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URANS Prediction of the Effects of Upstream Wakes on High-Lift LP Turbine Cascades Using Transition-Sensitive Turbulence Closures

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Abstract

A URANS solver has been applied to the analysis of unsteady effects induced by incoming wakes in high-lift, low-Reynolds-number cascade flows. The study has been carried out using a novel, transition-sensitive, turbulence model. It is based on the coupling of additional transport equations, one for the so-called laminar kinetic energy (LKE) and one for a turbulence indicator function, with an algebraic Reynolds stress formulation based on the \( k-\omega \) model. The transition modelling strategy and its coupling with the turbulence equations is conceived as an extension of the laminar kinetic energy concept for unsteady flow calculations.

Three high-lift bladings (T106A, T106C, and T2), recently tested in the framework of two European research projects were considered for the present study. The cascades are characterized by separated flow transition in steady conditions.

A detailed comparison between measurements and computations, in terms of blade loading distributions and cascade lapse rates will be presented and discussed. Some specific features of wake-induced transition will also be discussed. Results obtained with the proposed model show its ability to predict the major effects of passing wakes on the boundary layer development and loss characteristics of high-lift cascades operating in LP-turbine conditions.

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Keywords: low pressure turbine; laminar to turbulent transition; low Reynolds number flows

1. Introduction

The increasing demand for compact and light aircraft engines with high efficiency has lead to the development of high-lift and ultra-high-lift airfoils for the low pressure (LP) turbine. Low-pressure turbine blades work with relatively low Reynolds numbers. On isolated blade rows, such flow conditions are likely to produce boundary layer separation in regions of adverse pressure gradient, and an important loss penalty is associated to these circumstances. In the engine multistage environment, the unsteady wake induced transition plays a key role in reducing the separation effects up to a level compatible with acceptably low losses. Several studies demonstrate how high-lift and ultra-

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high-lift [1–3] airfoils can be operated with loss control by taking advantage of wake-induced transition in LPT low-Reynolds-number flows. The rising interest in boundary layer separation control by means of active or passive devices is also worth to be mentioned. The combined effect of flow-control devices and wake-induced transition seems to be promising in order to support and enhance the high-lift concept [4].

The suction side boundary layer behavior is modulated by its interaction with the incoming wakes. The velocity deficit and the high turbulence energy within the wakes can induce transition. Such a mechanism can reduce or even prevent the boundary layer separation. After the wake passing, the boundary layer tends to relax to its pre-transitional state. This determines a condition characterized by essentially laminar, but attached flow, referred to as calming [5, 6]. Once such an effect has decayed, if the wake passing frequency is not too high, the boundary layer begins to separate again. It’s the relative influence of laminar, separated, turbulent, and calmed boundary layer portions which is responsible of the loss reduction with respect to steady inflow cases.

The physical details of most of the flow features described above are hardly represented by any Reynolds-averaged model. Albeit LES or DNS approaches can be of great help in the physical understanding of the intimate structure of such mechanisms, those methodologies are way far from being feasible from an engineering point of view. Consequently, despite an unavoidable lack of physical details, URANS approaches that are able to model the main effects of wake boundary layer interactions, in terms of blade loading and losses, are strongly desirable.

Today, the transition/turbulence models employed in industrial applications are basically of three types: low turbulent Reynolds number formulations, intermittency based or laminar kinetic energy (LKE) based approaches.

