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DESIGN ASPECTS OF A GAPLESS HIGH-LIFT SYSTEM WITH ACTIVE BLOWING

C. Jensch[1], K. C. Pfingsten[1], R. Radespiel[1], M. Schuermann[2], M. Haupt[2], S. Bauss[3]

[1]Institute of Fluid Dynamics, Technische Universität Braunschweig, Bienroder Weg 3, 38106 Braunschweig,

[2]Institute of Aircraft Design and Lightweight Structures, Technische Universität Braunschweig, Hermann-Blenk-Str. 35, 38108 Braunschweig,

[3]Airbus Deutschland GmbH, Airbus-Allee 1, D-28199 Bremen, Germany

Germany

Abstract

Aerodynamic and structural design aspects of gapless high-lift systems with efficient active blowing are considered. Numerical simulations for the aerodynamic analysis of a circulation control airfoil at high Reynolds numbers are first discussed. Here the blowing power needed is a critical design driver. Major design parameters such as slot height, flap length and additional leading edge blowing as well as the Reynolds number are varied to demonstrate and improve blowing efficiency. The results show that a significant increase of the lift gain factor is possible. Additional blowing at the nose protects the leading edge against stalling at lower Mach numbers and may be used to enable very high lift coefficients. Moreover, two structure design concepts are studied on a preliminary level, in addition to aerodynamic analysis. Here the required slot for blowing is integrated either into the fixed trailing edge of the wing box or an integration into the flap structure is assumed.

1. INTRODUCTION

In recent years noise emissions from aircraft have become a major problem. Hence the interest in reducing the emitted noise during take-off and landing of aircrafts especially at airports located close to urban city centres is large. One contributor of the emitted noise are conventional high-lift systems as slats and slotted flaps [1]. It is presumed that novel gapless high-lift systems without slats have a high potential in reducing the noise. Previous investigations have shown that an active high-lift system using circulation control can achieve the same or even higher lift coefficients than conventional high-lift systems [2], [3], [4], [5]. Higher lift coefficients allow a shorter length of the runway for take-off and landing and possibly steeper trajectories which would reduce noise in airport surrounding areas. Additionally it is expected that the additional weight due to the integration of the circulation control system can be counter balanced by the lower mechanical complexity of a high-lift system without slats and Fowler flaps.

Internal blowing of a hinged high-lift flap as part of a supercritical airfoil was recently investigated at the Technische Universität Braunschweig [6], [7], [8]. The numerical simulations showed that high deflection angles without separation and relatively high lift coefficients are accessible. However, a substantial amount of electric power or bleed air is still necessary to provide the needed mass flow at high total pressure.

Hence further investigations were carried out to increase the efficiency of the circulation control airfoil. This paper presents some results of these computations that outline possible ways for improvement. Different parameters like the slot height h, flap angle η, flap length, c_{flap}, momentum coefficient of the jet c_{μ} and angle of attack α are covered. The impact of additional blowing at the leading edge on the performance of the airfoil is investigated as well.

Along with reviewing existing patents of structure designs for integration of powered lift systems [9], [10]. two selected design concepts were studied on a preliminary level. This works aims to indentify practical implementions of the present high-lift approach on a modern transport aircraft. One concept proposes the integration of the system into the fixed trailing edge; the other attempts integration into the flap.

2. COANDA EFFECT AND MOMENTUM COEFFICIENT

2.1. Coanda effect

The *Coanda* effect is named after *Henri Marie Coanda*, who discovered this phenomenon in 1910. He noticed that a tangentially blown air jet stays attached to a convex surface. Due to the turbulent momentum transport the air jet accelerates the air between the jet and the surface. The surface prevents inflow to the area between the jet and the surface and this reduces the pressure in this area. This results in streamline curvature towards the wall, and hence the jet attaches to the curved surface.

