JOURNAL OF THEORETICAL
AND APPLIED MECHANICS
45, 3, pp. 539-556, Warsaw 2007

TRANSITION MODELLING IN TURBOMACHINERY

Witold Elsner

Czestochowa University of Technology, Institute of Thermal Machinery, Częstochowa, Poland
e-mail: welsner@imc.pcz.czest.pl

The paper deals with the problems of boundary layer modelling in turbomachinery applications, where various mechanisms are present, especially under the conditions of upstream wakes. The paper presents a review of recent achievements in interpretation of by-pass, wake induced and separation induced transition processes as well as the discussion of most important aspects of transition modelling. This review is complemented by physical explanation of transition phenomena based on the recent literature data as well as on the results of numerical and experimental investigations performed at the Institute of Thermal Machinery. The two test cases, i.e. steam turbine blade profile N3-60 and gas turbine blade profile T106A are used as a basis for the discussion of applicability of modern transition models.

Key words: transition modelling, boundary layer, by-pass and wake induced transition, turbomachinery

1. Introduction

Laminar-turbulent transition in boundary layers influences performance of many technical devices. The location of the onset and the extension of transition are of major importance since they determine drag and lift forces and heat fluxes that are crucial for overall efficiency and performance of a variety of machinery and devices. Among the most common examples of the machinery, where the laminar-turbulent transition is of particular importance, are gas and aero-engine turbines. Despite technical maturity of gas turbines, the research optimisation and development concerning this technology still continues, as increasing the engine's performance by a fraction of percent or improving the turbine cooling in face of ever-increasing turbine inlet temperature provides enormous economic benefits. Hence, the understanding of the laminar-turbulent transition in gas turbine cascades plays a very important role in their optimisation (Mayle, 1991).

For real turbomachine conditions, due to complex aerodynamic interactions of multiple stages, the background turbulence attains levels of a few percent, while close to rotor or stator trailing edges the turbulence intensity may be as high as Tu = 10% and more. As a consequence of the high Tu level, turbulent spots in the boundary layer are created as a direct result of turbulence fluctuations of the outer stream, and this type of laminar-turbulent transition is known after Morkovin (1969) as a "bypass" one. This means that the transition is caused by diffusion of turbulence and by pressure coupling between the freestream and the laminar boundary layer. It is the mechanism present in the attached boundary layer. In modern designs of aero-engine turbomachinery, there is a tendency to apply heavily loaded turbine blades which are characterized by the frequent occurrence of laminar-separation regions at the blade suction surfaces. In such a case, the transition proceeds over the separation bubble due to shear layer instability, particularly in compressors and low-pressure turbines (Howell *et al.*, 2002).

It is necessary to mention that the flow in the turbomachinery stage is essentially turbulent and unsteady, where the non-stationary flow character results from the mutual rotor-stator blade row interactions. Periodic phenomena generated by blade row interactions excite the flow in both the blade passage and boundary layers on the blade surfaces, and they trigger an increased turbulent spot production and finally shift the location of laminar-turbulent transition upstream. This laminar-turbulent transition mechanism is known as "wake-induced transition" (Mayle, 1991).

Despite numerous experimental and numerical investigations, the physics of the unsteady phenomena in turbomachinery flows is not well understood. First of all it is not clear, what is the mechanism by which the disturbances from the outer stream interact with the boundary layer, and this problem is the main issue of the paper.

The understanding of this phenomenon is important in order to incorporate new modelling methods in CFD codes, which will be used in future by turbomachinery designers. In fact, despite a lot of effort directed to improve the modelling strategy, the transition modelling still largely limits the quality of the CFD codes today, and indeed the errors in estimation of the onset and extension of the transition can affect the calculated machine efficiency by several percent and the component life by more than an order of magnitude.

2. Wake induced transition – the effect of turbulence

As a consequence of high turbulence levels of the background flow, turbulent spots are created in the boundary layer as a direct result of turbulence fluctuations of the outer stream. The viscous wakes present in turbomachinery flows, which transport additional turbulence towards the blade surface, trigger turbulent spot production and shift the location of l-t transition upstream.

According to the evidence of Kendall (1985), the bypass transition is initiated by the interaction of freestream disturbances, and this mechanism is usually denoted as the receptivity mechanism. Initially, the small turbulence scales from the freestream are prevented to perturb the boundary layer by the mean shear (it is known as sheltering mechanism). Then the low-frequency fluctuations mainly caused by irregular motion of long structures with narrow spanwise scales (usually greater than 15-20 boundary layer thickness) appear inside the boundary layer, and they were denoted by Kendall (1985) as the Klebanoff mode. In fact, the Klebanoff mode is an ensemble-averaged view of streaky structures as it was observed in numerous experimental works (Kendall, 1985). Input for the understanding of bypass transition physics was given by Jacobs and Durbin (2001), who performed DNS simulation of such a type of flow, which proved that long streaks of streamwise velocity perturbation described above were initiated by low-frequency modes from the freestream. The longitudinal streaks with the turbulent spot in the center of the picture are seen in Fig. 1. Despite the broad inlet spectrum, energy within the boundary layer due to shear amplification, or essentially produced by vertical displacement of mean momentum, focused only onto low-wave number frequencies. The streaky structures are then disturbed by small-scale eddies from freestream, and irregularities similar to the Kelvin-Helmholtz instability are triggered. Finally, they develop into turbulent spots, which spread laterally and intensively propagate downstream the flow. As a result, spots originating from different locations merge to form a completely turbulent boundary layer.

