SUPERSONIC LAMINAR FLOW CONTROL STUDIES IN THE SUPERTRAC PROJECT

D. Arnal*, C.G. Unckel, J. Krier***, J.M. Sousa****, S. Hein*******
*ONERA Toulouse, France, **KTH Stockholm, Sweden
IBK Nürnberg, Germany, ****IST Lisbon, Portugal,**DLR Göttingen, Germany

Keywords: *boundary layer, laminar flow control, supersonic flow*

Abstract

The global objective of the SUPERTRAC project is to explore the possibilities to delay laminar-turbulent transition on supersonic aircraft wings. The following techniques are investigated: micron-sized roughness elements, anti-contamination devices, suction and shape optimization. This paper provides an overview of the project and describes in more detail the numerical investigations performed during the first year in order to design two wind tunnel models. These models will be used to assess the capabilities of the first three techniques listed above.

1 Introduction

The European project SUPERTRAC (SUPERsonic TRAnsition Control) was started on January 1st, 2005, with the co-ordination of ONERA as a Specific Targeted Research Project (STReP) of the 6th EU framework program. The global objective of this project is to carry out fundamental, numerical and experimental investigations for evaluating the possibilities of laminar flow control on supersonic civil aircraft wings.

Laminar flow can be achieved by delaying the onset of laminar-turbulent transition on the wings using specific tools such as shape optimization, suction, micron-sized roughness elements. Reducing the extent of turbulent flow is of considerable practical interest because it reduces the friction drag. It also contributes to satisfy the severe requirements on emission and noise, because drag reduction is directly related to the reduction of weight and size, as well as fuel burn and noise. Laminar flow control techniques have been widely tested for subsonic and transonic flows, but little is known about their extension to supersonic flows. This justifies the work undertaken within SUPERTRAC.

The SUPERTRAC consortium of 9 partners includes two European airframe manufacturers (Airbus and Dassault Aviation), 4 research centres (ONERA in France, CIRA in Italy, DLR in Germany, FOI in Sweden), 2 universities (IST in Portugal, KTH in Sweden) and one SME (IBK in Germany).

SUPERTRAC has a total run time of 36 months and will end in December 2007. The present paper gives an overview of the current achievements of the project. The general objectives, the overall structure of SUPERTRAC and the available theoretical / numerical tools are described in paragraph 2. The next two paragraphs are devoted to a more detailed description of the work performed for the preparation of two fundamental experiments on swept wings which will be carried out during the second year of the project.

2 Overview of the SUPERTRAC project

2.1 Transition mechanisms

2.1.1 Natural transition

"Natural" transition is triggered by the breakdown of unstable waves generated by the disturbances which are present either in the free-stream (noise) or at the wall (surface polishing).

On a swept wing, distinction is made between Tollmien-Schlichting (TS) and crossflow (CF) waves. TS waves are the result of the instability of the streamwise mean velocity profile. They develop in regions of zero or positive pressure gradients. CF waves are the result of the instability of the crossflow mean velocity profile. They are unstable in regions of negative pressure gradient, typically in the vicinity of the leading edge of swept wings where the flow is strongly accelerated. A peculiar feature of CF instability is that zero frequency waves are highly amplified. They take the form of stationary vortices practically aligned with the external streamlines. Their initial amplitude is strongly linked with the model surface polishing.

Delaying the onset of transition requires to modify the mean velocity field and/or the instability mechanisms in such a way that the growth rate of TS and CF waves is reduced. Three strategies are currently used in order to extend the laminar flow area: NLF (Natural Laminar Flow, i.e. optimization of the pressure distribution on the wing), LFC (Laminar Flow Control by application of a small amount of suction at the wall) and HLFC (Hybrid Laminar Flow Control) which combines the previous two approaches.

Quite recently, an innovative solution for transition control has been proposed by W.S. Saric at Arizona State University [1,2,3]. It is based on the fact that stationary vortices dominate the transition process when CF instability plays the dominant role. These natural stationary vortices have a wavelength which can be easily computed from the linear stability theory. The idea is to artificially create other stationary vortices by using a spanwise row of micron-sized roughness elements close to the leading edge. The wavelength of the new vortices corresponds to the spacing between the roughness elements. For particular values of this wavelength and for particular pressure gradients (to be optimized), the nonlinear interactions between natural and artificial vortices result in a reduction of the amplitude of the natural vortices (target modes); at the same time, if the amplitude of the artificial vortices (killer modes) remains below some critical threshold, transition is delayed.

