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Testing of a new algebraic laminar-turbulent transition model on a range of airfoils at moderate Reynolds numbers

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Abstract. High quality prediction of laminar-turbulent transition for flow around airfoils is an important task for industrial applications. Prediction of such flows is usually carried out using the RANS framework in combination with transition models. The present study shows the capability of a recently developed algebraic transition model for prediction flows around different airfoils. The results of the model demonstrate satisfactory agreement with the experimental data and with results of existing differential models.

1. Introduction

The problem of accurate prediction of airfoil characteristics in a wide range of angles of attack is of great importance for the aviation, wind energy and power plant industries. At low Reynolds numbers and angles of attack high quality solutions of this problem is usually impossible without taking into account laminar-turbulent transition. Turbulent transition models are used in the RANS framework to address this problem.

Existing transition models can be divided into two groups. The first group consists of differential models which solve additional transport equations for auxiliary transition specific variables. The most successful model in this group is γ-$Re_{\theta t}$-SST [1] model, which uses additional equations for turbulent intermittency γ and local critical transitional Reynolds number. The main drawback of differential models is poor convergence, which stimulated development of the models of the second group. These models use algebraic relations for prediction of laminar-turbulent transition.

Recently a new algebraic transition model was introduced [2], but as of now the range of flows it has been tested on is rather narrow. In the present study more detailed testing of the model is performed on a range of flows and the results are compared with two of the most successful differential transitional models γ-$Re_{\theta t}$ SST [1] and γ-SST [3].

2. Computational strategy

The model was tested on a wide range of boundary layer flows with different levels of freestream turbulence and pressure gradient magnitude as well as a range of airfoil flows at low Mach numbers. All the obtained solutions are grid independent. The first near-wall grid step in wall-normal direction was small enough to resolve the viscous sublayers and the expansion ratios in wall normal direction do not exceed 1.1. Grids were locally refined in the most grid sensitive regions: around the front tip of an airfoil ($\Delta y_1^+<1$) to allow the resolution of thin boundary layers and in the vicinity of laminar-turbulent transitions. Computations were carried out using the commercial software ANSYS Fluent and an academic NTS code.

3. Considered flows

3.1. Flat plate boundary layer cases

The T3 transitional boundary layer cases [4] have become a traditional necessity in testing of all laminar – turbulent transition models. For cases with zero pressure gradient (T3A-, T3A, T3B) the computational domain has a rectangular shape, for cases T3C2 - T3C5 the pressure gradient was imposed on the flow by shaping the upper boundary of the domain to match the experimental conditions (Figure 1). Boundary conditions were set as follows: no-slip wall at the plate surface, uniform profiles for velocity and turbulence characteristics at the inlet boundary. Symmetry boundary conditions were specified at the top free-stream boundary for slip wall imitation and constant pressure at the outlet. The inflow k and ω values were chosen to best match the experimental turbulence decay in the inviscid flow.

Figure 1. Computational domain and boundary conditions for flat plate boundary layer cases without pressure gradient (left) and with pressure gradient (right).

3.2. Computations of flows around airflows at low freestream turbulence levels.

The airfoils considered in the present work vary in thickness and shape: Eppler-387, S809, NLF-0414F and NLF-0416F. Wings based on these airfoils were experimentally studied in rectangular wind tunnels ([5]-[8]) in wide range of angles of attack, low turbulence intensity magnitudes ($T_u < 0.1\%$) and moderate Reynolds numbers based on airfoil chord length and freestream velocity. More detailed information about parameters in the experiments is presented in table 1.

The same numerical problem formulation presented on figure 2 was used for all airfoil simulations. Computational domain has a rectangular shape representing a 2D slice of a wind tunnel with the height H corresponding to experimental one. Inlet and outlet boundaries of the tunnel are located at a distance of about $10C$ upstream and downstream of the airfoil leading edge, where C is the airfoil chord. The angle of attack is set by rotating the airfoil in the tunnel.

The boundary conditions were set as follows. Airfoil surface has a no-slip wall condition. Uniform velocity and turbulence characteristics are specified at the inlet boundary. The value of kinetic energy chosen to represent experimental values and dissipation rate is calculated by $\omega = 10 \cdot U_\infty / C$. Constant pressure was set at the outlet and symmetry conditions were used at the wind tunnel top and bottom walls for slip wall imitation (boundary layer on this wall was not taken into account).

Table 1. Considered airfoils and experimental regimes.

Airfoil	H/C	Re	T_u,%
Eppler-387	15	$2{\cdot}10^5$, $3{\cdot}10^5$	0.06
S809	3	$2{\cdot}10^6$	0.04
NLF-0414F	2.5	$3{\cdot}10^6$	0.08
NLF-0416F	3.75	$4{\cdot}10^6$	0.10

Figure 2. Computational domain and boundary conditions for airfoil cases.

