Comparison of a Local Correlation-Based Transition Model with an e^N-Method for Transition Prediction

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Summary The γ-$Re_{\theta t}$ model, a parallelizable, correlation-based, transition transport model was implemented into the DLR TAU code. Its capability to predict transition has been investigated at one-element airfoils, such as Somers NLF(1)-0416 airfoil and a transonic airfoil of Messerschmidt-Bölkow-Blohm. The influence of relevant input parameters is discussed in terms of predicted transition locations and skin friction coefficient distributions. The standard transition prediction approach in the DLR TAU code is based on the e^N-method, a non-local, streamline based approach. Coupling TAU with a boundary layer and stability analysis code enables transition prediction within the RANS solver. The results of both transition prediction methods are compared to each other and the advantages and short-comings of either model are pointed out.

1 Introduction

The prediction of laminar to turbulent transition in the boundary layer is an important component in the computation of flows over airfoils and wings. Important flow quantities like friction or drag coefficients are affected by the transition process. As transition of flow is based on complex and still not completely understood mechanims, its prediction within a CFD code is a challenging task.

In the field of aerospace, the e^N-method is the most common approach to predict transition. It is the standard transition prediction method [2, 4, 5] in the hybrid Reynolds-averaged Navier-Stokes (RANS) solver TAU [3, 11, 12] of the German Aerospace Center (DLR). The method is based on linear stability theory and makes use of non-local boundary layer quantities like the disturbance growth along

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streamlines for predicting transition. These quantities are not easily accessible in RANS-based CFD codes and additional boundary layer and stability analysis tools are needed. The parallelization of these external tools and therefore, the total performance of the method in terms of parallel computation is limited. However, the e^N-method traces back on a wide experimental database and reasonable results for complex flows have been obtained.

Within the past years, an alternative approach came up to predict boundary layer transition. The γ-$Re_{\theta t}$ transition model is a two-equation transport model first proposed by Menter et al. [8, 9]. The motivation was to design a transition prediction method for RANS codes which can be easily applied to massively parallelized computation on unstructured grids. Only local variables, which can be provided at every grid point by a RANS code, are used for transition prediction. No additional codes are needed. The two transport equations of the model lean on the structure of transport equations of the well known two-equation turbulence models. One transport equation for the intermittency γ is used to trigger transition in the boundary layer. The intermittency is the dimensionless ratio of the time a flow is turbulent compared to a total time. The second transport equation for the momentum thickness Reynolds number $Re_{\theta t}$ transports the necessary information for transition onset from the freestream into the boundary layer. Its source term is mainly controlled by an empirical transition criterion, which takes into account the turbulence intensity and the pressure gradient. The γ-$Re_{\theta t}$ transition model is coupled to the SST k-ω turbulence model.

In the end of 2009, Menter and Langtry [10] published the complete model with the until then missing correlations for two empirical model parameters, F_{length} and $Re_{\theta c}$. Several approaches for these correlations had been already published by other authors before. Some of the known correlations have been implemented into TAU and validated by means of a flate-plate test case [13].

The aim of the present work is to identify the potentials of the γ-$Re_{\theta t}$ transition model and to assess its performance in terms of prediction accuracy and in comparison to the e^N-method for a test case with a high level of turbulence in the freestream.

2 Somers NLF(1)–0416 airfoil

The implementation of the γ-$Re_{\theta t}$ transition model into TAU has been validated by predicting the transition locations on the one-element 2D airfoil NLF(1)-0416 of Dan Somers [14]. Experiments were performed in the Langley Low-Turbulence Pressure Tunnel. Pressure coefficient distributions were obtained by pressure measurements at a Reynolds number based on the airfoil chord of Re = 4 Mio and a Mach number of M = 0.1. The turbulence intensity of the wind tunnel at the given chord Reynolds number was about $Tu_\infty = 0.03\%$.

The given results were computed on a mesh with 122 hexahedral cells on the upper and 134 hexahedral cells on the lower surface in streamwise direction. The total number of points is 25000. The boundary layer is resolved with 30 points normal to the wall and $y^+(1)$ is less than 0.5. The results of computations on a finer mesh did not differ significantly.