2.1.2 Leading edge contamination

In subsonic as well as in supersonic flow, the efforts to laminarise a swept wing can be annihilated by leading edge contamination. This phenomenon occurs when the turbulence convected along the fuselage (or along the wind tunnel wall) propagates along the swept leading edge and spreads over the wing surface. For low speed flows, the relevant parameter is the leading edge Reynolds number $\overline{R}$. For a cylinder of radius *R*, $\overline{R}$ is expressed as:

$$\overline{R} = \left[\frac{V_0 R}{\nu} \frac{\sin\varphi \, tg\varphi}{2} \right]^{1/2}$$

V_0 is the free stream velocity, φ is the sweep angle and ν is the kinematic viscosity. Experiments have shown that leading edge contamination occurs as soon as $\overline{R}$ exceeds a critical value around 250 [4,5]. For compressible flows, the same criterion can be applied by using a modified Reynolds number $\overline{R^*}$ deduced from $\overline{R}$ by an empirical compressibility function [6].

In many practical problems (flight conditions), the critical value of $\overline{R^*}$ is exceeded, so that leading edge contamination is likely to occur. To delay the onset of this parasitic phenomenon, specific tools need to be developed. In subsonic and transonic flows, Gaster bumps and localised suction along the attachment line have proven their efficiency [7], but the state-of-the-art is very poor for supersonic flows.

2.2 Natural transition prediction

The linear stability theory is widely used to describe the development of unstable waves (TS or CF) responsible for natural transition. In the framework of the so-called "local" approach, the disturbances are written as:

$$r' = \hat{r}(y) \exp\left[i(\alpha x + \beta z - \omega t) \right]$$

r' is a velocity, pressure or density fluctuation. $\hat{r}$ is an amplitude function. *x* and *z* are the directions normal and parallel to the leading edge, *y* is the direction normal to the wall. In the framework of the spatial theory, $\alpha = \alpha_r + i\alpha_i$ is the (complex) wave number in the *x* direction. β and ω are real and represent the wave number in the *z* direction and the frequency. Introducing the previous expression into the linearized Navier-Stokes equations and assuming that the mean flow is parallel, leads to a system of ordinary differential equations for the amplitude functions (eigenvalue problem).

The linear PSE (Parabolized Stability Equations) or "non local" approach provides an improvement to the classical theory [8]. The mean flow field and the amplitude functions now depend on both *x* and *y*, and α depends on *x*. With the assumption that the *x*-dependence is slow, the numerical problem consists in solving a set of (nearly) parabolic equations in *x*, with initial disturbance profiles specified at some starting point *x0*.

To predict transition, the most popular method is the e^N criterion, see review in [9]. The so-called *N* factor is the total growth rate of the most unstable disturbances. It is computed by integrating $-\alpha_i$ in the streamwise direction *x*. It is assumed that transition occurs for some specified value N_t of *N*; for instance, N_t lies in the range from 8 to 10 on two-dimensional (2D) airfoils in low turbulence wind tunnels.

The main interest of the linear PSE is to provide initial conditions for the nonlinear PSE which simulate the nonlinear wave interactions [8]. The disturbances are now expressed as a double series of (*n, m*) modes of the form:

$$r' = \sum_{n=-\infty}^{n=+\infty} \sum_{m=-\infty}^{m=+\infty} \hat{r}_{nm}(x,y) \exp\left[i\left(\int \alpha_{nm}(\xi)d\xi + m\beta z - n\omega t\right)\right]$$

α_{nm} is complex, β and ω are real numbers. The integers *n* and *m* characterise the frequency and the spanwise wave number, respectively. When these disturbances are introduced into the Navier-Stokes equations, a system of coupled partial differential equations is obtained; it is solved by a marching procedure, as it was already the case for the linear PSE. For 2D flows, nonlinear computations end with a sudden increase of the major modes and of their harmonics; this simulates the breakdown to turbulence. For three-dimensional (3D) flows governed by a pure CF instability, the nonlinear interactions result in a saturation of the amplitude of all modes.

2.3 Structure of the project

The possibilities of laminar flow control on supersonic aircraft wings are investigated through 6 Workpackages (WP).

In WP1 (from January to June 2005), a preparatory work has been carried out. The industrial partners provided a quantitative definition of the objectives (Mach number, Reynolds number of a supersonic aircraft), as well as the preliminary definition of a fully 3D wing which will serve as a reference shape. In parallel, a review of the available experimental data on supersonic transition in 3D flow has been made and recent swept wing experiments performed at DLR have been analysed.