The circulation control technology for airfoils uses the *Coanda* effect to realize large flow turning angles without separation of the flow. With this approach a thin jet of pressurized air is blown tangentially out of a slot directly upstream of a curved surface. The curved surface may be the knuckle shape of a deflected high-lift flap with the *Coanda* radius R. The wall jet is also used to accelerate the wake of the main-wing boundary layer and the near-wall flow downstream of the curved surface. Hence the flow around the flap can bear large adverse pressure gradients and very high flap deflection angles and large effective camber are achieved which leads to high lift coefficients.

2.2. Dimensionless momentum coefficient

An important parameter for comparison of circulation control airfoils is the dimensionless momentum coefficient of the air jet, c_μ. It is defined by the ratio of introduced jet momentum per time related to the onflow dynamic pressure q_∞ and the wing area S. The following equation for c_μ is calculated by jet velocity v_{jet}, jet massflow dm_{jet}/dt, onflow density ρ_∞ and onflow velocity v_∞:

(1) $$c_\mu = \frac{v_{jet}\dot{m}_{jet}}{q_\infty S} = \frac{v_{jet}\dot{m}_{jet}}{\frac{1}{2}\rho_\infty v_\infty^2 S}$$

For lower momentum coefficients the circulation control functions as a boundary layer control. In that case higher momentum coefficients move the point of separation further downstream on the upper surface of the flap until the flow stays attached up to the trailing edge. For a further increase of the momentum coefficient with the point of separation fixed at the trailing edge the circulation control functions as supercirculation. The efficiency of boundary layer control is usually higher than the efficiency of supercirculation. Hence airfoil configurations using circulation control should operate at the edge between boundary layer control and supercirculation for best performance. The momentum coefficient should be just as high as it is necessary to prevent flow separation at the trailing edge.

The efficiency of a circulation control system can be measured by the lift gain factor which is defined by the increase of the maximum lift coefficient over the required momentum coefficient, $\Delta c_{l,max}/c_\mu$. The increase of the maximum lift coefficient is given by the difference between the maximum lift coefficient of the investigated configuration using blowing and the clean configuration. For configurations using blowing at the leading edge and upstream of the flap the sum of both momentum coefficients is used for the calculation of the lift gain factor.

3. SET UP OF AIRFOIL DESIGN

The investigated airfoil was created by the integration of two slots into the so called FNG airfoil, which is provided by Airbus. The reference configuration features a large high lift flap with a relative flap chord of 30%. A slot for blowing is located on the upper surface of the airfoil directly upstream of the flap. The slot height is set to values between h = 0.0063R and h = 0.025R, where R is the knuckle radius used for a low-hinged flap. For the numerical simulations with additional blowing at the leading edge the second slot is located on the upper surface of the leading edge of the airfoil downstream of the suction peak. FIG. 1 shows the shape and the grid of the airfoil and its two slots. It is seen that a hybrid grid was

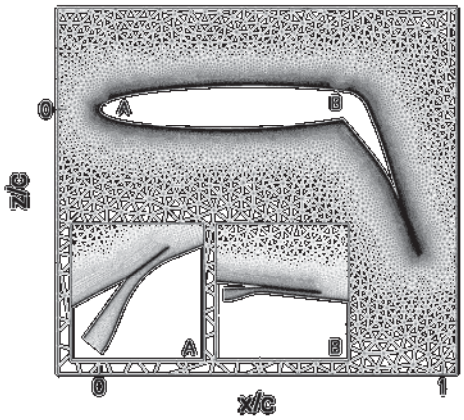

FIG. 1. Hybrid grid for the circulation control airfoil, slot details; *not to scale*

used here. The structured part for resolving the boundary layer consists of 1500 elements along the surface and 48 layers normal to the surface. The structured part has a height of 150% of the maximum boundary layer thickness. The first grid spacing close to the wall was chosen as $y^+ < 1$ even at the stagnation point. The complete grid consists of about 64000 nodes. The numerical solution of the Reynolds-averaged Navier-Stokes equations are performed using the TAU flow solver [11]. Techniques like local time stepping, residual smoothing and multi-grid are used for accelerating the convergence to steady state. The boundary layer is assumed to be fully turbulent. The *Spalart-Allmaras* turbulence model for Rotation and/or Curvature effects [12], [13] was previously shown to provide reliable predictions of the flow around circulation control airfoils [6], hence it is used for all computations.