Linear and non-linear eddy-viscosity models based on low-Reynolds number formulations of the transport equations are able to mimic boundary layer transition processes. This is accomplished via an unbalance between production and dissipation terms that allows turbulence kinetic energy amplification in laminar boundary layers [7]. The results of this mechanism strictly depend on the particular closure assumptions [8]. Intermittency based can be successfully embedded in transport models (e.g. [9, 10]), anyway they rely, at least to some degree, on non-local quantities or correlations. Methodologies based on the concept of the of laminar kinetic energy transport are theoretically more general, i.e. they are phenomenological models and they do not rely on global quantities [11, 12]. The pre-transitional fluctuating energy is gradually transferred to the turbulence field in order to trigger transition. This process have proven to be quite effective in steady flows affected by natural, bypass or separated flow transition phenomena [11, 13]. Such mechanisms play an important role also on the boundary layer behavior between successive passing-wake events. Indeed, wake-induced transition is essentially the result of the high turbulence level transported within the wake. A low Reynolds number turbulence model can give roughly satisfactory transition predictions in this circumstances, as it reacts to turbulence diffusion inside the boundary layer. Such considerations suggest a modelling strategy in order to extend a LKE based approach to engineering simulations of unsteady interactions in turbomachinery. According to the proposed approach, the laminar kinetic energy should not be produced in the wake-induced path, transition being triggered by the wake turbulence. It should be instead allowed to develop in the path between wakes in order to model the boundary layer instabilities and promote transition. A suitable mean to identify the fraction of time over which the boundary layer, at a given spatial location, is affected by the wake turbulence is then desirable. Lardeau et al. [14] used the conventional intermittency factor to combine the pre-transitional and turbulent components of their model obtaining good results on the T106A high-lift cascade. Here a novel approach is proposed, which is based on the coupling of two additional transport equations, one for the laminar kinetic energy, and one for a turbulent indicator function, to a low-Reynolds number formulation of the Wilcox $k – \omega$ model. The turbulent indicator function is used to weigh turbulent and laminar kinetic energies so that each of them contributes to the total fluctuation energy depending on the local turbulence level inside the boundary layer.

Two high-lift blade sections (T106 and T2), recently tested in the framework of the two European research projects UTAT (Unsteady Transition in Axial Turbomachines) and TATMo (Turbulence and Transition Modelling for Special Turbomachinery Applications), were considered for the present study. The analyzed Reynolds number values span the whole range typically encountered in aeroengines low-pressure turbines operations. Detailed comparisons between measurements and computations, in terms of blade surface isentropic Mach number distributions, cascade lapse rates and unsteady boundary layer quantities will be presented and discussed.
Nomenclature

- $c$: blade chord
- $\ell_T$: turbulence length scale, $\ell_T = k^{1/2}/\omega$
- $f_r$: bar wakes reduced frequency, $f_r = u_{bar}/(s_{bar}u_{2,ix})$
- $M$: Mach number
- $Re_T$: turbulent Reynolds number, $k/(\nu\omega)$
- $s$: blade pitch, curvilinear abscissa
- $S$: mean shear rate $S = \sqrt{2S_{ij}S_{ij}}$
- $Tu$: turbulence intensity
- $u$: velocity
- $\alpha$: flow angle
- $\delta_\Omega$: shear layer vorticity thickness, $\delta_\Omega = \frac{u_\infty}{2}(\frac{\partial u}{\partial y}_{\text{max}})^{-1}$
- $\nu$: kinematic fluid viscosity

2. Computational framework

The TRAF code [15] was used in the present work. The unsteady, three-dimensional, Reynolds-averaged Navier-Stokes equations are written in conservative form in a curvilinear, body-fitted coordinate system and solved for density, absolute momentum components, and total energy. Chorin’s artificial compressibility concept is adopted in order to handle incompressible flows. A dual-time-stepping method [16, 17] is used to perform time accurate calculations.

2.1. Transition and turbulence modelling

The proposed model is based on four transport equations for the laminar ($k_{\ell}$) and turbulent ($k$) kinetic energies, the specific turbulent-dissipation rate ($\omega$), and the turbulent indicator function ($I$) respectively:

\[
\frac{Dk_{\ell}}{Dt} = (1 - I) P_{\ell} - 2\nu \frac{k_{\ell}}{\nu} + \nu \nabla^2 k_{\ell} - R
\]

\[
\frac{Dk}{Dt} = IP_k - \beta^{*} f_k k\omega + \frac{\partial}{\partial x_j} \left[ (\nu + \sigma_k \nu) \frac{\partial k}{\partial x_j} \right] + R
\]

\[
\frac{D\omega}{Dt} = \alpha I \omega P_k - \beta \omega^2 + \frac{\partial}{\partial x_j} \left[ (\nu + \sigma_\omega \nu) \frac{\partial \omega}{\partial x_j} \right]
\]

\[
\frac{DI}{Dt} = P_I + \frac{\partial}{\partial x_j} \left[ (\nu + \sigma_I \nu) \frac{\partial I}{\partial x_j} \right]
\]

