



SUPERsonic TRAnSition Control
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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 final meeting was held at ONERA Toulouse on July 9, 2008.

The 9 partners of the project were:

Office National d'Etudes et de Recherches Aéropatiales (ONERA, co-ordinator)	FR
Airbus UK Limited (AI-UK)	UK
Centro Italiano Ricerche Aerospaziali ScpA (CIRA)	IT
Dassault Aviation S.A. (DAAV)	FR
Deutsches Zentrum für Luft- and Raumfahrt e.V. (DLR)	DE
Swedish Defence Research Agency (FOI)	SE
Ingenieurbüro Dr. Kretzschmar (IBK)	DE
Instituto Superior Tecnico (IST)	PO
Kungliga Tekniska Högskolan (KTH)	SE

Objective and structure of the project

The global objective of the project was 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 or 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 project was divided in 6 Workpackages (WP).

In the **WP1** (Specifications), the industrial partners (Airbus and Dassault Aviation) provided a quantitative definition of the objectives as well as the preliminary definition of a fully three-dimensional wing which was used as a reference shape in WP4 ("numerical" model). Another objective was to make a review of the (few) available experimental data on supersonic transition in three-dimensional flow (swept wings). In particular, swept wing experiments performed at DLR before the project starts were re-analyzed.

The first objective of **WP2** was to define a simple model (swept wing of constant chord) equipped with micron-sized roughness elements and anti-contamination devices. This

model was manufactured and tested in the S2 wind tunnel of the Modane-Avrieux ONERA centre. The analysis of the results was then shared between the partners.

WP3 was running in parallel with WP2. Another swept wing of constant chord, equipped with a suction panel in the leading edge region, was designed, manufactured and tested in the RWG wind tunnel of DLR Göttingen, then the results were analyzed.

WP4 used the “numerical” model defined in WP1. The objectives were i) to numerically investigate the concept of Natural Laminar Flow control by shape optimisation ii) to analyze the compatibility of the different control techniques, in particular those of WP2 and WP3. This resulted in the definition of the best compromise for skin friction drag reduction. The benefits which can be expected with the “best” wing shape were estimated by comparing the performances of the optimized wing and those of a fully turbulent wing.

The results of WP2 to WP4 were summarised in **WP5** by the industrial partners, with the objective of providing a quantification of the benefits and recommendations for practical applicability to future supersonic aircraft wings.

WP6 was devoted to the management and to the exploitation of the project.

Summary of the results

WP1- Specifications

A reference shape (business jet type) has been chosen by the industrial partners and the necessary information have been sent to the WP4 partners for a numerical optimisation.

Concerning the review of existing data, a report summarizing the available results on supersonic transition has been issued. Previous DLR experiments in the RWG wing tunnel on a swept wing have been re-evaluated, but some difficulties have been encountered for the computation of the N factors, which were surprisingly low.

WP2- Laminar flow control by micron-sized roughness elements and anti-contamination devices

In WP2, a swept wing model of constant chord has been defined for experiments in the S2MA wind tunnel. Then the experiments have been performed and analyzed.

Nonlinear Parabolized Stability Equations (PSE) and receptivity computations were aimed at defining experiments with transition control by micron-sized roughness elements (MSR). The objective is to place a row of MSR parallel to the spanwise direction, close to the wing leading edge. These MSR generate artificial vortices which can reduce the amplification of “natural” vortices responsible for transition. The computations resulted in the choice of the most interesting pressure distribution, flow conditions and roughness wavelength.

In parallel, RANS (Reynolds Averaged Navier-Stokes equations) computations allowed to partly understand the flow physics around anti-contamination devices (ACD). These devices are installed on the wing leading edge. If their shape and size are correctly designed, they are able to postpone the appearance of leading edge contamination by the turbulent structures coming from the wing-wall junction. Although the computations did not

show clearly any relaminarization, an engineering criterion based on the existence of a stagnation point has been adopted in order to choose the shape and the size of the most promising devices.