4. LEADING EDGE BLOWING

Early investigations demonstrated the effect of additional blowing from a second slot at the leading edge of the airfoil [14], [15]. The wall jet protects the near-wall flow against separation. Hence the angle of attack can be increased and higher lift coefficients can be achieved.

The height of the slot upstream of the flap was set to h = 0.0125R. The slot at the leading edge was set to the same height for a momentum coefficient of $c_\mu = 0.043$ and h= 0.003R was used for $c_\mu = 0.011$. The upper surface of the leading edge was modified along a length of four times the height of the leading edge slot as seen in FIG. 1, in order to accommodate the slot geometry. That is, the slot was positioned inside the surface. Thus, if the slot is closed the original contour of the airfoil is recovered. Hence there is no significant increase of drag in cruise flight due to the geometry design of the nose slot expected.

The potentials of leading edge blowing are investigated for a deflection angle of $\eta = 80°$. The Mach number was set to Ma = 0.125 in order to prevent transonic flow and a flight Reynolds number of $Re = 18 \cdot 10^6$ was used. As a reference case the momentum coefficient was set to $c_\mu = 0.083$ to keep the flap flow just attached up to the trailing edge. The lift curve of FIG 2 indicates that this configuration stalls due to the occurrence of a growing turbulent separation bubble on the upper surface at the leading edge. The lift gain factor for this configuration is 49. Additional blowing at the leading edge with a moderate momentum coefficient, $c_\mu = 0.043$, protects the leading edge against separation. Due to the additional blowing the circulation of the airfoil is raised and the maximum lift coefficient is increased by $\Delta c_{l,\ max} = 0.45$ compared to the configuration with blowing upstream of the flap only. Using $c_\mu = 0.126$ solely blown from the flap slot increases the maximum lift coefficient only by $\Delta c_{l,\ max} = 0.29$. This indicates that $c_\mu = 0.126$ is already in the region of supercirculation. Thus, the lift gain factor is only about 34.

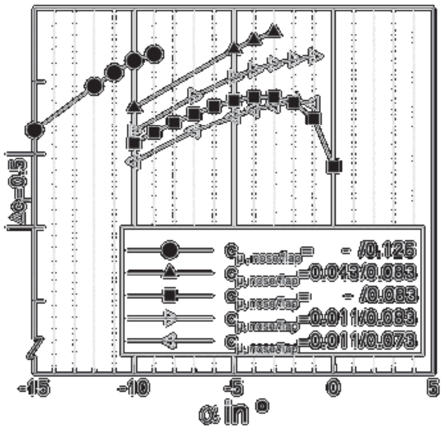

FIG. 2. Lift coefficient slopes for leading edge blowing; Ma = 0.125; Re = $18 \cdot 10^6$; $\eta = 80°$

Additional numerical simulations with smaller overall momentum coefficients close to the reference value of $c_\mu = 0.083$, where the edge between boundary layer control and supercirculation is expected, were also carried out. In FIG. 2 the lift curves for configurations using leading edge blowing of $c_\mu = 0.011$ and flap blowing with both $c_\mu = 0.073$ and $c_\mu = 0.083$ are displayed. Splitting the overall momentum coefficient of $c_\mu = 0.083$ to $c_{\mu,\ nose/flap} = 0.011/0.073$ leads to a lift gain factor of 48 while the momentum coefficient combination of $c_{\mu,\ nose/flap} = 0.011/0.083$ increases the maximum lift coefficient by $\Delta c_{l,\ max} = 0.28$ and an efficiency of 47. These results indicate that the blown flap configuration with $\eta = 80°$ is just on the edge where leading edge separation begins to dominate stalling behaviours. Thus leading edge blowing is presumably necessary for achieving maximum lift coefficients higher than about six.