A detailed description of the model can be found in [18]. Here, for conciseness, only its most significant features will be discussed. The turbulent indicator function $I$ is a key feature of the present modelling strategy. Physically it can be regarded as the probability that the flow, at a given spatial location, is turbulent, with $0 \leq I \leq 1$. Thus $I = 0$ refers to purely laminar flow, while $I = 1$ indicates a turbulent regime (see Rumsey et al. [19]). The role of the turbulent indicator function is to weigh the production terms of the laminar fluctuations and turbulence energy so that they are activated depending on the turbulence level inside the boundary layer. Therefore, the production term for the $I$ equation was assumed to be proportional to the turbulent Reynolds number, which gives a measure of the local turbulence intensity, and it was constructed as follows:

\[
P_I = c_I \frac{U^2}{\nu} (\bar{Re}_T - I)
\]
where: $\tilde{Re}_T = (Re_T - Re_{T,\infty}) / Re_{T,\infty}$, and $Re_{T,\infty}$ is the freestream value of the turbulent Reynolds number. The term $\nu/U^2$ represents a viscous time scale. Finally, the function $I$, as obtained by the integration of Eq. (4), is limited between 0 and 1.

With reference to periodic unsteady conditions, the turbulence indicator function can be regarded as a sensor which identifies the fraction of the period over which the boundary layer, at a given spatial location, is affected by wake turbulence. In this conditions the generation of laminar fluctuating energy is suppressed and the wake-induced transition process is controlled by the diffusion of wake turbulence into the boundary layer. This transition mode is made possible via the low-Reynolds formulation of the turbulent transport equations (2) and (3) (e.g. Wilcox [7]). In the path between wakes, the function $I$ goes to very low values. This allows transition to be determined by the laminar kinetic energy growth in the boundary layer. The LKE transport model, is based on the laminar kinetic energy concept of Mayle and Schulz [20], which enables to take into account the pre-transitional rise of the fluctuating kinetic energy. In attached and separated shear layers, the amplification of fluctuations is due more to conventional shear-stress/strain interaction (Lardeau et al. [21]) rather than to pressure diffusion (Mayle and Schulz [20]). Hence, a model of the production of the laminar kinetic energy can be formulated as follows:

$$P_L = \nu_L S^2; \quad \nu_L = C_1 f_1(T_{u_\infty}) \sqrt{k_\ell} \delta \Omega; \quad f_1(T_{u_\infty}) = \max \left\{ 0, 0.8 \tanh \frac{T_{u_\infty}}{4.5} \right\}$$

(6)

Once the laminar kinetic energy is created in the separated shear layer, it must be transferred to the turbulence field to trigger the transition process, as shown by numerical [22] and experimental investigations [23]. This is accomplished via the term $R$, which appears in both the laminar and turbulent kinetic energy equations, but with opposite signs, resulting in no net change of the total fluctuating kinetic energy $k_{tot} = k_\ell + k$. Rather there is a transfer of energy from $k_\ell$ to $k$. Following Walters and Leylek [11], this term is assumed to be proportional to $k_\ell$:

$$R = C_2 \beta^* f_2 \omega k_\ell$$

(7)

The damping function $f_2$ is used to control the transfer of energy from the laminar to the turbulent state [24]. The turbulence equations are derived from the Wilcox’s low-Reynolds number $k-\omega$ model [7]. The turbulence-production term is written as:

$$P_k = \tau_{ij} \frac{\partial u_i}{\partial x_j}$$

(8)

An explicit algebraic formulation for the Reynolds stresses $\tau_{ij}$ is obtained via the realizable quadratic eddy viscosity model (RQEV) proposed by Rung et al. [25]. The term $f_2(Re_T)$ in Eq. (2) is a closure function. Its definition is given in [18] together with the values of the various constants.

The inlet condition for the indicator function is: $I = \min [(Re_T - Re_{T,\infty}) / Re_{T,\infty}, 1]$. The boundary condition at a wall is zero normal gradient. The inlet condition for the laminar kinetic energy is $k_\ell = 0$. The boundary condition at a wall is $k_\ell = 0$. The turbulence equations of the present model yield the correct asymptotic behavior at solid boundaries [7].

