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Accuracy of flow simulation in a low-pressure turbine using a laminar-turbulent transition model

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Abstract. Nowadays, in order to decrease the aircraft engine weight, designers are forced to reduce the number of blades in the low-pressure turbine (LPT) since LPT is one of the heaviest components. The LPT operates in a wide range of Reynolds numbers, which can reach values of less than 10^5 at cruise mode. The correct modeling of the laminar-turbulent transition (LT) in the boundary layer of LPT blades is crucial for predicting the efficiency characteristics. The aim of the study is to evaluate the capabilities of several variants of the LT model for modeling the flow over the LPT blade. The SST $\gamma-\widetilde{\mathrm{Re}}_{\theta t}$ model with different closing correlations, which control the transition onset and transition length, is considered. They are implemented in the research code NOISEtte. Validation of the realization is done on the basis of computations of flat plate flows from the ERCOFTAC database (experimental series T3). The flow in the turbine high-loaded cascade T106C is considered. Together with the experimental data, the results of scale-resolving simulation are used as the reference. The influence of the choice of empirical correlations for the $\gamma-\widetilde{\mathrm{Re}}_{\theta t}$ model on the aerodynamic characteristics near the surface of the blade and at the outlet is evaluated. The results compared with those obtained using the same model and correlations within commercial code Numeca. The study revealed that the results of the same empirical correlations obtained using different flow solvers differ noticeably from each other.

Keywords: laminar-turbulent transition, transition model, low pressure turbine, EBR

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Материалы конференции
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О точности моделирования течения в турбине низкого давления с использованием модели ламинарно-турбулентного перехода

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Аннотация. Корректное моделирование ламинарно-турбулентного перехода (ЛТ) в пограничном слое лопаток турбины низкого давления (ТНД) имеет существенное значение для прогнозирования параметров эффективности. Целью исследования является оценка возможностей нескольких вариантов ЛТ модели для моделирования обтекания лопатки ТНД. Рассматривается модель SST $\gamma-\widetilde{\mathrm{Re}}_{\theta t}$ с различными замыкающими корреляциями, определяющими начало и продолжительность перехода. Модель реализована в исследовательском коде NOISEtte. Проверка реализации выполнена на базе расчетов плоских течений из базы данных ERCOFTAC (экспериментальная серия T3). Рассмотрено течение в высоконагруженной плоской решетке T106C.

Ключевые слова: ламинарно-турбулентный переход, модель перехода, ТНД, EBR

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Introduction

Nowadays, in order to decrease the aircraft engine weight, designers are forced to reduce the number of blades in the low-pressure turbine (LPT) since LPT is one of the heaviest components. At the same time, aerodynamic load on a given stage is maintained the same, which implies an increase of the loading per blade. The LPT typically operates in a wide range of Reynolds numbers reaching 10^5 and even less at cruise mode, so the boundary layer mostly remains laminar. Stronger pressure gradients arising from the higher loading on a blade may cause a separation of the laminar boundary layer and a formation of a separation bubble. So the transition occurs in the shear layer, but depending on the turbulence intensity and scales, the reattachment process may not happen. The separation-induced laminar-turbulent transition (LT) could lead to a significant loss in lift and a drop in efficiency. That is why the accurate numerical simulation of the laminar-turbulent boundary layer transition is crucial for the LPT characteristics prediction while its design.

The aim of the study is to evaluate the capabilities of several variants of the LT model for modeling the flow over the LPT blade.

We consider the widely used SST $\gamma-\widetilde{\mathrm{Re}}_{\theta t}$ model [1] with different closing correlations [1–4] which control the transition onset and transition length. We use the well-known ERCOFTAC T3 series flat-plate test cases [5] and the Schubauer and Klebanoff flat-plate test case [6] to validate the original $\gamma-\widetilde{\mathrm{Re}}_{\theta t}$ model [1] realization in the research code NOISEtte. Along with that, we consider the impact of alternative correlations [2–4].

