] and [16] for more details). The reference airfoil is a GARTEUR high-lift configuration [22]. The lift loss is significant, as presented in the right side picture of figure 5, obtained with a numerical study. The objective of the flow control, mostly performed numerically, is to retrieve as much lift as possible with a control applied to the flap shoulder region, i.e., in the vicinity of the separation point (blue part of the picture on the left). Note that some tests (not presented and not published) have shown that the classical use of vortex generators (mechanical or fluidic) is inefficient to delay the separation and retrieve lift on such a configuration.

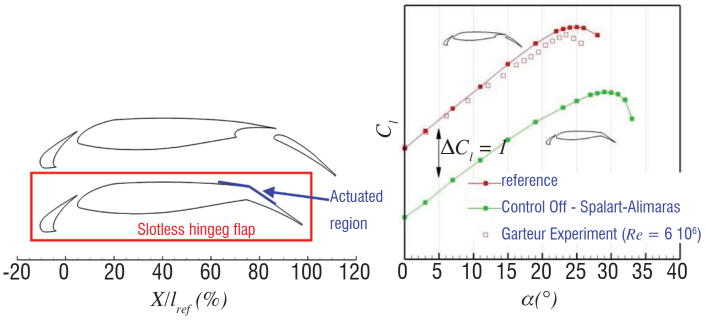

Figure 5 - Simplified slotless hinged flap configuration and resulting effect on the lift curve at $M = 0.2$ and $Re = 1.9\ 10^6$

A numerical optimization has been performed at Onera by Meunier [13],[14], to prepare experimental tests carried out in 2009 in the L1 wind tunnel of Onera Lille [3]. The optimization procedure is aimed at defining the optimum flow control parameters of a continuous blowing slot (location, mass flow, deflection angle) using a Kriging-based optimization method (see [13] and [14] for more details). The purpose of this optimization was to maximize the lift coefficient, which almost corresponds to the minimization of the separation size. Simulations were performed with the *elsA* software, using the chimera approach to simulate the slot and its surrounding flow. Automatic grid generation of the slot and its surrounding grid was performed to ensure the efficiency of the automatic optimization algorithm. The results are presented in the figure 6(a), which shows a Kriging mapping of the evaluations. Based on this study, a model was created and tested in the L1 wind tunnel of Onera Lille in 2009. Some comparisons between simulations and measurements, with and without steady blowing through the slot, are presented in figure 6(b). Note that the required mass flow to achieve this optimum is very high in terms of possible bleed-air drawn from the engine mass flow. Despite the fact that the wind tunnel data was uncorrected and the spanwise extension region of the control was limited to one third of the model, leading to a strong 3D behavior, simulations and experiments agree quite well and the control is very efficient, since it enables (according to simulations) the classical slotted flap performance to be retrieved (see figure 7(a)).

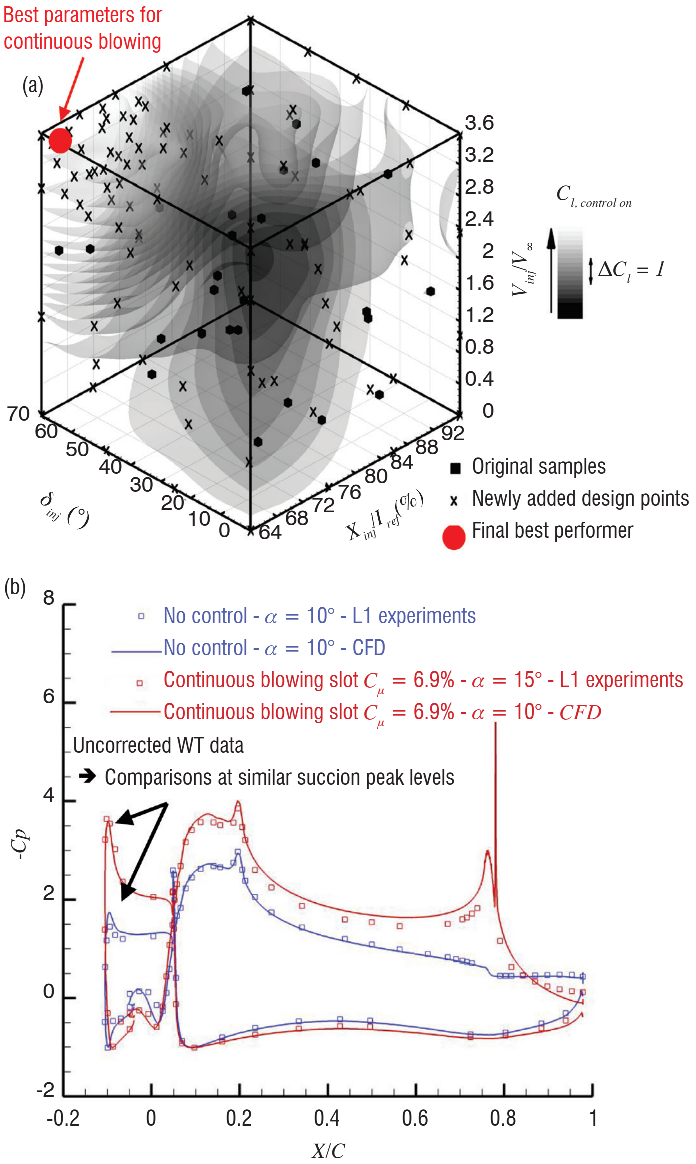

Figure 6 - (a) Sampling evolution and resulting Kriging interpolation for lift coefficient (CFD) – (b) Example of CFD / experiments obtained

In the literature (see [9] and [21] among many), many studies have shown that pulsed or synthetic blowing could allow a higher efficiency than the continuous one, thus limiting mass flow injection. One of the major drawbacks of such unsteady control is that the maximum control efficiency is often characterized by the generation of large structures, whose sizes are almost equal to half of the flap length. Hence, this maximum averaged lift frequently corresponds to a maximum lift unsteadiness. For 2D configurations, Meunier et al. [13],[14] and [16] show that this unsteadiness is of primary importance, but in recent 3D studies (Rudnik [18] and Ciobata [5]), the unsteadiness in lift levels caused by flow control is much more limited. Hence, though this unsteadiness is an important topic that must be taken into account, it is not obvious whether it could limit control efficiency or not.

