GARTEUR AD/AG-44
Application of transition criteria in Navier-Stokes Computations Phase II


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GARTEUR aims at stimulating and co-ordinating co-operation between Research Establishments and Industry in the areas of Aerodynamics, Flight Mechanics, Systems and Integration, Helicopters and Structures & Materials.
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Foreword

AD/AG-44 was launched in September 2005. Participants were QinetiQ, CIRA, Universita di Napoli, ONERA, TU Braunschweig, DLR Göttingen and INTA. Dr Malcolm Arthur from QinetiQ was chairman and Dr Chris Atkin, also from QinetiQ, was Monitoring Responsible. Chris Newbold took over as Monitoring Responsible when Chris Atkin left QinetiQ and as acting chairman when Malcolm Arthur retired. Some further participants left their organisations or retired during the AG. As a consequence, the final report was not delivered and the activities ended in an unorganized way.

This report compiles what was done in a simplified final report. All participants except ONERA have written internal reports or informal summaries describing each organisations activities. The internal reports are the backbone of this report. ONERA published two conference papers of their activities. Since other organisations have copyright of these articles, they are omitted, but references are included.

A summary of the work performed is included, based largely on the AD/AG-44 contribution to the GARTEUR 2010 Annual Report, written by Chris Newbold.

Some concluding remarks have been provided by Chris Newbold.
1. Objectives

AG35, Application of transition criteria in Navier Stokes Computations, saw the successful implementation and test of transition modelling for two-dimensional NS computations. Although in each case simple criteria were used to determine the location of transition onset, some partners applied these criteria to boundary layer solutions obtained from the Navier-Stokes pressure distributions, while some applied the criteria directly to the Navier Stokes solutions (usually with some modifications to take account of the generally poor prediction of laminar flows by NS). However it was felt that moving on to simple three-dimensional flows would pose far greater challenges for both approaches, and that this should be explored as a matter of course.

Another conclusion from AG35 was that the transition zone (rather than onset) was poorly modelled, but that this region had a significant influence on the overall solution quality.

Some partners felt that, despite the successful demonstration of transition criteria for two-dimensional flows, far greater geometric complexity could only be handled by low-Reynolds number turbulence models, and that these should be further investigated, particularly in the light of recent experience.

Finally, it was observed that many high-lift flows displayed bubble transition while the studies in AG35 had been unable to model transition after laminar separation, fixing transition onset upstream of or at the experimentally-observed separation point. It was agreed that an ability to include a small region of bubble flow (necessitating both better transition criteria and improved stream-wise mesh resolution) would be beneficial to the prediction of high-lift flows.

AG-44 will therefore aim to address all these issues raised in AG35, with a view to extending the applicability of the transition prediction capability in NS to more challenging flow fields. The proposed objectives are:

1. the coupling of empirical criteria or stability analysis to Navier-Stokes computations on simple three-dimensional geometries;

2. improved modelling of the transition zone and the impact on solution accuracy and robustness (especially relaxation requirements for transition position); and

3. to understand the relative merits of the low-Reynolds-number turbulence modelling approach (applied to external aerodynamic flows) as compared to the use of mechanism-specific criteria for complex configurations.

It is intended to demonstrate the validity of the approaches through the calculation of Reynolds number and angle of incidence trends, as well as one-off test cases. Participants will also be free to demonstrate capability on more complex configurations.
2. Plans

Task 1: Modelling of multiple transition mechanisms on complex configurations

This task is concerned with extending the capability developed in AG35 to model cross-flow-induced transition and attachment line physics. The tools will then be applied to complex configurations (civil/military) with necessary performance analyses such as mesh specification, number of transition iterations, relaxation requirements and repeatability. This activity will focus initially on the DERA transonic NLF swept panel model, for which infra-red and surface pressure measurements are available for a range of Reynolds and Mach numbers and angles of sweep and incidence. In particular the experiments demonstrate a clear crossover from CF to TS transition mechanisms with varying incidence. Test cases proposed for year 2 are the ONERA AFV complex, 3D multi-element high-lift configuration studied in EUROLIFT 1 and the M1303 UCAV configuration.

Task 2: Modelling of transition zone and laminar separation bubbles

This task is concerned with how the ‘switching on’ of turbulence accurately reflects the characteristics of the later stages of transition, and how this improves the quality of the computations. This task will include the calculation of LSB transition and re-attachment and comparisons with PIV data. Two test cases are proposed: the first corresponds to the low speed, axi-symmetric ogive-cylinder measurements conducted by Juillen and Arnal between 1976 and 1980. Different angles of divergence of the test section provide zero or positive pressure gradients. Velocity and turbulence profiles measured along the cylinder from hot wire anemometry (single or X-wire probes), are available as well as skin friction estimations. As the boundary layer thickness remains small with respect to the cylinder radius, computations can be done more easily with 2D planar meshes by imposing a correct adjustment of the upper boundary over which a slip condition can be applied. The second proposed test case is the Selig-Donovan low-Re SD7003 aerofoil at Re 60,000 for which PIV experimental data and NS computations have already been carried out by TU Braunschweig (also an RTO test case, from AVT-101).

Resources

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<th>Total</th>
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<td>2007</td>
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<td>Man-months (MM)</td>
<td>Actual/Planned</td>
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<td>Other costs (in K€)</td>
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Milestones

TP-156
Task 1:
1.1 Issue of test case geometry & flow conditions (including tunnel N-factors).  (M1)
1.2 Mesh generation & computation of Re/alpha trends.  (M2-6)
1.3 Meeting: comparison of cross-flow transition prediction.  (M6)
1.4 Diagnosis and modifications to methods, repeat computations.  (M7-9)
1.5 Implementation and test of attachment line transition criterion.  (M10-12)
1.6 Computation of complex configuration using transition criteria or low-Reynolds number turbulence models; capture of essential trends.  (M13-20)
1.7 Preparation of report discussing simplicity/accuracy/cost of transition modelling options for complex configurations.  (M21-24)

Task 2:
2.1 Literature search by partners, including existing experience; exchange of information.  (M1-3)
2.2 Release of ONERA test case data and measurements (zero and "strong" adverse pressure gradients) and computational meshes.  (M2)
2.3 Implementation of zone modelling by intermittency transport and turbulence kinetic energy production correction.  (M4-12)
2.4 Test of transition zone predictions against experimental data; model refinements.  (M6-12)
2.5 Release of SD7003 test case details and computational mesh.  (M10)
2.6 Review meeting/workshop.  (M12)
2.7 Phase 1 computation of SD7003 test case by Navier-Stokes and, dependent upon partner interest, viscous coupled approaches.  (M13-18)
2.8 Phase 2 computation of SD7003 test case.  (M19-21)
2.9 Preparation of report focussing on accuracy of transition-zone and LSB modelling.  (M22-24)

Benefits

Transition is now understood to be an important phenomenon even in the prediction of largely turbulent flows, since it has a major influence on friction drag, leading edge separation and boundary layer thickness, the latter impacting upon other key features such as shock position and wave drag in transonic flows. Achievement of agreement with experiment for high-lift flows, for example, is impossible without the correct prediction of transition. Likewise the extrapolation of wind tunnel results to flight scale by the use of CFD depends upon the accurate resolution of the transition phenomenon. The achievement of a reliable transition modelling capability in Navier-Stokes would therefore make a significant contribution to the efficiency of the industrial aerodynamic process, as well as increasing confidence in the eventual design.
## AG Membership

<table>
<thead>
<tr>
<th>Member</th>
<th>Organisation</th>
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</table>
3. Report from CIRA and UNINA

Flow around the SD 7003 airfoil

The incompressible flow around the Selig-Donovan (SD) 7003 airfoil presents interesting characteristics. At Reynolds number $6 \times 10^4$, a bubble is formed on the upper surface of the airfoil. The bubble is located in the rear zone close to the trailing edge at low incidences, and moves upstream as the angle of attack increases.

