



Research activities of ONERA on laminar airfoils in the framework of JTI Clean Sky SFWA-ITD: transition control

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Resume :

For more than three decades, the different scenarios to maintain a laminar boundary layer on wings are investigated by ONERA scientists. Experimental activities have been conducted in the framework of national or EU-funded research projects and numerical transitional models have been consolidated and implemented in our fluid solvers (elsA, 3C3D). The present paper deals with recent research activities carried out regarding transition control within JTI Clean Sky and more specifically in the framework of the SFWA-ITD (Smart Fixed Wing Aircraft Integrated Technology Demonstrator).

Two main topics are investigated here: the first one is the control of the attachment line transition using both passive and active devices and the second one is the control of a cross-flow (CF) transition process using a passive device. The first topic is of particular interest since all the efforts made on designing laminar airfoils can be annihilated by leading-edge contamination which is likely to occur on aircraft swept wings: the turbulence convected along the fuselage spreads over the wing root and propagates along the leading edge. In some cases, this turbulence can induce, through a non linear process, a sudden transition of the boundary layer which develops on the wing leading edge. Recently, ONERA scientists have numerically designed and optimized a passive chevron-shaped anti-contamination device (ACD) which has shown its ability to prevent contamination for realistic aerodynamic configurations. The issue of anti-contamination has also been investigated experimentally using an active device: the boundary layer which develops on the attachment line of our model has been submitted to steady wall suction through perforated panels. The results confirm that wall suction is a very efficient way to prevent contamination.

The second topic is the control of a CF transition process by means of micron-sized roughness (MSR) elements. The basic principle is to use a non-linear interaction between a CF instability artificially introduced inside the boundary layer and the target instability which induces natural transition and then turbulence. This passive control has been numerically investigated through non-linear stability computations and experimentally assessed on a realistic swept model. A significant delay of the transition has been measured downstream of the MSR elements by means of infra-red thermography.

Research activities of ONERA on laminar airfoils in the framework of JTI Clean Sky SFWA-ITD: transition control

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ABSTRACT

The present paper deals with recent research activities carried out in ONERA regarding laminar/turbulent transition control within JTI Clean Sky SFWA-ITD (Smart Fixed Wing Aircraft Integrated Technology Demonstrator). Two main topics are investigated here: the first one is the control of the attachment line transition using both passive and active devices, ie either an optimized Anti Contamination Device or wall suction through perforated panels. The second topic is the control of a cross-flow transition process using a passive device made of micron-sized roughness elements.

1. INTRODUCTION

Over the last decades, all civil aircraft manufacturers have made great efforts to reduce aircraft drag. The long term aim of this operation is to reduce the specific consumption of aircraft, which would lead to substantial economic benefits. Indeed, fuel consumption represents about 22% of the direct operating cost (DOC) for a typical long range transport aircraft. Drag reduction directly impacts this cost: a drag reduction by 1% can lead to a DOC decrease by 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 [1]. The two main sources of drag are skin friction drag and lift-induced drag,

approximately one half and one third of the total drag for a typical long range aircraft at cruise conditions. This is why aircraft manufacturers in association with research organizations invest a great deal of effort in finding new techniques for reducing skin friction drag. One consists in moving the laminar-turbulent transition point as far aft as possible, particularly on the wings, in order to obtain lower friction coefficient in the presence of laminar flow. This concept, called “laminarity”, is closely connected to the sweep and Reynolds number of the wings. Many strategies exist for maintaining laminarity (see [2] for a review), they have been investigated for more than three decades by ONERA scientists. In this paper we focus on two problematics that were addressed within JTI Clean Sky SFWA-ITD: control of attachment line transition (ALT), and control of a crossflow transition process by means of micron-sized roughness (MSR).

2. CONTROL OF ATTACHMENT LINE TRANSITION

A fin or an airfoil wing fixed on the fuselage may be “contaminated” by the turbulence of the boundary layer developing along the fuselage. In that case, no laminar flow can be hoped on the fin or the airfoil wing. It is thus of primary

importance for laminar flow purpose to avoid such leading edge contamination. As known since several years, see e.g. [3][4], the main control parameter in that topic is the so-called \bar{R} Reynolds number defined as

$$\bar{R} = \left(\frac{Q_\infty R \sin \varphi \tan \varphi}{2\nu} \right)^{1/2} \quad (1)$$

for a cylinder with the incoming infinite velocity, R the leading edge radius and φ the sweep angle. This relation is an exact one for a cylinder; it is then a good approximation for any shape when considering the cylinder which approximates the leading edge. The so-called Pfenninger and Poll's criterion (in case of low velocity and without suction applied at the wall) says that contamination occurs if $\bar{R} > 250$. As the leading edge geometry of aircraft wings or tail planes yields to much larger values, anti contamination strategies must be used.

