Comparative analysis of transition models in prediction of flow over NACA-0012 airfoils in tandem

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Abstract. Comparative analysis of several semi-empirical turbulence models taking into account laminar-turbulent transition ($\gamma$-Re$_{in}$ SST, $\gamma$-SST, $\gamma$-SA and $e^N$-SA) was carried out for flow around an airfoil in the wake generated by another upstream airfoil for different Reynolds numbers and distances between airfoils. Two dimensional Reynolds-averaged Navier Stokes equations were solved in different CFD codes on unstructured and chimera-type structured grids. Results of the considered transition models are virtually independent of the computational code. Results of the SST-based transition models are in reasonable agreement with experimental data while SA-based models predict too early transition.

1. Introduction
The flow over the blades of turbomachinery are usually highly three dimensional, turbulent, and unsteady due to their complex geometry and interaction between the rotating and nonrotating blades. The flows are transitional over a considerable part of the blade, especially in machines of compact design and small size. Therefore correct prediction of wall characteristics in the transitional boundary layer are important for developing highly efficient compressor blades.

In engineering practice these characteristics are mostly predicted with semi-empirical turbulence models which take into account laminar-turbulent transition (transition models). Generally, transition models are calibrated on simple flat plate boundary layer with zero and non-zero pressure gradient, or flows around airfoils with uniform freestream while the incoming flow on the blades of turbomachinery is no uniform. Thus, to determine the applicability of the transition models for prediction flow around turbine blades it is necessary to study the accuracy of these models when the blade is mounted in the wake of another blade. In this paper we considered the relatively simple flow over NACA-0012 airfoils in tandem which demonstrates the accuracy of different transition models and gives the recommendation of the most appropriate transition model for flow over blade cascade.

2. Considered transition models and CFD codes.
Incompressible numerical simulations of this flow were carried out using the commercial ANSYS Fluent and the academic NTS (Numerical Turbulence Simulation) codes using Reynolds-averaged Navier Stokes (RANS) equations in combination with four transition models solving additional equations together with k-$\omega$ SST [1] or SA [2] turbulence models. The considered transition models use different approaches for prediction of the locations of transition. The first method is based on solving additional transport equations for the turbulence intermittency ($\gamma$-Re$_{in}$ SST [3], $\gamma$-SST [4], and $\gamma$-SA [5]). The last model based on the $e^N$ method is $e^N$-SA [6]. SST based transition models ($\gamma$-Re$_{in}$ SST and $\gamma$-SST) are...
implemented in both considered CFD codes, while SA based models (γ-SA and eN-SA) are available only in the NTS code. The double precision version of the solvers was used in all the computations. For all transport equations, including the equations for turbulent variables, a second order discretization scheme for the convective terms was selected. For each test case, all simulations were started from the same uniform initial guess and the simulations were performed until the normalized maximum residuals of all the equations were below a value of 10⁻⁵.

3. Problem definition
Flow around NACA-0012 airfoils in tandem mounted in the centre of the wind tunnel was experimentally carried out for different regimes [7]. The Reynolds number based on incoming uniform flow and airfoil chord \( C \) was varied from \( 2 \times 10^5 \) to \( 6 \times 10^5 \) together with the distance between the airfoils. The parameters of flow configurations are shown in table 1. In the experiment strips of sandpaper were pasted on both sides of the upstream airfoil between \( X/C = 0.58 \) and 0.65 to generate a stable wake flow.

![Schematic of the arrangement of airfoils](image)

**Figure 1.** Schematic of the arrangement of airfoils

| Case  | Distance between airfoils, G | Reynolds Number \((\times 10^5)\) |
|-------|-----------------------------|-------------------------------|
| Case-1 | 1.00                        | 6.00                          |
| Case-2 | 1.00                        | 2.00                          |
| Case-3 | 0.50                        | 2.00                          |
| Case-4 | 0.25                        | 2.00                          |

The height of the computational wind tunnel \( H = 2C \) corresponds to the experimental one. Inlet and outlet boundaries were located 10\( C \) upstream of the leading edge of the first airfoil and downstream of the trailing edge of the second airfoil correspondingly. A constant velocity is specified at the inlet section of the computational domain. No-slip conditions are used on the airfoil boundary and constant pressure is specified on the outlet. Symmetry boundary condition was specified on the wind tunnel upper and lower walls for imitation of the slip-walls. For \( k-\omega \) based models, the inlet turbulent kinetic energy provides experimental turbulence intensity \( T_u = 0.3\% \) near the leading edge of the upstream airfoil and the specific dissipation rate is specified as \( \omega = 10 \cdot U_\infty / C \) [2]. For the SA-based model only the analogous value of turbulent viscosity was specified. In order to reproduce the sound paper on the upstream airfoil the onset of transition in the simulations was tripped at \( X/C = 0.58 \). The efficiency of this method is shown for distribution of skin friction coefficient over the upstream airfoil in Figure 2.
Figure 2. Distribution of the computational and experimental skin friction coefficient on the upstream airfoil for the Case-1

4. Computational grids
Considered CFD codes used different types of grids. For ANSYS Fluent a hybrid unstructured grid was generated using ANSYS Meshing. A hex grid was generated in the thin area around the airfoil and downstream in the wake while triangle cells were generated in the rest of the computational domain. A chimera type grid was used was used in the NTS code with structured grids generated in three overlapping areas: the domain around upstream and downstream airfoil and wind tunnel domains. In both codes $Y^+$ in the first near wall cell was less than 1, about 400 points were specified on the airfoil and the total number of cells was about $10^5$. The grid structure and parameters are presented in the Table.2.

