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OVERVIEW ON DRAG REDUCTION TECHNOLOGIES FOR CIVIL TRANSPORT AIRCRAFT

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Abstract. *Drag reduction is one of the main objectives of the transport aircraft manufacturers. The drag breakdown of a transport aircraft at cruise shows that the skin friction drag and the lift-induced drag constitute the two main sources of drag, approximately one half and one third of the total drag. Hybrid laminar flow technology and innovative wing tip devices offer the greatest potential for drag reduction. Aircraft performance improvement in off-design conditions can also be obtained through trailing edge optimisation, control of the shock boundary layer interaction and of the boundary layer separation. The paper will give an overview of the results obtained for the different mentioned topics and will try to evaluate the potential gains offered by the different technologies.*

NOMENCLATURE

h^+_w Height scaled with respect to the inner variables of the turbulent boundary layer taken at the wall

$\overline{R}$ Attachment line Reynolds number. $\overline{R}=W_e.\eta/\nu_e$ with $\eta=(\nu_e/k)^{1/2}$, where W_e is the mean velocity component parallel to the attachment line and $k=(dU_e/dX)_{AL}$, Ue the external velocity component in the direction normal to the leading edge and X is the curvilinear abscissa in the same direction, νe the free stream kinematic viscosity

K Suction parameter, $K=Vw\ .\ \overline{R}\ /\ W_e$ with Vw the wall suction velocity

ACRONYMS

DOC Direct Operating Cost
NLF Natural Laminar Flow
HLF Hybrid Laminar Flow
MEMS Microfabricated Electro-Mechanical Systems
VG Vortex Generators

1 INTRODUCTION

Drag reduction of civil transport aircraft directly concerns performance, but also indirectly, of course, cost, and environment. Fuel consumption represents about 22% of the DOC which is of utmost importance for the airlines, for a typical long range transport aircraft. Drag reduction directly impacts on the DOC : a drag reduction of 1% can lead to a DOC decrease of about 0.2% for a large transport aircraft. Other trade-offs corresponding to a 1% drag reduction are 1.6 tons on the operating empty weight or 10 passengers.

The environmental factors, such as noise, air pollution around airports and impact on climate change, which are well underlined in [1], will also play an important role for future growth of the civil aviation. The impact of air travel on the environment will then become an increasing powerful factor on aircraft design. It is also important to recall the main goals of the vision 2020 [2] launched by the European commission : a 50% cut in CO_2 emissions per passenger kilometre (which means 50% in fuel consumption in the new aircraft of 2020) and an 80% cut in nitrogen oxide emissions. These objectives cannot be reached without breakthrough in today technologies.

Drag reduction is a great challenge but there is certainly room for improvements. The drag breakdown of a civil transport aircraft shows that the skin friction drag and the lift-induced drag constitute the two main sources of drag, approximately one half and one third of the total drag for a typical long range aircraft at cruise conditions. This is why specific research on this topics have been initiated in European Research centres and it seems that Hybrid Laminar Flow technology and innovative wing tip devices offer the greatest potential. Aircraft performance improvement can also be obtained through trailing edge optimisation, control of the shock boundary layer interaction and of boundary layer separation. In the following sections, the different technologies which were investigated at ONERA will be presented and illustrated by experimental results.

2 SKIN FRICTION DRAG REDUCTION

Two methods are generally considered for skin friction drag reduction. The first one aims at reducing the turbulent skin friction while the second one aims at delaying transition to maintain large extent of laminar flow.

2.1 Turbulent skin friction reduction

A skin friction drag reduction can be obtained with the use of passive boundary layer manipulators. Among the various devices, V-groove riblets have demonstrated substantial reductions (up to 8%) of the local skin friction. An experimental verification [3] in a large wind tunnel was carried out in 1988 on a 1/11 scale complete model of the Airbus A320. For the test, 2/3 of the wetted model surface was covered with the riblets for which the previously mentioned V-groove cross-section has been chosen. Viscous flow computations on the wing and on the fuselage have shown that a riblet depth of 0.023 mm can allow a average value of $h^+_w=8$ to be obtained. Wind tunnel test was successful and total drag reductions up to 1.6% have been demonstrated at corresponding cruise Mach number conditions.

With the guidelines of the previous wind tunnel investigations and the recommendations coming from the structure, material and system teams, a flight test was prepared with the Airbus A320 No 1. 600 m^2 riblet film covering 75% of the wetted surface was installed on the aircraft and the tests took place in 1989. Overall performance and local data were measured with and without the riblets, and drag reduction predictions based on the wind tunnel tests were confirmed.

Operational aspect and maintenance problems [4] have then been investigated and in-service application has been decided by the Cathay Pacific Airways airline on an A340. Significant fuel consumption has been obtained. However, this in service application showed that the riblet film has to be replaced after 2-3 years. The applications of this technology depend now on the quality improvement of the riblet film: the characteristics of the film has to be maintained at least for 5 years in order to obtain benefits.

2.2 Hybrid laminar flow technology

A substantial reduction in fuel consumption and in CO_2 emissions will certainly require the adoption of laminar flow control in order to reduce the skin friction. For small aircraft with low swept wing, laminar flow can be maintained by shaping the airfoil (NLF concept) and this concept is currently considered for new small jet aircraft. However for high Reynolds number and high sweep encountered on a large transport aircraft, suction has to be applied.