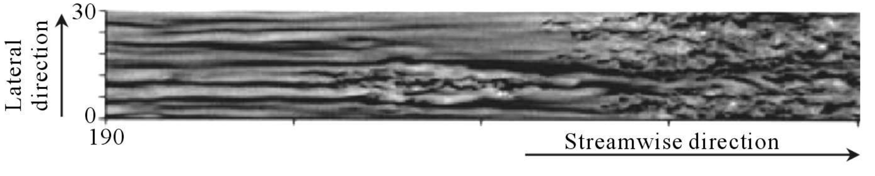

Fig. 1. Longitudinal streaks and transition in the boundary layer (Jacobs and Durbin, 2001)

The growth and merging of spots are the crucial features of the bypass mechanism. One of the basic concepts was Narasimha's concentrated breakdown hypothesis (Narasimha, 1957), stating that the spot production rate could be represented by the Dirac delta function. This is due to the fact that upstream of the start of transition the spots are unable to form, while downstream of the start the formation of spots is inhibited by calmed regions following spots which were formed earlier. Somewhat later, Schulte and Hodson (1998) proposed a continuous breakdown concept which is more appropriate, especially for wake induced transition.

Because of the high turbulence level in the wake, the physical mechanism of unsteady transition should be the same as in the case of bypass transition. The confirmation of this suggestion was given initially in the paper by Wu *et al.* (1999), who performed DNS analysis of the wake interaction with the boundary layer on a flat plate. Wu *et al.* (1999) proved that inlet wake disturbances inside the boundary layer evolved rapidly into longitudinal puffs during the initial receptivity phase. Small scale freestream vortices interacted with the boundary layer edge (longitudinal streaks) through a local Kelvin-Helmholtz instability, and then negative streamwise fluctuations associated with the inflectional profiles evolved into strong forward eddying motions, producing young spots.

No. of point	S_s
5	0.829
6	0.789
7	0.750
8	0.710
9	0.671
10	0.631
11	0.592
12	0.552
13	0.513
14	0.473

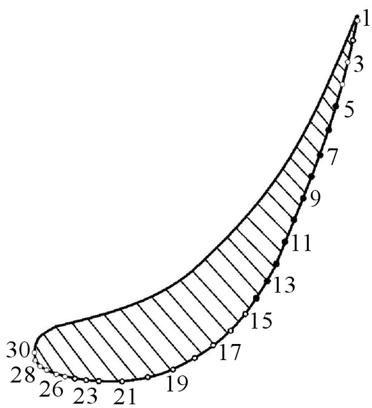

Fig. 2. Analysed N3-60 blade profile with location of measuring traverses

The evidence that in the boundary layer the mechanism of wake induced transition is the same as in the case of the bypass transition was recently given by Elsner (2004). In the experiment performed for the N3-60 turbine blade cascade disturbed by the wakes generated by a wheel with cylindrical bars rotating upstream the cascade (see Fig. 2), the existence of the Klebanoff mode in the pre-transitional phase was found. As it was stated above, the Klebanoff mode is the ensemble-averaged signature of the longitudinal streaky structures. Figure 3 shows the comparison of the streamwise velocity fluctuation profiles in the boundary layer taken from Jacobs and Durbin (2001) (a), from Elsner (2004) for steady (undisturbed) case (b), and for the unsteady case with upstream wakes (c). It is seen that for the pretransitional stage in both steady and unsteady cases, the rms distribution has the same characteristic *smooth* shape with maximum at $y/\delta \approx 0.4$, which is seen also for the reference data. One can also notice that the first appearance of a turbulent spot, seen as an increase of the rms level accompanied by a shift of the maximum towards the blade surface is observed at various streamwise locations in each case. For the steady case, the increase of energy of fluctuations appears for the streamwise non-dimensional coordinate $S_s = 0.67$ (point 9 in Fig. 2), while for the unsteady case it is shifted upstream, i.e. it is observed for $S_s = 0.55$ (point 12 in Fig. 2). This behaviour may be regarded as a proof of strong wake impact on the boundary layer development.

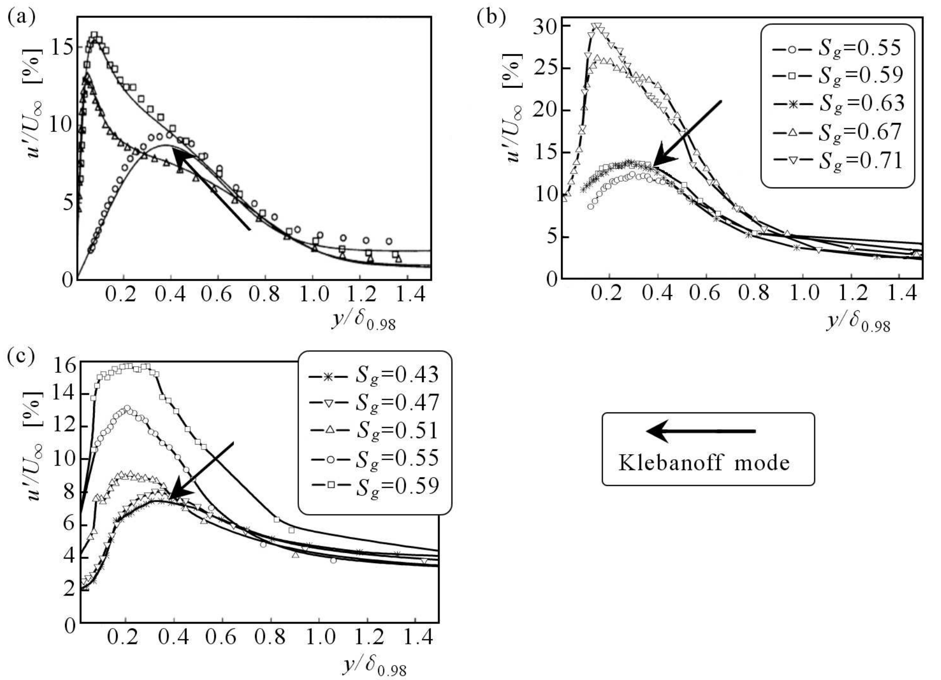

Fig. 3. Velocity fluctuation profiles u' versus y/δ, according to Jacobs and Durbin (2001) (a), for steady case (b), for unsteady case (c)