This is a widely-used test case for which experimental [1] and numerical [2] data are available in literature. RANS and large eddy simulations at several angles of incidence have been performed. The main aim is to analyze the limits of the RANS methods by comparison with LES results.

Reynolds Averaged Navier Stokes

The results have been obtained by running the turbulence model without specifying the transition location (flows is assumed turbulent everywhere). Laminar separation bubbles are detected if the turbulence model is robust enough to be run with very low values of free-stream turbulence.
The $\kappa$-$\omega$ SST turbulence model is applied at several angles of incidence with low values of the free-stream turbulence.
The friction and pressure coefficient as function of the angle of attack are presented in Figure 1.

![Figure 1: SD7003 Airfoil, Re=6.0x10^4: RANS $\kappa$-$\omega$ SST with laminar-turbulent transition not prescribed, $C_p$ and $C_f$ over the airfoil at different angles of attack](image)

A bubble is predicted in the trailing edge zone of the airfoil at $\alpha=0$, and then moves towards the leading edge as $\alpha$ increases.
Large Eddy Simulation

Large eddy simulations of the flow around the SD 7003 airfoil have been performed at several incidences. A RANS flow field has been used as initial solution and the simulation has been advanced in time with a time step $\Delta t = 1.5 \times 10^{-4}$.

Figure 2 shows the three-dimensional turbulent flow that develops in the rear part of the airfoil downstream the separation.

The time history of the lift and drag coefficients for the case at $\alpha = 4$ is shown in Figure 3.

The large eddy simulation has been advanced in time for more than 20 characteristic times, and then the results have been time-averaged.
RANS-LES Comparison

The RANS solutions are compared in terms of pressure and friction coefficients to the large eddy simulations data by the authors and Galbraith and Visbal [2] in the Figure 4, Figure 5, and Figure 6 at α=4, 6, and 8 respectively.

Figure 4: SD7003 Airfoil, Re=6.0 x 10^4, α=4. Pressure and friction coefficient; ○: ILES (Galbraith and Visbal), solid line: present LES, dash-dot line: RANS κ-ω SST with laminar-turbulent transition not prescribed.

Figure 5: SD7003 Airfoil, Re=6.0 x 10^4, α=6. Pressure and friction coefficient; ○: ILES (Galbraith and Visbal), solid line: present LES, dash-dot line: RANS κ-ω SST with laminar-turbulent transition not prescribed.

The pressure recovery in the zone of the bubble is much stronger in LES than in RANS data, as can be seen in all the $C_p$ and $C_F$ plots. The separation point is well predicted in the RANS simulations, but the RANS provide a re-attachment anticipated with respect to LES results.

Downstream the flow re-attachment, the RANS recover to a level of pressure lower than LES.

The present large eddy simulations are in excellent agreement with the ILES by Galbraith and Visbal [2] at α=4 and 8. Some discrepancies can be noted for the flow at α=6.

The RANS simulations have been performed without an “a priori” knowledge of the laminar-turbulent transition.
It has been shown that a laminar bubble is returned by the RANS methods with the $\kappa-\omega$ SST turbulence models used with low values of free-stream turbulence. The RANS satisfactorily predict the separation point and the flow in the “dead air” region. A shorter bubble length and a weaker pressure recovery is provided by RANS with respect to LES.

![Figure 6: SD7003 Airfoil, Re=6.0 x 10^4, $\alpha$=8. Pressure and friction coefficient; ○: ILES (Galbraith and Visbal), solid line: present LES , dash-dot line: RANS $\kappa-\omega$ SST with laminar-turbulent transition not prescribed.](image)

**References**


4. Report from DLR and TU-BS

This report summarizes the work of DLR, German Aerospace Center, Germany and University of Braunschweig (TU-BS), Institute of Fluid Mechanics, Germany for Garteur AG44. During the duration of the AG44, development and application of a transition prediction capability attached to a Navier-Stokes code at University of Braunschweig have been suspended and the work is now being completed at DLR.

For AG44, investigations on the M2355 NLF swept wing have been undertaken. For different flow conditions (see Table 1) calculations have been performed using the DLR TAU code. Transition has been predicted automatically with the TAU transition prediction capability [1]. Calculations have been performed for 6 different test cases: 5 test cases being provided generally to the participants of AG44, whereas one test case was considered for consistency checks. For this test case (data point 165), the provided Reynolds number could not be deduced from the report of the experiments [2], and hence, the most likely Reynolds number reported from the experiments was taken for an additional calculation. This was done to identify possible conversion errors between differently defined Reynolds numbers. For data point 165, a Reynolds number based on chord length parallel to free stream of $Re = 6.922 \times 10^6$ was provided, giving a Reynolds number based on chord normal to leading edge of $Ren = 6.3 \times 10^6$. However, this Reynolds number does not appear in the report of the experiments, but the Reynolds number $Ren = 5.7 \times 10^6$ could be identified, which can be converted into a Reynolds number based on chord parallel to free stream of $Re = 6.299 \times 10^6$ (see Table 1).

The provided structured grid for the M2355 NLF swept wing has been converted to TAU format. During the conversion process the sweep angle included in the original grid has been removed and the thickness of the airfoil has been rescaled. This means, that the converted grid resembles the profile of the experiment defined by a cut normal to the leading edge, whereas the original grid uses the profile parallel to the free stream. The sweep angle is then introduced in the calculations when using the converted grid by prescribing a yaw angle according to the wing sweep at the farfield. The steady calculations were carried out using the implicit LU-SGS time integration scheme, turbulent flow was modelled using the standard Spalart–Allmaras turbulence model. Transition has been predicted on upper and lower surface of the profile with linear stability theory in form of the eN-method. The input data for the stability analysis was determined by a boundary layer code for swept, tapered wings.

Table 1 summarizes the investigated test cases and resembles some of the results, namely the predicted transition locations for upper and lower surface as well as the instability mode (Tollmien-Schlichting or cross flow instability) that has lead to transition. No experimental data for transition is available yet for comparison, however the experimental pressure distribution is on hand and can be compared to the numerical data. In Figures 1 – 6 it can be seen, that the pressure distribution from the transitional calculations fit very well to the experimental data, major discrepancies are only visible for the capturing of the shock for data point 213 (Fig. 4).