Then the final model has been defined and designed. Its chord was 0.4 m. The experiments have been conducted for Mach numbers between 1.5 and 2.7, and provided original data (MSR have been tested for the first time in Europe). The sweep angle was between 15° and 30° for the MSR experiments and 65° for the ACD experiments, see picture below. The analysis of the results led to interesting conclusions:

- The infinite swept wing assumption was valid for supersonic leading edges, but fully three-dimensional computations were necessary to achieve a good agreement with measurements for subsonic leading edge.
- The MSR did not show the expected downstream movement of the transition location. The reason could be the too small number of elements in each row and the too large size of the roughness elements. The absence of positive effect on transition was clarified by nonlinear PSE and receptivity computations in some selected cases.
- One of the seven ACD tested in the S2MA wind tunnel was able to delay the onset of leading edge contamination up to rather large values of the attachment line Reynolds number. Although RANS computations are unable to mimic the physics of relaminarization, they can provide useful guidelines for the design of efficient ACD.



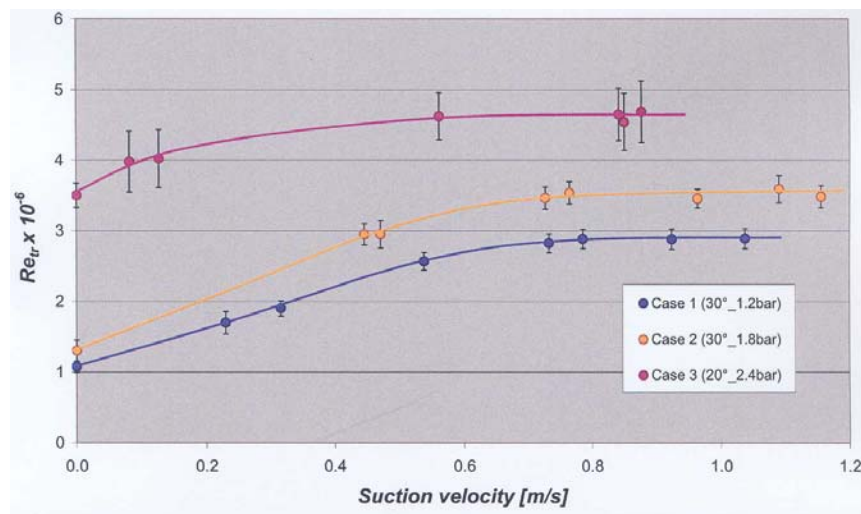
The model in the S2MA test section

WP3- Laminar flow control by suction

In this WP, a swept wing model of constant chord has been defined for experiments in the RWG wind tunnel at DLR Göttingen. The goal here was to look at the effect of suction on transition. The different steps of the model definition can be summarized as follows:

- Choice of the leading edge and of the relative thickness: finally, a sharp model with 13% relative thickness has been considered, for sweep angles of 20 and 30°, and a chord equal to 0.3 m.
- Choice of the suction velocity, analysis of the effects of suction location and extent: suction velocities of the order of 0.1% of the free-stream velocity, applied from 5% to 20% chord seemed to lead to a significant transition delay.
- Optimization of the suction distribution: it was demonstrated that a single suction chamber was a good approximation of the optimized suction distribution.

The layout and integration issues of the suction system have also been addressed. After the model manufacturing, the experiments were conducted in the RWG facility and showed a clear downstream movement of transition location with suction. These experiments provided a unique data base concerning the effects of suction on transition in supersonic conditions. Typical results are shown in the figure below, where the transition Reynolds number is plotted as a function of the suction velocity for three values of the stagnation pressure.



Measured transition position for stagnation pressures equal to 1.2, 1.6 and 2.4 bar

Although the transition movement was limited by parasitic shock-boundary layer interactions, the number and the quality of usable data were sufficient for a detailed analysis using the e^N method. The stability computations demonstrated that transition in the RWG wind tunnel was governed by travelling crossflow waves. This implies that transition was sensitive to the free-stream disturbances rather than to the surface polishing. The transition N factors for the travelling modes depended on the suction velocity and on the sweep angle but their variation was moderate enough (between 4 and 6) for assuming a constant value of the transition N factor for practical applications. It is obvious that larger values of the transition N factor must be used in flight conditions due to a much cleaner disturbance environment.

