Mechanics and Mechanical Engineering
Vol. 15, No. 3 (2011) 227–236

Numerical Study of Wake Effect on Rough Wall Boundary Layer

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Received (20 August 2011)
Revised (5 September 2011)
Accepted (26 September 2011)

The paper deals with the problem of wakes effect and surface roughness, which influences the performance and flow of axial turbine and compressor stages. The accurate and reliable prediction of both effects are of great interest of designers. The paper discusses the results of verification of boundary layer modeling approach, which rely on a $\gamma - Re_{\theta t}$ model proposed by Menter et al. (2004) extended by laminar–turbulent transition correlations proposed by Piotrowski et al. (2008) and Stripf et al. (2008) correlations, which take into account the effects of surface roughness.

Keywords: Transition modeling, wake effect, surface roughness, boundary layer

1. Introduction

It is well known that the unsteady environment in turbine stages, which is mainly due to the wakes of upstream blade rows, has an essential influence on machine efficiency. It is worth emphasizing especially, a beneficial effect of upstream wakes on the high lift profiles. It comes from a promotion of laminar–turbulent transition in the shear layer and reduction of the separation bubble. On the other hand the blade surface may experience significant degradation both in shape and surface smoothness due to harsh operating environment. Surface roughness generally adversely affects blade row aerodynamic efficiency due to thickened boundary layer and increase of blockage. The decrease of turbine efficiency was reported among the others by Waigh and Kind [13] and Boynton et al. [2]. The impact of surface roughness is however a function of Reynolds number. Boyle and Senyitko [1] showed that at high Reynolds number surface roughness doubled vane loss, but at low Reynolds numbers roughness improved aerodynamic efficiency. The last beneficial effect is present in case of the high lift blade profiles. Therefore, it is not surprising that recent studies on high–lift blades suggest that a blade with as–cast surface roughness could have a lower loss than a polished one [9].

The accurate and reliable prediction of the effect of surface roughness on fluid flow and heat transfer are of great interest of designers. Modeling of the flow on a rough surface should cover whole blade surface, so correct computations of the laminar, turbulent and transitional boundary layers are required. However, as shown by Stripf et al. [12], the roughness influence on the laminar boundary layer is negligible. Therefore the major tasks are modeling of turbulent boundary layer and transition process.

Modeling of laminar–turbulent transition is one of the challenges even for a smooth surface, especially in case of presence of upstream wakes. The proper description of the surface roughness as well as the unsteady flow in a blade channel is therefore very demanding for transition modeling. Among the most popular recently methods for modeling boundary layer on a smooth wall are methods based on intermittency parameter γ, where the most representative is model proposed by Menter et al. [7]. In the recent period the modification of $\gamma - Re_{\theta t}$ Menter's model has been proposed by Piotrowski et al. [10], which was further modified by Elsner and Warzecha [4], to reflect the influence of the surface roughness. This model was named Intermittency Transport Model (ITM_R).The paper discusses the results of verification of the new approach based on a flat plate data with zero and non zero pressure gradient as well as on the turbine blade test case.

2. Model Description

The modeling approach applied in this paper is based on SST turbulence model with a time scale bound according to Medic and Durbin and $\gamma - Re_\theta$ transition model by Menter et al. [7]. The advantage of the last model is that the start of the transition is achieved locally through the use of the vorticity Reynolds number. For this purpose apart from intermittency transport equation, momentum thickness Reynolds number $Re_{\theta t}$ transport equation has been introduced. This transport equation takes a non–local empirical correlation and transforms it into a local quantity, which is then compared to the local vorticity Reynolds number to detect transition onset. On top of this advantage, this model may easily be adapted for parallel calculations on unstructured grids and that is why this model is considered as a promising perspective. The extension of the Menter's model proposed by Piotrowski et al. [10] was done by development of two in–house correlations on onset location and transition length, which are confidential in the original Menter's model. The great advantage of Piotrowski approach is the possibility of unsteady calculations of interaction of upstream wakes with downstream blades, what is a basic feature of turbomachinery flows.