Fig. 1: (a) Analyzed cascades configurations; (b) T106C – single-block O-type grid 641×101.
Steady measurements were carried out on a range of Reynolds number going from conditions. Detailed traverse measurements within the wakes were made available for code validation purposes. The bar wake-generator which ensured a reduced frequency representative of actual rotor-stator interactions in cruise reproduced the actual cruise operation of modern aeroengine LP turbines. The test rig was equipped with a moving Institute during the UTAT and TATMo projects. Measurements were carried out in a high-speed facility conceived to analyze configurations are summarized in Tab. 1. The T106C and the T2 cascades were tested at the von Kármán Institute as a part of the UTAT research project. The main geometric and flow conditions for the analyzed configurations are summarized in Tab. 1. The T106C and the T2 cascades were tested at the von Kármán Institute during the UTAT and TATMo projects. Measurements were carried out in a high-speed facility conceived to reproduce the actual cruise operation of modern aeroengine LP turbines. The test rig was equipped with a moving bar wake-generator which ensured a reduced frequency representative of actual rotor-stator interactions in cruise conditions. Detailed traverse measurements within the wakes were made available for code validation purposes. Steady measurements were carried out on a range of Reynolds number going from $Re_{2,ls} = 0.8 \times 10^5$ to $Re_{2,ls} = 2.5 \times 10^5$. Unsteady experimental results were made available only for low freestream turbulence intensity and two values of the Reynolds number corresponding to $Re_{2,ls} = 1.0 \times 10^5$ and $Re_{2,ls} = 1.4 \times 10^5$. The T106A cascade was tested at the University of Cambridge in low speed (incompressible) conditions. Steady and unsteady measurements were carried out on a range of flow conditions similar to the one reported for the T106C and T2 cascades steady tests. In particular very detailed boundary layer measurements were provided, and this makes such a configuration a very interesting one for the validation of time-accurate procedures. The $641 \times 101$ O-type grid was used for all the calculations. The mesh size, that can be appreciated in Fig. 1(b), was selected in order to have sufficient grid density to prevent smearing of the incoming wakes [27]. About 40 cells lie inside laminar portions of boundary layers and the $y^+$ values of the mesh nodes closest to the wall are below unity in turbulent regions.

### 3. The test cases

Two of the test cases that were selected for the present study are based on the T106 blade section, while the third is based on the T2 profile. The airfoil geometries and the different pitch/chord ratios of the three configurations can be appreciated in Fig. 1(a). All the blade sections feature an aft loaded design, with a slightly greater deflection for the T2 airfoil. The T106 turbine blade section [26] is a widely used geometry for both experimental and numerical studies on high-lift LP profiles. Two different solidity values have been studied in the present paper, corresponding to the T106A and T106C cascades of Fig. 1(a). The T2 configuration is a high-lift cascade, which was designed at the von Kármán Institute during the UTAT and TATMo projects. Measurements were carried out in a high-speed facility conceived to reproduce the actual cruise operation of modern aeroengine LP turbines. The test rig was equipped with a moving bar wake-generator which ensured a reduced frequency representative of actual rotor-stator interactions in cruise conditions. Detailed traverse measurements within the wakes were made available for code validation purposes. Steady measurements were carried out on a range of Reynolds number going from $Re_{2,ls} = 0.8 \times 10^5$ to $Re_{2,ls} = 2.5 \times 10^5$. Unsteady experimental results were made available only for low freestream turbulence intensity and two values of the Reynolds number corresponding to $Re_{2,ls} = 1.0 \times 10^5$ and $Re_{2,ls} = 1.4 \times 10^5$. The T106A cascade was tested at the University of Cambridge in low speed (incompressible) conditions. Steady and unsteady measurements were carried out on a range of flow conditions similar to the one reported for the T106C and T2 cascades steady tests. In particular very detailed boundary layer measurements were provided, and this makes such a configuration a very interesting one for the validation of time-accurate procedures. The $641 \times 101$ O-type grid was used for all the calculations. The mesh size, that can be appreciated in Fig. 1(b), was selected in order to have sufficient grid density to prevent smearing of the incoming wakes [27]. About 40 cells lie inside laminar portions of boundary layers and the $y^+$ values of the mesh nodes closest to the wall are below unity in turbulent regions.