Table 2. Grid structure and parameters for ANSYS Fluent and NTS code.

|              | Fluent | NTS code |
|--------------|--------|----------|
| Grid structure | ![Grid structure](image1.png) | ![Grid structure](image2.png) |
| Grid in the vicinity of the airfoil | ![Grid vicinity](image3.png) | ![Grid vicinity](image4.png) |
| 400 points on the airfoil | 440 points on the airfoil |
| $\Delta Y^{+1,\text{max}} \sim 1.0$ | $\Delta Y^{+1,\text{max}} \sim 0.1$ |
| Aspect ratio in normal-wall direction | 1.1 | 1.2 |
| Total number of cells | $10^5$ | $1.2 \times 10^5$ |
5. Results and discussions

5.1 Cross-code comparison
Cross-code comparison of the skin friction on the downstream airfoil (Figure 3) shows good or even perfect agreement between transition models implemented in both ANSYS Fluent and NTS codes. The results of the $\gamma$-Re$_{θ}$-SST model are virtually identical for all the cases, only small differences are observed in the transitional area. The more visible difference for the $\gamma$-SST model in Case-1 (Figure 2 Left) contains higher sensitivity of the model to different numerical implementation.

| Case 1 | Case 2 |
|-------|-------|
| ![Graph for Case 1 and Case 2](image1.png) | ![Graph for Case 1 and Case 2](image2.png) |

**Figure 3.** Distribution of skin friction coefficient on the downstream airfoil for Case-1 (Left) and Case-4 (Right) predicted by the different transition models implemented in considered CFD codes.

5.2 Comparison of CFD results with experimental data
The comparison of computational and experimental distributions of skin friction coefficient over the downstream airfoil is shown in Figure 4. The SA-based transition models ($\gamma$-SA and $e^N$-SA) tend to predict too early laminar-turbulent transition. Meanwhile $e^N$-SA developed for the aerodynamic flows with low turbulence incoming flow predicts transition on the leading edge. The results of the SST-based transition models are in reasonable agreement with the experiment. The onset of transition, predicted by these models is close to the experimental value. However accuracy of the models also leaves much to be desired. These models as well as the $\gamma$-SA model predict shorter transition length defined as the distance between minimum and maximum values of skin friction in comparison to the experiment for all the cases (Table 3, Length of transition region).

![](image3.png)
Figure 4. Distribution of the computational and experimental skin friction coefficient on the downstream airfoil for different cases.

Table 3. Transition extents in cases tested

| Case  | EXP  | $\gamma$-Re$_{99}$-SST | $\gamma$-SST | $\gamma$-SA |
|-------|------|------------------------|--------------|-------------|
| Case 1| 0.20 | 0.20                   | 0.30         | 0.11        |
| Case 2| 0.35 | 0.35                   | 0.50         | 0.30        |
| Case 3| 0.32 | 0.37                   | 0.37         | 0.20        |
| Case 4| 0.28 | 0.35                   | 0.32         | 0.14        |

Onset of transition, $X_{s}/C$

| Case  | EXP  | $\gamma$-Re$_{99}$-SST | $\gamma$-SST | $\gamma$-SA |
|-------|------|------------------------|--------------|-------------|
| Case 1| 0.32 | 0.18                   | 0.14         | 0.07        |
| Case 2| 0.40 | 0.27                   | 0.21         | 0.15        |
| Case 3| 0.33 | 0.24                   | 0.24         | 0.10        |
| Case 4| 0.30 | 0.17                   | 0.16         | 0.05        |
6. Conclusions
The applicability of four different transition models for prediction of flow around turbine blades was carried out using the example of numerical simulations of flow over NACA-0012 airfoils in tandem in various regimes. The results of the considered transition models are virtually independent of the CFD code and type of the computational grid (hybrid unstructured vs. chimera-type structured). It is shown that the most accurate results correspond transition models based on the SST model ($\gamma$-Re$_\theta$-SST or $\gamma$-SST). The SA-based transition models tend to predict too early laminar-turbulent transition ($\gamma$-SA) or even fully turbulent flow ($e^\lambda$-SA) on the downstream airfoil. Therefore, the use of the $\gamma$-Re$_\theta$-SST or $\gamma$-SST transition models can be recommended for prediction flow over blade cascade.

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