We simulate the flow in the turbine high-loaded cascade T106C [7] to evaluate the capabilities of empirical correlations for the $\gamma-\widetilde{\mathrm{Re}}_{\theta t}$ model. The flow is characterized by the presence of LT transition caused by the separation of the laminar boundary layer with the formation of a short separation bubble at low Reynolds numbers. We evaluate the results in comparison with the reference data (experimental data [7] and the results of the scale-resolving large-eddy simulation, LES, [8]) and the results obtained using the same model within commercial code Numeca. We analyze the impact of Reynolds number and inflow parameters on the aerodynamic parameters near blade surface and at the outlet.

Mathematical models and numerical schemes

We exploit the numerical algorithm realized in the NOISEtte research code which is based on the Navier-Stokes equations for compressible ideal gas. The Reynolds Averaged Navier-Stokes (RANS) approach with the SST $\gamma-\widetilde{\mathrm{Re}}_{\theta t}$ [1] turbulence model considering LT transition is used as a closure. Along with the empirical correlations to control the transition onset and transition length from the original paper [1] (hereinafter referred to as Langtry), we consider the ones presented in the papers: [4] (Malan), [3] (Sorensen) and [2] (Kelterer).

The NOISEtte [9] algorithm realizes a vertex-centered numerical scheme on mixed-element unstructured meshes for spatial discretization. It is based on the family of edge-based reconstruction schemes EBR [10] for convective fluxes. It provides higher accuracy (in terms of absolute numerical error) on unstructured meshes and can locally reach order of accuracy up to the 5th.

The convective fluxes for the turbulence transport equations are discretized using the TVD3 [11] numerical scheme. Time integration is carrying out using the 1st order implicit Newton-based scheme BDF1. The system of algebraic equations is solved using the preconditioned BiCGSTAB solver [12].

Validation on T3 plate

We exploit the ERCOFTAC T3 series of flat-plate tests and the Schubauer and Klebanoff (S&K) [5, 6] flat-plate test cases to validate the implemented LT $\gamma-\widetilde{\mathrm{Re}}_{\theta t}$ model. These experiments are widely used to test the capability of turbulence models to predict transitional flow under the freestream turbulence effect at zero and varying pressure gradient conditions. The inlet conditions for the test cases are summarized in Table 1. The air properties, density ρ_0 = 1.2 kg/m^3 and viscosity $\mu_0 = 1.8 \cdot 10^{-5}$ kg/(m·s), are set for all the considered cases. The Reynolds number per meter is calculated as follows: $\mathrm{Re}_1 = \rho_0 \cdot U_{in} \cdot 1/\mu_0$.

Table 1

The inlet conditions for the test cases

Case	U_{in}, m/s	Tu_{in}, %	μ_t/μ	$\mathrm{Re}_1/10^6$	Case	U_{in}, m/s	Tu_{in}, %	μ_t/μ	$\mathrm{Re}_1/10^6$
T3A	5.4	3.3	12.0	0.36	T3C5	9.0	3.0	15.0	0.6
T3B	9.4	6.5	100.0	0.627	T3C2	5.29	3.0	8.0	0.353
T3A-	19.8	0.874	8.72	1.32	T3C3	4.0	3.0	5.0	0.267
S&K	50.1	0.3	1.0	3.34	T3C4	1.37	3.0	2.0	0.091

The T3A, T3B and T3A- cases are characterized by zero pressure gradients (ZPG) and varying levels of freestream turbulence intensity (FSTI) for the bypass transition occurrence. The S&K corresponds to the natural transition as it has a low FSTI. The T3C test cases are the flows over a flat plate with a favorable and adverse pressure gradient. For the T3A, T3A- and T3B and S&K cases the computational domain is a rectangle 3×0.5 m with mesh 230×158 nodes in x and y directions. For the T3C cases the computational domain has a length 2 m and the curved upper boundary, the mesh size is 257×129. The distance to the first near-wall node provides y^+ values below 1 to ensure no-slip adiabatic wall boundary conditions. The upper wall is specified as a free slip wall, the inlet turbulent quantities are specified in order to match the measured decay of freestream turbulence. All presented results are mesh converged. The data presented in this paper was obtained on meshes close in resolution to those used in [1, 13].