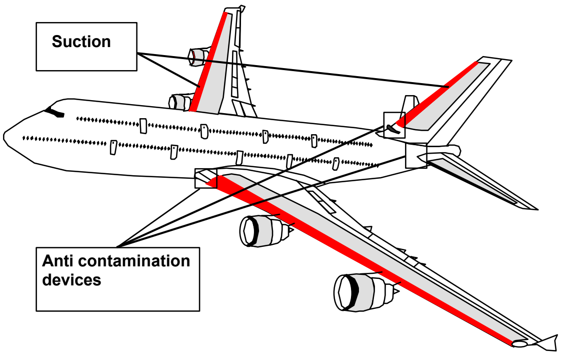

Figure 1 : Hybrid Laminar Flow concept.

In the Hybrid Laminar Flow concept, the laminar flow can be maintained by the application of suction in the region of the leading edge to control the development of crossflow and Tollmien Schlichting instabilities combined with favourable pressure gradients in the spar box region (Figure 1). It is first necessary to ensure that the attachment line remains laminar and to avoid contamination phenomenon. Anti contamination devices have to be used to avoid the contamination of the attachment line by the turbulent structures coming from the fuselage.

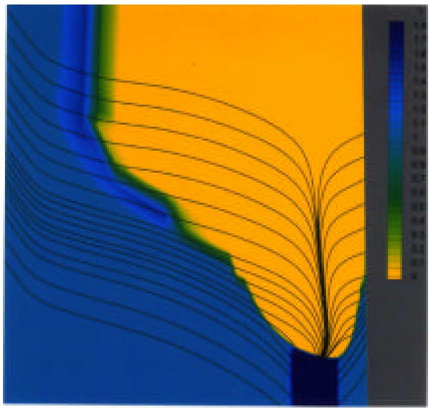

Figure 2 : Computed extent of laminar flow around a Gaster bump.

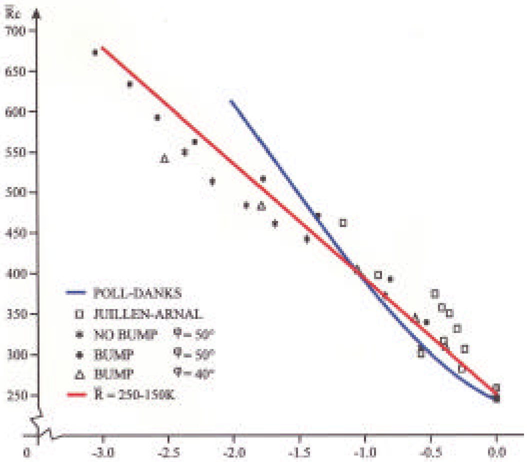

Figure 3 : Onset of leading edge contamination as a function of the suction parameter K.

Several means can be employed to delay the onset of attachment line contamination. The Gaster bump device which creates a stagnation point, allowing a new laminar boundary layer to be generated downstream, can be now designed by current CFD tools (figure 2). Some tests [5] carried out in the ONERA F2 wind tunnel showed that the Gaster bump delayed the contamination up to a value of $\overline{R}$=400 while the critical $\overline{R}$ value is 250 for a clean leading edge. For higher $\overline{R}$ applications such as large Airbus wings, it has been demonstrated [5, 6] that suction could be used to successfully relaminarise the attachment line (figure 3). According to [7], the proposed criterion seems to be optimistic for small suction rates by comparison with flight test results. However, the results presented here, demonstrate that dramatic improvements have been made in the control of attachment contamination by both passive and active means over the past few years and that attachment line transition can be avoided in flight.

The suction system has to be designed according to various aerodynamic and structure requirements. Main features of suction systems are laser drilled titanium panel and suction chambers controlled by independent ducts (figure 6). The geometrical characteristics of perforated panel such as hole diameter, porosity as well as chamber sizes are determined taking into account the suction velocity range, computed by stability approach, and pressure distributions for various aerodynamic conditions. With suction systems, premature transition can be caused by outflow and by roughness effects due to high velocities in the suction holes. Pressure drop methods and suction criteria [8] have to be used to avoid these premature transitions.

Figure 4 : Falcon 900 flight test with two HLF inboard wings

Figure 5 : Flight test of the A320 HLF fin

First classical suction designs were established in order to control accurately the suction distributions for flight test demonstrations. The Falcon flight test which took place in 1990 [9] and the A320 HLF fin flight test carried out in 1998 [10] represent important milestones in the further development of HLF technology (figures 4 and 5). The purpose of the Falcon 900 demonstration was to design, manufacture and certify an HLF aircraft and to analyse the behaviour of the HLF devices in operation. For high sweep and Reynolds number conditions, large extent of laminar flow were obtained at cruise on the A320 HLF fin.

A simplified and promising suction system (figure 7) has been designed by Airbus Deutschland and DLR [11] [12] in the ALTTA European programme. It allows a very efficient structure with stringers in span wise direction to be obtained. The local disturbances created by classical substructures are avoided and the whole leading edge box is used as a single suction duct. The system is also self-adapting and, therefore, works without controlling the internal flow with the help of valves and flow meters.