5. SLOT GEOMETRY

The efficiency of the *Coanda* effect depends strongly on the slot height [4]. For a given momentum coefficient a thinner wall jet will initially produce a stronger Coanda effect. However, a too thin jet vanishes before reaching the trailing edge due to strong turbulent momentum transport.

Previous numerical simulations [8], were done with a height of the slot upstream of the flap between h = 0.0125R and h = 0.0251R where the slot height of h = 0.0125R was the more efficient. Here, the slot height is reduced further to find the optimum. Slot heights between h = 0.0063R and h = 0.0125R were investigated for different deflection angles of the flap, using flap blowing only. The momentum coefficient was set to the minimum value required to keep the flow attached to the flap for each configuration. Thus for each slot height the configuration of maximum efficiency was investigated.

These investigations were performed for flap deflections of $\eta = 50°$ and $\eta = 65°$ at Ma = 0.15 and $\eta = 80°$ at Ma = 0.125. The results for $\eta = 50°$ are shown in FIG. 3. The reduction of the slot height yields a slightly smaller maximum lift coefficient, however at a much lower momentum coefficient and the lift gain factor increases from 58 to 72. By a further decrease of the slot height to the lowest value of h = 0.0063R no further increase of gain factor is achieved. It is found that slot heights around 0.007R are optimal. Similar results were observed for $\eta = 65°$. Here the reduction of the slot height from h = 0.0125R to h = 0.0078R increased the lift gain factor from 53 to 63. The slot height of h = 0.0078R was also found to be an optimum for a flap deflection angle $\eta = 80°$ at Ma = 0.125. For this configuration the lift gain factor was improved from 49 to 52 by reducing the slot height from h = 0.0125R to h = 0.0078R and it was slightly lower by a further reduction to h = 0.0063R.

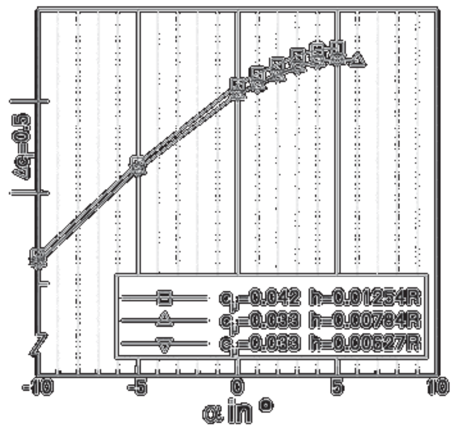

FIG. 3. Lift coefficient slopes for different slot heights; Ma = 0.15; Re = $21 \cdot 10^6$; $\eta = 50°$

The numerical simulations demonstrate that the investigated airfoil configurations have an optimum slot height of about h = 0.0078R where a maximum lift gain factor is reached. For the best performance at each flap deflection a minimum momentum coefficient is needed to prevent flow separation at the trailing edge. Thus for a given maximum lift coefficient a minimum momentum coefficient at an appropriate flap deflection angle is needed for achieving highest efficiency. The needed momentum coefficients for given maximum lift coefficients are plotted in FIG. 4 for different configurations. It is seen that the choice of slot height has a significant effect on the needed amount of blowing.

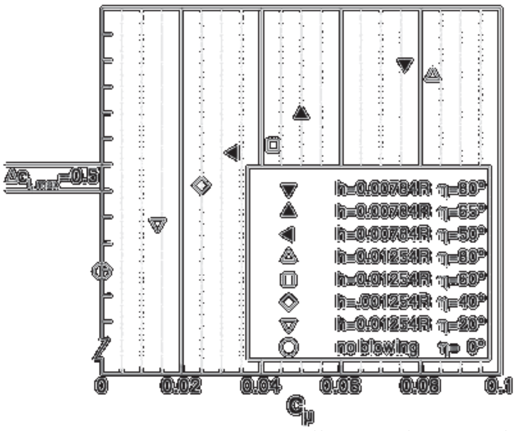

FIG. 4. Minimum momentum coefficients for specific lift coefficients for different configurations

6. FLAP LENGTH

The length of the flap is a major design parameter. The flap length related to the chord length has a strong impact on the aerodynamic characteristics of the airfoil as well as on the structural design of the wing. Airfoils with a longer flap length are generally assumed to achieve higher lift coefficients. But the higher lift coefficients and the increased length of the upper surface of the flap lead to higher momentum coefficients needed for blowing. Hence the lift gain factors obtained for different flap lengths need to be analysed.