The results of the simulations in comparison with reference data (experimental data [5, 6] and data obtained using the ANSYS CFX solver taken from [13]) are shown in Fig. 1. They are accompanied by those obtained using both the SST model [14] without taking into account the LT transition (marked as Turbulent) and without any turbulence model consideration (Laminar). The “laminar” solutions for the T3C cases are characterized by the absence of convergence so they are not shown in the graphs in Fig. 1 bottom. The distributions of friction coefficient obtained using the $\gamma-\widetilde{\mathrm{Re}}_{\theta t}$ model with the Langtry correlation correspond to the results from the original papers of Langtry and Menter [1] and Menter et al. [13]. Note that the transition for the T3C5 case with favorable pressure gradient is delayed when the LT Langtry model is applied. This is consistent with the ANSYS results taken from [13] and is explained by the fact that the original $\gamma-\widetilde{\mathrm{Re}}_{\theta t}$ model was tuned on higher inlet turbulence intensity for this test case: Tu_{in} was set to 4% in [1] while it is equal to the experimental value (3%) in both [13] and the present simulation.

The alternative (to Langtry) correlations are characterized by a different behavior, consistent with the reference data in various extents, as it is seen from Fig. 1. The usage of the Malan’s one yields similar behavior as the original $\gamma-\widetilde{\mathrm{Re}}_{\theta t}$ model for both ZPG cases and the cases with streamwise pressure gradient. The correlation of Kelterer leads to a better prediction for the T3C cases, compared with the remaining ones. The only case that is well captured by all the correlations is the T3C4 where the transition forced by separation of the laminar boundary layer is observed. Overall, we state that the validation of the $\gamma-\widetilde{\mathrm{Re}}_{\theta t}$ model realization within the NOISEtte code is done.

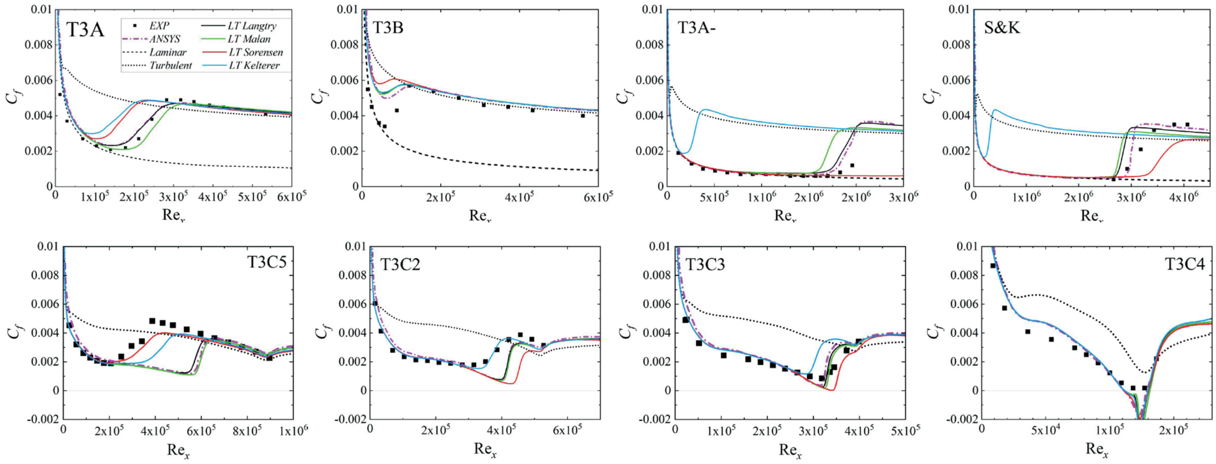

Fig.1. T3 plate results: friction coefficient (C_f) distributions

T106C LPT results

We consider the numerical investigation of the high-lift T106C low pressure turbine blade profile imposed to a uniform incoming flow. It is characterized by the presence of a separation bubble that occurs in the decelerating part of the blade suction side at low Reynolds numbers. The main geometrical parameters of the cascade T106C are presented in Fig. 2. In more detail the description of the experimental set-up is given in [7].