Two practical solutions exist: using an anti contamination device (ACD), as initially proposed by Gaster with the famous "Gaster bumps"[5]; or applying suction along the leading edge. Both concepts were investigated within SFWA workpackage 112 on "Active technologies for laminar flow and buffet control".

2.1. Design and experimental validation of an optimized Anti Contamination Device

Some preliminary requirements have to be verified to ensure the efficiency of an ACD. The anti contamination process is based on a stagnation point generated by the ACD that stops the turbulent boundary layer from the fuselage and enables a new laminar boundary layer to develop downstream. To be fully efficient, ACD has to be tall enough so that the stagnation point would be above the turbulent boundary layer coming from the fuselage. The pressure distribution around the ACD has to allow a region of attached laminar flow to be maintained along the attachment line downstream of the stagnation point. For aeronautics application, the ACD has to tolerate some angle of attack and sideslip variations that may occur during cruise. The ACD must have a very little impact on total drag in order to keep the potential benefit of a laminar boundary layer maintain.

From the initial shapes proposed by Gaster, ACDs have known some developments which have enabled to prevent contamination until values of between 350 and 450 [5]. Since several years, ONERA has worked on the design of a new ACD that could push back this current limit

in order to get closer to the laminar stability limit ($\bar{R} \approx 580$), above which attachment line intrinsic instability (Görtler-Hämmerlin unstable waves) will develop and trigger the transition to turbulence.

The shape of the optimized ACD was defined through RANS simulations performed with the elsA solver [6], in which a laminar/turbulent transition criterion was used. A view of the final design is shown in Figure 1. The Anti Contamination Device is mounted onto ONERA DTP-A model, which is a swept wing specifically designed in the 90's for studying leading edge contamination in the ONERA F2 low-speed wind tunnel [7].

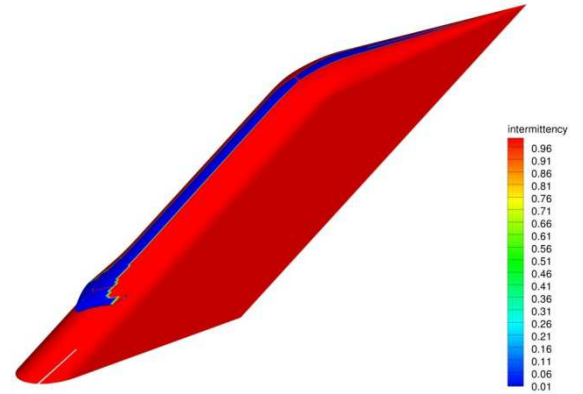


Figure 1 – Optimized ACD mounted onto ONERA DTP-A model. RANS computation with elsA solver, showing laminar (blue) and turbulent (red) regions. for an incoming flow velocity corresponding to $\bar{R} = 590$.

The efficiency of such an ACD was validated during an experimental campaign in the F2 wind tunnel. The DTP-A model equipped with the ACD was mounted onto the wind tunnel floor, so that the wall turbulence could mimic a fuselage turbulence. It was shown that the ACD was even more effective than expected, since leading edge contamination was prevented for \bar{R} values higher than 580. Indeed, as shown in Fig. 2, according to the infrared visualization with a transition witness, the attachment line boundary layer downstream the ACD is still laminar at $\bar{R} = 650$, which proves that no turbulent structure has come across the ACD. All details on this experimental campaign can be found in a recent journal paper [8].