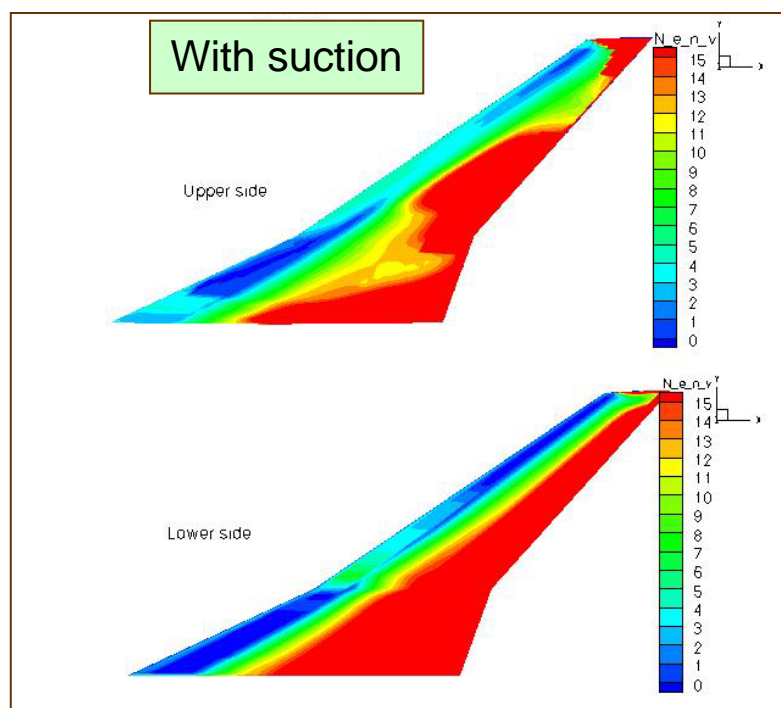
WP4- Natural laminar flow control (“numerical model”)

The objective of this WP was to numerically optimize the shape of the wing chosen in WP1 for the application of the Natural Laminar Flow concept. It turned out rapidly that the original baseline geometry was fully turbulent. A parametric study of some geometrical parameters did not improve significantly the results. As a consequence, it was decided to start again with a completely new wing shape. A new constant chord wing was defined by CIRA, then a fully three-dimensional basic shape was designed by Dassault-Aviation. Finally the optimization carried out by ONERA and CIRA resulted in two wings optimized for Natural Laminar Flow.

In parallel, fundamental studies have been performed with the original wing shape at reduced Reynolds numbers (in order to observe a significant laminar area). The effects of different boundary layer approximations and of different integration paths for the N factor computation have been investigated.

The implementation of additional devices (MSR, ACD and suction) was investigated for the two optimized wings. It turned out that:

- The pressure gradients optimized for Natural Laminar Flow were not compatible with the use of micron-sized roughness elements;
- Attachment line contamination was not expected for both wings at design conditions;
- Suction was very efficient to delay transition; it was much less efficient when applied to the original (turbulent) wing.



*Theoretical transition line with moderate suction and shape optimization
(turbulent regions are in red)*

The work plan of the WP was modified in order to take into account the fact that two optimized wing were available (only one optimized wing was expected in the DoW). Computations for different values of the lift coefficient finally resulted in the choice of the CIRA wing for further investigations. Three-dimensional boundary layer and stability computations allowed defining transition lines with moderate suction, see figure above.

Because attachment line contamination was likely to occur at low CL (lift coefficient), the leading edge was “numerically” equipped with an anti-contamination device. As a last step of this study, the drag reduction by shape optimization + suction (by comparison with the fully turbulent case) was estimated from RANS calculations. It was observed that the wing friction drag gain and the total drag gain were close to 47% and 6%, respectively. The evaluation of the benefits was one of the objectives of WP5.