Using a piezo-electric actuator, pulsed blowing was evaluated during the test in the L1 wind tunnel, in order to limit the injected mass flow and try to enhance the control efficiency using unsteady flow excitation. Despite a local efficiency being evidenced, the too limited spanwise extension of the actuated region does not allow an efficient control to be obtained and the following results are only based on unsteady simulations performed [14],[16] with the elsA software.

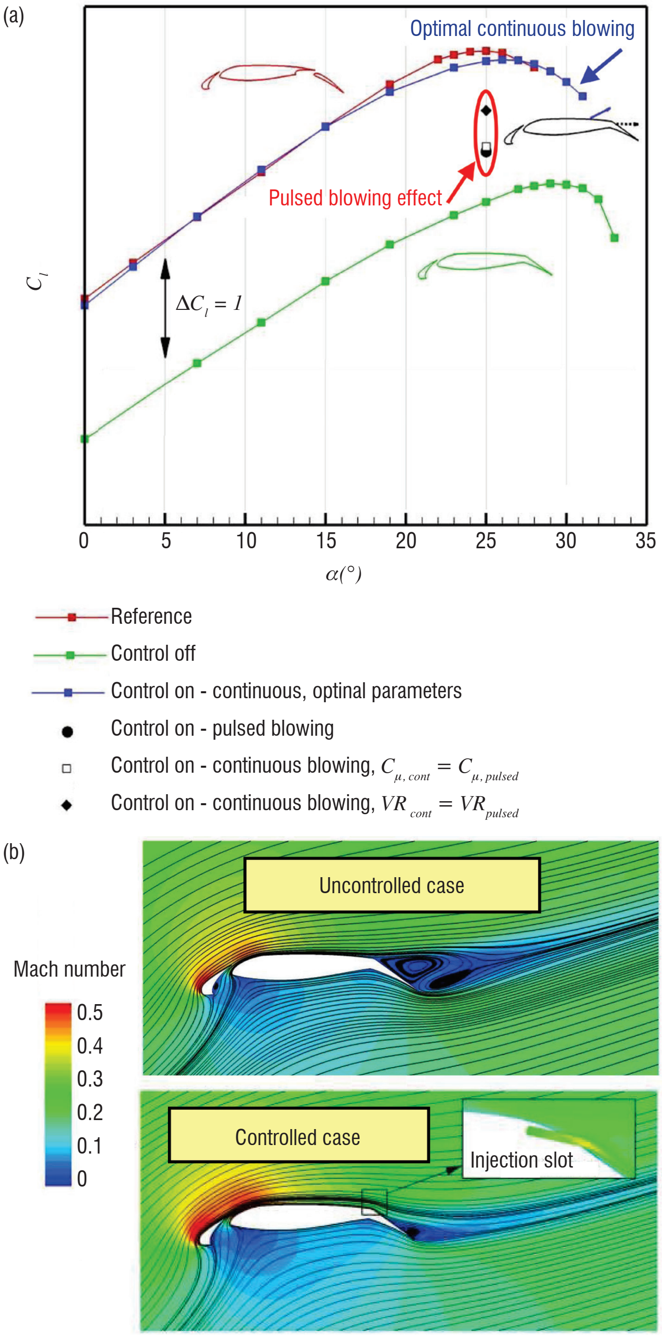

Figure 7 - (a) Efficiency of continuous and pulsed blowing on the lift curve – (b) Flow control effect on the flow field

A multi-objective optimization was carried out at Onera by Meunier [14],[16], for a single angle of attack close to stall, in order to both maximize the averaged lift coefficient and minimize lift fluctuations. To do so, unsteady RANS simulations were carried out and automatically post-processed during the optimization procedure. Based on a Kriging interpolation, two response surfaces were built and a single optimum point was selected for these two surrogate models. The results are presented in figure 7. In the left side picture presenting the lift versus the angle of attack, the great efficiency of the continuous blowing can be seen, with a high mass flow allowing more or less the performance of the classical configuration to be retrieved. The optimum, multi-objective optimization at a 25° of angle of attack presents a lower lift coefficient than steady blowing. The unsteady beneficial effect of the pulsed actuator is visible, since some steady blowing simulations carried out at the same velocity ratio (VR) or momentum coefficient C_μ present a lower efficiency. To better understand this beneficial effect, let us recall that for the same C_μ coefficient, the necessary mass flow is lower for the pulsed case than for the continuous one. Although the mass flow requirement is still too high to be installed on a real aircraft configuration, the required levels injected are in a correct order of magnitude. The figure 7(b) shows that the massive separation on the flap is mostly delayed, but a limited separation bubble still exists at the trailing edge.

In conclusion, the loss of efficiency of a slotless hinged flap can be entirely retrieved using a continuous blowing slot located in the vicinity of the flap shoulder, upstream of the massive separation. Nevertheless, the required mass flow is not realistic for aircraft. The use of pulsed blowing allows a reduction of the mass flow requirements and its efficiency is higher than steady blowing cases with the same mean mass flow injected. Hence, it has been shown that this kind of configuration can be envisaged, but the required mass flow to delay the separation is still too high and must be reduced. The exact necessary reduction is very difficult to quantify since it depends on the aircraft considered (business jets are different from classical civil aircraft), but it is roughly comprised between factors 2 to 5, compared with present studies at realistic Reynolds and Mach numbers. This could be considered with new actuators like synthetic jets which only require an electrical power.