To take into account roughness effect, according to the statement formulated above, it was necessary to describe the influence of roughness on a turbulent boundary layer and on the transition location. As shown in a work of Elsner and Warzecha [4], to predict the behavior of turbulent boundary layer two modifications of SST model are necessary. The first one is a change of wall boundary conditions for a specific dissipation rate ω. For an ideally smooth solid surface $\omega \to \infty$ while for a rough wall ω has a finite value of:

$$\omega_w = \frac{u_\tau^2}{\nu} S_R \tag{1}$$

where u_τ is the friction velocity and S_R is a coefficient, which is a function of the nondimensional sand grain height. This last parameter is defined as:

$$K_s^+ = \frac{u_\tau k_s}{\nu} \tag{2}$$

where k_S is a grain size.

The second modification of SST model, proposed by Hellsten and Laine [6], concerned a redefinition of eddy viscosity μ_t to prevent its limitation and hence the modeled shear–stress from being activated in the near–wall region i.e. sublayer or rough layer. To predict the onset location ITM$_R$ model uses the information obtained from the transport equation of the momentum thickness Reynolds number $-Re_{\theta t}$ i.e. $\tilde{R}e_{\theta t}$ values determined at the wall. For the purpose of current investigation it was decided to define new $\tilde{R}e_{\theta t\_R}$ according to Stripf correlation [12]:

$$\tilde{R}e_{\Theta t\_R} = \tilde{R}e_{\Theta t} \qquad \text{for} \quad k_r/\delta^* \le 0.01 \tag{3}$$

$$\tilde{R}e_{\Theta t\_R} = MIN\left[\left(\frac{1}{\tilde{R}e_{\Theta t}} + 0.0061 f_\Lambda \left(\frac{k_r}{\delta^*} - 0.01\right)^{f_{Tu}}\right)^{-1}\right] \tag{4}$$

$$\text{for} \quad k_r/\delta^* > 0.01$$

with displacement thickness δ^*, f_Λ which takes into account roughness topographies and f_{Tu} which is a function of the local free stream turbulent intensity Tu expressed as a percentage:

$$f_{Tu} = max(0.9;\, 1.61 - 1.15exp(-Tu)) \tag{5}$$

All the above formulations together with the transport equations for intermittency γ and Reynolds number $\tilde{R}e_{\theta t}$ form the complete calculation procedure for $l-t$ transition modeling. The transport equations for intermittency and momentum thickness Reynolds number as well as for SST turbulence model were implemented in the commercial package Fluent with the use of User Defined Functions (UDF's).

In order to model a proper behavior of boundary layer in unsteady environment it was necessary to introduce an adequate inlet conditions that vary in time. That is why in the present research, self-similar wake profiles were generated, based on the experimental data (more details can be found in the work of Piotrowski et al. [10]) and prescribed at the inlet of the computational domain. The profiles of velocity, turbulent kinetic energy (k) and specific rate of dissipation of turbulent kinetic energy (ω), which were prescribed are shown in Fig. 1. In the experiment for the simulation of upstream wakes moving cylindrical bars were applied. The diameter of the bars ($d = 4$ mm) was adjusted to produce wakes with characteristic parameters corresponding to those of the real blades. The profiles presented in Fig. 1 corresponds to the experimental data.

3. Test of the model on the flat plate with roughness

For the initial verification of the method described above simple test cases have been chosen i.e. a flat plate flow with zero pressure gradient published by Healzer [5] and a flat plate with non–zero pressure gradient published by Coleman et al. [3].