The relevant initial parameters for the γ-$Re_{\theta t}$ transition model are the turbulence intensity Tu_0 and the viscosity ratio $\mu_t/\mu|_0$ at the farfield boundary. They are set to $Tu_0 = 0.07\%$ and $\mu_t/\mu|_0 = 5$. The turbulence intensity for the present case is small. The decay of turbulence in the farfield is weak and Tu_0 at the farfield boundary can be set close to the freestream value Tu_∞. The transition location has been determined at the minimum of the skin friction coefficient distribution for the streamwise coordinate. Figure 1 shows the transition locations on both airfoil sides as a function of the angle of attack. The prediction is in good agreement with the experimental data and with the results of the e^N-method. For the latter, the critical N factor was set to 11. The boundary layer code, used within the e^N-method, can not handle separation of flow. Therefore, the transition location for separation-induced transition equals the separation point. The derived transition locations are slightly upstream of experimental data and results obtained by the γ-$Re_{\theta t}$ transition model.

3 Messerschmidt–Bölkow–Blohm airfoil VA-2

The second test case is a supercritical transonic airfoil of Messerschmidt-Bölkow-Blohm (MBB) Transport- und Verkehrsflugzeuge designated with VA-2. Experiments were performed in the NASA Ames High Reynolds Channel No. II by Mateer et al. [6], [7]. The case has been mainly chosen, because experimental data for skin friction coefficient distributions at different Reynolds numbers and angles of attack are available. For Reynolds numbers based on chord length of Re = 0.6 Mio. and Re = 6 Mio. the skin friction has been detected at an angle of attack of $\alpha = -0.5°$. For the Reynolds number of Re = 2 Mio. measurements were performed at the following angles of attack: $\alpha = -0.5°, 3.5°, 7.5°$ and $11.5°$. The Mach number for all cases is M = 0.2. The freestream turbulence intensity for the investigations is in the range of $Tu_\infty \sim 0.5$ %. Because of the high turbulence intensity, the test case is challenging in the sense of initializing turbulence intensity and viscosity ratio at the farfield boundary in an appropriate way for the γ-$Re_{\theta t}$ model.

The following uncertainties for the measurement data are indicated: the angle of attack can vary within $\pm 0.02°$, and the overall uncertainty in skin friction coefficient collection is about 7%.

Besides the measurements, computations were performed by the authors of [11]. They used two different 2D grids with a resolution of 521 x 121 and 321 x 91. Only small differences were observed when comparing the results. For flow computation the SST k-ω turbulence model was applied together with a transition prediction method of Drela and Giles [1]. The method simplifies the stability analysis which is carried out for the e^N-method and solves a single ordinary differential equation for the amplification rate n. It is assumed, that transition occurs if either n equals 9 or separation is detected.

For the present work a hexahedral mesh with a total number of 75000 grid points is used. The number of cells on the surface of the airfoil is 197 on the upper and 179 on the lower side. $y^{+}(1)$ is less than 0.5 and the resolution of the boundary layer perpendicular to the surface of the airfoil is about 90 cells.

Computations with the standard transition prediction approach based on the e^N-method were performed with a critical N factor of 3.6. This N factor has been derived from the formula of Mack estimating a freestream turbulence intensity of 0.7 %. From investigations with the γ-$Re_{\theta t}$ model for Re = 2 Mio. and $\alpha = -0.5$, it was found, that $Tu_\infty = 0.7\%$ led to results which are closer to the experimental data than computations with $Tu_\infty = 0.5\%$. For initialization of the γ-$Re_{\theta t}$ model, the turbulence intensity at the farfield boundary was set to $Tu_0 = 3$ % and the viscosity ratio to $\mu_t/\mu|_0 = 20$. Both parameters determine the level of turbulence in the vicinity of the airfoil. The turbulence quantities k and ω decay in the farfield because of the dominating sink terms in the associated transport equations. Therefore, Tu_0 and $\mu_t/\mu|_0$ are set to higher values at the farfield boundary, to compensate the decay. These settings were not changed for computation of flow for the different Reynolds numbers at $\alpha = -0.5°$. The same freestream conditions are assumed for all cases, respectively.

The experimentally determined skin friction distributions at Re = 0.6, 2 and 6 Mio. and $\alpha = -0.5°$ are compared to results obtained with the γ-$Re_{\theta t}$ transition model, the e^N-method and the numerical computations given by the authors. Figure 2 displays the skin friction coefficient c_f as a function of chord length x/c for Re = 0.6 Mio. Measured transition locations on upper and lower airfoil side are located at $x/c|_{tr,lower} \approx 0.5$ and $x/c|_{tr,upper} \approx 0.8$.

The transition location given by the γ-$Re_{\theta t}$ transition model at the lower airfoil side is in good agreement with the experimental data but on the upper side it is slightly upstream at $x/c|_{tr,upper} \approx 0.7$. The turbulent level of skin friction is below the experimentally determined level for both, lower and upper airfoil side. The deviation is significant for the given Reynolds number.