<table>
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<tr>
<th>Data Point</th>
<th>Ma</th>
<th>α</th>
<th>Re</th>
<th>Re</th>
<th>Re</th>
<th>x/c</th>
<th>x/c</th>
<th>mode</th>
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<th>N_{	ext{cr}}</th>
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<td>6.0</td>
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</table>

$c_n$: chord length normal to leading edge ($c_n = c \cos(\alpha)$); $c_n = 0.431m / c_n = 1.41ft$
$c$: chord length parallel to free stream ($c = c_n / \cos(\alpha)$); $c = 0.475m / c = 1.558ft$

$\alpha$: sweep angle; $\alpha = 25^\circ$

$Ma$: Mach number
$\alpha$: angle of attack parallel to free stream
$Re$: Reynolds number based on chord parallel to free stream
$Re_n$: Reynolds number based on chord normal to leading edge ($Re_n = Re \cos(\alpha)$)
$Re_{\text{ft}}$: Reynolds number per ft; $Re_{\text{ft}} = Re / c_n = Re / 1.41ft$

$x/c$: predicted transition location on upper/lower surface
$mode$: instability mode that lead to predicted transition location
$N_{\text{cr}}$: critical N-factor applied to the different modes

Table 1) Investigated cases and nomenclature

![Graph showing $c_{\infty}$ vs. $x/c$]
Figure 1) Pressure distribution. DP146, $Ma = 0.5$, $\alpha = 2.0$, $Re_n = 4.2 \times 10^6$

![Figure 1](image1)

Figure 2) Pressure distribution. DP165, $Ma = 0.6$, $\alpha = 1.0$, $Re_n = 5.7 \times 10^6$

![Figure 2](image2)

Figure 3) Pressure distribution. DP204, $Ma = 0.6$, $\alpha = 2.0$, $Re_n = 8.5 \times 10^6$

![Figure 3](image3)
5. Report from INTA

Transition can dramatically influence the main features of the flow (boundary layer separation) and have an important effect when considering the aerodynamics of aeronautical configurations such as high-lift configurations. The correct prediction of boundary layer transition from laminar to turbulent state is complicated by the strong interaction among different transition mechanisms and an accurate simulation of these phenomena is considered to be an open problem and an important requirement in current Navier-Stokes solvers.

A coupled approach consisting of a) computing the velocity profiles from surface pressure data by solving the boundary layer equations and b) detecting the transition outside the NS solver has been used for the achievement of this activity.

Two types of mechanism for transition have been considered 1) linear instability (by means of a Database Stability Method) and 2) leading-edge contamination (through a criterion based on the local attachment line Reynolds number) along with some assumptions: a) intermittency has not been considered b) separation of the boundary layer has been supposed to trigger transition at the separation point c) although not fulfilled near the root and the tip of a wing, flow has been assumed to be locally conical for the boundary layer computation and analysis.

This conical flow assumption has allowed to compute and analyze the boundary layer in several sections of the configuration and interpolate the results to the whole 3D domain in a 2.5D approach.

The transition prediction tool used in this activity can accurately compute a multicomponent configuration in 3D (e.g. a high-lift configuration consisting of a slat, a main wing and a flap) by predicting the location of the transition on both the suction side and the pressure side of each component. The tool has been conceived to be as geometry independent and easy to adapt to different flow solvers as possible and consists of four modules coupled with a in-house Navier Stokes solver:

1. A surface data post-processing module that extracts and processes all the information from the surface pressures and geometry to feed the other modules and checks the leading-edge contamination.
2. A boundary layer computation module that is a version of the Kaups-Cebeci code for the calculation of compressible boundary layers with suction on swept and tapered wings, assuming local conical flow and resolving the governing equations in sections with Keller’s box method.
3. A module that analyzes the stability of the boundary layer with the ONERA database method.
4. A transition prescription module implemented into the Navier-Stokes solver that uses the information on the “mean lines” and the transition lines to interpolate it to the 3D configuration.

- An in-house Navier-Stokes solver for multiblock structured grids (P-EMENS).

Fig. 2: Illustration of the NS computation, Surface data post-processing, BL & stability computation, and transition prescription steps on a 3D high-lift configuration.
General strategy for transition prediction

As seen in fig. 1, the transition prediction strategy is an iterative process beginning with a fully turbulent Navier-Stokes computation of the solution. The successive iterations follow this schematic procedure:
- Surface data post-processing module is run.
- In the first iteration, the transition lines in every section are set to be trailing edges (fully laminar boundary layers).
- For each side of each component in each section boundary layer computations are run and transition points are set to be the location of separation.
- Stability analysis is run up to the separation point, the transition criterion is evaluated and the transition point is set.
- Relaxation is applied to the transition lines.
- The resulting transition lines are prescribed in the Navier-Stokes solver and the next computation of the solution is run.

The boundary layer computation is sometimes too sensitive to pressure gradients and detects separation more upstream from the actual separation point. If at a given iteration the detected separation is located upstream from the real transition point in a section, in the following iterations the boundary layer is not going to be analyzed until the real transition location and the computation will not be able to converge to this point. To prevent this, a relaxation of the transition locations is needed along the iteration on the transition prediction process and so, the transition location in each section can only move upstream while iterating.

For the first iteration, the transition location in each section \( x_{tr} \) is set to represent a fully laminar boundary layer. The initial pressures for the boundary layer computation and stability analysis are taken out of a fully turbulent Navier-Stokes solution. In this way one starts at the first iteration with an overpredicted laminar zone as wanted, while avoiding a Navier-Stokes calculation with fully laminar boundary layers, which may not be physically relevant (depending on the case) and thus may cause convergence problems. For the successive iterations, a relaxation factor \( \omega \) is used in a relaxation relation of the form:

\[
x_{tr, i} = \omega \cdot x_{tr, detected} + (1 - \omega) \cdot x_{tr, i-1}
\]

To improve the accuracy of the boundary layer computation, the sweep angle that is used is not the geometric one but the effective one. It is calculated from the surface pressure distribution which also allows determining a local Reynolds number \( Re_\theta \) at stagnation point.

The stagnation point is obtained by looking for the maximum \( C_p \) point in the pressure distribution. As high precision is needed, the exact location of the stagnation point is determined by interpolating the pressure distribution around \( P_{stag} \) by cubic splines.

Along with the stagnation point, two additional points are picked out on each section by geometric criteria (limit in angle between two contiguous segments): the upper trailing edge and the lower trailing edge/corner of the cover. This leads to a couple of differentiated zones in each section: the “upper” boundary layer zone, located between the stagnation point \( P_{stag} \) and the upper trailing edge \( P_{trail} \), and the “lower” boundary layer zone, between \( P_{stag} \) and \( P_{turb} \) (lower trailing edge/corner of the cover, at which separation of the boundary layer is ensured).
Apart from the assumption of “separation-triggered” transition, the tool is able to detect two kinds of transition mechanisms: leading-edge contamination and linear instability. Leading-edge contamination is a particular kind of by-pass transition triggered by turbulence present in the flow upstream from an object, e.g. transition on the main wing because of turbulence created by the slat, or even transition on a slat caused by the turbulence inherent to a flow in a wind tunnel. In the tool it is modeled by a criterion on the local Reynolds number $Re_\theta$ at stagnation point: a section is considered contaminated (fully turbulent) if $Re_\theta > 100$.