#### 3.1. The T106 turbine cascade

For the T106C cascade, detailed steady numerical analyses were previously carried out, for the whole range of tested Reynolds numbers, using a three-equation $k – \omega$ model. Those results, which are thoroughly discussed in [24], are virtually identical to the ones obtained with the present model for steady inflow conditions. In the present paper the performance of the proposed methodology is assessed in periodic unsteady flow brought about by incoming wakes.

Moving bars were not included in the computational domain, but the experimental profiles of total pressure and flow angle were directly prescribed as boundary conditions for the time-accurate calculations. The turbulent kinetic energy within the wake was deduced from the turbulence intensity distribution, while the specific turbulent dissipation rate was obtained via a mixing length hypotesis as suggested by Wilcox [7]. Outside the wake, inlet turbulent quantities were deduced from the freestream turbulence level and turbulent length scale value reported in Table 1. On the basis of previous dependency analyses [18], all the unsteady cascade calculations discussed in the paper were carried out by using 200 time divisions per wake passing period.

As mentioned before, unsteady experimental data were available for two different values of the Reynolds number corresponding to $Re_{2,ls} = 1.4 \times 10^5$, and $Re_{2,ls} = 1.0 \times 10^5$ respectively. Steady and unsteady computed isentropic Mach number distributions are compared to experiments in Fig. 2. The agreement can be considered very good along the whole suction side for both the considered cases. The steady distributions show a clear evidence of separated
Fig. 2: T106C cascade: steady and time-averaged suction side isentropic Mach number distributions (a) $Re_{2,ls} = 1.4 \times 10^5$ (b) $Re_{2,ls} = 1.0 \times 10^5$.

Fig. 3: T106C cascade: distance-time diagrams of (a) turbulent kinetic energy, (b) laminar kinetic energy, and (c) wall shear-stress ($Re_{2,ls} = 1.4 \times 10^5$)

flow in the decelerating portion of the blade suction side. The separation bubble, which is of the short type for the higher Reynolds number (Fig. 2(b)), becomes of the long type for $Re_{2,ls} = 1.0 \times 10^5$ (Fig. 2(a)), as suggested by the relevant modification of the blade load distribution occurring in this case [24, 28]. The effect of the separation bubble is almost suppressed by the interaction with the incoming wakes for the case at $Re_{2,ls} = 1.4 \times 10^5$, and greatly reduced for $Re_{2,ls} = 1.0 \times 10^5$. The load reduction in the front part of the blade with respect to steady conditions is also worth noticing. It is caused by the decrease in incidence associated to the flow angle distribution within the wake. A convenient way to analyze the effects of the passing wakes is based on distance-time diagrams of boundary layer and turbulent quantities. For $Re_{2,ls} = 1.4 \times 10^5$ such effects are expected to cause major dynamic perturbations on the boundary layer, as they almost nullify the blade loading modifications due to the separation bubble found in steady cases (Fig. 2). Examples of distance-time diagrams for the suction side of the T106C cascade are then reported for this case (Fig. 3). They refer to averaged turbulent kinetic energy within the boundary layer (Fig. 3(a)), averaged laminar kinetic energy (Fig. 3(b)), and wall shear-stress (Fig. 3(c)) respectively. The distance from the leading edge is represented by the normalized curvilinear abscissa along the blade surface, while the time is non-dimensionalized by the wake passing period. Two wake passing events are reported. The trajectories of the wake leading (L) and trailing (T) edges are also shown as dashed lines in the diagrams. Their slopes have been computed from the values of the local velocity at the edge of boundary layer $u_e$. As it can be noticed from Fig. 3(a), the first evidence of the wake-induced transition appears at about $s/s_{tot} = 0.5$. Downstream this location, the turbulent kinetic energy increase along line T, evolves in the formation of a typical wake induced turbulent strip [5, 6]. This corresponds to the wedge shaped region (marked as ① in the distance-time diagrams) of turbulent and attached flow that can be identified in between the
lines T and W. Within this region, the high level of turbulence that originates along line T is gradually reduced, as the boundary layer tends to relax to its pre-transitional state. The result of this process is the formation of the region \( \mathcal{S} \), in between the lines W and C, which corresponds to a patch of essentially laminar and attached flow that extends almost to the blade trailing edge, i.e. the calmed region. Indeed the lines W and C were drawn with slopes corresponding to propagation velocities of \( 0.5u_e \) and \( 0.3u_e \) respectively, which are the typical values that Halstead et al. [29] reported for the leading and trailing edge of the calmed region itself. Once the influence of calming has decayed the boundary layer begins to separate. The wake reduced frequency is in fact not high enough to prevent the re-establishment of the separation, under the effect of the adverse pressure gradient beneath successive passing wake events. The separated flow patch is marked as \( \mathcal{S} \) in the distance-time diagrams. As the separation bubble grows in size, tending to return to its steady state configuration, a relevant level of laminar kinetic energy is created in the path between wakes. Such a circumstance is well depicted in Fig. 3(b). The maximum level of the LKE is recorded, approximately along line L, when the wake convects over the re-establishing separation bubble. Transition is triggered between \( s/s_{tot} = 0.80 \) and \( s/s_{tot} = 0.85 \), along the line marked as S, and it is responsible for an intense turbulent energy production in the breakdown region of the bubble. Note how, as a result of the dynamic effects associated to the transport of the turbulent indicator function, the laminar fluctuations energy is effective in promoting transition only in the absence of wake induced turbulence.