The goal of WP2 is to investigate two important concepts: the laminar flow control by micron-sized roughness elements, and the prevention of leading edge contamination by appropriate passive devices. This work comprises a numerical part and an experimental part. Extensive computations have been carried out in order to define a "large" but simple model (constant chord model) aimed at validating these concepts. Euler, boundary layer, linear and nonlinear stability computations were used to determine the most appropriate pressure gradient and the most efficient wavelength in order to validate the concept of laminar flow control by micron-sized roughness elements. In parallel, anti-contamination devices were defined from RANS computations. The model will be manufactured and tested at supersonic Mach numbers in the S2MA wind tunnel of the ONERA Modane-Avrieux centre.

The concept of laminar flow control by suction is studied in WP3. This concept will also be validated by wind tunnel experiments on a simple geometry. A constant chord swept wing equipped with a suction system was defined from Euler, boundary layer and stability computations. The model will be manufactured and tested in the RWG tunnel of DLR Göttingen. The complexity of this kind of experiments justifies the use of a research wind tunnel in which a suction system is easier to implement and to optimize than in a large, industrial wind tunnel.

Natural Laminar Flow (NLF) is the object of WP4. As this concept is technically simpler to apply than the concepts investigated in WP2 and WP3, it has been decided that the study will concentrate on the "numerical" model defined in WP1. Therefore this WP started at the completion of WP1 (July 2005). Here, it is expected that the complexity will come from the fully 3D nature of the flow, mainly due to the wing taper. The wing shape of WP1 is currently being optimized (i.e. the pressure distribution is optimized) for obtaining a laminar flow extend which will be as large as possible. Then the possibility of combining the optimized pressure distribution with the application of micron-sized roughness elements, anti-contamination devices and suction will be investigated. The objective is to search the best compromise(s) between the "pure" NLF control and additional laminar flow concepts of WP2 and WP3.

In the last year of the project (2007), the exploitation of the results of WP2, WP3 and WP4 will be addressed in WP5. This WP is managed by the industrial partners; it will provide a summary of the results, a quantification of benefits and recommendations for the applicability of the tools investigated in the previous WP.

In the next two paragraphs, attention is focused on the numerical work performed during the first year of the project for the definition of the two swept models which will be tested in 2006 in the S2MA and in the RWG wind tunnels (WP2 and WP3, respectively).

3 Definition of the S2MA model

Let us recall that this model will be used to validate the concept of transition control by micron-sized roughness elements and to test devices aimed at delaying leading edge contamination. The second problem is a local one, in the sense that the absence or the appearance of leading edge contamination depends on a single parameter, $\overline{R^*}$, which is strongly linked to the attachment line flow, i.e. to the leading edge radius and to the sweep angle. By contrast, the problem of transition control by micron-sized roughness elements involves the pressure distribution all along the wing because one has to take into account the development of stationary vortices from the leading edge to the transition point. Therefore both problems have been studied independently of each other and will be examined successively. In all cases, the computations have been performed in the conditions of the future experiments, i.e. for Mach numbers between 1.5 and 2, stagnation pressures from 0.50 to 1.25 bar and a total temperature of 300 K.

3.1 Leading edge contamination

As leading edge contamination is a local problem, a simplified geometry was considered. It consists of a half-cylinder (radius = 10 mm) followed by a flat plate, see figure 2. It is fixed at a sweep angle of 65° to a solid wall representing the wind tunnel wall. It is important to keep in mind that leading edge contamination is not a *transition* problem, but a *relaminarization* problem; the goal not to predict transition but to model the mechanisms by which the turbulence coming from the wall can be damped (or not) by a change in the Reynolds number or by appropriate devices placed on the leading edge. For this purpose, RANS computations using several turbulence models have been performed in a computational domain comprising the simplified model and the lateral wall.