Flow control at the leading edge

During the EUROLIFT II project [18], a high-lift slatless configuration (based on the AFV wing of Onera) was studied in the Airbus-UK F-LSWT wind tunnel. To delay the early stall of the simplified configuration, steady blowing at the leading edge through a slot was used. The control was efficient, even at realistic Reynolds and Mach numbers, but the required mass flow was again too high. It appears again that a strong effort must be made in order to drastically reduce the necessary mass flow for control, keeping efficiency acceptable. To do so, two main strategies can be considered. The first is to limit the physical complexity of the flow control using a suction peak reduction close to the leading edge. This idea was tested at Onera during the European AVERT project using a droop nose configuration. The second way is to the keep this leading edge unchanged and work on more efficient actuations, like pulsed or synthetic jets.

Droop nose configuration

First, the droop nose configuration studied during the European AVERT project is considered. The same basic GARTEUR high-lift configuration [22] used previously for a slotless flap is considered. As presented in figure 8, the slat replacement by a droop nose induces an earlier stall. A model was manufactured and tested in the L1 wind tunnel of Onera Lille to evaluate the control efficiency close to the shoulder in the blue region of the left side picture of figure 8. A first numerical analysis was carried out to optimize flow control parameters.

As presented in [16], control by mechanical and fluidic vortex generators was inefficient on this configuration, both in the numerical and experimental studies. Indeed, the generated vortices are convected away from the airfoil immediately downstream of the shoulder, because of the too strong geometry change. Hence, these vortices could not act on the separation, which occurs immediately after the slat shoulder and it appears that flow control based on blowing slots must be considered, to allow an efficient effect on the separation.

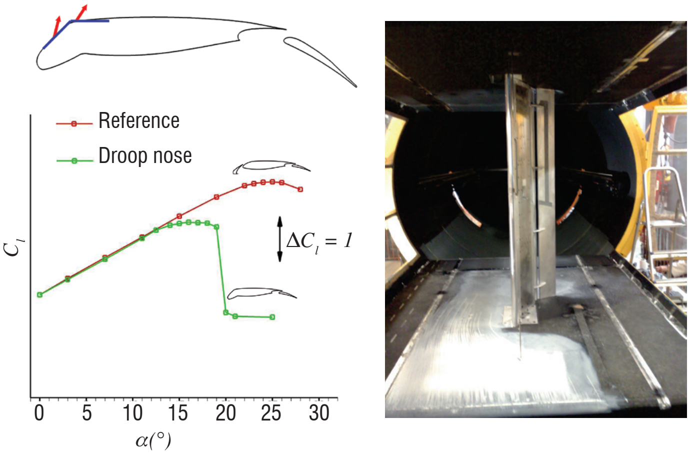

Figure 8 - Droop nose configuration, its effect on the lift curve (CFD) and corresponding model installed in the L1 wind tunnel

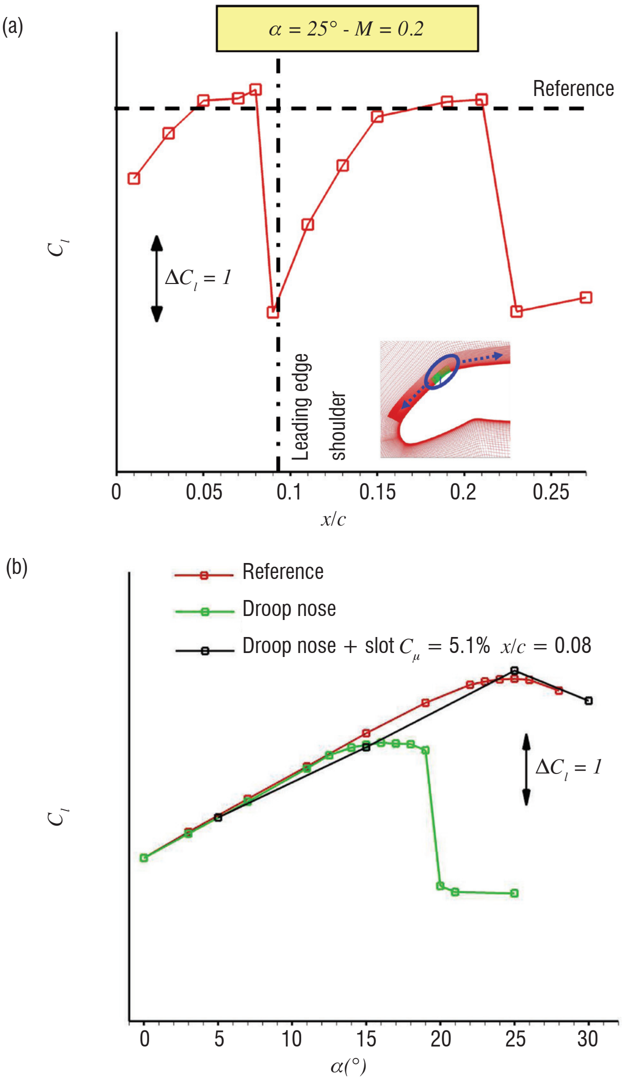

Figure 9 - (a) CFD simulations to optimize slot location - (b) Resulting lift curve with best continuous flow control parameters

Based on the chimera approach available in the elsA software, simulations were carried out to define the optimum slot location to be tested during the tests. Several flow control parameters (C_μ, slot location, injection angle) were studied [16], in order to find the optimum ones. Hence, the slot location effect at $C_\mu = 5.1\%$ and $\delta_{inj} = 70°$ is presented in figure 9(a), the resulting lift coefficient being presented figure 9(b). The optimum location is immediately upstream of the shoulder, or slightly downstream of it. The lift curve obtained with the location upstream of the shoulder shows that the original lift performance with a slotted slat can be retrieved. Once more, despite this remarkable efficiency, the required mass flow is far from being realistic for an aircraft and more work must be carried out to reduce it. To do so, pulsed jets or synthetic jets must be considered.