Instability is the dominant mechanism in the most interesting cases. The amplitude of the instabilities are estimated thanks to N-factors, on which a criterion has to be set to detect transition. This threshold represents the amplitude at which instabilities break down into turbulence. The instability computation outputs three kinds of N-factor:
- NCF, corresponding to inflectional instabilities in the cross-flow (CF) direction,
- NTS, corresponding to Tollmien-Schlichting (TS) instability waves,
- Ntot, resulting from the higher local amplification rate between CF and TS.

The tool enables a criterion on NTS and NCF or on Ntot. These criteria are not absolute and depend on various environmental factors, such as the free-stream level of turbulence, and can only be used for comparison between similar cases. Moreover, these criteria fail to perform correct detection where the transition mechanism is unclear or mixed (i.e., where NTS and NCF are of the same order of magnitude). This is one of the reasons why this tool cannot be used as a “black box”: one has to keep an eye on the physical phenomena which trigger transition.

In order to get sufficient information to interpolate the data on the whole 3D configuration and check if any given cell fulfills the transition criteria independently from the data structure of the solver, the information has to be transmitted in a geometrical way. This is done by generating two “mean lines” on each component of each section, the “upper” one (MLU) linking Pstag and Ptrail, the “lower” one (MLL) linking Pstag and Pturb.
Fig. 4: “Mean lines” on the three components. Red: “upper mean line”. Blue: “lower mean line”.

These “mean lines” are generated by a recursive algorithm setting up a segment between Pstag and Pturb or Ptrail and looping over the points of the profile, if there is any point Pi not fulfilling the condition for the “mean line” (Both “mean lines” MLU and MLL are intended to discriminate points on the suction/pressure side of a profile from the rest), the segment is split into two and the process is repeated on each.

Fig. 5: Example of the generation process of the upper mean line on a section of the main wing at iteration 1 (a and b), iteration 2 (c) and iteration 3 (d).
The information on the “mean lines” and the transition lines is used to interpolate it to the 3D configuration; the output being a variable TR (set to 0 where the flow is laminar and to 1 where it is turbulent). The turbulent viscosity and the source terms in the turbulence models are multiplied by TR, so that they vanish in the laminar zone.

A loop over the boundaries of type wall is executed to check every surface cell. To identify the zone (upper, lower or none) associated to an arbitrary surface cell C of the 3D configuration, the same criterion on which the “mean lines” are based is used in an XZ-plane containing C. An interpolation procedure between two sections Si and Si+1, is used.

Fig. 6: Zone determination between two sections of a flap.

Once the component and the zone have been identified, the state of the surface cell is determined by checking the location of C with respect to the transition line. This is done by projecting C on the line determined by Ti and Ti+1 (the transition points on sections Si and Si+1 surrounding C) in the X-direction; point P is obtained and if xC < xP, C is set to laminar.

Fig. 7: Determination of the state of a surface cell between two sections of a flap.
Once the state of the surface is known, the laminar/turbulent state of the cells in the whole computational domain can be prescribed determining, for all the cells C\textsubscript{vol} of the computational domain, the closest surface cell C and the distance of C\textsubscript{vol} to the wall; if it is lower than the laminar zone thickness associated to C, then the cell C\textsubscript{vol} is set to laminar.

**Results**

**ONERA M6 wing**

This swept and tapered wing configuration has been selected to carry out test with following parameters of computation: \( M = 0.262 \), \( Re = 3.5 \cdot 10^6 \) and angles of attack of 0°, 5°, 10° and 15°. Eleven sections have been used for “mean lines” to be defined and transition analysis have been performed on them. The runs converged in 10 transition cycles, with a relaxation factor of 0.9. Experimental results in the section at 45% of span have been used to compare to quantitative results obtained by computation.

![Fig. 8: Outline and meshing of the ONERA M6 wing.](image)

Except for 0° angle-of-attack, where both CF and TS instabilities were greatly amplified at the same time and so the transition mechanism was unclear, the transition on the pressure side turned out to be driven by CF instabilities. Criteria on N-factors have been calibrated at 5° angle of attack using boundary layer solutions computed from fully turbulent pressures, resulting in \( N_{CF,\text{Criterion}} = 5.75 \), \( N_{TS,\text{Criterion}} = 7.15 \). \( N_{TS,\text{Criterion}} \) has been arbitrarily set, as TS-triggered transition has been supposed not to occur.
Fig. 10: Comparison of experimental and computed transition location in the section at 45% span of the ONERA M6 wing.

The transition locations on the upper set of points (pressure side) have been accurately predicted (except for $0^\circ$ angle-of-attack, as expected). Possibly due to a exaggerated sensitivity of the boundary layer computation to adverse pressure gradients, the transition locations on the lower set of points (suction side) have been predicted a bit upstream. Local conical flow assumption is not valid in the outboard region of the wing and this might have caused an inaccurate prediction of the transition compared to visualizations of the laminar/turbulent state in wind tunnel experiments.
AFV wing

The swept high-lift AFV configuration consists of a slat, a main wing and a flap with a sweep angle of 40º. It has been studied at 0.2 Mach number, 3.0·10⁶ Reynolds number, 30º of slat deflection, 20º of flap deflection and several angles of attack. 46 sections were used for “mean lines” to be defined and transition analyses were performed on 13 of them. The N-factor criterion was based on Mack's relation and set to $N_{env} = 7.15$. Most of the runs converged in 10 transition cycles, with a relaxation factor of 0.9. Fully turbulent simulations were performed.

Taking transition into account during the computations turned out not to have significant effects in the linear part of the $C_P(\alpha)$, $C_L(\alpha)$ and $C_D(\alpha)$ curves. This implied the lift, the induced drag and the pressure drag coefficients, which are the preponderant ones for high-lift configurations, remained nearly unchanged. The small sensitivity to transition of the drag coefficient observed in this case between turbulent and transitional computations can be explained by the fact that the main component of the AFV wing is always turbulent due to contamination.
Fig. 12: Pressure distribution at $y/b = 0.552$ for $\alpha = 22.5^\circ$. Comparison between experiment, PEMENS in fully turbulent mode and INTA’s transition prediction tool.

Computations using SALSA and $k$-$\varepsilon$ turbulence models have been performed detecting a small impact on performance close to maximum lift and beyond that seemed to be clearer with the last than with the former but no qualitative conclusion could have been drawn from these results as they did not agree with experimental data due to a fail in the solver (not in the transition prediction methodology itself) to correctly simulate the stall mechanism.

Fig. 13: Experimental and computed force coefficients for the AFV wing.
Fig. 14: Friction coefficient on the upper side of the main element, in a central section of the AFV wing at 5º angle of attack.