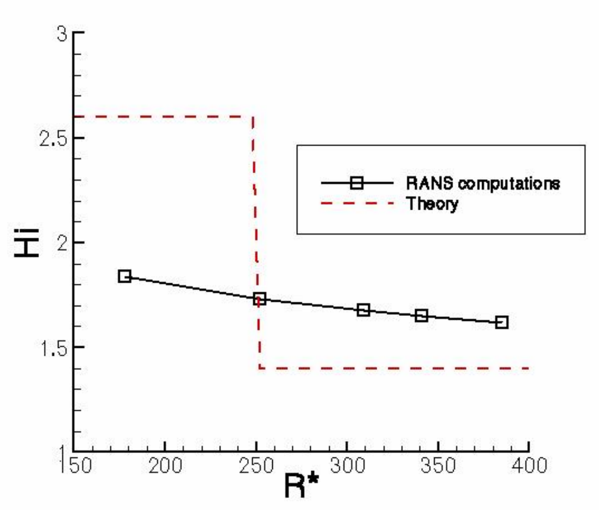

Fig. 1. Variation of the shape factor Hi with $\overline{R^*}$

As a first step, computations were carried out for the "clean" leading edge (without anti-contamination devices). The parameter chosen for detecting the nature of the boundary layer is the incompressible shape factor *Hi*. In the experiments, increasing the value of $\overline{R^*}$ by increasing the stagnation pressure results in the evolution of *Hi* which is schematically represented by a dotted line in figure 1; as soon as the critical value $\overline{R^*} \approx 250$ is exceeded, there is a rapid decrease of *Hi* from the laminar value (close to 2.6) to the turbulent one (close to 1.4). This behavior is not well captured by the RANS computations. As shown by the continuous line and the symbols in figure 1, the numerical results indicate a smooth and continuous evolution of *Hi*. This trend was found by the three partners involved in this Task (IBK, CIRA and ONERA) using different turbulence models. This means that RANS computations provide the right trends but are unable to mimic the complex physics of leading edge contamination.

In a second step, anti-contamination devices were installed on the leading edge. Figure 2 shows the typical shape of a "bracelet", i.e. a "positive" device of rectangular cross section (upper half of the leading edge region) According to Creel [10], this kind of device can be efficient to relaminarize the attachment line flow at supersonic Mach numbers. Computations were also made for positive devices of triangular cross section and for "negative" devices of triangular and trapezoidal cross sections.

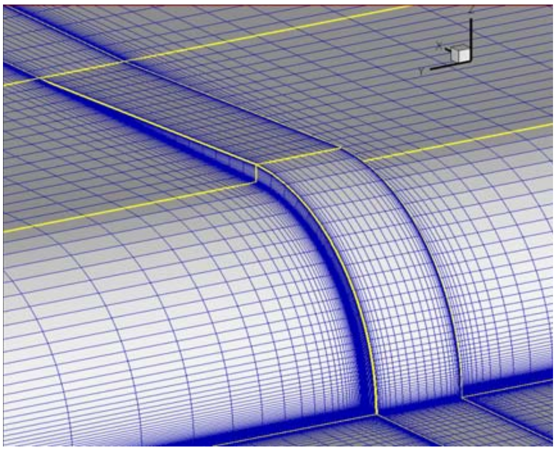

Fig. 2. Leading edge (upper half) with a positive bracelet. Grid for RANS computations

For the positive devices represented in figure 2, a parametric study was performed by varying the height *h* of the bracelets by keeping the value of $\overline{R^*}$ constant and equal to 440. The main results are:

- For small values of *h*, the turbulence coming from the wall "jumps" over the bracelet without any significant modification;
- For larger values of *h*, a stagnation point is created on the windward face of the device. The streamlines reveal the existence of vortices with axes roughly in the chordwise direction. However, the new boundary layer generated at the stagnation point becomes rapidly turbulent further downstream in the spanwise direction. A clear relaminarization is never observed.

The numerical results exhibited similar trends with the other shapes. The second observation above could lead to the conclusion that avoiding leading edge contamination is impossible with this kind of devices. However, as RANS models have shown their inability to model leading edge contamination on a clean leading edge, this conclusion could be too pessimistic. In other words, it is difficult to claim that the "numerical" turbulence generated downstream of the stagnation point of the large devices is physical or not. Therefore it was decided that the appearance of a stagnation point would be the criterion for an efficient anti-contamination device.

3.2 Micron-sized roughness elements

Here, the whole shape of the wing needs to be taken into account *via* the streamwise pressure gradient distribution which can be more or less suitable for an efficient transition control by small roughness elements. For this reason, the work was undertaken for two different (theoretical) wing profiles, one proposed by ONERA, the other proposed by DAAV (Dassault-Aviation). The first one is a symmetrical airfoil profile at zero angle of attack, with a blunt nose and a circular main body; its relative thickness is 20%. The second profile is not symmetrical and much thinner (around 6%), with a very small leading edge radius; the computations were done for an angle of attack of 3.5°. In both cases, the chord normal to the leading edge was fixed to 0.4 m. The free-stream Mach number, the sweep angle and the unit Reynolds number were varied systematically in the calculations, which were shared between the partners involved in this Task.