4. Results

4.1. Cross-code comparison for the γ-alg-SST model.
Figure 3 compares results from implementations of the model in the two computational codes. Results for the flat plate case T3A and NLF(1)-0414F airfoil demonstrate that results between two codes are generally in good agreement with each other. NTS code shows a tendency to slightly delay the transition onset in comparison to ANSYS Fluent, however the difference is not substantial. The most likely reason for these discrepancies are differences in the numerical methods used in the codes.

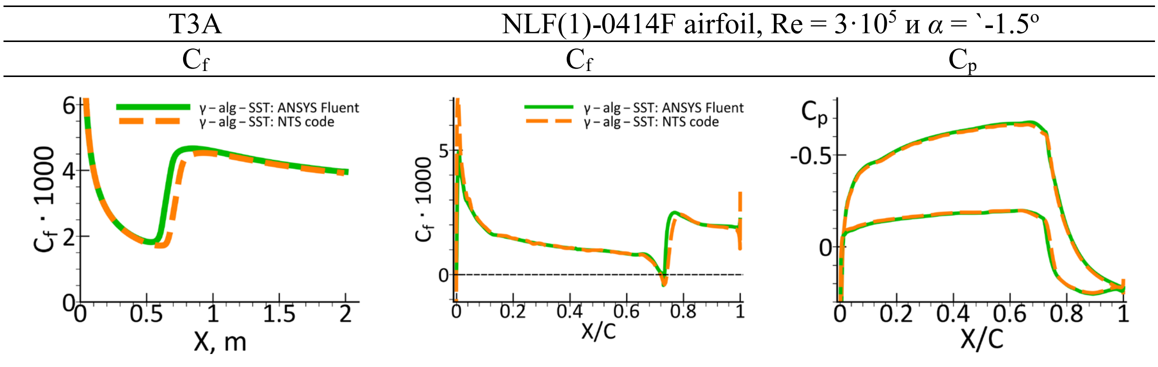

Figure 3. Comparison of results obtained using studied model as implemented in the two codes for the cases of the flat plate boundary layer [4] and the NLF(1)-0414F airfoil [5].

4.2. Model comparison.
Results for the simple cases presented in figure 4 demonstrate that the transition location predicted by the considered algebraic model is in good agreement with the results of the differential models and experimental data for the flows with zero pressure gradient (T3A- and T3A). For flows with non-zero pressure gradient (T3C2, T3C5) the algebraic model tends to predict an earlier transition location than the differential models do. However the results of the algebraic model are in satisfactory agreement with the experimental data.

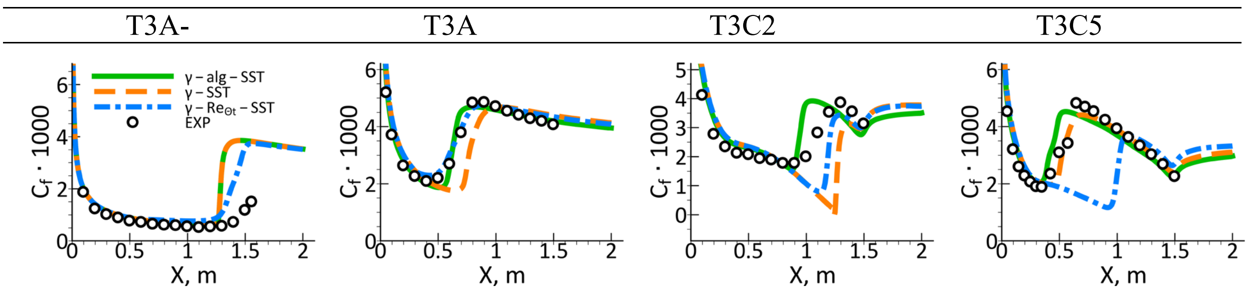

Figure 4. Skin friction distributions for flat plate boundary layer cases [4].

Results for more complex flows around airfoils are shown on figures 5-8 and can be divided in two main groups: prediction of natural transition and transition induced separation (so-called bubble transition).

The first type of transition is presented in prediction of flow around a NLF(1)-0416F airfoil at $Re = 4{\cdot}10^6$. For this case the algebraic model predicts earlier natural transition than differential models. The transition location on the upper airfoil surface for various angles of attack is shown on figure 5 (Left). In the experiment the transition location could only be determined as lying somewhere between two adjacent orifices where laminar (open symbols) turbulent flow (solid symbols) was detected. The comparison CFD results with the experimental data shows that that transition location predicted by the γ-$Re_{\theta t}$-SST model lies out of the possible experimental range for all the considered angles of attack. This model tends to predict bubble transition (negative skin friction coefficient on figure 5, right). The one equation γ-SST model predicts natural transition and its results are in better agreement with the experimental data, however for high negative angles of attack the model delays transition as much as the γ-$Re_{\theta t}$-SST model does. Only the algebraic model prediction of the transition location is in satisfactory agreement with the experimental data for all the considered angles of attack ($\alpha = -12^o - 12^o$).