Different flap lengths between c_{flap}/c = 0.25 and c_{flap}/c = 0.35 have been investigated at Ma = 0.15, Re = $21{\cdot}10^6$ and a flap deflection angle of η = 50°. For each configuration the momentum coefficient was set to the minimum which is necessary to prevent flow separation at the trailing edge. As expected an increased flap length leads to a higher lift coefficient at a significantly higher momentum coefficient. The configuration with c_{flap}/c = 0.35 achieves a lift gain factor of 55. This is rather low compared to the results of the configuration with c_{flap}/c = 0.30 which achieves a lift gain factor of 74. The configuration with c_{flap}/c = 0.25 achieves a lift gain factor of 73, as seen FIG. 5.

The results show that an optimum flap length is found between c_{flap}/c = 0.25 and c_{flap}/c = 0.30. The aerodynamic efficiencies for these configurations are comparable. Defining suitable flap lengths should therefore be an interdisciplinary process using both aerodynamic and structural design sensitivities.

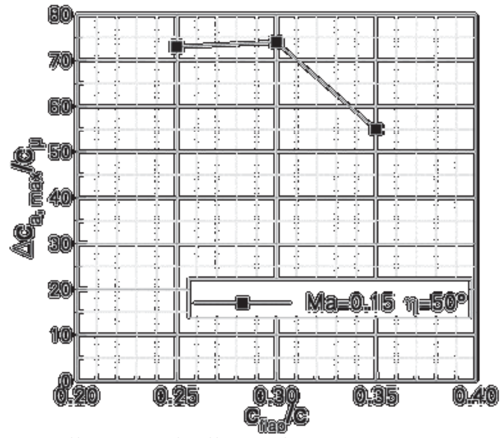

FIG. 5. Efficiency of different flap length

7. INFLUENCE OF REYNOLDS NUMBER

Most published investigations of circulation control airfoils, especially experimental investigations, were previously undertaken at rather low Reynolds numbers of about 10^6, while the Reynolds number of the present work is set to values around $20{\cdot}10^6$ to represent a wing section of a medium-size transport aircraft at flight conditions. Therefore one would like to know more about the influence of the Reynolds number on the design sensitivities of circulation control airfoils. For this purpose numerical computations for the flap deflection angle of η = 65° at Ma = 0.15 at Re = $1{\cdot}10^6$ are discussed here. FIG. 6 displays the computed lift curves for the flap slot heights of h = 0.0125R and h = 0.0078R.

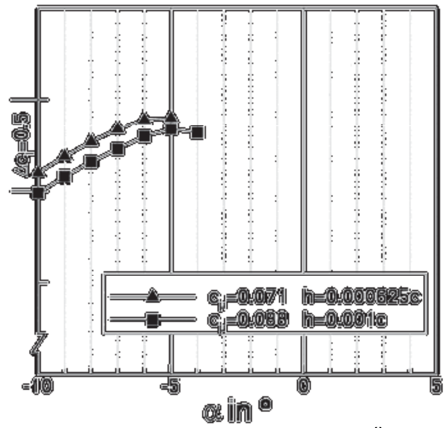

FIG. 6. Lift coefficient slopes at Re = $1{\cdot}10^6$; Ma = 0.15; η = 65°

In contrast to the results at Re = $21{\cdot}10^6$ the reduction of the slot height at Re = $1{\cdot}10^6$ leads to slightly higher maximum lift coefficients at much smaller momentum coefficients. The lift gain factor increases from 34 for h = 0.0125R to 43 for h = 0.0078R. Note that the gain factors are significantly smaller at the lower Reynolds number. Obviously, the larger momentum coefficients are needed to compensate the larger momentum losses of the boundary layer. The angle of attack for maximum lift is reduced by 5° for the smaller Reynolds number. That is, the thicker boundary layers at lower Reynolds numbers lead to less effective flow turning by the blown flap and this yields airfoil stall at lower angles of attack.