Surface imperfections such as isolated roughness, gaps, steps, waviness can provoke premature transition. It is then necessary to study their effects on transition and to develop calculation methods and criteria in order to estimate these effects [13]. Recent studies have shown that modern manufacturing techniques can provide smooth surfaces, compatible with laminar flow.

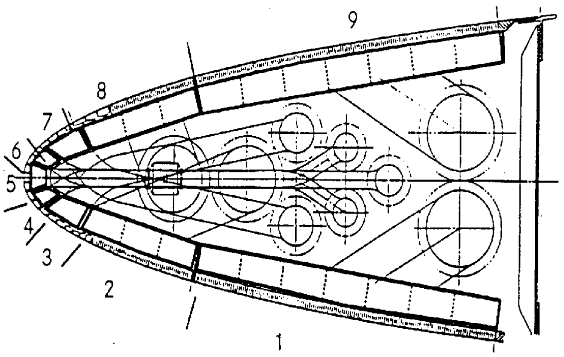

Figure 6 : Classical suction system

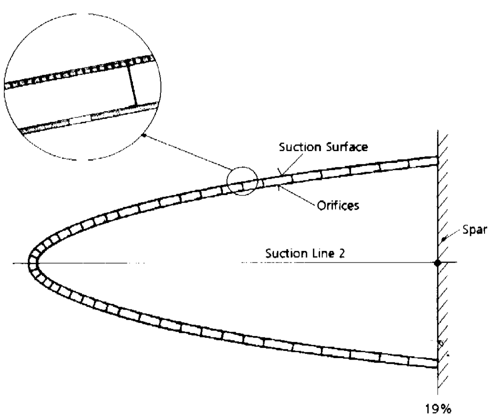

Figure 7 : Simplified suction system

In the more realistic HLF concept, suction is applied only to the upper surface of the wing, ahead of the front spar, allowing a high-lift device like a Krueger to be installed on the lower surface. ONERA studies have shown that drag reduction of 7% can be obtained. With the laminarisation of fin, horizontal tail plane and nacelles, the total drag reduction reaches 11%. Taking into account suction power, it seems that the fuel consumption can be reduced by respectively 6% and 10%. These reductions in fuel burn could be greater for an aircraft optimised to exploit the HLF concept [14], close to 15% taking into account the mentioned drag reduction values.

Recent progress carried out towards the understanding of transition characteristics of swept-wing flows would allow to control the transition by passive means. Some experiments presented in [15] have shown that transition governed by crossflow instabilities can be delayed using artificial roughness. In this concept, the artificial vortices interact nonlinearly with the natural vortices in such a way that the natural vortices is strongly reduced. In this approach, the drag reduction could be lower than the one expected with the HLF concept, but the drawbacks could also very limited (no weight penalties). It is worthwhile to investigate these passive means through basic experiments and non-linear PSE computations [16], because they can contribute to the system simplification needed for a future laminar aircraft.

3 LIFT-INDUCED DRAG REDUCTION

The second major drag component is the lift-induced drag. The classical way to decrease the lift-induced drag is to increase the aspect ratio of the wing. This has been done in the past and the A340 wing aspect ratio reaches 9.3. However, wing aspect ratio is a compromise between aerodynamic and structure characteristics and it is clear that for a given technology there is not a great possibility to increase aspect ratios. The alternative is to develop wing tip devices acting on the tip vortex which is at the origin of the lift-induced drag.

Many wing type devices have been studied these last years at ONERA using the CFD approach and in particular the Euler and Navier-Stokes solvers, and the far-field drag extraction technique [17] allowing accurate drag predictions to be carried out. Basic studies [18] have shown that drag reduction can be obtained with variations in planform geometry along a small fraction of the wing-span and with aft-swept configurations. Furthermore, the figure 8 presents, as examples among the investigated shapes, the wing tip turbine, the wing tip sails, the winggrid, the blended winglet and the spiroid tip.

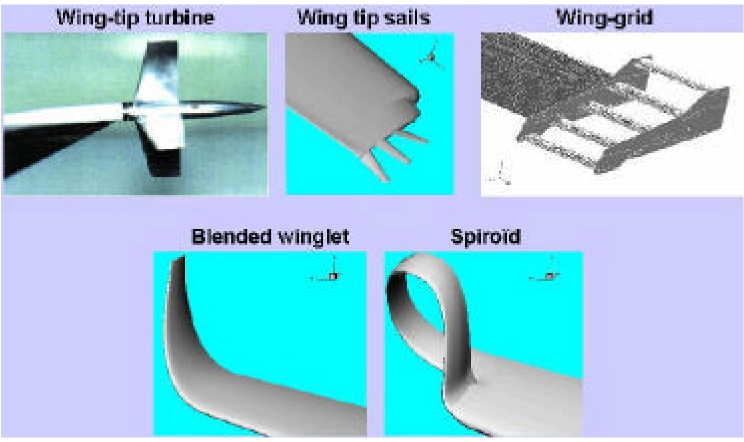

Fig. 8 – Various wingtip devices investigated at ONERA

The concept of the blended winglet is to modify a large part of the wing tip together with the winglet itself in order to obtain a very smooth blended shape. The blended winglet is expected to be more efficient than a narrow one to reduce the flow acceleration that occurs in the crossflow curvature and to decrease the vortex intensity as important chord variation is avoided. The spiroid tip is a spiral loop obtained when joining by their tip a vertical winglet and an horizontal one. This unconventional device seems promising to reduce the tip vortex intensity but has a complex geometry difficult to optimize.