WP5- Results evaluation for further development

As a first step, the industrial partners (Airbus and Dassault-Aviation) summarized the results obtained within SUPERTRAC. Airbus deduced an evaluation matrix in which the technologies investigated during the project have been analyzed from an industrial point of view. Their advantages and shortcomings have been identified, and their TRL (Technology Readiness Level) was estimated.

As a second step the quantification for operational cost and performance “benefits” has been done. Airbus considered a commercial reference aircraft and Dassault-Aviation studied a business jet. Considering a laminar flow extent around 50% on both wing sides, both partners found a similar drag reduction. Airbus demonstrated that, in order to gain the full benefits of laminar flow technologies, the effects must be snowballed, i.e. these technologies have to be integrated into the design right from the beginning. Finally some recommendations for future work have been suggested.

Lessons learned

When SUPERTRAC started, there were practically no published results concerning the possibilities to laminarize a supersonic wing. Therefore a large part of the numerical and experimental studies performed in the framework of the project can be considered as innovative.

Theoretical and numerical aspects

The consortium used the most advanced numerical tools for the investigation of laminar flow control devices in supersonic conditions. These tools have been improved when necessary for solving the particular problems encountered within SUPERTRAC, and the knowledge of the partners has been substantially increased in many aspects.

The transition control by MSR is a new approach, which had never been validated in Europe, at least for supersonic conditions. The computations allowed a critical assessment of the capabilities of this concept. A strategy for the use of nonlinear Parabolized Stability Equations (PSE) was developed by the partners, so that systematic applications of this control technique are now possible, at least numerically. On the other side, the theoretical

difficulties associated with nonlinear PSE have been identified; for instance, the spacing of the roughness elements can be determined but their height and their diameter remain unknown. Advanced receptivity theories (as used by DLR) provided some answers.

Leading edge ACD are rather well known for low speed problems (Gaster bumps), but the available information were very scarce for high speed flows. Three-dimensional RANS computations made it possible to improve our knowledge on leading edge contamination in supersonic conditions and to build an original numerical database. As for MSR, the limitations of the numerical approach have been pointed out.

As far as suction is concerned, the numerical definition of the DLR model made use not only of classical tools (linear stability theory) but also of advanced optimization methods (adjoint-based) for the final design of the suction chamber.

The numerical optimization of a fully three-dimensional supersonic wing for the purpose of Natural Laminar Flow led to unexpected difficulties (for the partners, this was the first application of this concept to supersonic flows), which needed to propose a specific strategy. CIRA and ONERA developed a complete optimization chain specific to the SUPERTRAC activities. The use of genetic algorithms was one of the most interesting achievement of the project.

Experimental data bases

Wind tunnel experiments allowed to judge the validity of the theoretical modelling and to answer (some of) the open questions. It must be pointed out that the MSR, ACD and suction experiments were **the first ones of this type in Europe** for supersonic conditions. All the results were made available to all the partners as electronic files and CD roms.

The MSR experiments did not lead to the expected positive results in term of transition control. A careful examination of the experimental data base and a detailed analysis of the results using advanced numerical tools allowed understanding the possible reasons for these disappointing results. There is no doubt that the knowledge gained within SUPERTRAC will be useful for future investigations on transition control by MSR.

Before the SUPERTRAC S2MA test campaign, the ACD concept had been studied at NASA in the early 90's. One of the tested devices seemed to work rather well in some conditions, but no detailed information was published concerning the optimum shape and size of the device. A similar device was considered within SUPERTRAC, but its performances were found to be very poor. Much better and quite spectacular results were obtained with a completely original shape, the size of which was estimated from RANS computations. It is guessed that the best SUPERTRAC device could be used at lower speed and could exhibit a better efficiency than the classical Gaster bumps.

The demonstration that a small amount of suction is able to delay transition on a swept wing in supersonic conditions constituted one of the major achievements of the project (as pointed out by one of the experts at the final meeting). To our knowledge, there is no similar experimental data base available on this problem, at least in Europe. Beside their intrinsic interest, the results contributed to calibrate the e^N method with suction. As for MSR and

ACD, the suction investigations illustrated the strong link established during the project between experiments and computations.