8. DESIGN CONCEPTS

In order to implement the active high-lift system on an aircraft, certain evaluation criteria have to be met. Limited deformations of the slot are obviously important to make the system work. Furthermore, not more than 10% of the slot's cross section is allowed to be used for support structure, e.g. small elements that keep the slot's geometry. With these two criteria in mind the following two concepts have been studied.

A general wing design with blown flaps is presented in FIG. 7 showing that bending stiffness is distributed in an unfortunate way. This already indicates that the very first idea to simply use the slot between the wing and flap structure for blowing will not work.

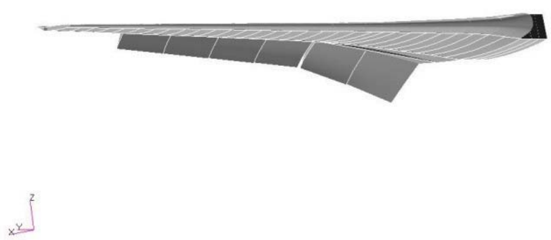

FIG. 7. Wing with 6 blown flaps and nondeflected aileron

8.1. Integration of the slot and Coanda plate into the Fixed Trailing Edge

The slot and the Coanda plate are integrated into the fixed trailing edge, FTE, as indicated in FIG. 8. Hence there is only one slot necessary to serve all flap positions. The curved Coanda plate reaches into the flap, which means that the design of the Coanda plate is one factor that determines the position of the spar of the flap. This position has an essential influence on the stiffness of the flap.

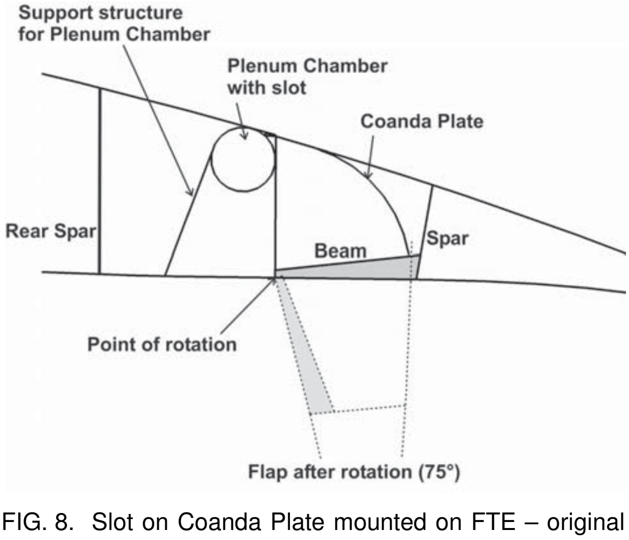

FIG. 8. Slot on Coanda Plate mounted on FTE – original design

Should the Coanda plate not be of circular shape, for example for reason of aerodynamic performance, a gap will exist between the Coanda plate and the flap's upper surface while the flap is deployed. Its size depends on the detailed design of the Coanda plate. The slot is supported by structure elements to keep its shape. The plenum chamber that supplies pressurized air to the slot is integrated right upstream of the slot. It is borne on an own support structure.

In order to address the above mentioned design issues the following steps or combinations thereof need to be undertaken.

– To increase the stiffness of the flap a beam needs to be integrated to support the spar. Therefore the Coanda plate needs to be designed in a way which allows the beam to be installed. This modification seems to be more critical for thin profiles, e.g. in the outer wing region.
– An additional way of increasing the stiffness is to move the flap's spar further towards the Leading Edge of the flap. This can be done by using an alternative point of rotation for the flap.
– To close the gap between the Coanda plate and the flap's upper surface, plate and surface need to be jammed. However, it is uncertain at this point that the deformations that occur using this measure can be adequately controlled in transport aircraft operation.