Design of both wing tip devices were carried out in [19] using numerical optimization approach and an Euler solver. The pressure distributions obtained on a blended winglet and on the spiroid tip at cruise conditions at M=0.85 are shown in figures 9 and 10. It can be seen that in both cases, flow velocities have been limited to avoid wave drag penalties and flow separation.

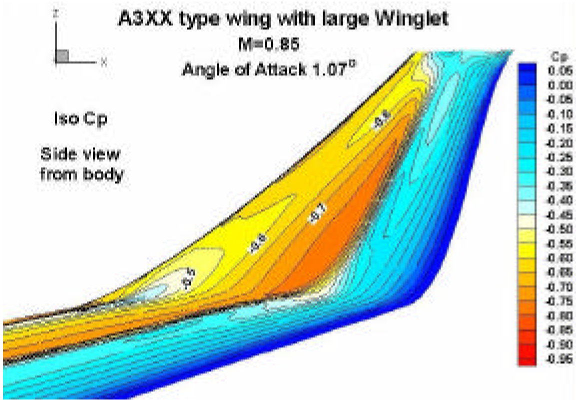

Figure 9 : Computed pressure distributions around a blended winglet at cruise

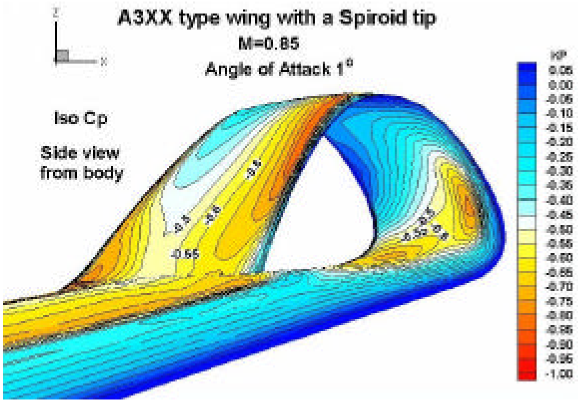

Figure 10 : Computed pressure distributions around a spiroid at cruise

The far-field drag extraction technique which allows a physical drag breakdown to be done, has been used. The figure 11 presents the crossflow kinetic energy downstream of the reference wing and of the two studied devices. The tip vortex intensity has been dramatically reduced. It appears that the lift-induced drag is reduced by 4% with the blended winglet having a height of 6% of the half-wing span and by 3.3% with the spiroid having a height of 3.8% of the half-wing span.

However, it should be kept in mind that a greater wetted area may lead to an increase of the viscous drag and that maximum total drag reduction is obtained through a compromise on the size of the tip device. In addition, the modification of the root bending moment which induces an important variation of the mass of the wing structure, has to be taken into account in the design process.

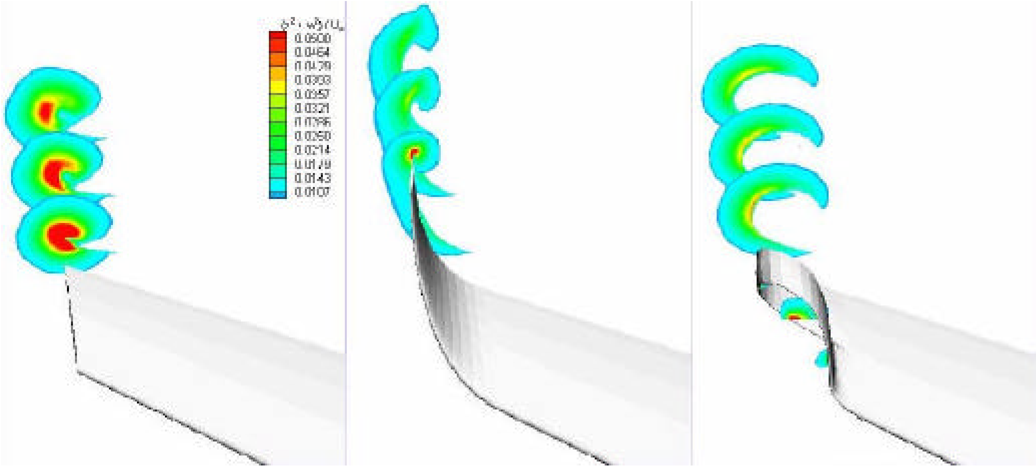

Figure 11 : Cross flow kinetic energy at cruise downstream of several wing tips

Large winglets with a height of about 12% of the half-wing span are investigated in the AWIATOR programme supported by the European commission. Total drag reduction of about 2% can be expected with such wing tip devices. However, for industrial applications, wingtip devices have a strong influence on the wing structure and aeroelastic effects have to be taken into account through a multidisciplinary optimisation approach.

4 WAVE DRAG REDUCTION

Even if the wave drag contribution to the total drag of a modern transport aircraft is not high, there is room for some significant improvements through adaptation of the aircraft to the variation of the flight conditions : an increase of the cruise Mach number for example. This aerodynamic adaptation can be realized with shock control or trailing edge devices.