The e^N-method predicts transition upstream of the experimentally derived transition locations for both airfoil sides. As the same turbulence model in TAU is used for computation of turbulent flow for the e^N-method and the γ-$Re_{\theta t}$ transition model, the turbulent level of both approaches is similar.

Results obtained by the authors with the transition prediction method according to Drela leads to a transition location close to experimental data at the lower side of the airfoil. At the upper side, transition is predicted downstream of the experiment. Here, transition is induced by separation. Although, the computation has been performed on a different grid with a different code, the turbulent level of c_f equals the distributions predicted by the TAU code and deviates significantly from the experimental data.

Figure 3 shows c_f as a function of chord length x/c for Re = 2.0 Mio. and $\alpha = -0.5°$. The transition locations from the experiment are at $x/c|_{tr,lower} \approx 0.3$ and $x/c|_{tr,upper} \approx 0.2$. With the same initial conditions as before, the γ-$Re_{\theta t}$ transition model predicts transition at the lower side in agreement with the experiment. At the upper side of the airfoil, transition is predicted downstream of the transition location found from the experiment. The results are similar for the e^N-method, but the transition location at the upper side of the airfoil is determined further downstream compared to the experiment and the γ-$Re_{\theta t}$ transition model. Finally, the numerical computation of Mateer et al. predicts transition far downstream of the experimental data for both airfoil sides. For the given Reynolds number, all applied transition models fail to predict transition at the experimentally derived transition locations on the upper airfoil side. Furthermore, comparing the different transition prediction approaches, the results deviate significantly from each other. Caused by the high turbulence intensity for the present case, bypass transition may occur on the upper airfoil side, which can not be handled by the e^N-method and the approach of Drela.

In figure 4, c_f is plotted for Re = 6.0 Mio. at an angle of attack of $\alpha = -0.5°$. In the experiment, transition is detected at $x/c|_{tr,lower} \approx 0.1$ and $x/c|_{tr,upper} \approx 0.05$. The γ-$Re_{\theta t}$ transition model predicts transition correctly on the upper side, but on the lower side, the transition location is upstream compared to the experiment. The turbulent level of skin friction coefficient is overpredicted. Transition locations resulting from the e^N-method are in good agreement with the experimental data for both airfoil sides. The slope of c_f at the lower side deviates and also the turbulent level is below the experimental data. The numerically obtained transition locations given by the method of Drela are far downstream of the experimental data.

For the latter case, the γ-$Re_{\theta t}$ transition model was not able to predict transition correctly on the lower airfoil side. If the viscosity ratio at the farfield boundary is reduced, transition locations on both sides of the airfoil move downstream and neither on the upper nor on the lower side, transition is predicted correctly.

The setting of turbulence intensity and viscosity ratio at the farfield boundary influences the predicted transition locations significantly for the γ-$Re_{\theta t}$ transition model. The need to account for the decay of turbulence in the flow field and the estimation of an appropriate viscosity ratio is clearly a disadvantage of the model. The estimation of Tu_0 might be removed by modifying the SST k-ω turbulence model with the approach of Spalart and Rumsey [15]. This modification includes the extension of the transport equations for k and ω with constant source terms. These source terms prevent k and ω from falling below a certain boundary. The estimation of $\mu_t/\mu|_0$ is still necessary to achieve the correct transition locations.

Figure 5 shows the skin friction distribution for the modified SST k-ω model for Re = 2 Mio. and $\alpha = 7.5°$. The turbulence intensity at the farfield boundary now equals the freestream turbulence intensity, which has been set to $Tu_\infty = 0.7\%$. A viscosity ratio $\mu_t/\mu|_0 = 5$ led to reasonable transition locations. At the upper side, transition occurs near the leading edge while at the lower side both approaches predict transition slightly downstream the experimentally derived transition location. In the laminar region, computation with the modified SST k-ω model leads to slightly increased c_f distribution. On the contrary, in the turbulent region, c_f is below the original model formulation.

4 Conclusions

Both, the e^N-method and the γ-$Re_{\theta t}$ transition model are able to compute transition locations accurately on standard test cases like the airfoil of Somers, which is characterized by a low freestream turbulence level. As the γ-$Re_{\theta t}$ transition model is designed for turbomachinery applications, it should be able to predict transition for cases with higher turbulence levels like the MBB VA-2 airfoil. However, estimating adequate values for the initial turbulence intensity and viscosity ratio at the farfield boundary makes the application of the model difficult.

Modifying the turbulence model according to the approach of Spalart and Rumsey simplifies the setting of initial conditions for the turbulence intensity. Reasonable results are obtained for the given case. Further investigations on other test cases are necessary to verify the modified turbulence model approach and to improve the initial setting for the viscosity ratio to allow more precise application of the γ-$Re_{\theta t}$ transition model.