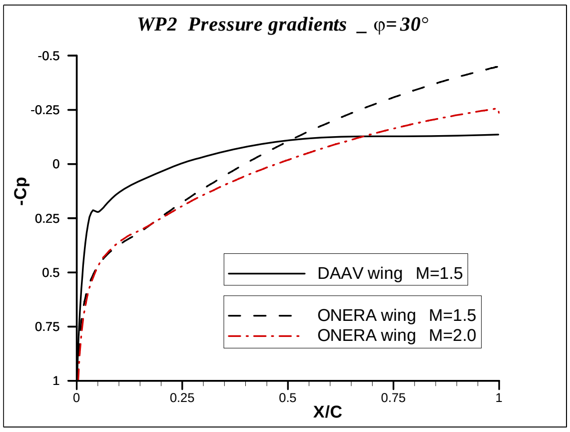

Fig. 3. Cp evolution for the DAAV and ONERA airfoil profiles, sweep angle = 30°

Euler and laminar boundary layer computations were performed to provide base flows for stability analyses. The theoretical *Cp* distributions are plotted in figure 3 for the two airfoils at a sweep angle of 30°. The flow acceleration around the leading edge is stronger for the DAAV airfoil, and rather weak further downstream. Then a linear stability analysis gave an estimated point of transition as well as an indication of modes that are most likely to cause transition. In particular, the calculation provided the values of the spanwise wave numbers β corresponding to the most amplified stationary disturbances (target modes). On the basis of these computations, a few cases were selected that had an estimated transition point in the first half of the chord.

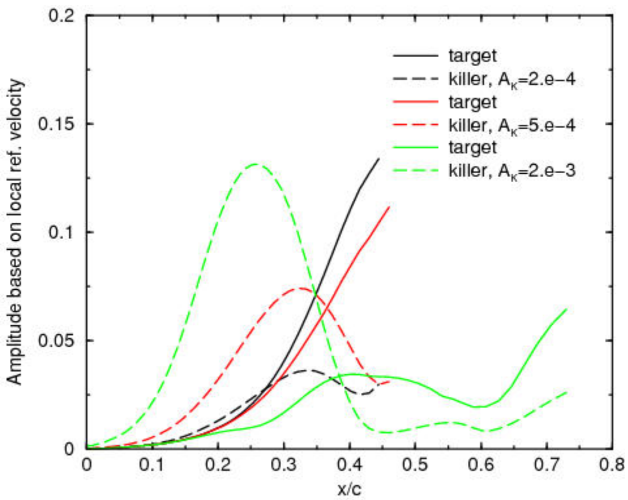

Fig. 4. Nonlinear PSE computations for the ONERA airfoil profile

Non linear stability analyses were carried out on the selected cases. Many interaction scenarios were investigated by systematic variations of the killer mode initial amplitude and wavelength. Sometimes, the growth of the target mode remained unaffected by the killer mode; in other cases, powerful interactions were identified. Figure 4 presents examples of “interesting” results for the ONERA airfoil at Mach 1.5. The stagnation pressure is 0.75 bar and the sweep angle 20°. The target mode corresponds to $\beta = 3000$ m^{-1}, i.e. $\lambda = 2\pi/\beta$ = 2.1 mm. Its initial amplitude A_t is equal to 5 10^{-4} u_e, where u_e is the local free-stream velocity. The killer mode corresponds to $\beta = 4500$ m^{-1}, i.e. $\lambda =$ 1.4 mm. The figure shows the evolution of the amplitude of the killer modes (dotted lines) and of the target modes (full lines) for three values of the initial amplitude A_k of the killer mode: $A_k = 2\ 10^{-4}$, $5\ 10^{-4}$ and $2\ 10^{-3}$. Different values of A_k correspond to different roughness heights. Numerically, the target is the (0,2) mode, the killer is the (0,3) mode, the (0,1) mode corresponding to $\beta = 1500\ m^{-1}$. This mode and other modes up to (0,9) have been taken into account in the computations but are not plotted for the sake of clarity. Increasing A_k clearly reduces the growth of the target mode but at the same time accelerates the growth of the killer mode (and of the other modes), so that it is difficult to estimate how the combination of these phenomena will affect the point of transition. One can imagine that there exists an optimum value of A_k for which transition is delayed. However, the link between A_k and the roughness height needs to be established.

3.3 Final choice and main characteristics of the model

After the non linear computations have been completed, a comparison between the performances of the ONERA and DAAV airfoils led to the conclusion that the most promising interaction scenarios were found for the ONERA airfoil. The explanation is the following. As shown in figure 3, the DAAV airfoil exhibits a weak negative pressure gradient beyond 25% chord. This implies that transition is not completely governed by CF instability in this region, so that the control by roughness elements (which is based on the properties of the CF waves) becomes more difficult. Technological arguments are also in favor of the ONERA airfoil. Due to the small relative thickness of the DAAV airfoil, sticking the roughness elements on its thin leading edge could be very difficult; in addition, risks of flutter and bending during the wind tunnel runs cannot be neglected.