Transition location on the upper surface	Airfoil characteristics, α=0°

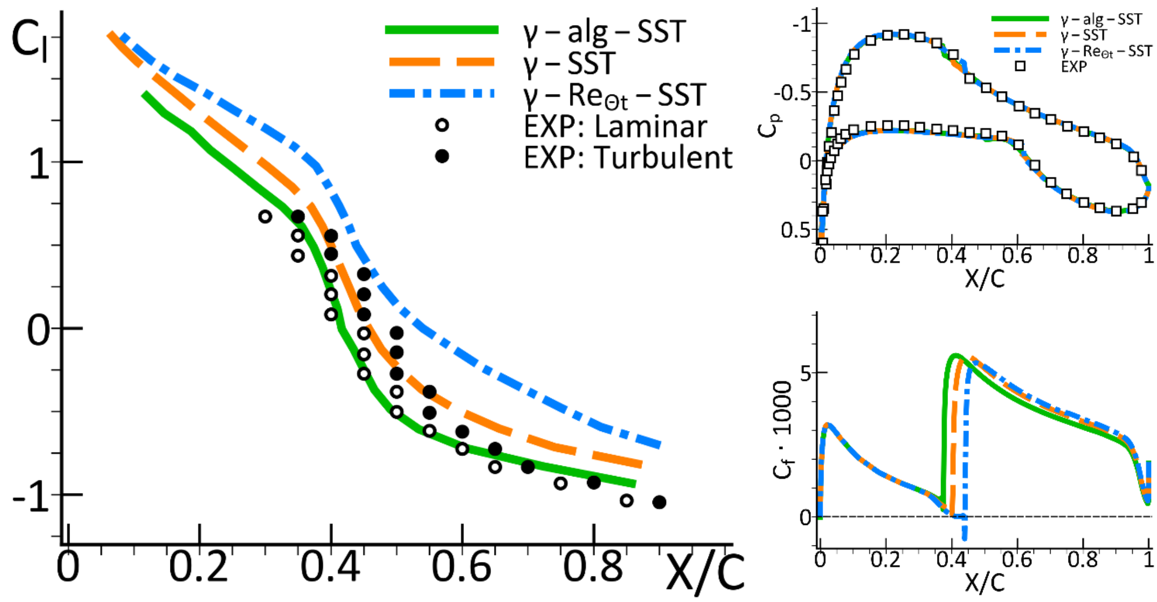

Figure 5. Transition locations (Left) and aerodynamic characteristics (Right) for NLF-0416F airfoil at $Re = 4{\cdot}10^6$ [7].

For the rest of the considered cases the main mechanism of the transition is laminar separation bubble. For the relatively low Reynolds number case (Eppler-387 airfoil) all the considered models predict a laminar separation bubble on the suction side of the airfoil (Figure 6). However the size of the bubble depends on the model. The algebraic model tends to predict smaller laminar separation bubble than differential models which leads to slightly better agreement with the experimental data for $Re = 3{\cdot}10^5$. The distribution of the skin friction and on figure 7 (Left) also show that the smaller bubble of the algebraic model fits the experimental pressure coefficient (Figure 7, right) better than other models.

For the higher Reynolds number S809 airfoil case the smaller bubble size for the algebraic model leads to earlier vanishing of laminar separation bubble ($\alpha = 6^o$) than for the differential models ($\alpha = 7^o$). Figure 8 illustrates this effect for different models. In the experiment this phenomenon was observed at lower $\alpha \sim 5^{\circ}$. Thus all the models delay transition prediction for $\alpha > 5^{\circ}$, however results of the algebraic model are in better agreement with the experimental data. For low angles of attack all the models predict bubble transition as well as the in the experiment. In the experiment the transition was detected in the reattachment position. For this flow regime differential models predict the reattachment point slightly better than the algebraic model.