4.1 Shock control devices

Among the different passive shock boundary layer control concepts investigated, the bump concept proposed by P. Ashill [20] seems promising. This concept is based on the local modification of the airfoil surface in the shock region. The straight shock is transformed into a lambda shock configuration and its strength is reduced by the presence of the compression waves.

This concept was first applied in 2D on a laminar airfoil in the framework of a co-operation with Airbus Germany. The figure 12 presents RANS results obtained on the 2D configuration having an optimum bump location and a bump height of 0.3%. It suggests that the shock structure consists of a weak inclined supersonic / supersonic shock originating from close to the leading edge of the bump and intersecting the normal shock wave. Important wave drag reduction and total drag reduction have been obtained on this configuration as shown in figure 13.

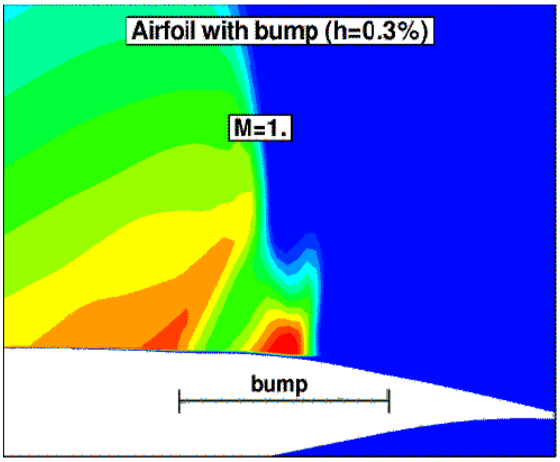

Figure 12 : Navier-Stokes computations around a 2D configuration with bump

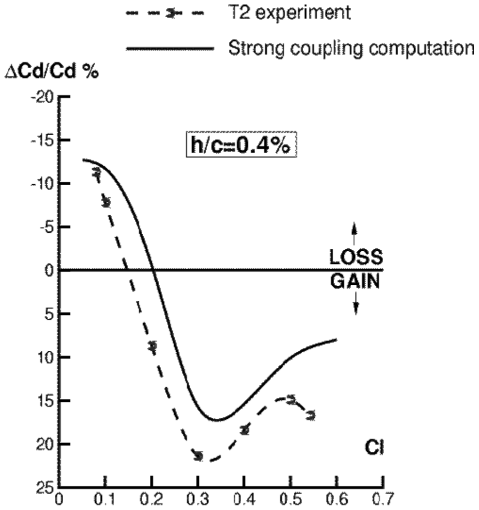

Figure 13 : Measured and computed drag reductions on a 2D laminar airfoil. M=0.77, Re=6 10^6.

The application of the 3D shock control bump on a transonic wing body configuration was studied within the framework of a cooperation between DLR, Airbus Germany and ONERA [21]. A variable-height bump is expected to improve the aircraft performance in high speed off-design conditions. The bump was designed through 3D RANS computations and adapted to a generic large aircraft wing. The tests were carried out with a half-model in the S2MA wind tunnel. The information about the local pressure distributions was obtained with the PSP technique.

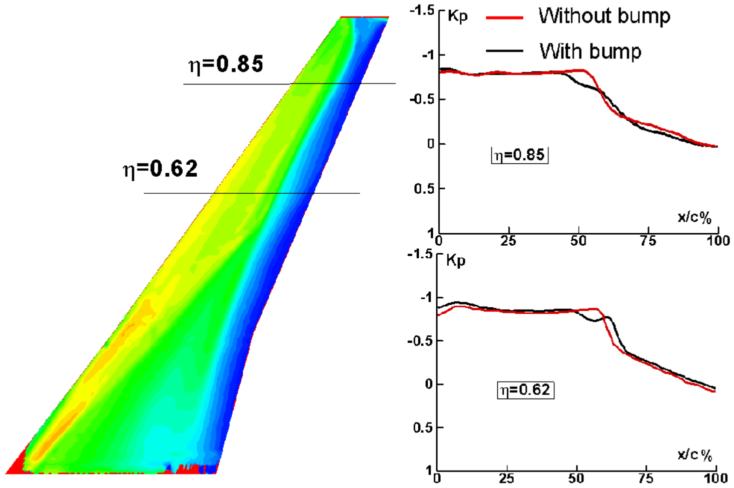

Figure 14 : Application of the 3D bump concept in 3D. PSP Measurements

The figure 14 presents the measured pressure distributions on the wing for two sections located at 62% and 85% of the span. The Mach numbers upstream to the shocks and the pressure gradients are clearly reduced. However, experimental drag polars showed smaller drag reduction than the predicted values of 2.9%. Some inaccuracy related to the half-model technique and to the limited bump span (37% of the span) may be the cause of these results. But, it is clear through local measurements that shock intensity can be reduced for high speed off-design conditions and that fuel consumption should be reduced on a typical long range mission.

4.2 Trailing edge devices

For wave drag reduction, the concept of the thick cambered trailing edge which increases the rear loading and reduces the upper surface pressure recovery seems also very promising. After preliminary studies carried out within the framework of a co-operative project (Airbus Industrie, ONERA, DLR, DRA), ONERA has launched an important programme :

- To understand the flow field pattern downstream of such thick trailing edge concept [22] ;
- To determine carefully the limit of the concept.