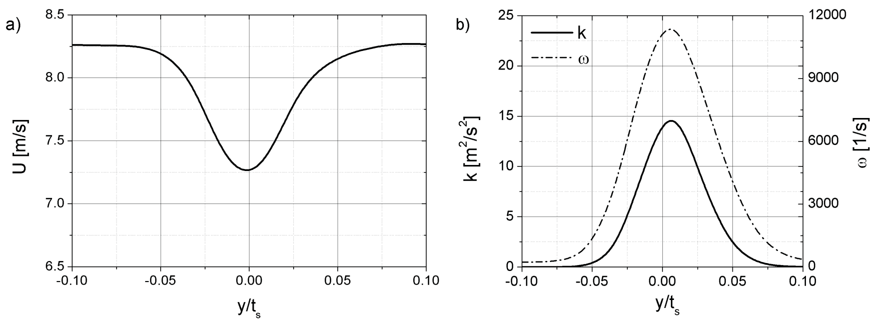

Figure 1 Inlet profiles for unsteady calculations: velocity U (a) turbulent kinetic energy k and specific dissipation rate ω (b)

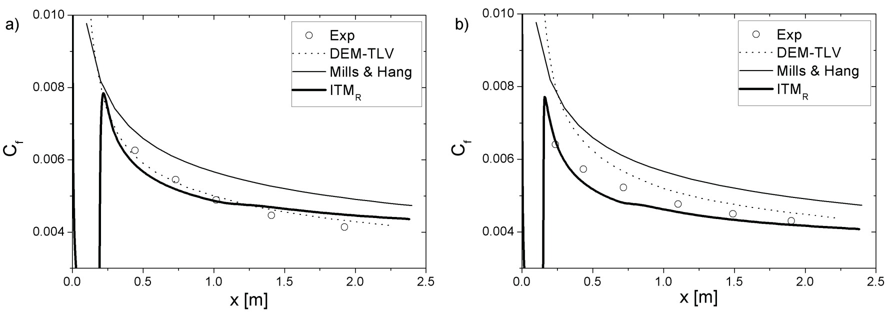

Figure 2 Skin friction coefficient C_f for zero–pressure gradient test case: $U_\infty = 27$ m/s (a) $U_\infty = 42$ m/s (b)

The test section had a dimension of 2.4 m in length, 0.508 m wide and 0.102 m in height. For the test case with non–zero pressure gradient, height of the test section becomes smaller in the distance of 0.98 m from the leading edge. The roughness was obtained by means of copper balls with a diameter of $d_0 = 1.27$ mm brazed together in a most dense configuration. The equivalent sand roughness needed to model the flow was $k_s = 0.62 \times d_0 = 0.79$ mm. The inlet turbulence intensity was equal $Tu = 0.4\%$ while inflow velocity was set to $U_\infty = 27$ m/s and $U_\infty = 42$ m/s for the zero pressure gradient test case and $U_\infty = 26$ m/s for the non–zero pressure gradient test case.

Fig. 2 shows experimental and numerical results for skin friction coefficient distributions. The results shown in solid lines (bold) for ITM$_R$ model are compared to experimental results (circles) and results obtained by Stripf with DEM–TLV model [11] shown as dotted lines. Additionally, distributions plotted in accordance with semi–empirical formula proposed in 1983 by Mills and Hang [8] are shown. This formula:

$$c_f = (3.476 + 0.707 ln(x/k_s))^{-2.46} \tag{6}$$

defines skin friction coefficient on sand–roughened flat plate, which is valid in the full–rough regime. It is seen that ITM_R model predict the experimental data with high accuracy. It gives slightly lower values in comparison with DEM–TLV model and Mills and Hang [8] correlation for the higher velocity case, but fits better the experimental data.

Fig. 3 shows the velocity profile along the test section (Fig. 3a) and the distribution of skin friction coefficient (Fig. 3b). In the experiment the velocity distribution in the second part of the test section was chosen in such a way to have a constant skin friction distribution. It is seen that the shape of the velocity curves is consistent with experimental data. Skin friction coefficient corresponds well to the measured values, although the resolution of the experimental data seems to be too low. A slight discrepancy with the DEM–TLV model is seen, which takes slightly higher values. In summary, it is clear that the performance of the ITM_R model is sufficient to calculate rough wall turbulent boundary layer and may be applied for more demanding test cases.