The main characteristics of the model have been defined. As mentioned before, the chord normal to the leading edge is 0.4 m. The span is around 1.5 m. Due to the uncertainty in the theoretical definition of the "best" roughness elements, several wavelengths and heights will be considered. For the same reason, several shapes and sizes of the anti-contamination devices will be tested.

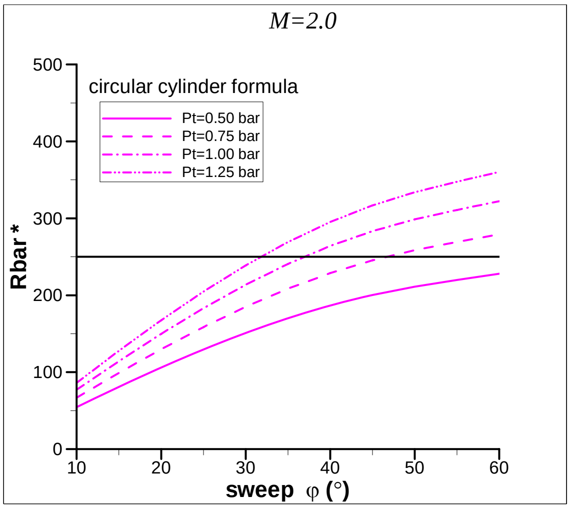

Fig. 5. Variation of $\overline{R}^*$ as a function of the sweep angle and of the stagnation pressure

As it can be seen in figure 5, the model presents an interesting property. The figure shows the variation of $\overline{R}^*$ as a function of the sweep angle φ for the stagnation pressure range available in the S2MA wind tunnel. The lines represent the values deduced from analytical relationships applied for a circular cylinder having a radius equal to the leading edge radius of the model (around 6 mm). The non linear stability computations have been performed for $\varphi = 20$ and 30°; for these sweep angles the value of $\overline{R}^*$ is lower than the critical value 250. As a consequence, the roughness experiments will be free of any risk of leading edge contamination. The anti-contamination devices will be tested at larger sweep angles, for φ equal to 60 or 70°. The results of figure 5 were obtained for a free-stream Mach number $M = 2$. Up to $\varphi = 60°$, the Mach number Mn normal to the leading edge is supersonic. The results for $M = 1.5$ are not very different. The main difference is that Mn becomes subsonic for φ greater than 48.2°.

The experiments in the S2MA wind tunnel are planned in October 2006. They will be carried out at zero angle of attack for $M = 1.5$ and 2, for several sweep angles and stagnation pressures. Transition will be detected by infrared thermography and by hot films.

4 Definition of the RWG model

As explained in paragraph 2.3, this part of the SUPERTRAC project is aiming at the extension of the technology of laminar flow control by suction to aircraft operating at supersonic speeds. More precisely, it is planned to investigate the suction effects on pure CF transition. As for the S2MA model, the first year of the project was devoted to the numerical definition of the swept wing model to be tested in the RWG wind tunnel at DLR Göttingen. Again a model with constant chord is considered for the sake of experimental and numerical simplicity.

The characteristics of the wind tunnel imposed the following constraints: Mach number $M = 2$, chord normal to the leading edge $c = 0.3$ m, stagnation temperature = 244 K, stagnation pressure from 1.2 to 3.6 bar, sweep angle $\varphi = 20$ to 30°.

4.1 Choice of the airfoil profile

At the beginning, it was decided to use a symmetrical airfoil at zero angle of attack, but the relative thickness of the model had to be specified. In addition it was not obvious whether a sharp or blunt leading edge would better meet the demands. Therefore in the preliminary definition phase both alternatives were considered for a relative thickness of 10%. It turned out that in this case the CF instability was too weak. Additional computations demonstrated that increasing the relative thickness would provide better results. Therefore airfoil profiles of 13% relative thickness with sharp and blunt leading edges were selected for detailed further analyses. In order to avoid any risk of leading edge contamination, an upper limit of the nose radius of $R \approx 1$ mm was found for the blunt model. The corresponding profile contours for the two candidates are shown in figure 6.

