Comparative analysis of transition models at different farfield turbulence intensities

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Abstract. Four differential models for laminar-turbulent transition prediction were tested with different freestream turbulence levels on two cases: turbulent boundary layer and flow around NACA0021 airfoil. Computational results show that none of the considered models are able to predict transition in a wide range of freestream conditions. SA $\varepsilon$ model is applicable only for natural transition scenario with low freestream turbulence intensity and predicts fully turbulent solutions in other cases. Among $\gamma$-based models SST $\gamma$-Re$_{\theta}$ and SST $\gamma$ have shown better agreement with experiment than SA $\gamma$.

1. Introduction
Though most of engineering flows are turbulent, they often contain laminar areas. The most important example is the boundary layer, initial part of which is laminar due to low local Reynolds number. Downstream, with growth of the Reynolds number, the boundary layer becomes turbulent. Since laminar and turbulent boundary layers develop differently it is very important to predict location of laminar-turbulent transition precisely. Unfortunately, it is impossible in the frame of traditional turbulence models for Reynolds-Averaged Navier-Stokes equations closure [1]. This circumstance has led to creation of special models for prediction of laminar-turbulent transition which can be considered as an extension of traditional RANS models.

The location and type of laminar-turbulent transition in the boundary layer are dependent on different factors, with the most significant of them being the freestream turbulence level $Tu = 100\% \cdot \overline{u'^2}/U_0$, where $\overline{u'^2}$ is the intensity of turbulent fluctuations and $U_0$ is the freestream velocity. At low turbulence levels ($Tu < 0.8\%$) natural transition is observed whereas bypass transition is typical for higher turbulence levels. Sometimes, in flows with adverse pressure gradient and low freestream turbulence levels (often takes place on wings and airfoils), another type of transition takes place - the so-called “bubble” transition, which occurs when a laminar boundary layer detaches from the surface, instantly becoming turbulent and reattaching.

Sensitivity of the transition type and location to turbulence level is very difficult to model. The present work aims to check the ability of different transition models to catch this effect correctly.

2. Considered models
Four differential transition models were chosen for testing. Two of them, SST $\gamma$-Re$_{\theta}$ [2] and SST $\gamma$ [3], are based on the SST [4] turbulence model. Both are developed to predict all types of transition and
use an additional transport equation for turbulent intermittency $\gamma$ to control the turbulent kinetic energy production. These models are widely used and are implemented in a range of commercial CFD codes.

The third model, SA-$\gamma$ of Coder and Maughmer [5], is an example of applying the $\gamma$ approach to Spalart–Allmaras one-equation turbulence model [6]. Intermittency equation in this model was derived by adaptation of the SST $\gamma$-$Re_\theta$ model equation.

The last considered model, SA $e^N$ of Coder [7], contains a differential equation for the growth factor $N$ with source terms based on the Drela [8] realization of $e^N$ method [9] which was initially developed for natural transition prediction. For extension of this method to higher $Tu$ levels, Mack [10] correction was used. It proposes a way of changing the magnitude of the critical disturbance growth rate factor from constant value, equal to 9, to one depending on the turbulence level.

3. Test cases

This study addresses two test cases: flat plate boundary layer and flow around NACA0021 airfoil. For both cases experimental data with different turbulence intensities is available.

All the computations were carried out using the NTS CFD code [11]. The code uses a finite volume method and structured multiblock overlapping grids (the so-called “Chimera” technology). Convective fluxes in the equations for an incompressible fluid were approximated with the third order Rogers-Kwak upwind scheme [12] and in the turbulence models equations with a second order upwind scheme. All of the presented solutions are fully converged and grid-independent.

3.1. Flat plate transitional boundary layer

Experiments with transitional boundary layers at different turbulent intensities and pressure gradients (T3 series) were conducted in Rolls Royce [13]. Three cases with no pressure gradient from these series were considered in the present work, namely T3A- with 0.87 % freestream intensity, T3A with 3.3% and T3B with 6.2%. Even at the lowest intensity bypass transition takes place.

The computational domain contains a freeflow region upstream of the plate’s leading edge to minimize the pressure gradient effect. The boundary conditions are as follows: uniform velocity profile was set at the inlet boundary, constant pressure at outlet and upper boundaries, no-slip wall at the plate. Turbulence characteristics at the start of the plate were chosen to coincide with experimental values. A computational grid of 305x146 cells was used.

Experimental and computational skin friction coefficients distribution for all cases and models are presented on figure 1. One can see that there is a significant difference in the transition location between models and it is mostly pronounced for the lowest turbulence intensity.