Nevertheless, the jump from lower to higher friction coefficient (Cf) values close to the prescribed transition location, compared to the smooth curve in the fully turbulent case, indicated that the transition was well captured by the solver.

In agreement with the analysis of experimental data, the leading-edge contamination analysis indicated that, for a threshold value of Re = 100 at stagnation point, neither the slat nor the flap should be subject to contamination. In contrast, the whole main wing was contaminated. The case of the slat is ambiguous at incidences of 15º and 17.5º.
Fig. 15: Effective sweep angle at various angles of attack for each of the three elements of the AFV wing.
Fig. 16: \( \phi \) at various angles of attack for each of the three elements of the AFV wing.

In the transition computed on the slat, fully laminar flow was replaced by Tollmien-Schlichting instability and then separation-triggered transition with increasing angle of attack, developing from the wing root towards the tip. This transition was in good agreement with the experiments except for 5º angle-of-attack where the upper side of the slat was fully laminar in these computations whereas it was subject to transition in the experiments.

![Fig. 17: Type of transition on the upper side of the AFV wing’s slat for a) 5º, b) 12.5º, c) 15º, d) 17.5º, e) 20º and f) 22.5º angle-of-attack. The dark blue color stands for turbulent flow, other colors for laminar flow: cyan in sections where the flow is fully laminar, light green in sections where TS instabilities trigger transition, and red in sections where the flow is considered to transition at separation point.](image)

**Conclusion**

During the development of this activity some crucial issues have been identified: The results depend greatly on the setting of the N-factor criterion when natural transition is the dominant transition mechanism. This criterion is often based on empirical rules that do not work well in general cases. This is the case when using the envelope N-factor, and when CF and TS transition are mixed like at 5º angle of attack on the AFV wing or at 0º angle of attack on the ONERA M6. The performance of the solver reproducing phenomena like the stall mechanism in the case of the AFV wing has a deep impact on the ability of the tool to correctly simulate flows where transition is an important phenomenon.

**REFERENCES**


6. Report from ONERA

ONERAS activities in AD/AG-44 are documented in references [1] and [2].

REFERENCES


**7. Report from QinetiQ**

This report summarizes the work performed during AG44 by QinetiQ. This work has largely used linear stability analysis through the QinetiQ BL2D and CoDS methods (as used in previous exercises in 2D) coupled to the JUPITER RANS flow solver. The methods have been applied to the M2355 swept-panel wing and 1303 UCAV test cases.

**Description of methodology**

As noted above, the QinetiQ methodology uses the BL2D\(^0\) and CoDS\(^0\) methods. BL2D is a finite-difference Newton method for swept-tapered laminar boundary layers employing a fourth-order-accurate compact-difference scheme in the wall-normal direction. BL2D is used to produce laminar boundary layer profiles for input into CoDS, because the generation of accurate profiles directly from RANS is very computationally expensive. CoDS is a robust \(eN\) method solving for the eigenvalues of the stability equations for three-dimensional parallel-flow boundary layers, also employing a fourth-order-accurate compact-difference scheme. Both methods are quasi-two-dimensional and are therefore applied to line-of-flight ‘strips’ distributed over the aerodynamic surfaces.

The interface between the transition prediction modules and the main flow solver is implemented as a loose coupling, through a module called Neptune. The methodology proceeds as follows:

- an initial RANS solution, in this case using JUPITER, is generated with an assumed transition locus, which is set by the user to be downstream of the likely actual transition;
- a series of line-of-flight pressure distributions is extracted from the RANS solution at different positions across the span. These are separated into upper and lower surface flows (i.e. they are separated at the attachment line) and are passed to the BL2D laminar boundary layer prediction code to enable the boundary layers to be computed. In coupling to RANS solvers (as opposed to viscous-coupled methods) the principal assumption of first-order boundary layer theory is invoked and the surface pressures are used to determine the total velocity at the boundary layer edge. The flow vector is determined using a swept-tapered flow assumption and the sweep angles, line-of-flight geometry and total velocity distributions along each analysis strip;
- the laminar boundary layer profiles from BL2D are fed into CoDS which outputs a transition point on each extracted section;
- new transition locus is determined from these points by Neptune and applied to the RANS solver;
- this process is repeated until convergence is obtained. In practice, an under-relaxation scheme is employed during the iterative process to reduce the risk of the predicted transition locus moving upstream of what should be its converged location.

The process is described in more detail in [0].

In JUPITER, transition is specified by a set of continuous loci on the wing surface each enclosing a laminar “zone”. This approach removes the need, present in some methods, to distinguish between wing upper and lower surfaces, which can be over-constraining for complex wing geometries.
M2355 test case

The QinetiQ M2355 test case\(^0\) is variable-sweep, untapered, untwisted panel wing model with a constant NLF aerofoil section. It was tested in the DERA/QinetiQ 8’ high speed wind tunnel in 1995 for a wide range of combinations of sweep, Mach number and Reynolds number. Measurements included balance forces, surface pressures, hot films and infra-red thermography for detection of transition. The model had shaping at the root and a tip body designed for each sweep so that 2.5D flow was obtained over large proportion of the span and in particular in the measurement region where the hot films were located.

For AG44 2.5D flow (i.e. infinite swept flow) was assumed and hence a block-structured grid was generated by QinetiQ consisting of identical 2D grid-planes stacked along a swept generator. In fact QinetiQ adopted the common practice for 2.5D flow of using a grid only one cell wide with periodic boundary conditions applied at the end faces. As such this test case is really only a “stepping-stone” to a genuinely 3D case. There is a spanwise component to the flow and hence crossflow transition can occur, but the geometric aspects of the transition prediction (e.g. the attachment line) are effectively no different to the 2D case. One of the multiblock grid planes is shown in Figure 1.

![Multiblock grid plane for M2355](image)

*Figure 1 – Multiblock grid plane for M2355*
A small subset of test cases, extracted from the full experimental dataset, were proposed for use in AG44, as described in Table 1. All these cases are for the wing at 25° sweep.

<table>
<thead>
<tr>
<th>DP</th>
<th>M&lt;sub&gt;3&lt;/sub&gt;</th>
<th>Re/ft (x10&lt;sup&gt;6&lt;/sup&gt;)</th>
<th>Alpha(°)</th>
<th>x/c&lt;sub&gt;onset&lt;/sub&gt;</th>
<th>x/c&lt;sub&gt;peak&lt;/sub&gt;</th>
<th>x/c&lt;sub&gt;comp&lt;/sub&gt;</th>
<th>Mode</th>
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<td>3.0</td>
<td>2.0</td>
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<td>0.37</td>
<td>0.42</td>
<td>T-S</td>
</tr>
<tr>
<td>165</td>
<td>0.600</td>
<td>4.5</td>
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<tr>
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<td>0.09</td>
<td>0.10</td>
<td>0.14</td>
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<tr>
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<td>0.15</td>
<td>0.165</td>
<td>0.23</td>
<td>C-F</td>
</tr>
</tbody>
</table>

Table 1 – AG44 test cases from M2355 dataset

Figures 2 to 6 show the surface pressures predicted by JUPITER for these cases compared with experiment and the associated N-factor envelopes, including the most critical crossflow and Tollmien-Schlicting modes. N-factors are only provided for the upper surface as transition was only measured on this surface in experiment.