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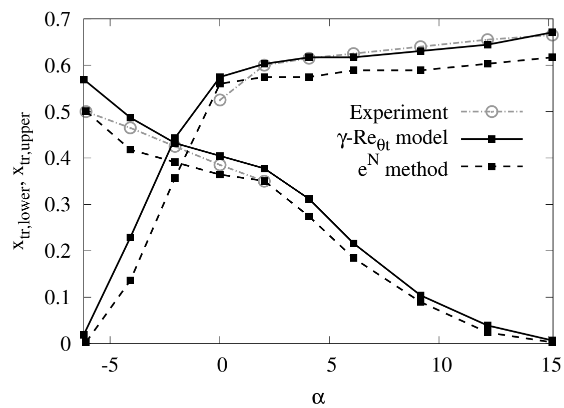

Fig. 1: Transition locations on upper and lower side of Somers airfoil

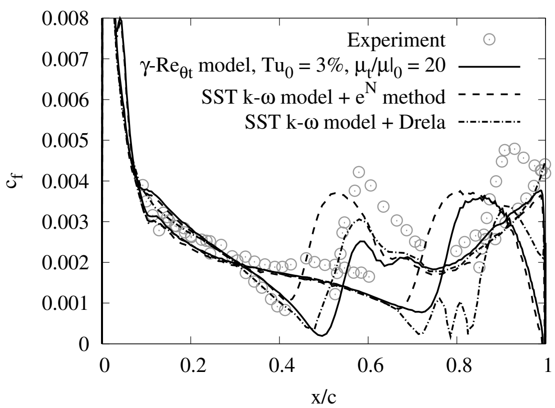

Fig. 2: Skin friction coefficient distribution for $\alpha = -0.5°$ and Re = 0.6 Mio.

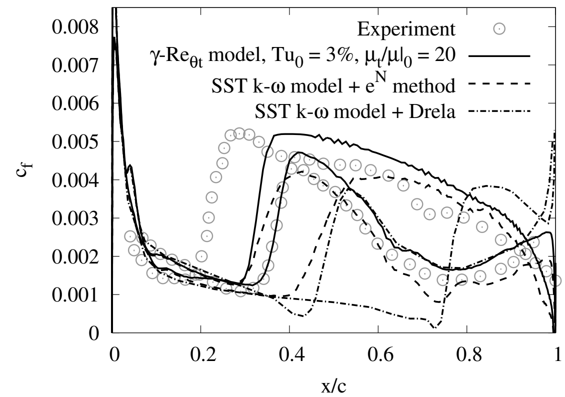

Fig. 3: Skin friction coefficient distribution for $\alpha = -0.5^\circ$ and Re = 2 Mio.

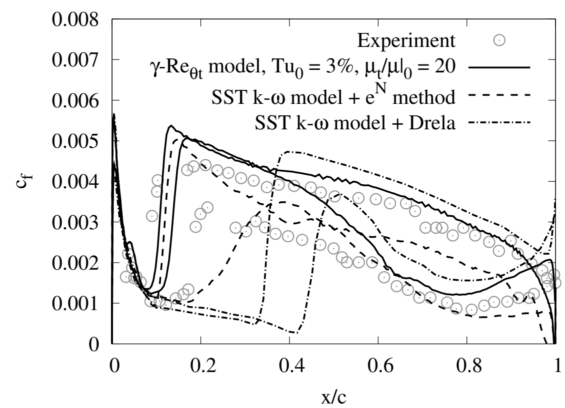

Fig. 4: Skin friction coefficient distribution for $\alpha = -0.5^\circ$ and Re = 6 Mio.

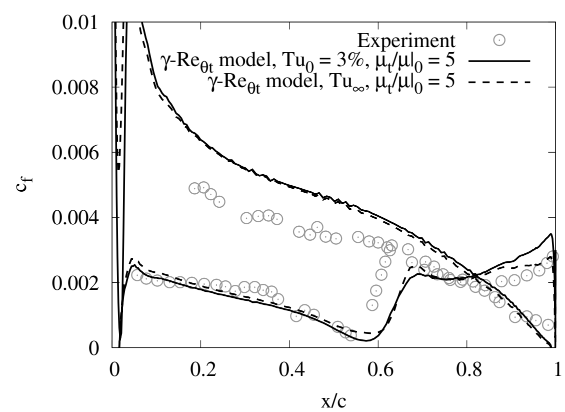

Fig. 5: Skin friction coefficient distribution for $\alpha = 7.5^\circ$ and Re = 2 Mio.