3. Wake induced transition – the jet effect

As it was already mentioned, heavily loaded blades used in modern turbine aero-engines are subjected to strong adverse pressure gradients. Such conditions together with relatively low Reynolds numbers, which is the case for LPT turbine of aero-engines, lead to development of separation on the suction side of the blade and, as a consequence, increased profile losses. It means that the location of velocity peak, the diffusion distribution and danger of separation are the most important problems which should be dealt with. The presence of upstream wakes, transporting high energy medium, has a positive effect visible as a periodical reduction of the area covered by the separated boundary layer. The suppression of the separation bubble is not only due to the turbulence but also due to calmed regions that follow the wake induced turbulent flow in the boundary layer. The flows associated with the turbulent and calmed regions produce less entropy than the steady separation, and this leads to reduction of losses in the meantime.

However, as it was shown by Stieger and Hodson (2004), the transition to turbulence on heavily loaded blades could not only be due to an increased turbulence level, but also due to the negative jet of the wake. The jet effect results from the velocity deficit in the wake, which forces the relative movement of the fluid from the pressure side to the suction side of the turbine blade profile. Close to the suction side in front of the wake, one may observe acceleration of the flow followed by its deceleration in reference to the mean velocity. It was experimentally confirmed (Stieger and Hodson, 2004) that such a kinematic wake impact, which introduces inflectional velocity profiles, causes breakdown of the separated shear layer as a result of Kelvin-Helmholtz instability, which then develops into roll-up vortices of the scale of the separation bubble. The roll-up vortices produce high levels of turbulent kinetic energy which leads to the transition development. The sketch of rollup mechanisms after Stieger and Hodson (2004) is shown in Fig. 4. The negative jet impinging on the blade sur-

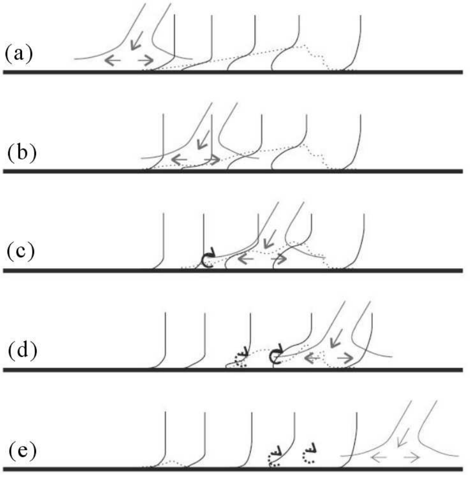

Fig. 4. Sketch of rollup mechanism (Stieger and Hodson, 2004)

face and then splitting onto two streams is shown by the arrows. As the wake approaches separation, the outer region of the boundary layer is accelerated, which results in increased shear in the separated shear layer. Finally, in the unstable shear layer due to the Kelvin-Helmholtz mechanism, inviscid rollups develop and propagate downstream at half the freestream velocity. The vortices formed by the rollup of the shear layer rapidly break down to turbulence thereby causing boundary layer transition. After the passage of the rollup vortices and the turbulent boundary layer, a calmed region is formed that has also a positive effect onto the stability of the boundary layer.

The authors also pointed out that for a quasi-steady flow the mechanism could be similar, although in this case the roll-up vortices have much smaller scale. These observations were lately confirmed by Opoka and Hodson (2005), who additionally discovered that a higher freestream turbulence delayed the appearance of inflexional velocity profiles and reduced the chance for forming roll-up vortices.

The evidence of the way how the wake interacts with the separation bubble and the description of the new transition mechanism is crucial for the development of transition models applied especially for highly decelerated boundary layers.

4. Transition modelling

The variety of possible transition mechanisms in turbomachinery flows makes it difficult to propose the general strategy for numerical simulation. Intuitively, the best solution for the modelling of the transitional boundary layer is the application of Direct Eddy Simulation (DES) or Large Eddy Simulation (LES). However, in LES, which unlike DNS resolves only dynamically important (large) scales, the effect of unresolved small scales is modelled. One question that arises when applying LES to the transition problem regards its capability to predict the development of the shear layer and vortices with scales, which are close to the numerical filter (Huai *et al.*, 1997). A subgrid scale model should not dissipate the energy of low level perturbations during the initial stages of transition, but should reproduce the energy transfer to the unresolved scales during non-linear stages when these marginally resolved structures are generated. LES was already successfully used in simulating the bypass transition on a flat plate, among the others by Voke and Yang (1995) and Huai *et al.* (1997) who were able to show the pretransitional linear instability modes, the secondary instability Λ-vortex structures and the streaky like structures. However, the application of LES for the modelling of the transition is still limited to the low Reynolds number flows as for higher Reynolds numbers the difference between the largest and the smallest eddies increases, and a progressively wider range of scales needs to be resolved by the subgrid scale model. The second limitation is the required numerical mesh and resulting high computational time, because when approaching the wall, the scales diminish their dimension so that finer and finer grid is required.