The unsteady transition mechanism described above results in the prediction of relevant cascade loss reductions with respect to steady inflow conditions. This is well evident from Fig. 4 which compares computed and measured cascade lapse rates, in terms of kinetic energy loss coefficient, with and without incoming wakes. Two sets of steady experimental data are included for comparison. They originate from different tests performed within the European research programs UTAT and TATMo, respectively. The numerical results for the steady cases slightly underestimate the experimentally recorded steady losses for \( Re_{2,1s} < 10^5 \), otherwise the agreement is very good. A detailed discussion of such discrepancies can be found in [28]. The comparison between computed and measured values of the unsteady loss is also reported in Tab. 2 for the sake of clarity. The agreement is very good. Unsteady calculations have been carried out in the range of Reynolds numbers between \( Re_{2,1s} = 1.0 \times 10^5 \) and \( Re_{2,1s} = 2.5 \times 10^5 \). In such a range the computed cascade lapse rate lies always below the steady one. Although the experimental data are not sufficient to confirm this trend, the same behavior was evidenced experimentally by [4] in low speed tests on the T106C cascade.

In order to gain more confidence in the discussed time-accurate predictions, unsteady calculations were performed also for the T106A cascade. The computed steady and unsteady pressure coefficients are shown in Fig. 5(a), and they agree well with experimental data. The Reynolds number value corresponds to \( Re_{2,1s} = 1.6 \times 10^5 \), the freestream turbulence level and the wake reduced frequency are those reported in Table 1. With respect to the T106C cascade, the suction side separation bubble is much smaller for steady inflow conditions and it practically disappears, in a time-averaged sense, under the effect of the passing wakes. This is due to the lower pitch/chord ratio that characterizes this configuration which is located at the lower edge of the high-lift domain.

The time evolution of the boundary layer shape factor gives a comprehensive picture of the boundary layer state during the wake passing period. For the sake of conciseness, the comparison between computed and experimental unsteady results will be reported only in terms of this quantity, in the form of the time-distance diagrams of Fig. 5. Regions characterized by low values of the shape factor \( H \approx 1.4 \) are representative of turbulent flow, while high value of this parameter \( H \approx 3.5-4.0 \) are associated to separated, or nearly separated laminar boundary layer. The reported

<table>
<thead>
<tr>
<th>( Re_{2,1s} \times 10^5 )</th>
<th>( \zeta(%) ) Exp.</th>
<th>( \zeta(%) ) Comp.</th>
</tr>
</thead>
<tbody>
<tr>
<td>1.4</td>
<td>2.20</td>
<td>2.25</td>
</tr>
<tr>
<td>1.0</td>
<td>2.42</td>
<td>2.45</td>
</tr>
</tbody>
</table>

Fig. 4: T106C cascade: steady and unsteady cascade lapse rates.
Fig. 5: T106A cascade: (a) steady and unsteady pressure coefficient distributions. Experimental (b) and computed (c) distance-time diagrams of boundary layer shape factor ($Re_{2,ls} = 1.6 \times 10^5$)

Trajectories were deduced from the measurements. The computed unsteady transition pattern closely resembles the experimental one in terms of shape and location of the different flow patches characterizing the suction side boundary layer during the wake passing period. Anyway, wake-induced transition effects seems to start slightly upstream in the calculations with respect to the measurements. The wedge shaped turbulent patch is then slightly larger, while the high shape factor region, that establishes between successive passing wakes events, is consequently smaller. A similar behaviour has been observed by other researchers in this case [14].