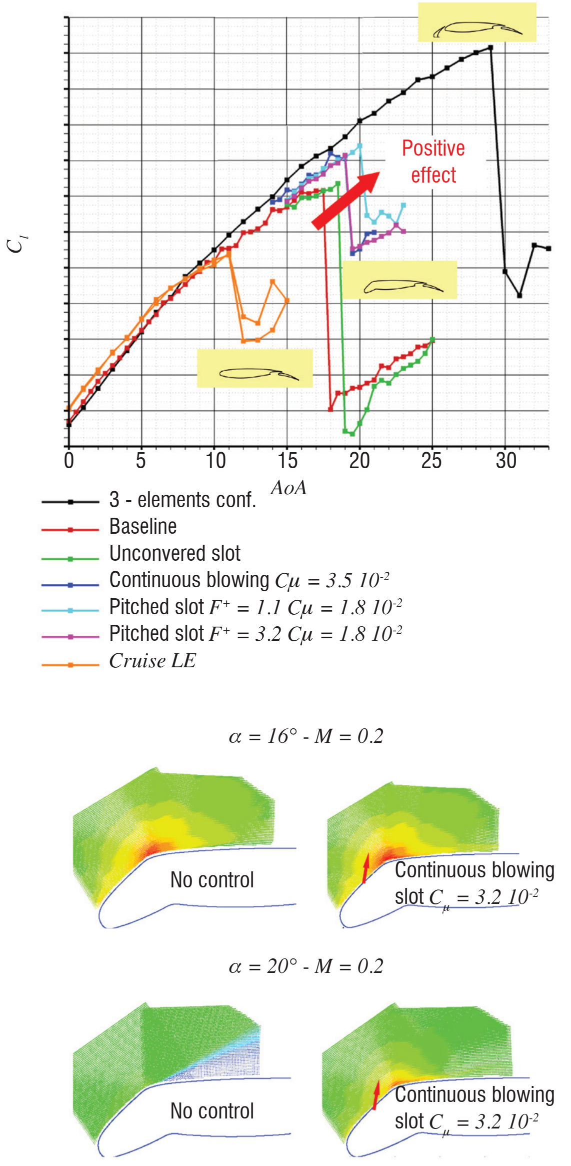

Figure 10 - Experimental lift coefficient of a continuous or pulsed slot and PIV fields for two different points ($M = 0.2 - Re = 2\ 10^6$)

During wind tunnel tests in the L1 wind tunnel of Onera Lille, a piezo-electric actuator was designed and manufactured by Onera, in order to perform pulsed blowing up to 1,000 Hz. Only one third of the spanwise extension of the model was controlled and the actuators were placed either upstream or downstream of the shoulder, as predicted by optimum steady simulations. The results on the lift curves are presented in figure 10. The reader can immediately see that the controlled cases exhibit only a slightly delayed stall, compared to the baseline in black. This rather limited effect, strongly underestimated compared to the numerical studies, is probably mostly caused by the too limited spanwise controlled extension. Furthermore, the high momentum values ($C_\mu = 5.1\%$) for numerical steady blowing could not be fully reached with the installed actuator (maximum $C_\mu = 3.5\%$). Nevertheless, several interesting effects can be observed. First of all, pulsed blowing allows at least the same beneficial effect as continuous blowing for $F^+ = 3.2$, or even higher for $F^+ = 1.1$. Indeed, several frequency effects were evaluated and a maximum efficiency was observed at about $F^+ = 1$, which is fully consistent with the literature [8]. This beneficial unsteady effect allows a significant mass flow reduction, compared with steady blowing cases. To better evaluate this, it would have been necessary to pursue the tests and apply flow control to the full span of the model.

In figure 10(b), several PIV measurements are presented, just before and after the stall of the uncontrolled case. Before the stall, no flow control effect is clearly observable on the global flow, except a higher velocity value close to the wall in the shoulder region. In stalled conditions, a massive separation occurs after the shoulder for the uncontrolled case. The control suppresses this separation in the measured field showing the control efficiency, but the high velocity region is reduced compared to the case before stall.

In conclusion, for the droop nose configuration, it appears that the original performance of the reference slotted slat can be recovered using flow control. With a large mass flow rate value, this objective can be easily achieved, but a lot of work must still be performed with pulsed blowing to achieve the necessary efficiency. Indeed, an unsteady beneficial effect has been shown at about $F^+ = 1$, compared to steady blowing. A full spanwise control is necessary, to better evaluate the efficiency level.

Cruising slat configuration

Although the previously presented droop nose configuration seems to be "receptive" to flow control, it is clearly more interesting to work on a slatless leading edge, since this configuration presents no moving part and thus corresponds to the most simplified leading edge for high-lift configurations. Nevertheless, due to the very high suction peak characteristic of such a configuration, it is clearly a "challenging" case. Based on the same GARTEUR high-lift airfoil as the previous ones [22], a numerical and experimental study was carried out on the slatless configuration [3]. The conclusions of this study carried out at Onera (not presented in this paper, see [3]) were that once more the required mass flow rate is too high to delay separation and stall. Furthermore, the spanwise control extension was too limited and the slot located too far downstream. In the end, control by continuous or pulsed fluidic slot only allows a smoother stall to be obtained. To be more efficient, it is necessary to extend the actuation as much as possible all along the span and place it upstream of the separation point, very close to the leading edge.

Recently, in 2010, a new model with a laminar leading edge was designed and manufactured by Dassault-Aviation. This model, presented in figure 11, was studied in the L1 wind tunnel of Onera Lille and it has a reference chord length of 630 mm. The transition trip (bottom left picture) was carefully studied with a CADCUT technique, in order to properly distinguish control and transition effects. In the end, two Kruegers were installed at either side of the model (picture on the right), in order to limit corner separations arising from the interaction between wind tunnel walls and the model. These Kruegers were simply designed, based on the original airfoil shape, to limit the suction peak at the leading edge and thus postpone delay separation in a much more downstream location. Then, immediately downstream of the Kruegers, rather significant mechanical VGs are installed (The same ones as presented in a previous study [3]) and thanks to Kruegers they are efficient, since they are installed in an attached region. This combined wind tunnel set-up flow control methodology helped to limit the influence of corner flow separation and it ensured symmetrical flow on this limited span to chord ratio configuration.