Hence the RANS methods and, for unsteady calculations URANS, with the appropriately modelled transitional boundary layer remain the only presently applicable engineering tool to study the transitional flows. It means that it is worth to make effort to improve and look for new RANS or URANS modelling approaches, especially because of strong interest from the industry.

Application of the existing low-Re turbulence models for the laminar-turbulent transition boundary layer, as reviewed by Savill (2002) and Menter *et al.* (2002), is a highly empirical procedure which requires experimental data for proper calibration. It means that no model generates a reliable result for various combinations of Reynolds numbers, freestream turbulences and pressure gradients. Additionally, the results are sensitive to initial conditions, boundary conditions and grid resolution. In these methods, usually various experimental correlations are used to determine the onset of transition. According to Menter *et al.* (2002), the ability of a low-Reynolds turbulence model to predict the transition seems to be coincidental, as the calibration of the damping functions is based on the viscous sublayer behaviour and not on the transition from laminar to turbulent flow.

The transition process could be described by the intermittency parameter γ, which gives information about the fraction of time when the flow is turbulent. That is why the coupling with intermittency seems to be the best way to take into account the physical mechanism of transitional flow and to model the transition in a proper way. One of the most classic methods for the modelling of the transition with applications of the intermittency parameter is a model formulated by Dhawan and Narasimha (1958). The estimated intermittency factor at the current location and in time (for unsteady calculations) is usually used as a multiplier of the production term in the turbulence model. In the pretransitional regime, γ is set to zero, and when it attains the positive value, the transition is initiated.

Recently, some new methods have been developed, and all of them rely on the intermittency parameter. The first one is the Prescribed Unsteady Intermittency Model (PUIM) developed at Cambridge University (Vilmin *et al.*, 2003), which solely relies on empirical correlations. PUIM calculates a distance-time intermittency distribution as a function of space and time fields (constant in time in the case of steady flow simulation). To have this information, PUIM employs the Mayle (1991) and Abu-Ghannam and Shaw (1980) correlations for the transition onset and also the Mayle (1991) or Gostelow *et al.* (1996) correlations for the spot production rate. The spreading of turbulent spots is prescribed using functions of the edge velocity and the pressure gradient parameter. For a separated flow, the other Mayle correlation gives the spot production rate from the momentum-thickness Reynolds number at separation. The detection of the separation arises from the skin friction and Thwaites criterion. Such a solution ensures that not only attached flow transition onsets but also separated onsets could be identified. The high quality of this approach was confirmed among the others in T106A (Vilmin *et al.*, 2003) and on N3-60 test cases (Elsner *et al.*, 2004).

A more general description of the intermittency is obtained from the dynamic intermittency convection-diffusion-source equation, where the first method was developed by Lodefier and Dick (2006) at Ghent University, and the second is a result of the work performed by Menter and co-authors (2004). According to the first approach, named L&D hereafter, two dynamic equations for the intermittency: one for the near-wall intermittency γ and one for the free-stream-intermittency ζ were proposed. The near wall intermittency takes into account the fraction of time during which the near-wall velocity fluctuations caused by transition have a turbulent character and tend to zero in the free stream region, while on the wall it attains unity. The free-stream factor ζ describes the intermittent behaviour of turbulent eddies coming from the free stream and impacting into the underlying pseudo-laminar boundary layer. Near the wall, the eddies are damped and the free-stream factor goes to zero while in the free-stream it reaches unity. For the onset detection in the case of bypass and turbulence wake induced transition, the model employs the Mayle (1991) correlation. For a quasi-steady separation transition, a criterion proposed for such a type of flows by Mayle (1991) is applied. An additional criterion is used in the case of wake induced transition over a separation bubble. This method shows to be an efficient tool for prediction of wake interaction with the separation bubble and especially for the wake interaction with the attached flow (Lodefier *et al.*, 2005).

A different strategy is proposed by Menter *et al.* (2004). In this method, only local information is used to activate the production term in the intermittency equation, and the link between the correlations and the intermittency equation is achieved through the use of the vorticity Reynolds number. The proposed model is based on the SST turbulence model and two transport equations. The first one is the intermittency equation used to trigger the transition process. The second transport equation of the momentum thickness Reynolds number $\mathrm{Re}_{\theta t}$ is implemented for avoiding non-local operations introduced by experimental correlations. Outside the boundary layer the transport variable is forced to follow the value of $\mathrm{Re}_{\theta t}$ given by the correlations. For this purpose, the standard and in-house correlations are used for the natural, bypass and separation induced transition. This input is then diffused into the boundary layer with the use of the standard diffusion term. Due to this methodology, strong variation of the turbulence intensity and pressure gradient, which are typical for turbomachinery, can be taken into account. The local information used to trigger the onset of the transition in this model is the vorticity Reynolds number Re_v. This quantity depends only on density, viscosity, wall distance and vorticity, so it could be easily computed at each grid point. It is the main advantage of this methodology which could be applied for parallel calculations on unstructured grids. The authors' own experience (Piotrowski and Elsner, 2006) shows that this model, despite the lack of physics in the proposed additional equation for $\mathrm{Re}_{\theta t}$, is able to properly predict the periodical evolution of the boundary layer under the influence of impinging wake with adequate quality. Recently, the Intermittency Transport Model (ITM), which was derived on the basis of Menters' approach discussed above, has been proposed by Piotrowski and Elsner (2006). Encouraging results for the N3-60 turbine profile both for steady and unsteady inflow conditions have been obtained. One should notice however, that some tuning of the correlation for length of the transition should be done.