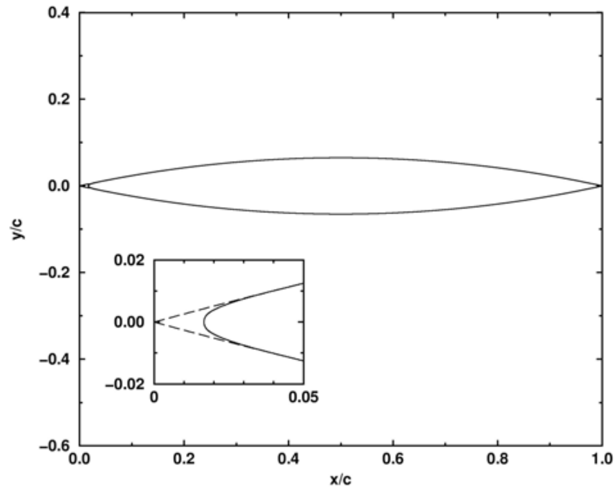

Fig. 6. Sharp and blunt profile contours

The computational work was shared between the partners of this Task. From Euler data, laminar boundary layer computations were performed in order to obtain the mean flow field suitable for stability computations and transition prediction. The numerical results were used to assess the advantages and drawbacks of the sharp and blunt leading edges. The technological difficulties for the implementation of the suction panel were also taken into account. The comparison showed that a sharp leading edge is probably superior. Thus, only the sharp leading edge model was considered in the subsequent analysis for the identification of the optimal position and extent of the suction panel. The sweep angle φ was fixed to 30°, because for $\varphi = 20°$, no transition or a late transition is expected on the model.

4.2 Definition of the suction panel

A large amount of computations was shared between the partners in order to investigate systematically the effect of the following parameters:

- the starting point and the streamwise extent of the suction panel;
- the stagnation pressure, i.e. the unit Reynolds number;
- the suction mean velocity V_w, with values from 0 to -0.46 ms^{-1} (it was

assumed that V_w was constant in the sucked region).

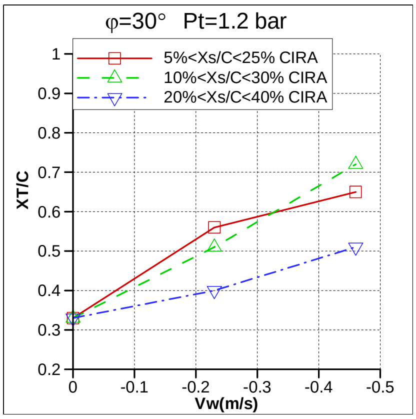

Fig. 7. Effects of the suction velocity and length on the transition location

Linear stability computations, both local and non local, were carried out and transition was assumed to occur for a critical *N* factor equal to 8. As an example of result, figure 7 presents the theoretical variation of the transition location as a function of the suction velocity V_w, for $\varphi = 30°$ and a stagnation pressure equal to 1.2 bar. Suction starts at 5, 10 or 20% chord, and is applied along a constant streamwise distance of 20% chord. Its effect on transition is very strong. As found previously in subsonic and transonic applications, this effect is more pronounced when suction begins close to the point where the unstable waves start to be amplified (between 5 and 10% chord in the present case).

The previous results were obtained assuming a constant value of V_w along the suction panel length. Additional computations were performed in order to optimize the streamwise mass flow distribution $m_w = \rho_w V_w$ (ρ_w is the density at the wall). The total mass flow rate is imposed, as well as the position and length of the suction panel. The goal is to minimise the disturbance kinetic energy *J* in a given control domain. The problem is solved using a steepest descent algorithm, the gradient of the objective function *J* being evaluated using the adjoint of the boundary layer equations and the adjoint of the PSE equations. Figure 8 shows typical results where the optimal suction distribution is compared to the constant suction velocity case V_w = -0.30 ms^{-1} (a penalty has been added to the objective function in order to minimise the mass flow peak at the beginning of the suction panel). By comparison with the constant suction velocity case, the effect on the *N* factor is not negligible, see figure 9.