The flow parameters at the inlet and outlet are defined by the theoretical (design) exit Mach number Ma_{2th} and Reynolds number Re_{2th} under the assumption of isentropic flow in the cascade:

$$Ma_{2th} = \sqrt{\frac{2}{\gamma-1}\left[\left(\frac{P_{t1}}{P_k}\right)^{\frac{\gamma-1}{\gamma}} - 1\right]} \quad (1)$$

$$Re_{2th} = \sqrt{\frac{\gamma}{R}}\frac{l}{C_s}\frac{Ma_{2th}\cdot P_k\cdot\left[T_{t1}/\left(1+0.5\cdot(\gamma-1)\cdot Ma_{2th}^2\right)+S\right]}{\left[T_{t1}/\left(1+0.5\cdot(\gamma-1)\cdot Ma_{2th}^2\right)\right]^2} \quad (2)$$

Here P_{t1} is the inlet total pressure, P_k is the outlet static pressure, C_S and S are the constants of the Sutherland's law for dynamic viscosity, R and γ are the universal gas constant and heat capacity ratio, correspondingly. The total temperature at the inlet is equal to T_{t1} = 303.15 K.

We present the results of RANS simulations using the $\gamma-\widetilde{\mathrm{Re}}_{\theta t}$ model for zero incidence angle at Re_{2th} = 90·10³, 200·10³ and 500·10³. The turbulence intensity Tu of the incoming flow in the experiment [7] is in the range of 2.9–3.1%, the streamwise integral length scale is Λ = 20 mm. In order to reproduce the experimental flow conditions, we set the parameters at the inlet boundary as follows: total pressure P_{t1} according to the regime (7860.8 Pa, 17468 Pa and 43667.6 Pa for Re_{2th} = 90·10³, 200·10³ and 500·10³, correspondingly), total temperature T_{t1} = 303.15 K, flow direction (V_x = 0.79, V_y = 0.61), turbulence intensity Tu = 3% and turbulent length scale Λ = 20 mm. The static pressure values P_k are fixed at the outlet according to the regime (5900 Pa, 13110 Pa and 32775 Pa). To estimate the total pressure loss (ζ), the measurements are made in the section located at 0.4_{lx} downstream the blade trailing edge:

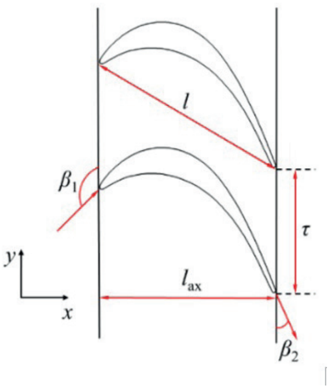

Fig. 2. T106C profile. l=100 mm is chord length; l_{ax}=l_x=85.9 mm – axial chord length; τ=0.95 – pitch to chord ratio; β_1=127.7°, β_2=29.4° – inlet and outlet flow angles

$$\zeta = \frac{P_{t1} - P_{t2}}{P_{t1} - P_k} \cdot 100\% \quad (3)$$

The computations are performed for the 2D cross section of the blade using an unstructured mesh, which has 128k nodes. It is the twice coarsened 2D section of the mesh used for the LES simulation [8]. It is built so that the key and sensitive areas of the flow field are covered with the mesh of high resolution. Among these areas is the region near the blade surface with the mesh wall-tangential step $\Delta_\tau = 3 \cdot 10^{-3} l$, the wake region downstream the trailing edge with the isotropic mesh step $\Delta = 2 \cdot 10^{-3} l$. The first wall-normal mesh step is chosen in such a way that the value y^+ does not exceed 1 for the maximal Reynolds number $Re_{2th} = 500 \cdot 10^3$. The periodicity boundary conditions are used along the Y axis.