Numerical and experimental investigations have been carried out using the OAT15A supercritical airfoil as reference and considering two 2D thick cambered trailing edges TEO0250 and TEO0450 [23]. These two airfoils have a trailing edge angle of 50° and an incremental thickness respectively of 0.2% and 0.4% of the chord length.

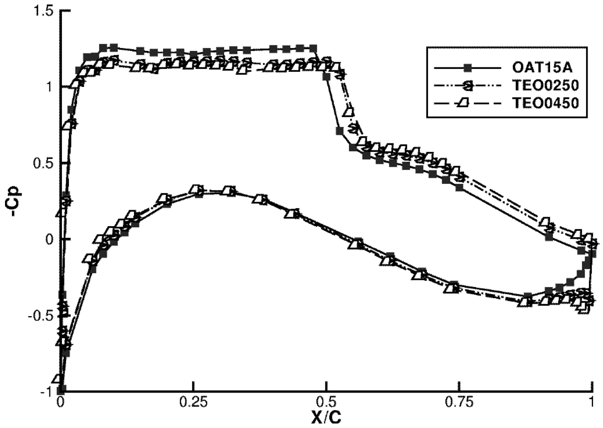

Figure15 : Measured pressure distributions in 2D for thick cambered trailing edges

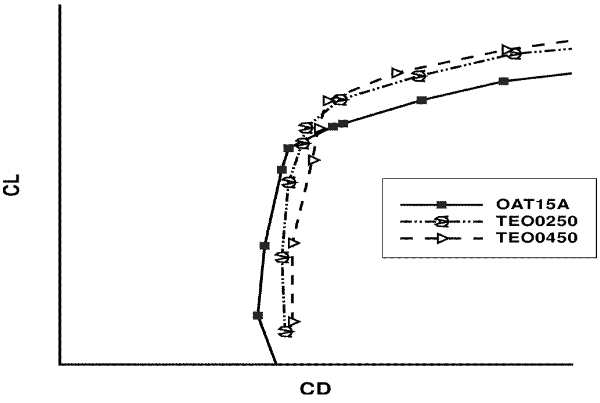

Figure16 : Measured polars in 2D for thick cambered trailing edges

The pressure distributions measured on the three 2D airfoils in the T2 wind tunnel are presented in figure 15, for a free-stream Mach number of 0.73. In these tests, the Reynolds number is 3 10^6 and the transition is fixed at 7% of the chord. With the trailing edge modification, the rear loading is increased and the upper surface adverse pressure gradient is reduced. The experimental drag polars presented in figure 16 show that the airfoil performance is increased for high lift coefficients due to the wave drag reduction while a viscous drag penalty appears at low lift coefficients. The optimum shape will then be obtained through a compromise.

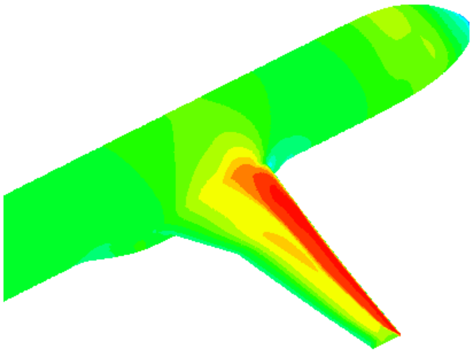

Figure 17 : Application of the thick cambered trailing edge concept on a Airbus type configuration

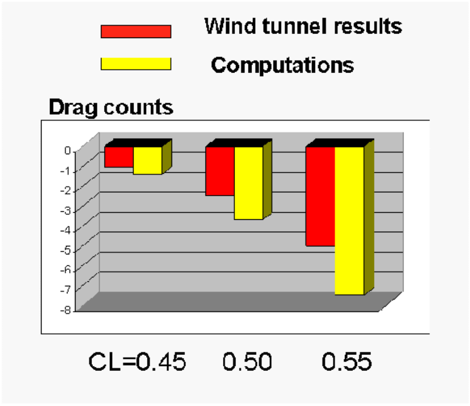

Figure 18 : Computed and measured drag reduction obtained with the TED device installed in the outer part of the wing

This concept has then been investigated on a wing body configuration (figure 17) under a co-operation with Airbus France. Tests were carried out on a half-model in the S2MA wind tunnel and the results have been carefully analysed through RANS computations and far-field drag extraction techniques. The computed and measured drag reduction obtained when the thick cambered trailing edge is installed in the outer part of the wing is presented in figure 18. The figure shows that the gains are strongly dependent on the lift-coefficient and indicates that CFD approach can be used for trailing edge optimisation.

It is clear that the thick cambered trailing edge concept can be used by the designer as an additional degree of freedom. Its effects can also be obtained through a trailing edge deflector (TED). This device which has a very small chord (between 1 and 3% of the airfoil chord), has an effect on the flow depending on its static deflection angle (any values between 0 and 50°). The figure 19 presented in [24] shows for a 3D model at M=0.82 that the device can also be used to delay the buffet onset (TED device can also be used with dynamic movements).

These results show that characteristics of the flow can be strongly modified with the use of a trailing edge device which allows drag reduction and greater buffet margin to be obtained. Important investigations are currently carried out in the AWIATOR European programme to adapt the wing geometry to the different flight conditions : cruise, take-off and landing.