Two means of control are presented in this paper. In both cases, the control was applied only on two thirds of the model span width, to reduce manufacturing costs for the actuators and also because of the limited mass blowing that could be provided. In the end, the spanwise blowing region corresponds to the region between Kruregers. First, continuous fluidic vortex generators (co-rotating or counter-rotating) are placed in the lower side, but very close to the leading edge, in order to allow the vortex convection towards the upper side. This lower side placement is defined in order to place them far enough upstream of the separation to allow a correct vortex development and increase the local velocity ratio. This efficient setting for fluidic VGs was originally proposed by Scholz et al. [19] and later further studies show that generated vortices survive the flow acceleration/deceleration around the leading edge (See Scholtz et al. [20] and Wild et al. [24]). The second means of control is tangential slots (pitched at 60°) placed at the upper side of the model, close to the separation point, i.e., $x/c = 1\%$. Three different slot widths were considered (0.25 mm / 0.37 mm / 0.5 mm) and a piezo-electric actuator allows either steady or pulsed blowing (up to 1,000 Hz) to be performed, with a maximum mass flow in continuous mode of up to 100 g.s-1 for a one meter span. The default duty cycle (DC) for pulsed jets is set to 50%, but some tests have been performed at 25% also.

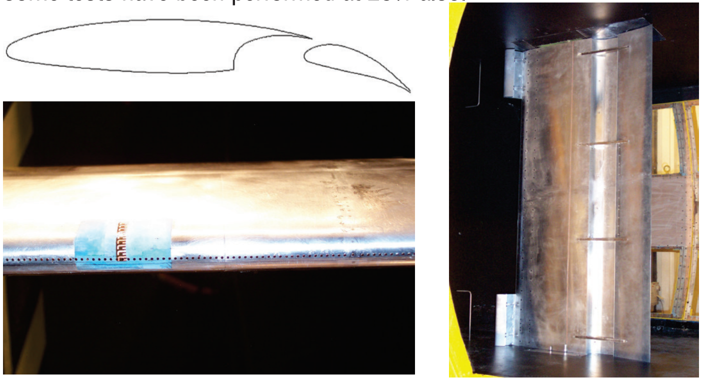

Figure 11 - The slatless model studied (top left), used transition trip (bottom left) and set-up in the test section (right)

A preliminary numerical study was carried out with the elsA software, to evaluate the control efficiency. These simulations were performed with the 0.25 mm slot width, in a continuous mode and at the maximum blowing mass flow rate. Control efficiency was observed, but strong compressibility effects and limitations were pointed out also. Hence, as presented in figure 12 (a), the control efficiency to delay stall strongly decreases when the freestream Mach number increases. One can say that it is linked to the flow control momentum coefficient, but a deeper analysis of the numerical solutions shows that the origin is linked to compressibility effects, as presented in the figure 12(b). Indeed, at high angles of attack and Mach numbers, a supersonic region appears with a shock recompression. This supersonic region is reinforced by the blowing slot and thus its beneficial effect is compensated by this strong recompression, which leads to an earlier separation. Thus, during the tests, two different freestream Mach numbers were considered ($M = 0.115$ and $M = 0.175$), in order to better evaluate the control efficiency and the compressibility effects. In the future, special care for the slot design, location and mass flow must be taken in account, to limit these compressibility constraints.

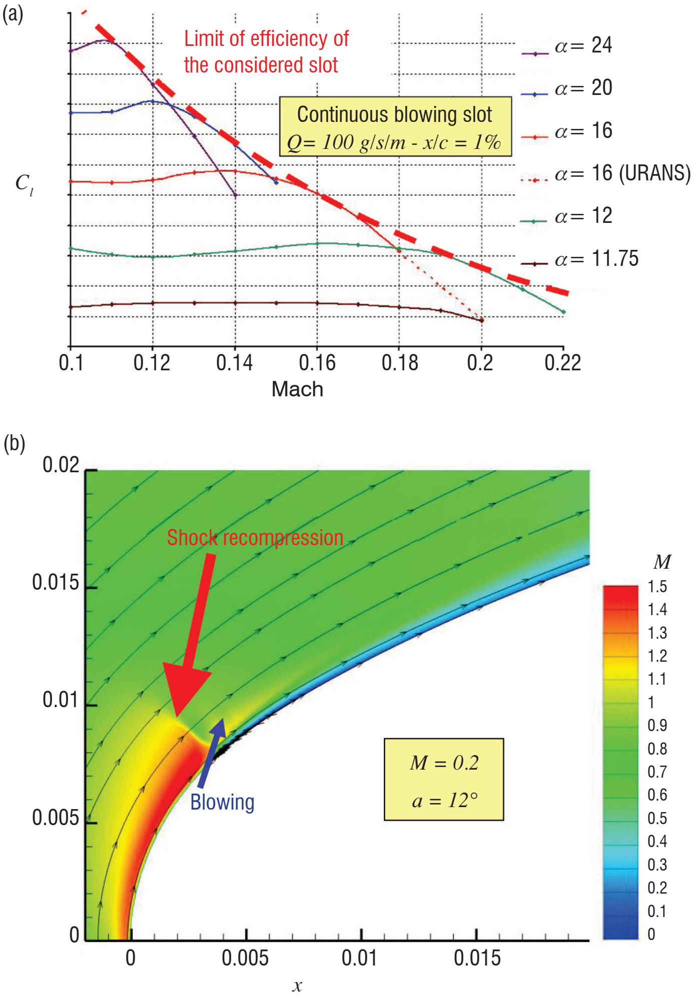

Figure 12 - *CFD* simulation - (a) Mach number effect on the control efficiency - (b) Detailed flowfield computed

All results obtained during the L1 tests cannot be presented in this paper. Only the most representative part is summarized. Thus, in figure 13, the normal force coefficient curves versus the angle of attack are presented, for the different tangential slots without pulsing. The two tested Mach numbers are shown. A clear beneficial effect is evidenced, especially at the lower Mach number. The increase in momentum coefficient highly delays the stall, but it can be noted that the mass flows presented are again very high, but pulsed blowing should strongly reduce them for the same aerodynamic effect. In regard to the slot width effect, it is strongly reduced compared to the momentum coefficient effect. Nevertheless, it can be seen that for the maximum mass flow injected, the efficiency is reduced for wider slots corresponding to limited velocity ratios and reduced momentum coefficient. As a conclusion, it is very interesting to reduce the slot width to enhance flow control efficiency through the velocity ratio and momentum coefficient increase. To better analyze the control efficiency, it is necessary to compare the maximum normal force coefficients. Despite the large spanwise actuated region, three dimensional effects were observed during the tests, caused by the low span to chord ratio. These complex effects have an influence on the normal force coefficient obtained by pressure tap integration. These effects are visible in figure 13, where the stall is sometimes difficult to determine. To partially solve this problem, the following comparisons are based on the minimum value of the wall pressure coefficient at the suction peak at the leading edge. This "solution" is not fully satisfactory, but it allows clearer conclusions to be obtained.