The results of the simulations are presented in Fig. 3–4 (surface and outflow profiles) and 5 (integral total pressure losses). Fig. 3–4 present distributions of isentropic Mach number (left), friction coefficient to static pressure ratio at section where the total pressure losses are measured (right). They are accompanied by the results obtained using the Numeca commercial code. We evaluate the $\gamma - \widetilde{Re}_{\theta t}$ LT model performance by comparing with the reference data, both experimental [7] and results of the LES simulations [8]. Analyzing the figures 3 and 4 it could be stated that the main mechanism of LT transition (separation of laminar boundary layer and its reattachment followed by its turbulization) is predicted by all the considered correlations, albeit with varying extent of accuracy. The following features of the presented results are striking. First of all, a different behavior of the results obtained when using the same correlations but different codes is revealed. Among others, the following is distinct: the correlation from the original model (Langtry) is more consistent with the reference for NOISEtte in contrast to the Numeca. This fact confirms correctness of the realization of the $\gamma - \widetilde{Re}_{\theta t}$ model within NOISEtte.

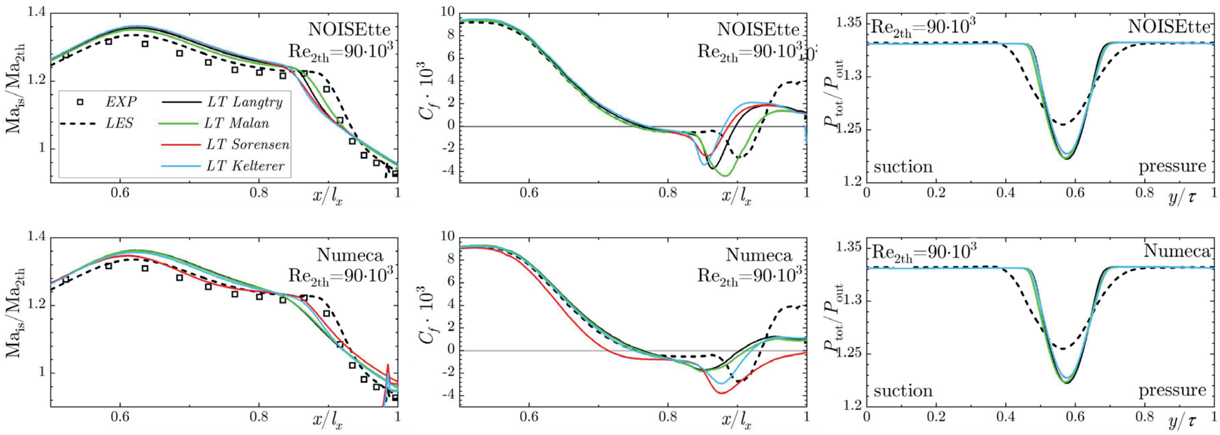

Fig.3. T106C results for $Re_{2th} = 90 \cdot 10^3$

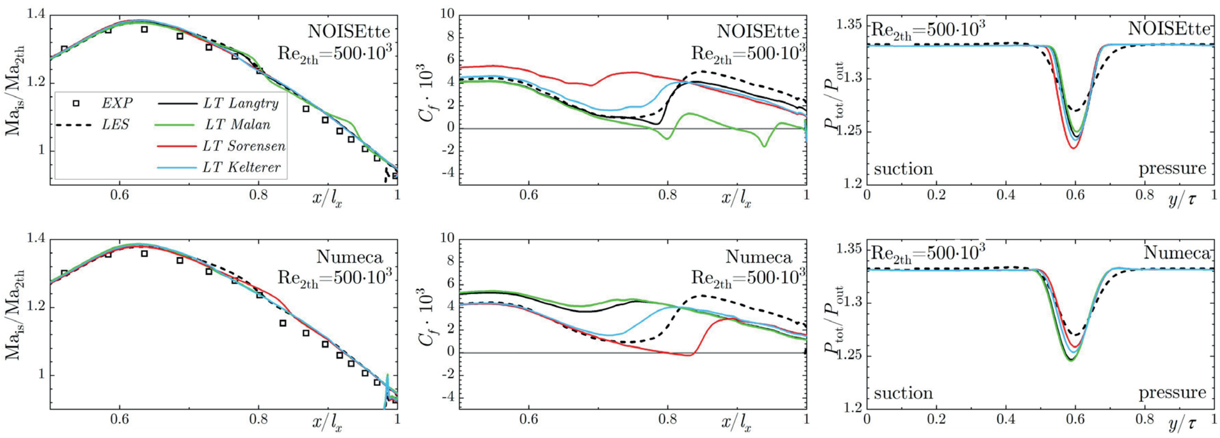

Fig.4. T106C results for $Re_{2th} = 500 \cdot 10^3$

As for alternative correlations, the Malan leads to separation for $Re_{2th} = 500{\cdot}10^3$ using NOISEtte while it does not for Numeca and the Sorensen behavior is noticeably discrepant for the codes too. The difference can be explained by the use of distinguishing numerical algorithms in the considered codes. This effect has been also found in other works (in particular, in [2]). However, we see that the most stable, less "code-dependent" behavior of the solution is achieved using the Kelterer correlation. Analyzing the graphs in Fig. 5, one finds that total pressure loss predictions differ less for lower Reynolds numbers than for higher ones. It yields to a greater scatter of the computational results for relative losses (Fig. 5) that is more pronounced for the Numeca ones.