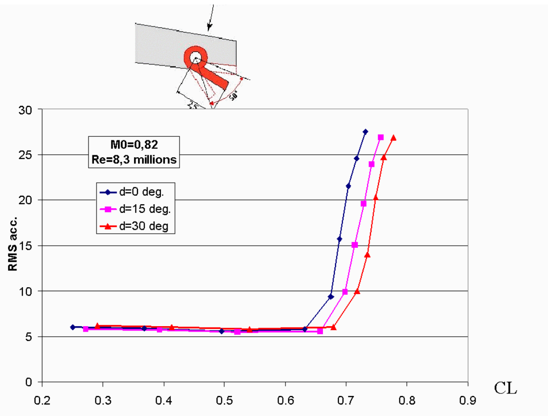

Fig.19 - Effects of the trailing edge deflector on the buffet onset on a wing body configuration

5 AIRCRAFT PERFORMANCE IMPROVEMENT IN OFF-DESIGN CONDITIONS

5.1 Sub-layers vortex generators

Control of separations in off-design conditions by sub-layer vortex generators and MEMS technologies can also contribute to increase aircraft performance.

Vortex generators have been tested on a supercritical airfoil in the T2 wind tunnel. The chosen vortex generators are co-rotating with a rectangular shape and with a 30° VG angle of attack. The VGs are placed upstream to the shock and the device height is $h/\delta=1$, with δ the height of the boundary layer. However, recent studies have shown that device heights may only need to be 0.2 of the boundary layer height with a 20° VG angle of attack with the same benefits.

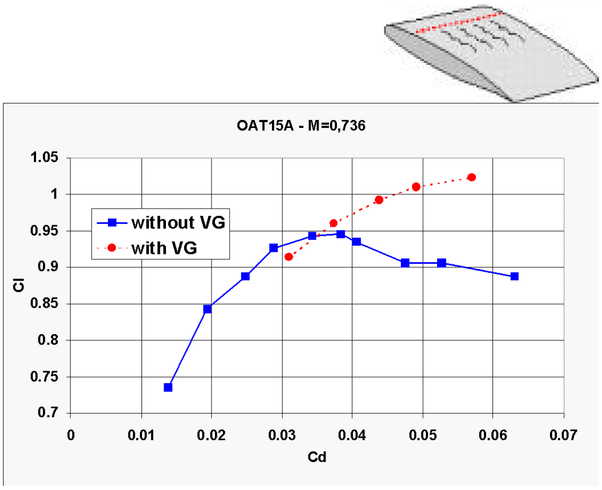

Figure 20 : Effects of Vortex generator on the polar of a 2D configuration

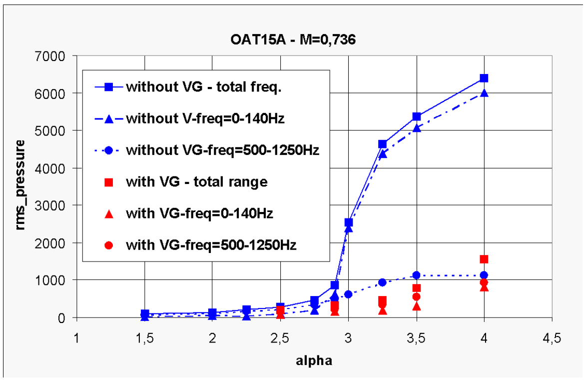

Figure 21 : Effects of Vortex generator on the buffet onset on a 2D configuration

The measurements have been carried out at M=0.73 and Re=4.5 10^6. The experimental results show, at high lift coefficients, a strong influence of the vortex generators on the separated area. The pressure and shock fluctuations are dramatically reduced and the buffet onset is delayed (figures 20 and 21). These results show that large flow modification can be obtained with sub-boundary layer vortex generators.

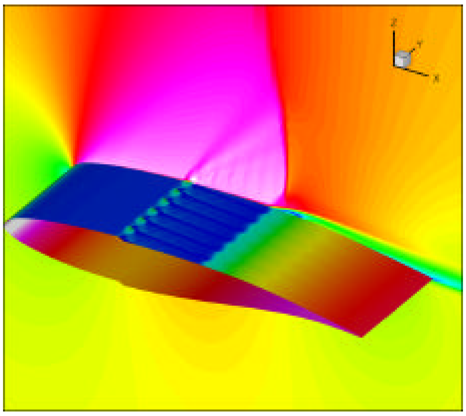

Figure 22 : RANS computations around an airfoil equipped with VGs (flow field)

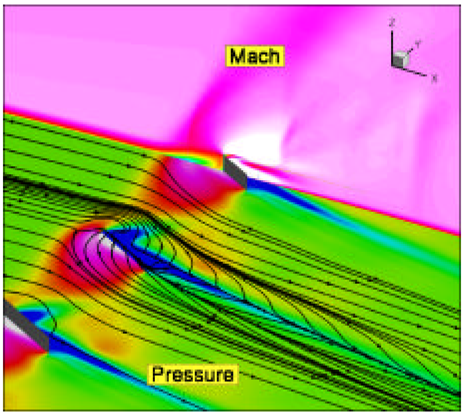

Figure 23 : RANS computations around an airfoil equipped with VGs (friction lines)

The previous 2D configuration has been computed on a fine grid (5 10^6 points) using the RANS approach and the Spalart-Allamras turbulence model. The figure 22 presents the computed flow field around the airfoil equipped with the VGs. The complex flow associated with vortices created by the VGs is underlined by the figure 23 (zoom of the figure 22).