On the pressure curves the predicted transition locations for the upper and lower surfaces are also marked. These are derived using assumed critical N-factors of 7 and 6 for crossflow and Tollmien-Schlicting respectively. These are commonly selected values and in fact match those used by DLR/TUB in AG44.

For these relatively simple cases, convergence of the transition location was achieved robustly and in a few iterations of the process in all cases.
Figure 2 – Case 146, $M=0.5$, $Re_{\overline{ft}}=3 \times 10^6$, $\alpha=2.0$, (a) surface pressure distribution & predicted transition location, (b) $N$-factors on wing upper surface

Figure 3 – Case 165, $M=0.6$, $Re_{\overline{ft}}=4.5 \times 10^6$, $\alpha=1.0$, (a) surface pressure distribution & predicted transition location, (b) $N$-factors on wing upper surface

Figure 4 – Case 204, $M=0.6$, $Re_{\overline{ft}}=6 \times 10^6$, $\alpha=2.0$, (a) surface pressure distribution & predicted transition location, (b) $N$-factors on wing upper surface
These figures confirm that the transition methodology is functioning in a robust and consistent manner for this test case.

In detail, comparing the predicted transition positions with the experimental values in Table 1, it can be seen that transition tends to be predicted upstream of the measured transition onset location. Obviously the predicted transition location is highly dependent on the chosen critical N-factors, which is an inexact science. However working in reverse to extract values for critical N-factor from the known transition positions does not yield a clear, single value which would produce consistently accurate results. For the cases with T-S transition, the critical N-factors derived this way lie in the range 6 to 8.

Of the cases where experiment indicated crossflow transition, Case 213 suggests that the chosen critical N-factor for crossflow of 7 is not unreasonable. However using this value for Case 219, it is found that the predicted crossflow N-factors are substantially below the level required for transition. Instead T-S transition occurs further downstream. The reason for this discrepancy is not clear, but it is interesting to note that DLR/TUB experienced the same. Hence it is likely that the error is due to inherent weaknesses in the use of linear N-factors rather than the RANS-coupling process.
1303 UCAV test case

Once the basic functionality of the JUPITER-Neptune process had been confirmed it was applied to the 1303 UCAV test case. This represents a greater challenge because the geometry and flow is genuinely three-dimensional.

The 1303 UCAV shape has been used on various wind tunnel models and tested in a range of facilities. All the test cases for AG44 were taken from wind tunnel studies at low-speed and high-speed which were carried out on a 1:10.8-scale model of the 1303, designated M2445, by QinetiQ in the 5m pressurised wind tunnel at Farnborough and by the Aircraft Research Association in the ARA 9ft x 8ft transonic wind-tunnel at Bedford. The intake on model M2445 was covered with a blended fairing and the rear of the body centre-section was modified with a cylindrical fairing to accept a sting mount. The model is shown installed in the 5m wind tunnel in Fig. 7a. The model was equipped with chordwise lines of pressure taps at spanwise intervals of 0.1η between η = 0.3 and η = 0.9. These taps were limited to the leading-edge region with the exception of the set mounted at η = 0.6, which ran full chord. A schematic of the pressure-tap layout is included as Fig. 7b. No transition trips were employed during the low-speed wind-tunnel testing at QinetiQ since one of the objectives was to investigate the effects of varying Mach and Reynolds numbers independently. For the tests in the ARA tunnel, transition was fixed by application of Ballotini in a straight-line strip from 5% of the model length at the centerline aft of the leading edge to 5% chord at η = 0.8 and continuing to the wing tip.

For all the results included here a previously generated multiblock CFD mesh with approximately 2.7 million cells was used. The basis for this selection was a mesh refinement study reported in [0]. Some initial work with transition prediction coupled to JUPITER is also reported in [0], but these results did not compare well with experiment, especially on the outer wing. The reason for this was found to be in the detail of the specification of transition locus rather than an underlying problem in the process as whole. This highlights that many of the challenges of coupling transition prediction to RANS in 3D relate to geometric and topological issues, rather than aerodynamic or numerical ones.
The application of the process coupled to JUPITER with the transition specification corrected and the resulting effects on the prediction of pressure, forces and flow topology are described in detail in [0]. Some of the key results taken from this paper are presented below.

For most cases, JUPITER was run with both the k-ε and k-ω turbulence models, fully turbulent and with natural transition. For the latter a value of critical N-factor of 9.0 was used. The use of different turbulence models enabled the specific effects of including transition prediction to be isolated from other factors affecting the accuracy of the CFD. Furthermore, a companion exercise using the Cobalt CFD method with the SARC and k-ω SST turbulence models (fully turbulent calculations) was performed by DSTL in parallel to the QinetiQ work in AG44 and these results are included in some figures. This helps identify which differences can be attributed specifically to use of transition prediction and which relate to the specific CFD method.

Some figures also include results labelled “Original k-ε”. This refers to the original, erroneous results from 2006, but these are included for completeness.

Figure 8 – Distribution of surface pressure coefficient.
\( M_\infty = 0.25, \alpha = 5.62^\circ, Re = 5.6 \times 10^6 \)

Figure 8 shows the surface pressures from the various CFD runs compared with experimental results from the QinetiQ 5m wind tunnel. Apart from the “Original k-ε” results (which can be ignored) all the CFD predictions compare closely with each other and with experiment across most of the span. At \( \eta = 0.9 \) the fully turbulent results with k-ω with both JUPITER and Cobalt show a premature flow separation. This is not present in JUPITER k-ω results once transition prediction is included.
Figure 9 – Distribution of surface pressure coefficient.

\(M_\infty = 0.25, \alpha = 7.77^\circ, \text{Re} = 5.6 \times 10^6\)

Surface pressures from the same set of CFD variants at higher incidence, \(\alpha = 7.77^\circ\), but the same Mach and Reynolds numbers, are compared with experiment in Figure 9. Cobalt predicts the onset of vertical separation outboard of \(\eta = 0.5\). Fully turbulent JUPITER k-\(\omega\) predicts separation at the leading edge outboard from \(\eta = 0.7\), but there are no indications that this separation is vertical in nature. However with natural transition include, k-\(\omega\) predicts pressures close to experiment, including the same separation characteristics at \(\eta = 0.9\). On the other hand, even with natural transition, JUPITER with the k-g model does not predict any significant separation.

The surface pressures in Figure 10 are for a higher Mach number case, \(M_\infty = 0.35\), and use data from the tests in the ARA TWT. As noted above, transition was fixed for the ARA tests, but nonetheless a number of investigators had found it difficult to match the experiment with CFD assuming fully turbulent flow. It can be seen in Figure 14 that including natural transition appears to improve the prediction of the pressures on the outer wing and in particular it removes the premature prediction of flow separation from the leading edge.