The changes in the minimum Cp values at the leading edge versus the momentum coefficient for the lower side fluidic vortex generators and upper side tangential blowing cases are presented in figure 14. On the one hand, fluidic vortex generators have only a limited effect and the momentum coefficient increase does not amplify this effect. On the other hand, the tangential blowing, continuous or pulsed, is clearly efficient and the reduced efficiency with increasing Mach number observed in numerical simulations is not retrieved here. Indeed, the control delayed stall seems almost proportional to the momentum coefficient and independent of the freestream Mach number. Strangely, the slot width effect has almost no influence on the control efficiency on these curves for pulsed blowing cases, but for continuous cases the efficiency decreases with the slot width. This could show that the control mechanisms are different between the continuous and pulsed cases. It can be noted that the momentum coefficient is the appropriate non-dimensionalized parameter to scale the control efficiency. The complete post-process of the various tests shows (no curves plotted in this paper) that a pulsed blowing, at a dimensionless coefficient F^+, equal to about 1, allows a higher efficiency compared to continuous blowing cases with the same mean mass flow rate. At higher or lower frequencies, the pulsed blowing is "only" as efficient as the continuous blowing at the same C_μ value. Nevertheless, considering the $C\mu$ formula for pulsed blowing presented at the beginning of this paper, it leads to a reduced mass flow by a factor of the square root of DC between pulsed and continuous blowing cases, whatever the actuator frequency is. Thus, even though the unsteady flow control is not always more effective than the continuous one, it could result in a significant mass flow reduction, provided that the forcing frequency is well chosen.

To summarize the results obtained during this wind tunnel test campaign, figure 15 shows the changes in the maximum normal force coefficient gain ΔC_{Nmax} with C_μ, for different freestream velocities, slot widths, duty cycles and forcing frequencies (optimal F^+ only). The results of the fluidic VGs are not plotted in this figure, since no maximum normal force coefficient gain is observed, contrary to figure 14, where there was a small decrease of the minimum pressure. Figure 15 (left) shows a linear increase in the maximum normal force with the momentum coefficient. Once again, this figure shows that, in this case, the momentum coefficient is the appropriate non-dimensionalized parameter to compare test cases with different freestream velocities, slot widths and duty cycles, but also to compare continuous and pulsed blowing, since all of the results fit rather well on a linear curve. For information, if a different definition of $C\mu$ had been used (Eq. (2) without the factor $1/DC$), as is often found in the literature with pulsed blowing, the case with $DC = 0.25$ (orange triangle) would not have been on the linear curve. Figure 15 (right) shows the effect of F^+ on ΔC_{Nmax}. The lower the tested frequency is, the higher ΔC_{Nmax} is. The optimal reduced frequency among all those tested seems to be around $F^+ = 0.7$.