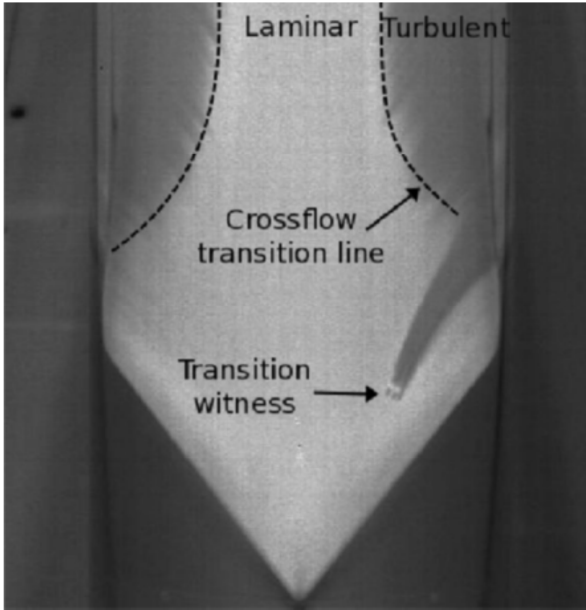


Figure 2 – Infrared visualization of the leading edge downstream of the ACD, in flow conditions corresponding to $R_{bar}=650$. A tripping element is used as transition witness.

2.2. Control of attachment line transition with wall suction

Another strategy for preventing leading edge contamination by fuselage turbulence consists in applying suction along the leading edge, through perforated panels. A dedicated experimental campaign was conducted within ONERA F2 wind tunnel, in cooperation with Airbus and the German SME BIAS, who manufactured perforated panels suited to the ONERA DTP-A model. Three panels were tested, with the same porosity but various holes diameters.

The aim of this campaign was to confirm and extend results obtained in the 90's on the same model, but with different perforated panels (see [4]). During these pioneer experiments a relationship was found between the suction parameter κ and the critical Reynolds number above which leading edge contamination would occur:

$$\bar{R}_{crit} = 250 - 150 \kappa \quad (2)$$

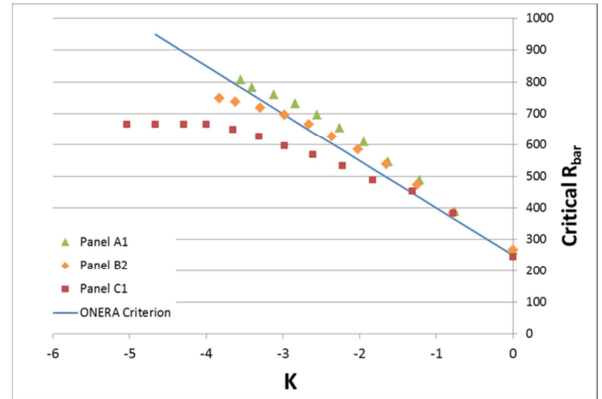


Figure 3 - Threshold value of the Reynolds number for leading edge contamination as function of the suction parameter K for the three tested suction panels.

Results of the new experimental campaign are plotted in Fig. 3, which shows the global efficiency of the suction to delay the leading edge contamination for each of the three tested suction panels. In addition, the “old” ONERA criterion given by Eq. 2 is plotted as a straight line in blue. This criterion provides a fair assessment of the critical Reynolds numbers but fails to represent the asymptotic saturation behaviour which may occur for high suction velocity, especially when the holes diameter is large.

The knowledge of such a criterion is of primary importance for designing an efficient suction law for wings or fins on which Hybrid Laminar Flow Control (HLFC) is used for maintaining laminarity.

3. CONTROL OF CROSSFLOW TRANSITION BY MICRON-SIZED ROUGHNESS

The basic idea of standard HLFC control techniques is to modify the boundary layer mean flow in order to reduce the growth rate of the unstable waves in their linear phase of amplification. Another idea is to act directly on the disturbance development without any change in the mean flow field. As stationary vortices dominate the transition process when crossflow instability plays the major role, Saric proposed to artificially create other stationary vortices by using a row of micron-sized roughness elements parallel to the leading edge at a chordwise position corresponding to the critical point, i.e. close to the attachment line [9]. Through non-linear interaction, these artificial stationary waves are able to damp the “natural” vortices responsible for crossflow transition. The characteristics of the MSR generating artificial disturbances are the spanwise wavelength λ , the

height k , the diameter d and the chordwise location X_{roug} .

ONERA investigated this control strategy both numerically and experimentally, still within SFWA-ITD 112 workpackage. The numerical study involved not only linear stability calculations but also non-linear computations to analyse CF transition control. In the smooth configuration (i.e., without control by MSR), the natural transition is triggered by the most amplified CF instability called the target mode. The idea is to create a second instability, identified as the killer mode, using an array of roughness elements, in

order to damp the amplitude of the target mode by non-linear interaction.