All the above transition models are used in connection with the linear turbulence model. Another approach is proposed by Lardeau and Leschziner (2004), where the intermittency based formulation is coupled with the low-Re algebraic Reynolds-stress model. From this assumption, it results that this model should return properly all the Reynolds-stress components, which is especially important for the near wall flows where strong turbulence anisotropy is present. The advantage of this modelling approach is the ability to model the pretransitional rise of turbulence intensity, which was experimentally confirmed, among the others by Elsner *et al.* (2004). This ability is achieved mainly due to the introduction of parameters modifying damping functions which control its cross-flow and streamwise variations by taking into account the Klebanoff mode properties observed in the pretransitional phase of boundary layer development. The experimental verification of this methodology based mainly on ERCOFTAC data (www://ercoftac.mech.surrey.ac.uk) shows improvement in the prediction of onset transition and its length (Lardeau and Leshziner, 2004). They also obtained reasonably good results for the unsteady test case of T106A aero-engine turbine profile with the low background turbulence intensity. However, to incorporate the effect of a higher background turbulence intensity they had to introduce a supplementary algebraic equation for the intermittency, what limits the general applicability of this method.

5. Sample applications of transition models for turbine flows

To show the applicability of the models described above, some sample results are given below. The results concern the traditionally designed N3-60 steam turbine blade, where the attached boundary layer bypass transition is present as well as in the advanced, heavily loaded, gas turbine blade T106A with a separation bubble on the suction side.

The important information for the analysis of the boundary layer development on the blade profile is the pressure distribution. The importance of the pressure gradient manifests itself by the presence of shorter or longer acceleration and deceleration zones. Figure 5 presents the pressure coefficient C_p distributions around the N3-60 blade profile obtained from the experiment and numerical modelling performed by Piotrowski and Elsner (2006). The numerical results are obtained with the use of PUIM, L&D and ITM models. The pressure coefficient C_p is defined as

$$C_p = \frac{p - p_\infty}{\frac{1}{2}\rho U_\infty^2} \tag{5.1}$$

where: p is the static pressure on the blade, p_∞ – free stream static pressure, ρ – density, U_∞ – free stream velocity, $\rho U_\infty^2/2$ – dynamic pressure. One may observe a good agreement between the experimental data and calculations. The numerical simulation even confirms the small deceleration zone close to the leading edge, which is due to blade non-linearity in the region where the circular leading edge matches the further part of the profile.

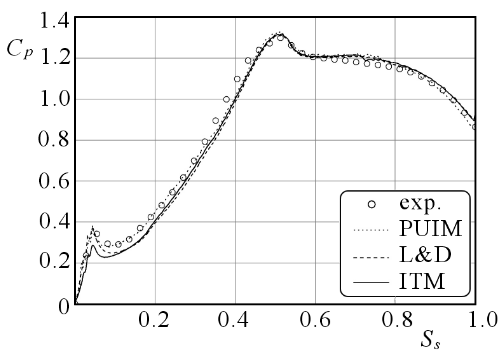

Fig. 5. Pressure distribution on the tested N3-60 blade profile

A more advanced evaluation of the numerical procedures may be performed with boundary layer characteristics. Figure 6 presents distributions of the shape (Fig. 6a) and intermittency factors at the wall (Fig. 6b) for the suction side of the blade. One may observe that the numerical shape factor distributions follow the experiments on almost the entire blade surface. After a small separation behind the leading edge, the boundary layer remains laminar with a rather small value of the shape factor due to the accelerating flow. Then, after the minimum pressure peak, an elevated value of the shape factor is seen, which shows the tendency towards separation. The most important region is the rear part of the profile, where the boundary layer development determines the magnitude of the losses. One may notice a very good agreement between the simulations and experiment. The key variable in the computational description of the boundary layer during the transition from a laminar to turbulent flow is the intermittency factor γ. One may observe in Fig. 6b that the simulated intermittency lags the experimental intermittency factor and that the evolution of γ is steeper. The reason is that the intermittency used in the modelling aims to reproduce the intermittency evolution which historically has been derived from the evolution of global parameters such as the turbulent skin friction and shape factor. So, the modelled intermittency factor in Fig. 6b very closely follows the shape factor change shown in Fig. 6a. In modern experimental techniques, the intermittency factor is determined directly from the frequency analysis of the velocity signal in the flow. It is then observed that the increase of intermittency starts prior to the change of general flow properties as indicated by the rise of skin friction and drop of the shape factor. The streaky structures at the beginning of the transition zone have a frequency content that is interpreted as a turbulence by the intermittency detector. However, as it is proven by literature data (Jacobs and Durbin, 2001) there is almost no Reynolds stress associated to the streaky structures before their three-dimensional breakdown. Further, an experimental intermittency factor based on signal analysis never becomes unity. The observation that the evolution of the shape factor is very well reproduced by the modelling techniques proves that the modelling technique based on the intermittency concept can describe very accurately the transitional behaviour in steady flows.