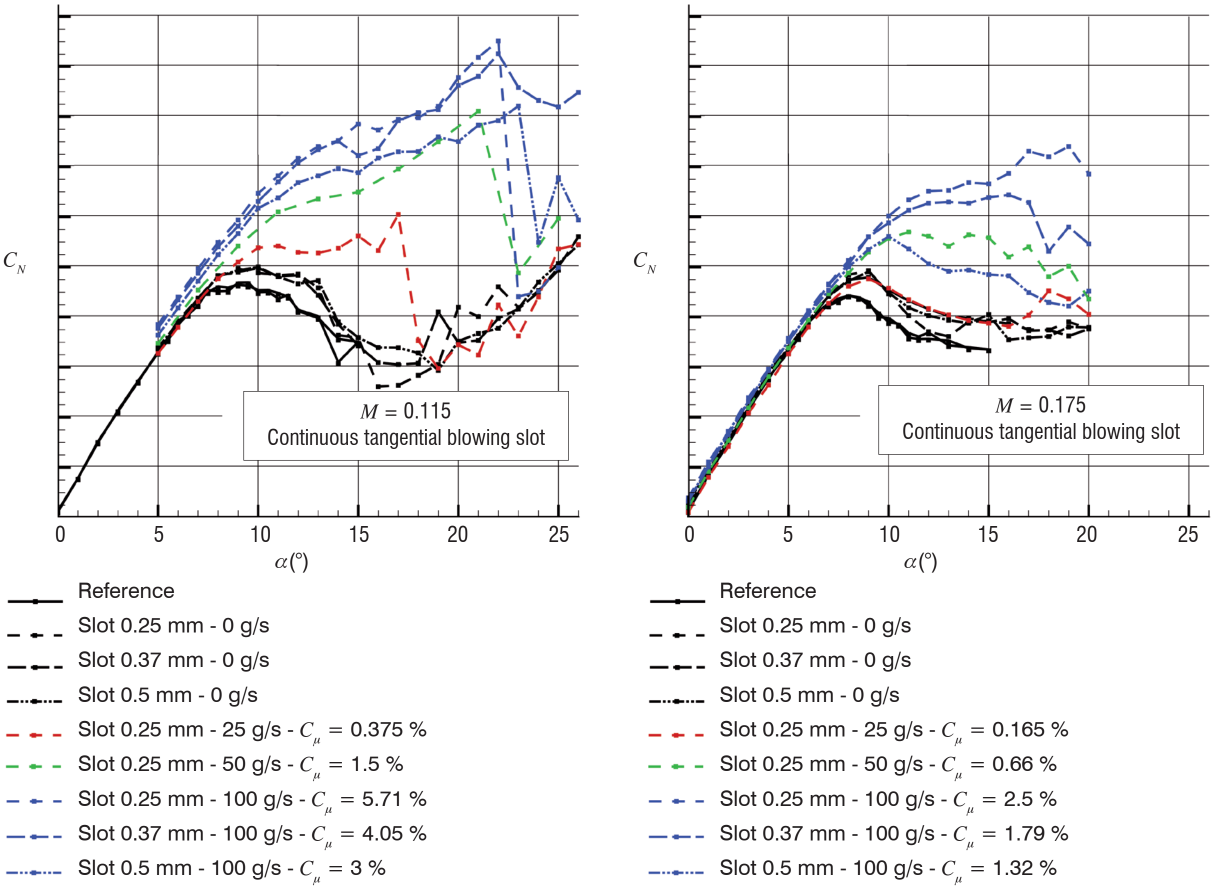

Figure 13 - Continuous control efficiency on the lift curves at M = 0.115 and M = 0.175

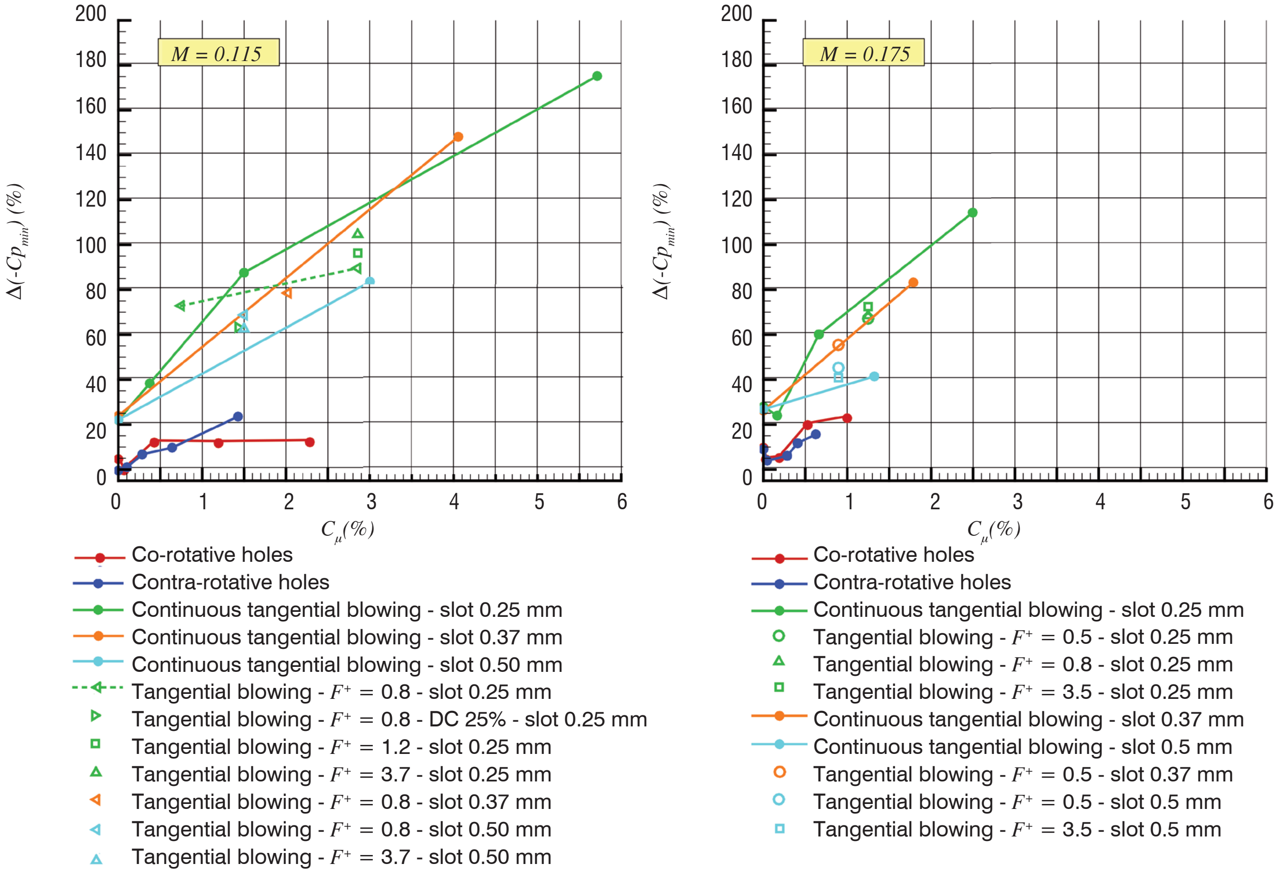

Figure 14 – Pulsed and continuous blowing effect on $-Cp_{min}$ at M = 0.115 and M = 0.175