The predicted transition locus for this case on both the upper and lower wing surfaces is shown in Figure 11. On the lower surface the predicted natural transition on the inner wing is close to the transition fix in experiment. Moving outboard the predicted natural transition occurs aft of the experimental fix to a degree which increases with span. The reverse “wedge” around \(\eta = 0.1\) appears to be related to an effect of the wing/fuselage blending in this region. In practice it is unlikely a tapering laminar region like this would be maintained. This highlights one of the challenges of creating a valid transition locus from stripwise data.
On the upper surface the predicted transition is very close to the leading edge and in fact ahead of the trip used in the wind tunnel tests. This may explain some of the difficulties experienced by CFD investigators in trying to
match the experiment in this case. Also striking is that, despite transition being very close to the leading edge, the
effect of having a laminar rather than turbulent attachment line has a very large effect on the predicted surface
pressures on the outer wing.

At the same time as AG44 was active, but outside the scope of the AG, QinetiQ was leading the collaborative
development of a fully 3D transition capability, i.e. using genuinely 3D – rather than strip-wise - boundary layer
and transition prediction methods. In the latter stages of the active period of AG44, the method was applied to the
1303 UCAV test case, as reported in [0].

Conclusions

The coupling of a transition prediction method using linear N-factors and working on a stripwise basis has been
successfully coupled to the JUPITER RANS solver for 3D flows. Many of the major issues with the coupling
relate to handling geometric and topological issues.

The method has been shown to give reasonably consistent predictions of transition location on the M2355 2.5D
test case when compared to the 3D wind tunnel results. The remaining discrepancies can be attributed to inherent
weaknesses in the linear N-factor approach rather than limitations of the coupled process itself.

The same process has also been successfully applied to the 1303 UCAV test case, which has more complex 3D
flow, although the geometry remains relatively simple. The addition of natural transition has been shown to
generally improve the accuracy of the RANS CFD for this test case.

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M.T. Arthur, H.P. Horton and M.S. Mughal. “Modelling of natural transition in properly three-
8. Summary of work

Most of the technical work of the programme was completed before or during 2008. All partners have demonstrated flow prediction with natural transition in three dimensions. The contribution of each partner is summarised below, where all figures are taken from the earlier partner reports.

CIRA/University of Naples
The CIRA/UNINA work concentrated on the SD 7003 aerofoil test case. In this case a laminar separation bubble forms on the upper surface near the trailing edge at low incidences and moves upstream as the incidence increases.

Using large eddy simulation (LES), CIRA/UNINA were able to reproduce the LES results of other authors, including the prediction of the laminar bubble. They also showed that RANS with a k-ω SST turbulence model was able predict a “laminar” bubble even without specifying transition, if very low values for freestream turbulence were specified. However predictions did not match well to the equivalent LES results (see figure 1).

![Figure 1 - SD7003 Aerofoil. Pressure coefficient and skin friction coefficient, Re=6.0x10⁴, α=8°. Solid line: present LES, dash-dot line: RANS k-ω SST with predicted laminar-turbulent transition, o: ILES (Galbraith and Visbal)](image1)

Nonetheless the simple RANS method is able to predict the growth and upstream movement of the bubble with incidence, as shown in Figure 2.

![Figure 2 - SD7003 Aerofoil, Re=6.0x10⁴: RANS, k-ω SST with laminar-turbulent transition not prescribed, variation of skin-friction coefficient at different angles of incidence.](image2)
DLR/TU-Braunschweig

DLR/TUB completed all the proposed test cases for the M2355 infinite swept wing geometry. Thereafter no further work on the test cases was undertaken at DLR where, instead, effort has been concentrated on large, three-dimensional full aircraft configurations outside AG44 for exploitation of the capability.

DLR/TUB used a linear N-factor transition method (based around the COCO and LILO methods) coupled to the Tau RANS solver. They used the supplied multiblock mesh but transformed it to a single plane with the normal to leading edge section geometry. The infinite wing sweep was then imposed via the flow solver.

The method was shown to work robustly and to produce consistent results. Using values of $N_{\text{crit}}$ of 6.0 for T-S and 7.0 for crossflow, transition was predicted significantly upstream of the measured location for transition onset for T-S dominated case, but significantly downstream for crossflow-dominated cases.

INTA

INTA implemented a coupled prediction method with external boundary layer and transition calculations. This included a process to identify and flag the transition lines based purely on geometric considerations and hence independent of the specific RANS solver and its data structure.

The method was applied to the ONERA M6 wing test case. The resulting predictions of the variation with incidence of the upper and lower surface transition locations at the 45% span section are compared with experiment in Figure 3. The critical N-factors for crossflow and T-S transition were calibrated for the $\alpha = 5^\circ$ case using data from a fully turbulent CFD calculation.

![Transition position NCF+NTR Method](image)

*Figure 3: Comparison of experimental and computed transition location in the section at 45% span of the ONERA M6 wing.*

INTA also completed a set of calculations with coupled transition prediction on the EUROLIFT AFV high lift wing at ranges of incidences up to and beyond maximum lift. The predicted variation with incidence of the transition location on the slat upper surface is shown in Figure 4.
Figure 4 - Type of transition on the upper side of the AFV wing slat for a) $5^\circ$, b) $12.5^\circ$, c) $15^\circ$, d) $17.5^\circ$, e) $20^\circ$ and f) $22.5^\circ$ angle-of-attack. The dark blue color stands for turbulent flow, other colors for laminar flow: cyan in sections where the flow is fully laminar, light green in sections where TS instabilities trigger transition, and red in sections where the flow is considered to transition at separation point.

**ONERA**

ONERA completed calculations of the flow over the EUROLIFT AFV 3D multi-element high-lift configuration and the axi-symmetric ogive-cylinder configuration early in the AG. For these calculations the Arnal-Habiballah-Delcourt-Gleyzes (AHD-GL) criterion was coupled to the elsA RANS code. A leading edge contamination criterion based on $\tilde{R}$ was also included. For the EUROLIFT AFV case, the use of transition coupling with elsA generally improved the prediction of the lift behaviour close to and at maximum lift relative to fully turbulent calculations.

Although not included in its original plan, ONERA has concentrated on implementing and validating the Menter-Langtry transport-equation-based transition model in the ONERA elsA flow solver. The model has the potential advantage that it is a ‘local’ model (i.e. it uses only local values of quantities) which should make it easier to apply to complex geometries and flows. Implementation of the model involves considerable effort because two significant functions which control intermittency production were not provided in the original formulation and so have to be determined through correlation with reference data. The validation test cases comprised the ogive-cylinder (AG44) test case together with the NLF(1)-0416 Somers laminar flow aerofoil. Figure 5 shows the computed skin-friction coefficient for one of the ogive-cylinder test cases, Case D, for which there was a positive
pressure gradient in the wind-tunnel. The parameter $\sigma_0$ is a diffusion coefficient in one of the transport equations of the Menter-Langtry model and the value $\sigma_0=2$ was used by Menter et al. Increasing $\sigma_0$ decreases the history effect on the momentum thickness Reynolds number at transition and a value $\sigma_0=10$ was found to give better agreement in this case. The additional result shown in the figure, denoted 3c3d, was obtained using a boundary layer code in which the Menter-Langtry transition model has also been implemented.