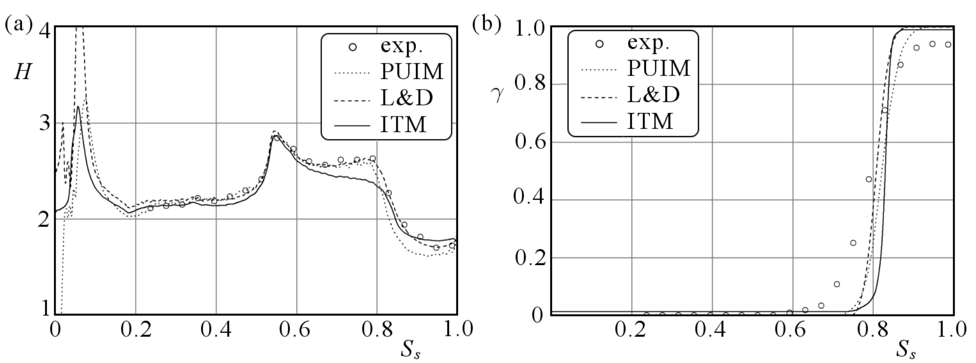

Fig. 6. Steady flow: shape factor H (a) and intermittency factor γ (b) for $\mathrm{Tu} = 3.0\%$

The flow unsteadiness strongly affects the time dependent location of the laminar-turbulent transition region on the blade surface. The proper modelling of the unsteady flow is therefore very challenging. Figure 7 presents instantaneous solutions of turbulent kinetic energy for the PUIM method, where the

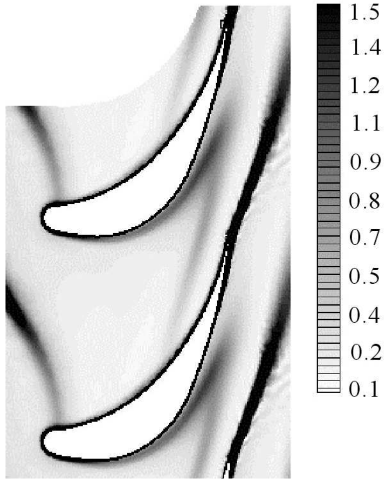

Fig. 7. Instantaneous solutions of Turbulent Kinetic Energy (TKE) obtained with the PUIM model

development of the wake inside the blade channel could be noticed. The impinging wakes periodically shift the transition position upstream, what is seen on the s-t diagrams (Fig. 8) showing how the shape factor varies with the surface distance on the abscissa and with time on the ordinate axis. The shape factor is a good indicator of the state of the boundary layer, i.e. it indicates whether it is laminar, transitional, turbulent or separated. Figure 8 presents the comparison of numerical results obtained with the PUIM, L&D and ITM models with experimental results, and it can be easily seen that a good qualitative agreement was obtained among these distributions. The elevated value of H at $S_s = 0.52$-0.58 (black colour) confirms the observation of nearly separated flow seen in the steady flow results. The most encouraging is the evolution of the turbulent wedge under the wake (light colour), which for all methods has a similar shape and size, which means that the start of the transition under the wake was found to be almost identical with the experimental results for all methods. It is shifted a bit upstream for the L&D method in comparison with the experimental results, and also a bit downstream for the PUIM method. As it is seen, the best results are obtained for the ITM model. Summing up the above analysis, one can say that despite their different formulations all models are able to reproduce properly the transition due to wake turbulence.

The results of transition modelling for highly loaded profiles is described based on the paper by Lodefier and Dick (2006). The calculations with their model were performed on the T106 LP turbine blade for the Reynolds number $\mathrm{Re} = 1.6 \cdot 10^5$, where the inflow was disturbed by incoming wakes from a moving bar system located upstream of the cascade. As it was stated already, in that case the mechanism of transition is different than for the attached

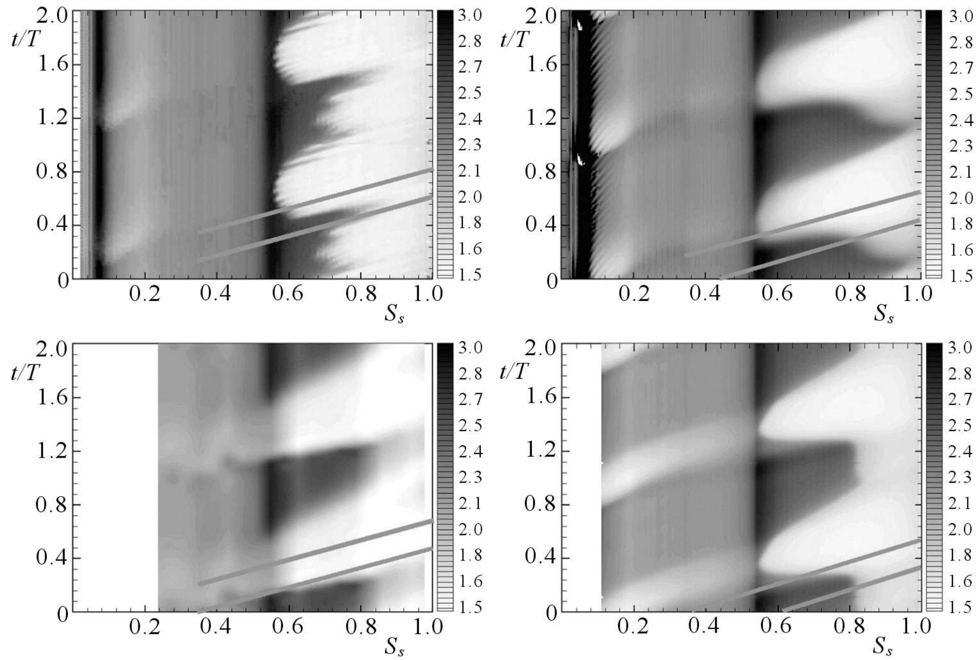

Fig. 8. Time-space diagrams of the shape factor for N3-30, $\mathrm{Tu} = 3.0\%$, PUIM model (top-left), L&D model (top-right), experiment (bottom-left), ITM model (bottom-right)