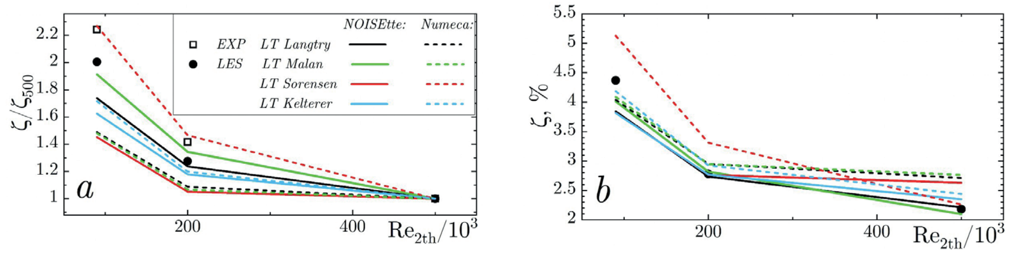

Fig. 5. T106C integral total pressure losses: relative (*a*) and absolute (*b*)

Conclusions

The study deals with a laminar-turbulent transition model towards prediction of flows typical for turbomachinery. The SST $\gamma - \widetilde{Re}_{\theta t}$ model [1] with different closing empirical correlations [1, 2, 3, 4] which control the transition onset and transition length is considered. The results of simulations using their realizations in the research code NOISEtte are evaluated. We have carried out the validation based on the ERCOFTAC T3 series [5] and the Schubauer and Klebanoff [6] flat-plate test cases. The impact of the alternative (to those used in the original SST $\gamma - \widetilde{Re}_{\theta t}$ model) correlations [2, 3, 4] on the flat plate flows are considered. They are characterized by a different behavior, consistent with the reference data in various extents.

The simulations of the flow in the turbine high-loaded cascade T106C [7] are carried out to evaluate the capabilities of the empirical correlations for the $\gamma - \widetilde{Re}_{\theta t}$ model. The results are compared with reference data (both experimental and LES simulation results) and data obtained using the same model and correlations implemented in the commercial code Numeca. The study revealed that usage of the same empirical correlations realized in different flow solvers (NOISEtte and Numeca) differ noticeably from each other. At the same time, the correlation of the obtained results is more consistent with the reference for NOISEtte, in contrast to the Numeca results. Among the considered correlations, the most stable, "code-independent" behavior of the solution is achieved using the Kelterer. It can be argued that the implementation of the $\gamma - \widetilde{Re}_{\theta t}$ model in the NOISEtte numerical algorithm is validated.

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