The modified solution is shown in FIG. 9.

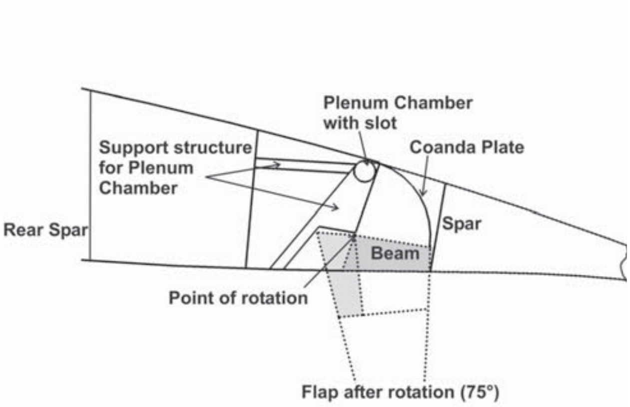

FIG. 9. Slot and Coanda Plate after modifications

8.2. Integration of the slot into the flap

This solution is based on the integration of the Coanda System into the flap. Therefore the slot will be integrated into the flap's nose. As for the above mentioned solution, the slot is supported by elements to keep its shape. The plenum chamber that supplies the pressurized air is integrated into the flap.

One disadvantage of this solution is that multiple slots are needed in order to make the system work for different flap angles. A flap deployed at 70° with a single slot is shown in FIG. 10.

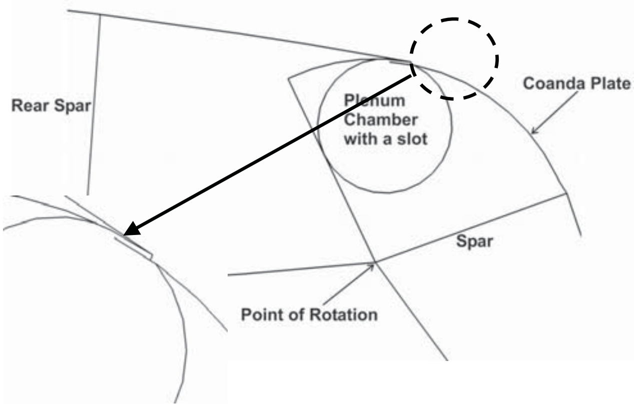

FIG. 10. Slot integrated into the flap and detailed view of the slot

At this point both concepts seem to be appropriate for installation into a transport aircraft wing. However, further detailed design work is needed to verify this preliminary assessment and to allow quantitative comparisons.

9. CONCLUSION

Steady-state Reynolds-averaged Navier-Stokes calculations for a two-dimensional airfoil using circulation control were carried out to increase the efficiency of circulation control to be used as high-lift system of transport aircraft. Varying the slot height at different flap deflections angles, various flap lengths as well as leading edge blowing and the influence of the Reynolds number were analysed to optimize the high lift performance.

The numerical simulations for an airfoil using a second slot at the leading edge demonstrate that this blowing prevents leading edge separations. For a configuration at Ma = 0.125 with deflection angles of about $\eta = 80°$ it is found that additional blowing at the leading edge is needed to achieve higher maximum lift coefficients than those achieved with flap blowing alone.

The numerical simulations showed that slot height and flap length are important design parameters to maximise efficiency of flap blowing. A slot height of about h = 0.0078R and a flap length around $c_{flap}/c = 0.30$ were found to be close to the aerodynamic optimum.

A design study was carried out on a preliminary basis, to demonstrate the feasibility of integrating the proposed high-lift system into a transport aircraft wing. Two concepts were studied. One concept suggests to integrate the Coanda plate and its plenum chamber into the fixed trailing edge of the wing. Another concept shows the integration into the flap as a possible solution. At this point of the study, both concepts seem to be feasible but need further detailed analysis in order to allow quantitative assessment.

10. ACKNOWLEDGEMENTS

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