flow. The wake impact on a separation bubble causes almost immediate breakdown of the free shear layer due to Kelvin-Helmholtz instability, which then develops into roll-up vortices. The vortices formed by the rollup of the shear layer rapidly break down to turbulence. It means that, contrary to the bypass transition, this process is abrupt and needs special treatment in the modelling framework. In the intermittency transport equation of the Lodefier and Dick model (Lodefier and Dick, 2006) sudden transition of the separation bubble is expressed in such a way that the intermittency is forced almost immediately to unity. The comparison of the numerical results with the experimental data is given in Fig. 9. The zone between lines (A) and (B) shows the extension of the wake impact. High values of the shape factor H indicating the separation region occur at the relative coordinate S from 0.6 to 0.8. The wake impact modifies the separation bubble and induces rollup vorticies (their traces are shown by dotted lines). The inclination angle of dotted lines reveals that the rollup vortices travel with much lower velocity than the wake. The general conclusion is that the physics of this transition mechanism was correctly reproduced in computations and that the appearance of the separation and the transformation into roll-up vortices was faithfully represented.

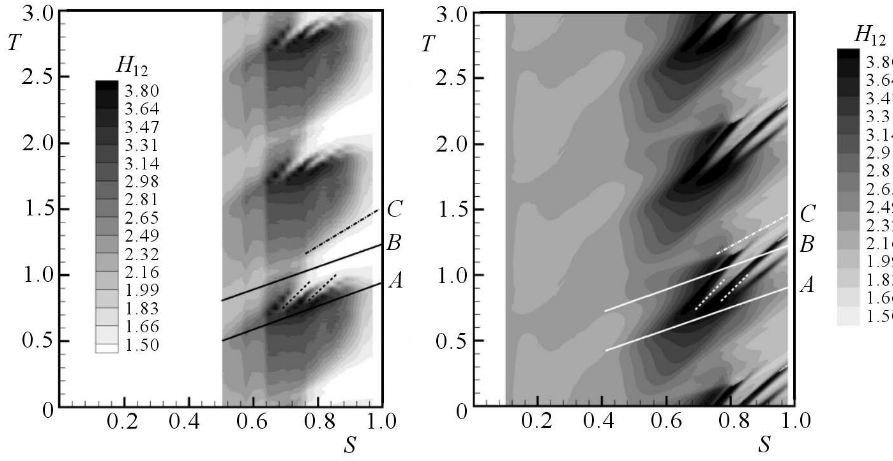

Fig. 9. Time-space diagrams of the shape factor for T106A, Tu = 0.5%, experiment (left), L&D model (right) (Lodefier and Dick, 2006)

6. Conclusions

The paper proves that the accurate modelling of complex geometries in turbomachines is of primary importance. The experimental results discussed in the paper show the complexity of the process of the transition from a laminar to turbulent state, especially under the conditions of wake impact. It is concluded that this process induced by freestream turbulence consists of the formation and growth of streaky structures, followed by the development of secondary instabilities, formation of spots which finally coalescence with a fully developed turbulent boundary layer. Another mechanism is present when the wake interacts with the separation bubble, where the kinematic forcing by Kelvin-Helmholtz instability induces development of roll-up vorticies.

The paper reveals that currently only the mechanisms of generation, amplification and convection of isolated turbulent spots could be modelled, while the pretransitional phase is only mimicked by various experimental correlations for the transition onset. The exception is the Lardeau and Leschziner model (2004) which attempts to model the pretransitional Klebanoff mode fluctuations.

It is also shown that currently the only feasible way to take into account the physical mechanism of transitional flow and to model the transition in a proper way is to couple the turbulence model with intermittency.

The numerical results discussed in the paper show that the modern transition models are basically able to reproduce the periodic evolution of the boundary layer under the influence of impinging wakes, no matter whether the attached or separated boundary layer is considered. The study performed at the Institute of Thermal Machinery demonstrates that the results of numerical simulations of the laminar-turbulent transition are very sensitive to inflow conditions and to the type of the numerical method. In this context, the proper modelling of an unsteady movement of the upstream wake and so the grid quality in the blade passage, the number of time steps per one wake period and methods for the wake parameters prescription at the inlet to the computational domain, are important.

Acknowledgements

The research was supported by the Polish Ministry of Education and Science under the statutory funds BS-1-103-301/2004/P as well as research grant No. PBZ-MEiN-4/2/2006.