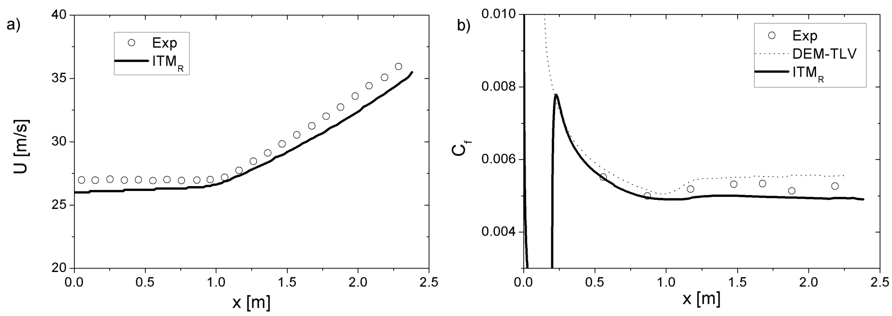

Figure 3 Evolution of velocity U (a) and skin friction coefficient C_f (b) for non–zero pressure gradient test case ($U_\infty = 26$ m/s)

4. N3–60 turbine blade – steady test case

Validation of the proposed approach for high pressure turbine vane (HPTV), of a chord $c = 93.95$ mm, experimentally and numerically investigated at Karlsruhe University was presented in [12]. The current analysis concerns N3–60 high pressure stator turbine vane experimentally studied at the Institute of Thermal Machinery at the Czstochowa University of Technology by Zarzycki and Elsner [14]. This test could be treated as a blind test as no experimental results are available for rough surface. Tab. 1 contains the basic roughness parameters as well as boundary layer data needed for flow calculations. The boundary layer parameters (displacement thickness, wall shear stresses, friction velocity and turbulence intensity) contained in

Tab. 1 are related to the $l-t$ transition point detected during the calculations. The roughness model was validated on the basis of the Reynolds number, $Re = 6 \cdot 10^5$, and the turbulence intensity, $Tu = 0.4\%$.

Table 1 Roughness parameters and basic boundary layer parameters

Test Case	Roughness parameters			Boundary layer parameters		
	k_r $[mm]$	K_S^+ $[-]$	k_r/δ^*	$\delta^*[mm]$	τ $[Pa]$	u_τ $[m/s]$
K10	0.01	3.3	0.05	0.197	2.26	1.37
K20	0.02	6.7	0.1	0.198	2.26	1.37
K40	0.037	11.9	0.187	0.198	2.27	1.37

The characteristic of the blade profile is given by the pressure coefficient C_p distribution presented in Fig. 4a for a suction side of the blade. On the plot one can distinguish a small diffusion area close to the trailing edge indicating a separation bubble. The key variable describing the boundary layer evolution during transition from laminar to turbulent state is intermittency factor γ seen in Fig. 4b.

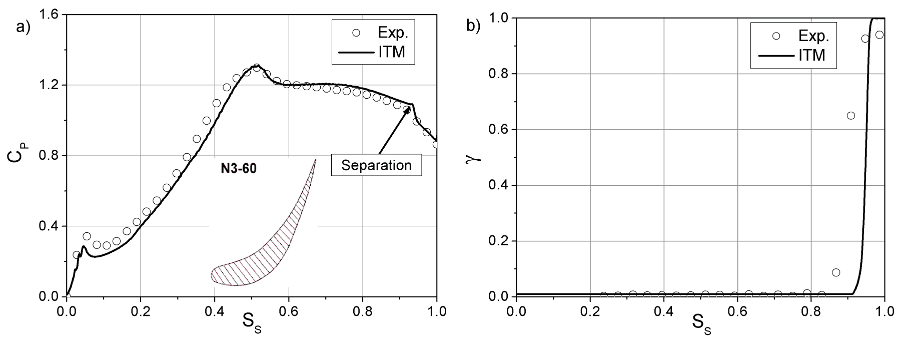

Figure 4 Evolution of pressure coefficient C_p (a) and intermittency γ (b) for the N3-60 test case ($Tu = 0.4\%$)

One can notice that numerically obtained intermittency slightly lags the experimental data. The reason is that the intermittency factor determined from the hot wire signal starts to increase prior to the change of general flow parameters like skin friction or shape factor, while numerical γ value historically has been derived from the evolution of global parameters.