All numerical results were compared to experimental ones. Experimentally, MSR transition control has been studied on the pressure side of the DTP-B airfoil in the ONERA F2 wind tunnel (see Fig. 4). Wavelengths of CF instabilities amplifying in the boundary layer have been measured using total pressure probing and acenaphthene visualisations. Simultaneously, transition locations were detected using infra-red thermography technique.

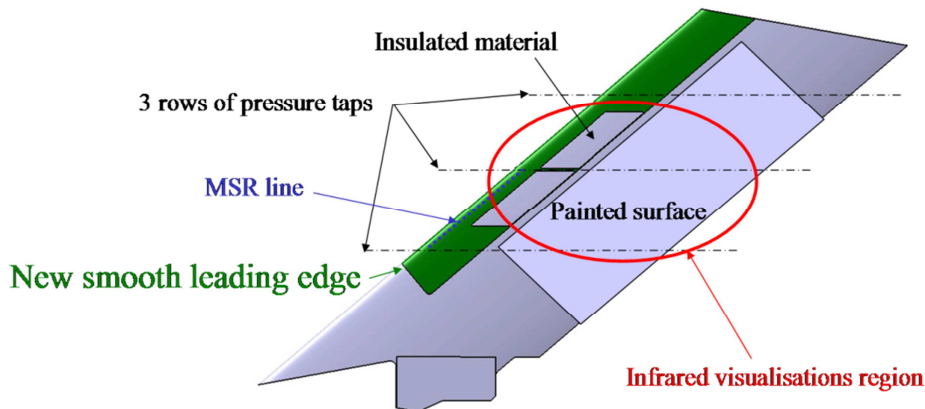


Figure 4 – The DTP B model in the F2 wind tunnel; experimental set-up.

The MSR row was placed at $X_{roug}/C \approx 2\%$. Without control, free transition appeared at $X/C \approx 0.25$. It was delayed up to $X/C \approx 0.31$ downstream of the MSR row. These experiments demonstrated the feasibility of transition control by MSR. The downstream movement of transition was modest but unquestionable, as shown in Fig. 5.

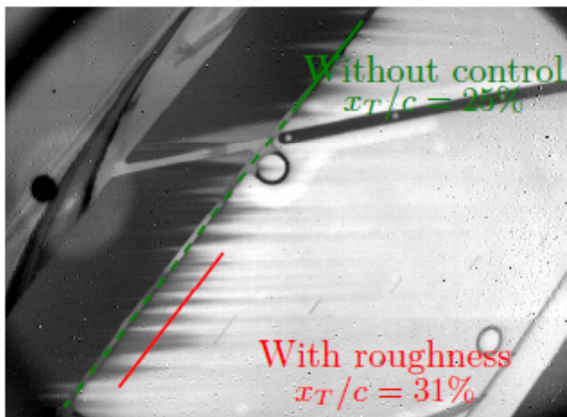


Figure 5 – Transition line visualization, without and with Micron-Sized Roughness control

All details on the numerical and experimental results can be found in a journal paper [10].

4. CONCLUSION

ONERA was deeply involved into JTI Clean Sky SFWA activities dedicated to laminarity, in close collaboration with industrial partners. Many activities were performed on transition control, especially about attachment line transition and passive control of crossflow transition. ONERA scientists have numerically designed and optimized a passive chevron-shaped anti-contamination device (ACD) which has shown its ability to prevent contamination for realistic aerodynamic configurations. The issue of anti-contamination has also been investigated experimentally using an active device: the boundary layer which develops on the attachment line of our model has been submitted to steady wall suction through perforated panels. The results confirm that wall suction is a very efficient way to prevent contamination, and that the suction law proposed by ONERA in the 90's

is quite accurate. Two challenges need to be tackled now: check the reliability of this suction law in transonic conditions, and establish a similar suction law when perforated panels are combined with an optimized ACD. Indeed, the suction rate required to maintain laminar flow downstream of such an efficient ACD is expected to be significantly smaller than without any Anti-Contamination device: preventing from development of attachment line linear instability is much less demanding than suppressing the large turbulent structures coming from a fuselage boundary layer.

Finally, a passive control of crossflow instability by means of Micron-Sized Roughness was numerically investigated through non-linear stability computations and experimentally assessed on a realistic swept model. A significant delay of the transition has been measured downstream of the MSR elements by means of infra-red thermography, as already demonstrated by Saric's team. Such a control strategy is however very tricky, and its maturity, at that time, is far from an industrial application.

5. ACKNOWLEDGMENTS

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