Practical results

SUPERTRAC also provided information of practical/industrial interest concerning the possibilities of laminar flow control at supersonic speeds. Some of them are extrapolations of results already established in the transonic regime. For instance: suction is more efficient for a wing designed for Natural Laminar Flow (NLF) than for a turbulent wing. Other practical results have been obtained for the first time. For instance: NLF is not compatible with the use of MSR.

As a final achievement of the project, the “best” supersonic 3D wing has been defined and the expected benefits (in term of drag and fuel consumption reduction) have been estimated. It is clear that for the large sweep angle wing considered here, NLF alone is not sufficient for obtaining significant skin friction gains. However the application of a small amount of suction makes it possible to increase the laminar flow extent in a significant manner. Of course, many technological problems, such as the compatibility with leading edge high lift devices or the effect of surface imperfections need to be studied. These issues were out of the scope of the present project but could be addressed in future projects dealing with laminarity at high speed.

Publications, presentations

C.G. Unckel: *ERCOFTAC Nordic meeting*, Oslo, October 20-21, 2005 (oral communication)

C.G. Unckel: Transition control in supersonic boundary layer flows with micron-sized roughness elements, SIG33 Workshop, Stockholm, 30 May, 2 June 2006

D. Arnal et al: Supersonic laminar flow control studies in the SUPERTRAC project, 25th ICAS congress, Hamburg, 3-8 September 2006

D. Arnal: Supersonic laminar flow control techniques within the SUPERTRAC project, ECCOMAS CFD 2006, Egmond aan Zee, 5-8 September 2006

D. Arnal: presentation at the Aeronautic Days, Vienna, 19-21 June 2006

D. Arnal (presented by J. Reneaux): SUPERTRAC (SUPERsonic TRAnsition Control), KATnet II Workshop on Strategy, Airbus Spain, Madrid, 23-24 April 2007

J.P. Archambaud et al: Transition control experiments in the supersonic S2MA wind tunnel (SUPERTRAC project), ERCOFTAC SIG33, Kleinwalsertal, Austria, 17-20 June 2007

D. Arnal: Supersonic laminar flow control investigations within the SUPERTRAC project, CEAS Conference, Berlin, 10-13 September 2007

S. Hein: Laminar flow control by micron--sized roughness elements at supersonic Mach numbers within SUPERTRAC. AG STAB Workshop, Göttingen, 14.-15. November 2007.

S. Hein, E. Schülein: Preparation and analysis of an RWG experiment on laminar flow control by suction at Mach 2 within SUPERTRAC. AG STAB Workshop, Göttingen, 14.-15. November 2007.



E. Schülein: Experimental Investigation of Laminar Flow Control on a Supersonic Swept Wing by Suction. AIAA Paper 2008-4208, 4th AIAA Flow Control Conference, Seattle, Washington (USA), 2008-06-23 - 2008-06-26, 14p, 2008.

J.P. Archambaud, D. Arnal: use of laminar flow technologies for supersonic drag reduction. Results of the FP project SUPERTRAC, 5th ECCOMAS congress, Venice, 30 June-4 July 2008

J. Krier, T. Sucipto: Anti-contamination device for swept wing aircraft, The International Conference on Hydraulic Machinery and Equipments, Timisoara, Romania, October 16-17, 2008

D. Arnal: Overview of the SUPERTRAC project, KATnet II Workshop on Drag Reduction, Ascot, UK, 14-16 October 2008

J.M.M. Sousa: Numerical simulations of three-dimensional effects in "infinite" swept wing tests at supersonic flow conditions, 1st Workshop on Computational Engineering, IST, Lisboa

S. Hein, E. Schülein: Transition control by suction at Mach 2, 7th ERCOFTAC SIG33-FLUBIO Workshop on Laminar-Turbulent Transition Mechanisms, Prediction and Control, 16-18 October 2008, Santa Margherita Ligure, Italy