The data above concerns the smooth surface. To evaluate the influence of roughness height k_r onto the boundary layer development a shape factor H has been calculated. Figure 5a shows the distribution of H for the N3-60 steady test case with various level of the surface roughness. It is seen that for the smooth surface, numerical data follow the experiment almost all over the blade surface and that the boundary layer separates for the relative coordinate $S_s = 0.92$ (where H exceeds the level 3.5). The introduction of surface roughness (test case K10) moves the location of boundary layer separation upstream. Further increasing in surface roughness causes decay of boundary layer separation (test case K40). From the results one may see that the surface roughness has no impact on the boundary layer in the front part of turbine blade. This does not depend also from the fact that the ratio of roughness height k_r to the displacement thickness δ^* (which takes part in determining the laminar–turbulent transition onset) reaches its maximum value in the accelerating part of the blade. It is due to the fact that the momentum thickness Reynolds number $\tilde{Re}_{\theta t}$, which comes from transport equation is still small enough to activate an intermittency source term. The respond of boundary layer onto surface roughness is observed from the relative coordinate $S_s = 0.82$. The higher roughness level promotes an earlier transition of the boundary layer, reducing the size of the separation bubble, which disappears already for the lowest values of K_s^+. It is a beneficial effect from the point of view of turbomachinery efficiency as the maximum bubble thickness is well correlated with profile losses.

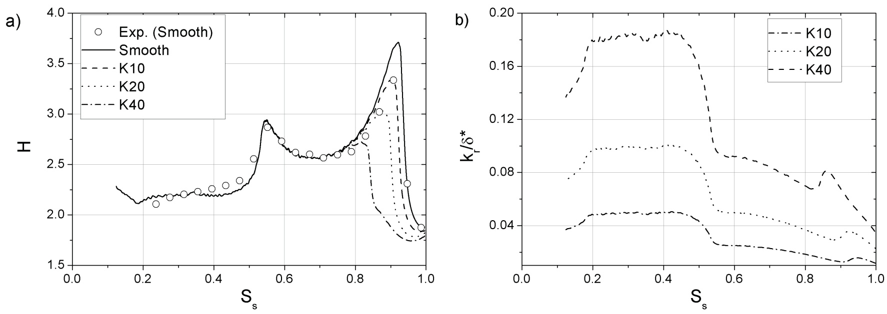

Figure 5 Shape factor H (a) and k_r/δ^* (b) for the N3-60 test case ($Tu = 0.4\%$)

5. N3–60 turbine blade – unsteady test case

Flow unsteadiness strongly affects the time dependent location of the laminar–turbulent transition region on the blade surface. The proper modeling of the unsteady flow is therefore very challenging. The analysis of the response of the boundary layer to the passing wake is based on the shape factor H plotted on so called $s-t$ diagrams. Fig. 6 presents $s-t$ diagrams of H over the suction side of the blade for two cases, the smooth surface and the rough surface (K20 case). The dark wedges (of very low H) show turbulent regions, which are the results of the influence of upstream wakes. The bright region close to the trailing edge, in Fig. 6a, shows the location of laminar boundary layer separation, which appears temporarily between wakes impact. One cannot see the clear difference between those two cases, apart from clearly broader wake–induced regions and less evident symptom of separation. It is however clear, that the roughness hardly influences the location of wake induced transition.

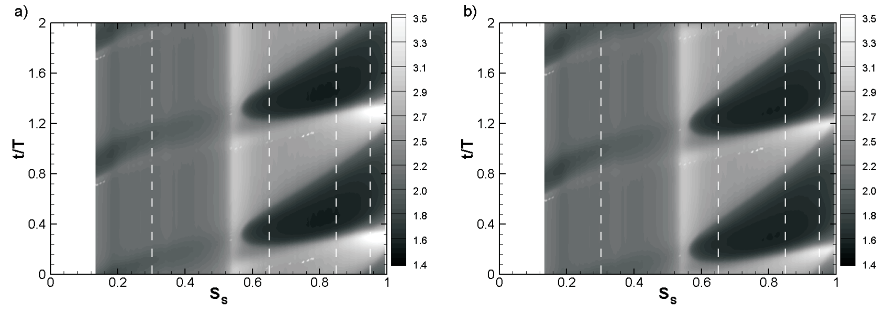

Figure 6 S–t diagrams of shape factor H over the suction side for test cases: smooth surface (a) with roughness – K20 (b)