![Figure 5 - Ogive-cylinder test case D. Comparison of skin-friction coefficient computed using the elsA RANS code with experimental values.](image)

QinetiQ
QinetiQ completed all its planned test case calculations (i.e. M2355 and 1303 UCAV). A linear N-factor method (based around BL2D and CoDS) coupled to the JUPITER RANS solver was used throughout. For the M2355 test case, values of $N_{crit}$ of 6.0 and 7.0 for T-S and crossflow transition respectively were used. For the T-S dominated cases, transition was predicted upstream of the measured position, indicating that a larger value for $N_{crit}$ should be used. The transition location was well predicted for one of the crossflow-dominated cases, but for the other crossflow transition was not predicted at all and transition was said to occur further downstream due to T-S.

For the 1303 UCAV case, the inclusion of natural transition was found to improve the accuracy of the prediction of surface pressures on the outer wing by delaying the onset of separation at the leading edge. This was true for both lower Mach number cases, as tested in the Farnborough 5m wind tunnel, and for cases at slightly higher Mach number compared to tests in the ARA Transonic Wind Tunnel, as illustrated in Figure 6. In the latter case, transition on the upper surface was predicted to occur upstream of the transition fix applied in the wind tunnel tests (Figure 7). This helped explain poor comparisons obtained previously outside AG44, where transition was specified at the locations of the fixes on the wind tunnel model.
In additional work, the laminar boundary layer and stability analysis methods were replaced by fully three-dimensional methods coupled to the RANS flow solver. The method has been demonstrated in calculations of the flow over the AFRL 1303 UCAV concept though further work to improve the robustness is required.
9. Concluding remarks

With reference to the original objectives of AG44 some conclusions are drawn as follows:

**Coupling of empirical criteria or stability analysis to Navier-Stokes computations on simple three-dimensional geometries**

All partners have successfully demonstrated transition prediction models working in combination with RANS CFD codes for three-dimensional geometries. The test cases completed include the axisymmetric ogive-cylinder, the M2355 infinite swept wing, the ONERA M6 wing, the EUROLIFT AFV high-lift wing and the 1303 UCAV wing/body. All the cases studied in AG44 are relatively simple; in particular none has any breaks or interruptions (such as an engine/pylon) across the entire span (or around the circumference in the case of the cylinder).

In all cases the transition prediction methodology uses stripwise rather than fully 3-dimensional information. With this approach, the implementation challenges of moving from 2 to 3 dimensions are mostly related to the logic of handling the geometric and topological issues, rather than the boundary layer and transition tools themselves.

Where experimental data exists, reasonable accuracy was generally obtained. Any limitations on accuracy appear to relate to the underlying weaknesses of the transition tools (e.g. linear N-factor methods), but these are no greater in simple 3D cases than in 2D.

Some partners demonstrated effective approaches to including the prediction of leading edge contamination on 3D cases, using established attachment line transition criteria. However validation of the methods within AG44 was limited, partly by the lack of reliable experimental data.

Some also demonstrated the inclusion of simple criteria to capture transition caused by a laminar separation bubble. These approaches are not able to model the bubble itself in any detail.

**Improved modelling of the transition zone and the impact on solution accuracy and robustness (especially relaxation requirements for transition position)**

Only one partner (CIRA) examined this issue in any detail, focusing on the issue of predicting the laminar separation bubbles on the SD7003 aerofoil. Results from other authors using LES were reproduced.

CIRA showed that it was possible to obtain a form of “laminar” bubble with a fully turbulent RANS calculation provided very low values of freestream turbulence are specified. However the location and extent of the bubble and the post-bubble behaviour were not accurately captured.

Modelling of the transition zone, and particularly laminar bubbles, in RANS continues to pose a significant challenge.

**Understand the relative merits of the low-Reynolds-number turbulence modelling approach (applied to external aerodynamic flows) as compared to the use of mechanism-specific criteria for complex configurations**

Only ONERA addressed this item. ONERA successfully implemented a version of the Menter local-correlation-based transition and derived correlations for the unpublished functions in that model. A change to the diffusion coefficient from the published value was found to be beneficial for accuracy.
Predictions on two aerofoil cases using the new model were broadly in line with results using conventional criteria-based models coupled to RANS. The local model is intended to show advantages in useability for geometrically complex cases.
Appendix A – Resources & Milestones

- **Resources**

<table>
<thead>
<tr>
<th>Resources</th>
<th>Year</th>
<th>Total 06-10</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>2006</td>
</tr>
<tr>
<td>Person-months</td>
<td>Actual/Planned</td>
<td>A1 P2</td>
</tr>
<tr>
<td>Other costs</td>
<td>Actual/Planned</td>
<td>A0 P0</td>
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</table>

- **Completion of milestones**

<table>
<thead>
<tr>
<th>Work package</th>
<th>Planned</th>
<th>Actual</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Initially</td>
<td>Currently (updated)</td>
</tr>
<tr>
<td>Mesh generation &amp; computation of Re/a trends</td>
<td>May 2007</td>
<td>Sep 2008</td>
</tr>
<tr>
<td>Meeting</td>
<td>May 2007</td>
<td>May 2007</td>
</tr>
<tr>
<td>Modifications to methods, repeat computations</td>
<td>Aug. 2007</td>
<td>May 2009</td>
</tr>
<tr>
<td>Implementation of ALT criterion</td>
<td>Nov 2007</td>
<td>May 2008</td>
</tr>
<tr>
<td>Comp. of complex config. using trans. criteria or low-Re-turbulence models</td>
<td>Aug. 2008</td>
<td>May 2008</td>
</tr>
<tr>
<td>Literature search by partner; exchange of information</td>
<td>Feb. 2007</td>
<td>Feb 2007</td>
</tr>
<tr>
<td>Event Description</td>
<td>Start Date</td>
<td>End Date</td>
</tr>
<tr>
<td>----------------------------------------------------------------------------------</td>
<td>------------</td>
<td>------------</td>
</tr>
<tr>
<td>Test of trans. zone predictions; refinements</td>
<td>Nov. 2007</td>
<td>May 2008</td>
</tr>
<tr>
<td>Release of SD7003 test case and mesh</td>
<td>Sep. 2007</td>
<td>Oct 2007</td>
</tr>
<tr>
<td>Review meeting/workshop</td>
<td>Nov. 2007</td>
<td>-</td>
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<tr>
<td>Phase1 comp. of SD7003 case by NS and viscous coupled approaches</td>
<td>June 2008</td>
<td>May 2008</td>
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<tr>
<td>Phase2 computation of SD7003 test case</td>
<td>Sep. 2008</td>
<td>May 2009</td>
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<tr>
<td>Report on accuracy of transition-zone and LSB modelling</td>
<td>Dec 2008</td>
<td>April 2010</td>
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