The best agreement with experimental data is obtained using SST $\gamma$-$Re_0$ and SST $\gamma$ models, which is not surprising since they were calibrated using T3 series experiments. The SST $\gamma$ results are slightly closer to experimental in T3A and T3B cases while in T3A- both models predict an early transition, SST $\gamma$-$Re_0$ being much closer to experiment.

Results of SA-based models are in less consistency with experimental data than of the SST-based models for all considered cases: SA $\gamma$ predicts too early transition in all instances, while SA $e^N$ predicts the earliest transition in case of T3A- (fig. 1a), and in cases T3A (fig. 1b) and T3B (fig. 1c) with higher turbulence intensity the solution is fully turbulent with no observable transition at all. This result is predictable and is in agreement with the nature of $e^N$ method. It can be concluded that SA $e^N$ model can only be used for low turbulence intensities when natural transition is observed, despite the Mack critical N-factor correction [10].
3.2. NACA0021 Airfoil
Symmetrical airfoil NACA0021 with relative thickness of 21% was considered under conditions that were used in the experiment [14]. The computations are carried out at Reynolds number equal to
2.7·10^5, based on the chord and freestream velocity and three different levels of turbulence intensity: 0.6%, 3% and 6%. Angles of attack from 0º to 30º were considered.

Computations were performed on a structured 593x200 cells C-grid in a 40C x 40C computational domain, where C is the airfoil chord.

Dependence of lift and drag coefficients on the angle of attack for the low turbulence level (Tu=0.6%) is shown on Figure 2. For the attached flows (angles of attack less than 10º) all of the considered models’ results are close to each other and are in good agreement with experimental data. The difference between solutions for higher angles of attack is mostly connected with underlying turbulence model (SST or SA) than with transition prediction approach.

Results of SST γ-Re_θ and SST γ models are close and in better agreement with experimental data than SA based models’ results. The SST γ leads to fully detached flow regime (boundary layer at suction side separating from the leading edge of the airfoil) at lower angles of attack. Despite the different transition modelling approach both SA based models also show similar results. The fully detached flow appears at higher attack angles than in the experiment, which leads to 15-20% difference in maximum lift coefficient. The good agreement with experimental data at high angles of attack (22-30º) seems to be a coincidence and is most likely caused by error cancellation.

For the investigation of turbulence intensity effect the 15º angle of attack flow was considered. Skin friction coefficient distributions (Fig. 3) show that this effect strongly depends on the specific transition modelling approach rather than baseline turbulence model. For the low freestream turbulence intensity (Tu=0.6%) all models predict similar flow structure (Fig. 3a): bubble transition on the suction part of the airfoil and laminar flow on the pressure side. However, the bubble size is approximately two times longer for all γ-based models than for the SA eN model.

With increasing turbulence intensity a significant difference occurs between solutions obtained with different models. In the case of Tu=3% (Fig. 3b) SA eN model shows fully turbulent behavior on both sides. This fact confirms once more that eN-based methods are inapplicable at high turbulence intensities. On the pressure side both SST-based models predict laminar flow whereas SA γ predicts transition at about ¾ of the chord. The type of transition on the suction side depends on the model: bubble transition is obtained with SST γ and bypass transition - with SST γ-Re_θ and SA γ. Further increase of turbulence intensity (Tu=6%) results in transition on pressure side for all considered models (Fig. 3c), while the type of transition on the suction side is similar to that at Tu=3%.
Effect of turbulence intensity on the drag $C_d$ and lift $C_L$ coefficients is shown on Figure 4. One can see that none of the models are able to predict rapid drag coefficient growth with turbulence level increasing (Fig. 4a). Only SST-$\gamma$ predicts monotonous growth for the lift coefficient, which is consistent with experiments (Fig. 4b), but the slope is approximately three times lower than in the experiment. Other models predict quantitatively wrong dependence: lift coefficient is decreasing for the SA-based models and not monotonous for SST-$\gamma$-$Re_\theta$.

Fig. 4. Dependence of skin friction (a) and drag coefficients (b) on turbulence level for all studied models
4. Conclusions
The main conclusion from the present work is that existing transition models are far from perfection. None of the considered models are able to adequately predict transition in a wide range of freestream turbulence intensities. SA eN model is applicable only for cases with low $Tu$ values where natural transition is observed, while at high $Tu$ it is inclined to predict fully turbulent solutions. SST $\gamma$-Re$_\theta$ and SST $\gamma$ have shown better agreement with experimental results and thus surpass the SA $\gamma$ model. However, it should be noted that SST-based models are more complex and often lead to poorer convergence and higher computational cost than SA-based models.

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