Sub-layer Vortex Generator can also be applied in regions dominated by separations or having a high risk of separations. For example, rear fuselage flow is generally dominated by 3D important effects, the rear fuselage upsweep creating a lift-induced vortex system amplified by the wing downwash [25]. Reduced fuselage after body drag could be obtained through the control of the vortex flow by using small devices such as vortex generators.

In any applications, vortex generators can have a great impact on the performance if they are employed early in the design process of the aircraft. This is why it is important to model their effects with CFD on with suitable meshes or with the use of an additional source term. A better aircraft design could then be obtained by the use of flow control to reduce the system complexity and the structural weight.

5.2 MEMS Technology

Reduction of boundary layer separation regions can also be obtained by an active system avoiding the drawbacks of vortex generators which increase the drag coefficient at low lift coefficient. Emerging MEMS technologies can be used to control the flow through an active manipulation of the coherent structures that are developed in the near-wall region of the boundary layer. Fluidic actuators such as suction/blowing devices offer many perspectives [26] [27]. However the concept is not yet mature and the development of this new technology can be pushed by the use of computational tools such as the Large Eddy Simulation (LES).

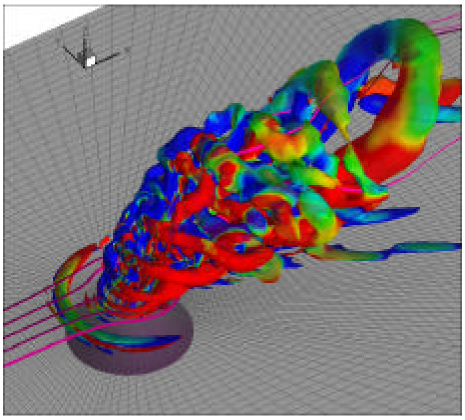

Figure 24 – Flow pattern around a synthetic jet with external flow computed with LES approach

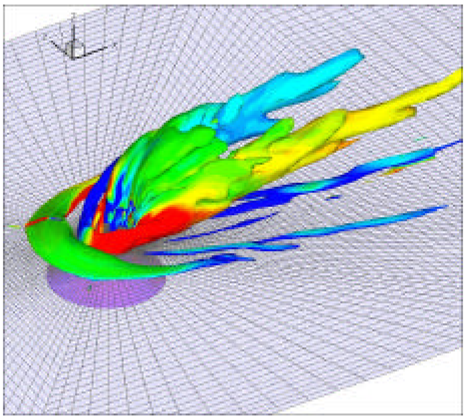

Figure 25 – Effect of a synthetic jet on the mean flow computed with the LES approach

As an example, the figures 24 and 25 present a three-dimensional compressible simulations of the interaction between a synthetic jet and a turbulent boundary layer performed using the LES approach. The blowing/suction condition varies as a sinusoidal function with a maximum velocity of about 1.5 times the stream-wise external flow and a frequency of 150 Hz. The computed flow pattern shows one horseshoe vortex and several ring vortices and hairpin vortices. The influence of the synthetic jet on the mean flow is presented in figure 24. These vortices which modify the turbulence downstream, could have an influence on the separation.

Such a result will help to understand and to modelise the control mechanisms and it is clear that the next step is to compute the postponement of the flow separation. Applications of MEMS technologies have been investigated in AEROMEMS 1 and current studies are carried out in AEROMENS 2. It is expected that high-lift devices can be improved with this technology particularly in landing conditions and that drag reduction can also be obtained through the use of MEMS in the design optimisation process.

6 CONCLUDING REMARKS

During these last years, drag reduction studies have been oriented towards the investigation of the potential benefits which can be expected by applying various new technologies.

The different concepts which have been studied are listed hereafter with their respective average potential drag reduction :

- The turbulent skin friction drag reduction by the use of riblets ($\Delta C_D/C_D$ of about 1-2%)
- The hybrid laminar flow technology ($\Delta C_D/C_D$ of about 10%) ;
- The innovative wing-tip devices ($\Delta C_D/C_D$ of about 2%) ;
- The shock control and trailing edge devices which allow to adapt the wing geometry to flight conditions (variation of the lift coefficient or of the Mach number), ($\Delta C_D/C_D$ of about 1%) ;
- The sub-layers vortex generators and MEMS technology which can be used to control flow separation.

These technologies can be associated to maximize the drag reduction. Future laminar flow aircraft can, for example, be fitted with wing tip devices and equipped with riblets in the rear part of the wing upper surface.

The use of flow control will reduce the system complexity and the structural weight of the aircraft by the use of a smaller wing, a reduced sweep, a thicker wing or smaller and simpler high-lift systems. It is then important to model the effects of sub-layer vortex generators and synthetic jets with the CFD approach. This will allow the gain in performance to be estimated.

Furthermore, the listed technologies can have a greater impact on the performance if they are employed early in the design process of the aircraft.

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