Re = $3 \cdot 10^5$	Re = $2 \cdot 10^5$

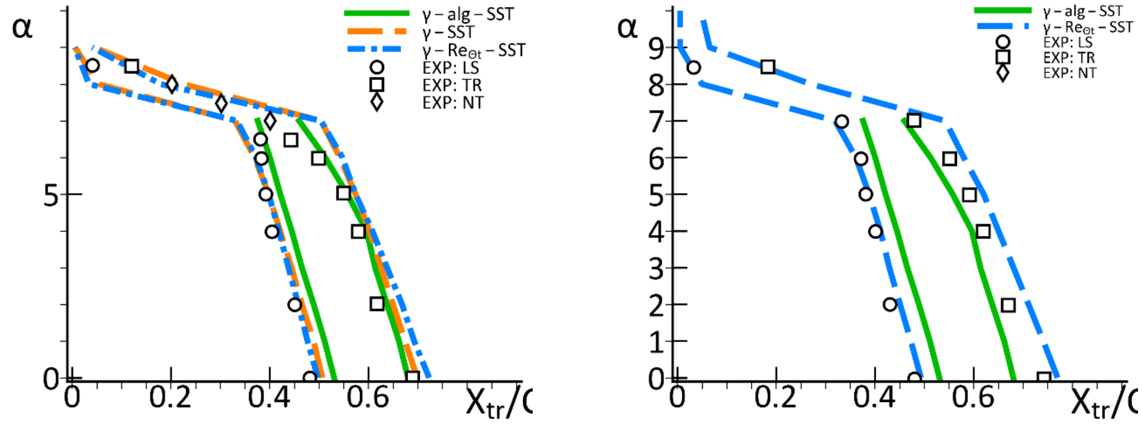

Figure 6. Transition location on the suction side for Eppler-387 airfoil [6] at different Reynolds numbers.

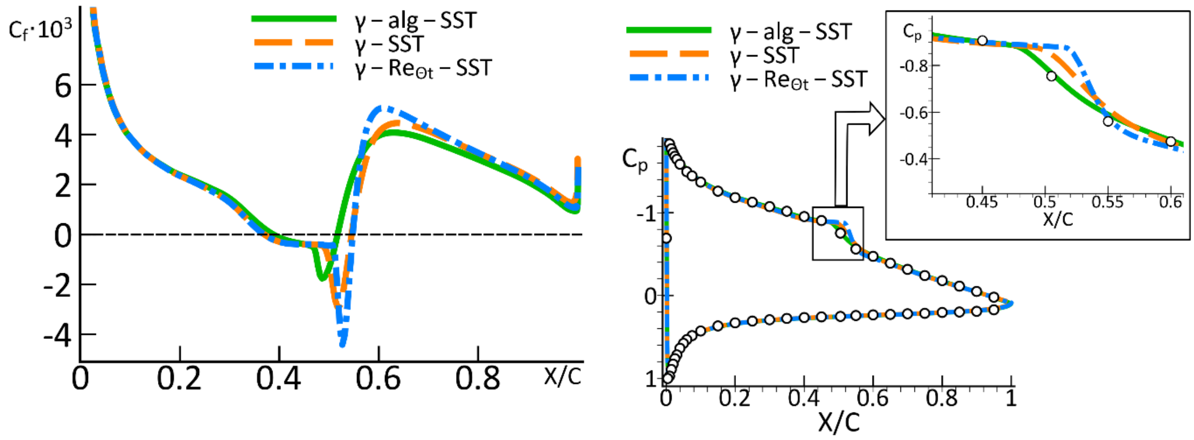

Figure 7. Skin friction (left) and pressure coefficient (right) distributions for Eppler-387 airfoil [6] at Re=$3 \cdot 10^5$ and α = 6°.

γ-alg-SST	γ-SST	γ-Re$_{\Theta t}$-SST

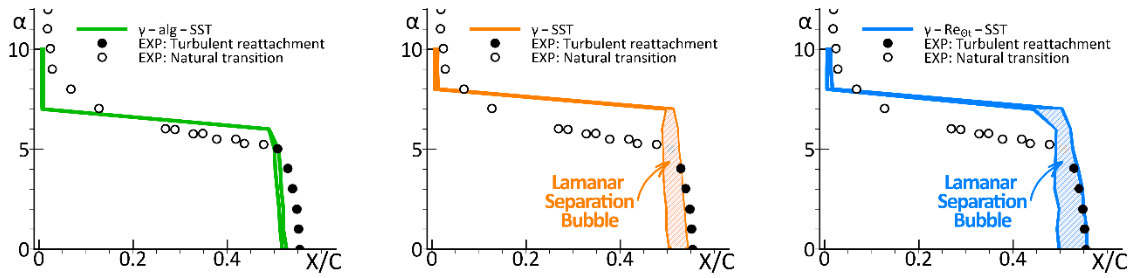

Figure 8. Transition location on the suction side of the S809 airfoil [8] at Re=$2 \cdot 10^6$.

5. Conclusion

The present work presents tests of the algebraic transition model for SST on boundary layers and airfoil flows at moderate and high Reynolds numbers using commercial ANSYS Fluent software as well as the academic NTS code. Results from the two codes coincide well with each other, considering the different numerical methods that are used in the codes. Comparison with differential models shows that the algebraic model is not inferior to them for boundary layer with and without pressure gradient. On airfoil flows with low freestream turbulence intensities the algebraic model predicts smaller separation bubble sizes and an earlier change to natural transition which leads to better agreement with experimental results than obtained by the differential models.

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