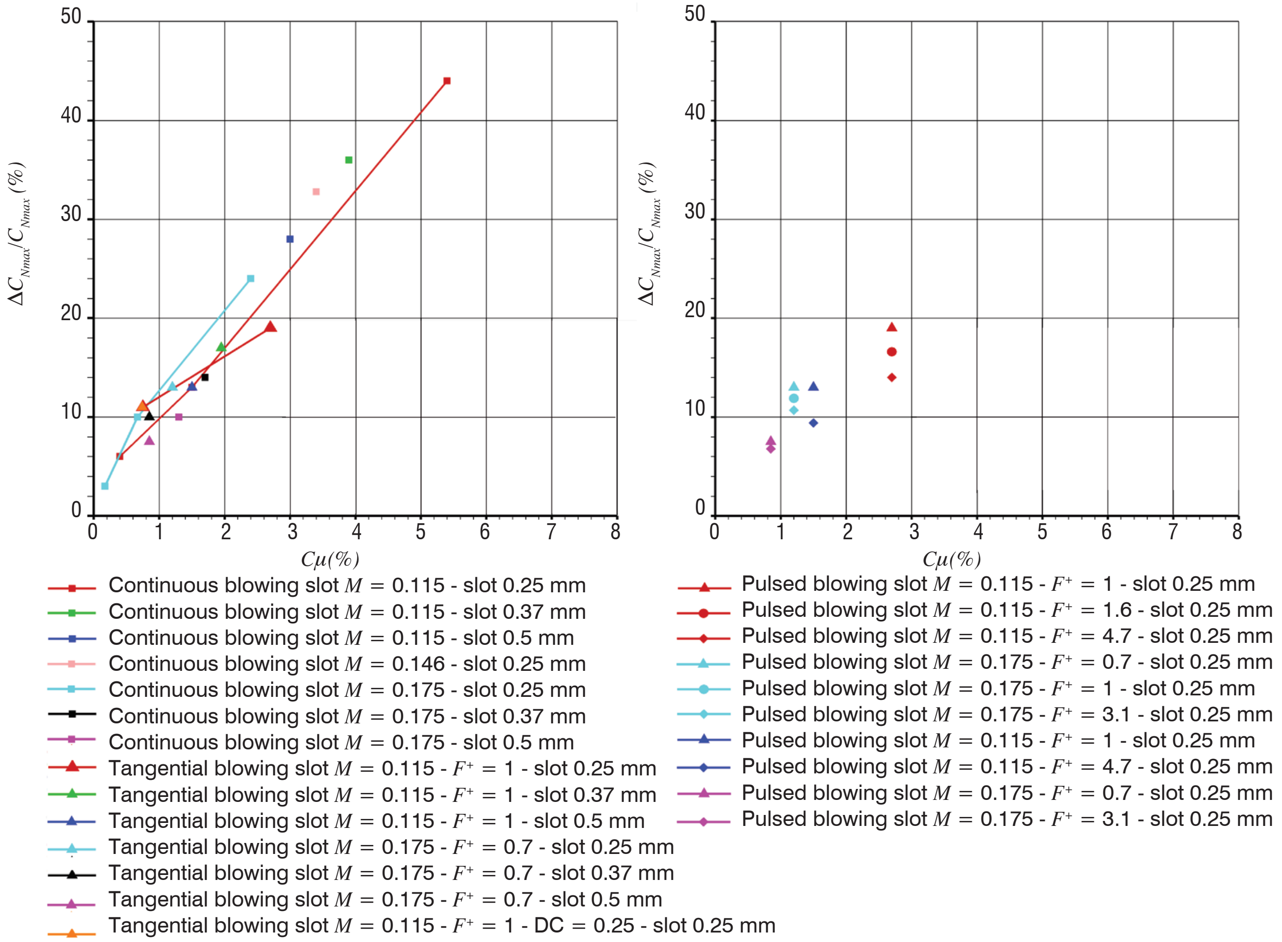

Figure 15 – Changes in ΔC_{Nmax} with $C\mu$ for different freestream velocities, slot widths, duty cycles and forcing frequencies

In the end, despite compressibility limitations on this configuration, a clear beneficial effect has been evidenced. Fluidic vortex generators placed on the lower side have a positive, but limited effect. Tangential blowing at the upper side seems to be more efficient and some additional beneficial effects were observed at a pulsed frequency of about $F^+ = 1$. Nevertheless, required mass flow is still too high to be considered on a realistic aircraft and a strong optimization of the slot width, shape, location and frequency must still be performed to enhance its efficiency, directly leading to a mass flow reduction. Additional pulsed or synthetic effects must be sought carefully, in order to limit the mass flow injected.

Conclusions and perspectives

The beneficial use of flow control technologies for high-lift configurations has been shown through various studies performed at Onera. For classical slotted slat and flap configurations, the use of mechanical or fluidic vortex generators at the flap leading edge is very efficient to delay the separation that may occur in a landing phase on its upper side. This simple means of control, already used under flight conditions, may be used to enhance the high-lift performance or simplify its mechanisms, such as a reduction of the flap size and gap. For more “aggressive” designs, the slot suppression is very interesting from the point of view of aircraft manufacturers. Nevertheless, this solution is much more complex to control and classical vortex generators seem to be inefficient to delay separation and stall for such configurations. Thus, tangential blowing is a promising approach and demonstrations performed at Onera, both numerically and experimentally, have shown that the original slotted configuration performance can be entirely recovered. Unfortunately, the most efficient cases are based on continuous blowing and the required mass flow is too high to be realistically considered. Thus, pulsed blowing has shown an additional efficiency at some frequency “exciting” the unsteadiness of the flow at a reduced required mass flow, but it is still a little too high. Thus, a lot of work must still be performed to upgrade actuator efficiency or use “advanced” actuators like synthetic jets, which do not use air blowing. Another interesting way to be considered, is to define new airfoil geometries more “receptive” to flow control, i.e., taking into account the flow control directly in their design phase.

The following table summarizes the conclusions obtained in our studies, which could be slightly different from those of the very broad literature. Note that only conclusions obtained here at "realistic" Mach (almost 0.2) and Reynolds numbers (almost 2 million) are considered. Many additional parameter studies carried out outside of Onera may lead to different conclusions.

	Mechanical of fluidic *VGs*	**Continuous blowing slot**	**Pulsed blowing slot**
Classical Flap	Efficient	Not tested yet at Onera	Not tested yet at Onera
Slotless Flap	Not efficient	Efficient but significant mass flow necessary	Efficient
Droop Nose Leading Edge	Not efficient	Efficient but significant mass flow necessary	Efficient
Slatless Leading Edge	Some limited efficiency at the lower side	Efficient but significant mass flow necessary	Efficient

Several studies are still in progress at Onera on this topic. The first main objective is to develop efficient and new actuators to show flight feasibility. Secondly, more realistic configurations, including swept wing, winglet and engine, will be studied to validate the efficiency and to control local separation also, which may cause earlier stall ■

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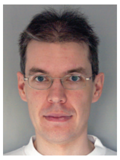

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