### 3.2. The T2 turbine cascade

As for the T106C cascade, unsteady experimental data are available only for two Reynolds numbers, corresponding to: $Re_{2,ls} = 1.0 \times 10^5$ and $Re_{2,ls} = 1.4 \times 10^5$. Such measurements include wake traverses downstream the moving-bar wake generator that were used as unsteady boundary conditions according to the same methodology discussed for the T106C cascade.

Computed steady and unsteady isentropic Mach number distributions compare quite well with the experimental ones for both the analyzed Reynolds numbers, as it can be appreciated from Fig. 6(a), and 6(b). Due to the very low cascade solidity (about the 15% less than with respect to the T106C cascade) the suction side separation bubble of the steady cases was found to have the structure of a long bubble up to $Re_{2,ls} = 1.6 \times 10^5$ [24]. Actually the steady cases of Figs. 6(a)-(b) fall in the domain of open separations. The effect of the suction side flow separation is still quite evident in the time averaged distributions for both the analyzed conditions, but the impact of passing wakes on the blade loading is seen to be dramatic for this cascade. The effect on loss reduction is likewise pronounced, as it can be seen in Fig. 7, which reports computed and measured cascade lapse rates with and without passing wakes. Overall, the kinetic energy loss coefficient as a function of the exit isentropic Reynolds number is quite underestimated in the steady case [24], but in good agreement with experiments when unsteady conditions are considered (see also Table 3). As for the T106C cascade, the remarkable benefits associated to the influence of the incoming wakes extend for whole range of considered Reynolds numbers.
Fig. 6: T2 cascade: steady and time-averaged suction side isentropic Mach number distributions (a) $Re_{2,ls} = 1.4 \times 10^5$ (b) $Re_{2,ls} = 1.0 \times 10^5$.

Table 3: T2 cascade: kinetic energy loss coefficient for different Reynolds numbers.

<table>
<thead>
<tr>
<th>$Re_{2,ls} \times 10^5$</th>
<th>$\zeta$%(Exp.)</th>
<th>$\zeta$%(Comp.)</th>
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<tr>
<td>1.4</td>
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<td>2.35</td>
</tr>
<tr>
<td>1.0</td>
<td>2.80</td>
<td>2.85</td>
</tr>
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Fig. 7: T2 cascade: steady and unsteady cascade lapse rates.

4. Conclusion

A new transition model, based on the laminar kinetic energy concept and the transport of a turbulent indicator function, has been coupled with an algebraic Reynolds stress approach based on a low Reynolds number formulation of the Wilcox’s $k-\omega$ model to predict wake-boundary layer interactions in high-lift cascades operating in LP turbine-like conditions. The laminar fluctuations energy transport equation allows separated-flow transition to be triggered between passing wake events. The wake-induced transition path is triggered by turbulence diffusion into the boundary layer. The two different transition mechanisms are made to act separately via the switching of source terms by means of the turbulent indicator function.

The computational procedure was applied to the T106 and T2 cascades subjected to incoming wakes and in steady inflow conditions as well. The validity of the calculations was demonstrated by comparisons with cascade measurements obtained in realistic LP turbine conditions. A good agreement was found in terms of time-averaged blade-surface isentropic Mach number distributions and cascade lapse rates. The study of time-distance diagrams of turbulent and boundary layer integral quantities helped to show how the major features of the wake-induced transition process were reproduced by the proposed modelling strategy. A reasonable agreement with experimental, time-resolved, boundary layer data is observed even when the incoming wakes characteristics are deduced via a simplified modelling and not prescribed from experimental data. Discrepancies appeared in the prediction of the wake-induced transition onset which seems to be located slightly earlier with respect to measurements. It is concluded that the present URANS approach offers an affordable and quite accurate mean for engineering simulations of unsteady wake interactions in low pressure turbine cascades.

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