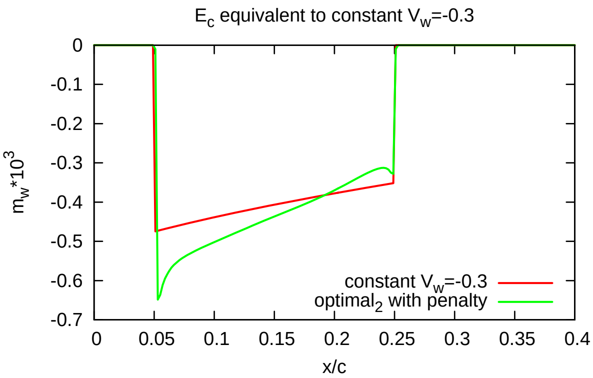

Fig. 8. Distributions of the mass flow rate for constant and optimal suctions

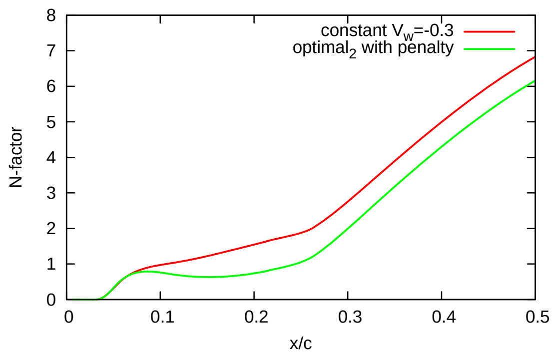

Fig. 9. N factor for constant and optimal suctions

4.3 Final design of the model

During the final design of the suction system, it was decided that the suction panel will extend from 5 to 20% chord. Moreover, assuming a constant pressure in the suction chamber and using an empirical law for the pressure drop across the perforated wall led to the conclusion that the resulting suction velocity distribution was close to the optimal suction distribution. Therefore a single suction chamber seems to be sufficient to meet the objectives.

Two different materials for the suction panel were analysed: a sinter metal filter (hole diameter around 10 µm, thickness = 3 mm) and a classical micro-perforated metal sheet (hole diameter from 20 to 30 µm, thickness = 0.5 mm). The porosity of the sinter material (20 to 30%) is much larger than that of the metal sheet (around 1%). Wind tunnel tests on a simplified flat plate model with inserts will be performed that should enable meeting the final decision.

The model is currently in the phase of manufacturing. The experiments will start by the end of June 2006. Transition will be detected by optical methods, infrared thermography and/or global interferometry skin friction.

5 Conclusion

In the first year of the SUPERTRAC project, two wind tunnel models have been designed from numerical investigations. Both models are swept wings of constant chord. One will be tested in the S2MA wind tunnel to investigate the efficiency of anti-contamination devices and of micron-sized roughness elements. The other will be used for studying the effect of wall suction on laminar-turbulent transition in the RWG wind tunnel. Beside classical techniques based on the local, linear stability theory, advanced numerical tools were employed in the design phase of the models: non linear PSE for small roughness elements, 3D RANS computations for anti-contamination devices, optimization procedures for suction. Optimization techniques are also currently used for the problem of natural laminar flow control (not described in this paper).

The limitations of these techniques have been identified; for instance, it has been demonstrated that the RANS computations do not describe properly the leading edge contamination process; on the other side, the nonlinear PSE provide the spacing of the roughness elements, but the height of these small obstacles is not determined. Therefore the experimental results will be of great interest, not only for the assessment of the laminar flow control techniques, but also for the validation and the improvement of the numerical modeling.

Acknowledgement

The investigations presented in this paper have been obtained within the European research project SUPERTRAC under contract No AST4-CT-2005-516100. The authors are grateful to the SUPERTRAC partners for providing the results discussed in the paper.

References

[1] W.S. Saric, R.C. Carrillo, M.S. Reibert: Leading edge roughness as a transition control mechanism, AIAA Paper 98-0781, 1998

[2] W.S. Saric, H.L. Reed: Supersonic laminar flow control on swept wings using distributed roughness, AIAA Paper 2002-0147, 2002

[3] W.S. Saric, H.L. Reed: Crossflow instabilities. Theory and technology, AIAA Paper 2003-0771, 2003

[4] W. Pfenninger: Flow phenomena at the leading edge of swept wings, AGARDograph 97, Part 4, 1965

[5] D.I.A. Poll: Some aspects of the flow near a swept attachment line with particular reference to boundary layer transition, Technical Report 7805/K, Cranfield, College of Aeronautics, 1978

[6] D.I.A. Poll: Boundary layer transition on the windward face of space shuttle during reentry, AIAA Paper 85-0899, 1985

[7] J. Reneaux, J. Preist, D. Arnal, J.C. Juillen: Control of attachment line contamination, 2nd European Forum on Laminar Flow Technology, Bordeaux, June 1996

[8] T. Herbert: Parabolized Stability Equations, AGARD Report 793, 1993

[9] D. Arnal: Boundary layer transition prediction based on linear theory, AGARD Report 793, 1993

[10] T.R. Creel: Effects of sweep angle and passive relaminarisation devices on a supersonic swept-cylinder boundary layer, AIAA Paper 91-0066, 1991