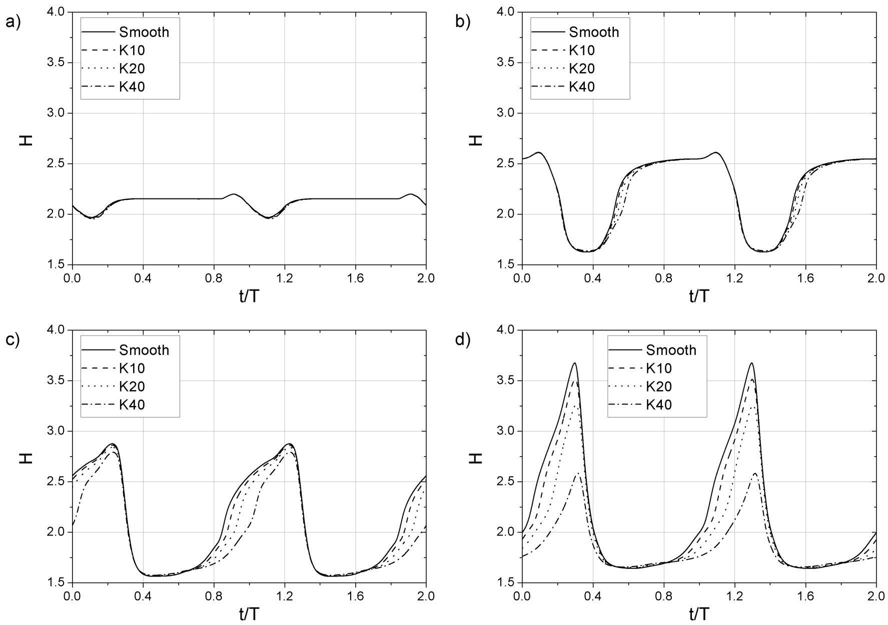

Figure 7 Time traces of shape factor H at the location S_s=0.3 (a) S_s=0.65 (b) S_s=0.85 (c) S_s=0.95 (d)

To have the quantitative information on the extent of these changes cross–sections of the s-t diagrams of Fig. 6 a and b are presented for the location $S_s = 0.3$, $S_s = 0.65$, $S_s = 0.85$ and $S_s = 0.95$. The graphs show the data from the full range of roughness parameter variation. Indeed, the expansion of the turbulent region for the rough surface is noticeable. It is most the apparent in the last traverse near the edge of the trailing edge ($S_s = 0.95$), where the relative change is of the order of

28%. It is accompanied by the drop of the shape parameter between wakes from 3.7 to 2.6. This means that the combined impact of wakes and the surface roughness can be beneficial for the efficiency of the blade rows, especially in the case of strong separation occurring on highly–loaded blade profiles.

6. Conclusions

In the paper the influence of wakes and surface roughness effects on the boundary layer development were studied numerically. The research proved that the new modeling approach (ITM_R) appeared to be sufficiently precise and enabled a qualitatively correct prediction of the boundary layer development for the tested simple flow configurations.

For the N3–60 turbine blade test case the proper respond of boundary layer onto surface roughness was demonstrated. The higher roughness level promotes an earlier transition of the boundary layer and prevents the boundary layer separation both for the steady as well as unsteady inflow conditions. For the last case it was demonstrated that the roughness hardly influences the location of wake induced transition, but has an impact on the flow in between the wakes. One can deduced that the combined impact of wakes and the surface roughness can be beneficial for the efficiency of the blade rows, especially in the case of strong separation occurring on highly–loaded blade profiles.

7. Acknowledgements

The research was supported by the Polish State Committee for Scientific Research under the statutory funds BS/PB1–103–3010/11/P.

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