References

1. Abu-Ghannam B.J., Shaw R., 1980, Natural Transition of boundary-layers the effects of turbulence, pressure gradient and flow history, *J. Mech. Eng. Sci.*, **22**, 5, 213-228
2. Dhawan S., Narasimha R., 1958, Some properties of boundary layer flow during transition from laminar to turbulent motion, *J. Fluid Mech.*, **3**, 418-436
3. Elsner W., 2004, *Influence of Nonstationary Interactions on Laminar-Turbulent Transition Process on a Turbine Blade Profile*, CzUT Publishing, Ser. Monographs, **103**, Czestochowa [in polish]
4. Elsner W., Vilmin S., Drobniak S., Piotrowski W., 2004, Experimental analysis and prediction of wake-induced transition in turbomachinery, *ASME paper no. GT2004-53757, ASME TURBO EXPO 2004*, Vienna
5. Gostelow J.P., Melwani N., Walker G.J., 1996, Effects of streamwise pressure gradients on turbulent spot development, *ASME Journal of Turbomachinery*, **118**, 737-743
6. Howell R.J., Hodson H.P, Shulte V., Stieger R.D., Schiffer H.P., Haselbach F., Harvey N.W., 2002, Boundary layer development in the BR710 and BR715 LP turbines – the implementation of high-lift and ultra-high-lift concepts, *ASME J. of Turbomachinery*, **124**, 385-392
7. Huai X., Joslin R., Piomelli U., 1997, Large-eddy simulation of transition to turbulence in boundary layers, *Theoret. Comput. Fluid Dynamics*, **9**, 149-163
8. Jacobs R.G., Durbin P.A., 2001, Simulations of bypass transition, *J. Fluid Mech.*, **428**, 185-212
9. Kendall J.M., 1985, Experimental study of disturbances produced in a pre-transitional laminar boundary layer by weak free stream turbulence, *AIAA Paper 85-1695*

10. Lardeau S., Leschziner M., 2004, Modelling bypass transition with low-Reynolds-number nonlinear eddy-viscosity closure, *Flow, Turbulence and Combustion*, **73**, 1, 49-76

11. Lodefier K., Dick E., 2006, Modelling of unsteady transition in low-pressure turbine blade flows with two dynamic intermittency equations, *Flow, Turbulence and Combustion*, **76**, 2, 103-132

12. Lodefier K., Dick E., Piotrowski W., Elsner W., 2005, Modelling of wake induced transition with dynamic description of intermittency, *6th European Turbomachinery Conference.*, Paper No. 071_05/66, Lille

13. Mayle R., 1991, The role of laminar-turbulent transition in gas turbine engines, *ASME J. of Turbomachinery*, **113**, 509-537

14. Menter F.R., Esch T., Kubacki S., 2002, Transition modelling based on local variables, In: *Engineering Turbulence Modelling and Measurements*, W. Rodi and N. Fueyo, Edit., **5**, 555-564

15. Menter F.R., Langtry R.B., Likki S.R., Suzen Y.B., Huang P.G., Völher S., 2004, A correlation – based transition model using local variables. Part I – Model formation, *ASME Paper GT2004-53452, ASME TURBO EXPO 2004*, Vienna

16. Morkovin M.V., 1969, *On the Many Face of Transition Viscous Drag Reduction*, C.S. Wells, Edit., Plenum Press, New York, 1-31

17. Narasimha R., 1957, On the distribution of intermittency in the transition region of a boundary layer, *J. Aero. Sci.*, **24**, 711-712

18. Opoka M.M., Hodson H.P., 2005, *An Experimental Investigation on the Unsteady Transition Process on the High Lift T106A Turbine Blade*, Paper No. 1277 ISABE Munich

19. Piotrowski W., Elsner W., 2006, Modelling of laminar-turbulent transition with the use of intermittency transport equation, *Chemical and Process Engineering*, **27**, 3/1, 669-684

20. Savill M., 2002, New strategies in modelling by-pass transition, In: *Closure Strategies for Turbulent Transitional Flows*, Launder B.E., Sandham N., Edit., Cambridge University Press, 493-521

21. Schulte V., Hodson H., 1998, Prediction of the becalmed region for LP turbine profile design, *Trans. ASME, J. of Turbomachinery*, **120**, 839-846

22. Stieger R.D., Hodson H.P., 2004, The transition mechanism of highly-loaded LP turbine blades, *Trans. ASME, J. of Turbomachinery*, **126**, 536-543

23. Vilmin S., Savill M.A., Hodson H.P., Dawes W.N., 2003, Predicting wake-passing transition in turbomachinery using a intermittency-conditioned modelling approach, *33rd AIAA Fluid Dynamics Conference and Exhibit*, Orlando, June

24. Voke P.R., Yang Z., 1995, Numerical study of bypass transition, *Phys. Fluids*, **7**, 2256-2264

25. Wu X., Jacobs R.G., Hunt J.C.R., Durbin P.A., 1999, Simulation of boundary layer transition induced by periodically passing wakes, *J. Fluid Mech.*, **398**, 109-153

Modelowanie przejścia laminarno-turbulentnego w maszynach przepływowych

Streszczenie

Artykuł poświęcony jest zagadnieniom modelowania warstwy przyściennej w maszynach przepływowych, w których występują różne mechanizmy przejścia laminarno-turbulentnego, w tym obecne zwłaszcza w warunkach napływających śladów. W artykule przedstawiono przegląd najnowszych osiągnięć w interpretacji przejścia typu by-pass, indukowanego śladem i oderwaniem warstwy przyściennej oraz przedyskutowano najważniejsze aspekty modelowania przejścia laminarno-turbulentnego. Przegląd ten został uzupełniony opisem fizykalnej interpretacji zjawiska przejścia w oparciu o najnowsze dane literaturowe, jak również w oparciu o własne wyniki badań eksperymentalnych i numerycznych prowadzonych w Instytucie Maszyn Cieplnych. Dla udokumentowania własności nowoczesnych modeli przejścia laminarno-turbulentnego wykorzystano dwa przypadki testowe, dotyczące profilu łopatkowego turbiny parowej N3-60 oraz profilu łopatkowego gazowej turbiny lotniczej T106A.

Manuscript received May 10, 2007; accepted for print June 8, 2007