Unsteady RANS modelling of wake-induced transition in linear LP-turbine cascades

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Unsteady wake-blade interaction is an inevitable consequence of the relative motion between rotors and stators in turbomachines. The flow in a low-pressure stage has a relatively low Reynolds number, of order 10^5, based on chord length, and a substantial proportion of the boundary layer on the blade surface is thus laminar or transitional. While the flow in a turbine accelerates, globally, the middle-to-rear portion of the suction side of a highly-loaded turbine blade is subjected to an adverse pressure gradient. This can easily lead, especially in laminar and transitional conditions, to separation and thus to a serious deterioration in performance. In this environment, the introduction of unsteady wakes reduces the trend towards boundary-layer separation, in a time-mean sense, resulting in a potentially important reduction in losses.

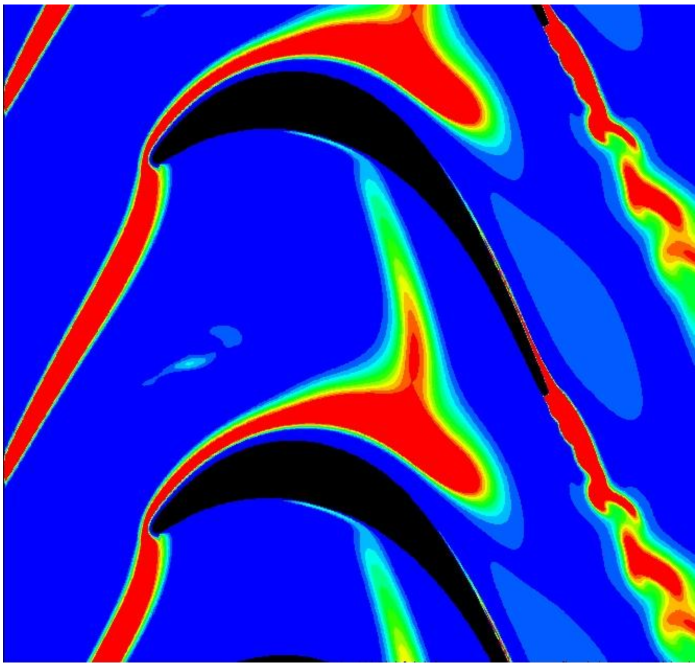


Fig. 2: Representative view of wake-blade interaction scenario investigated in a linear cascade, with the wakes generated by moving rods

The transitional nature of blade flows makes the computational prediction of unsteady wake-blade interaction an especially challenging task. The transition process is preceded by the growth of instabilities, whether transition is natural, following laminar separation provoked by wake dynamics, or of the bypass type, initiated by high freestream turbulence in attached conditions. In the latter case - the one more pertinent to turbomachinery - both simulations and experiments show that the boundary layer contains a substantial level of highly anisotropic (pseudo-turbulent) fluctuations well before the boundary layer *bursts* into a truly turbulent state, at which point the skin friction rises rapidly and the shape factor drops correspondingly.

Most of the above transitional features cannot be represented in a physically meaningful manner by any Reynolds-averaged modelling strategy. Conventional turbulence-transport models account, at best, for the process of turbulence diffusion from the free stream into the boundary layer, favouring bypass transition, and the opposing effect of viscosity-containing damping terms, effective in the viscous near-wall layer. Transition is then mimicked as a bifurcation of the mathematical system constituting the turbulence model, this bifurcation reflecting amplification by turbulence generation exceeding damping by dissipation.

A recent study by Lardeau et al. (2004) addresses the question of how conventional turbulence models can be combined with an intermittency-type approximation and a component for pre-transitional fluctuations to yield a modelling framework that is superior existing formulations. The cornerstone of this framework is the low-Re explicit algebraic Reynolds-stress model of Abe et al. (2002) (noted as AJL model in the following). This model distinguishes itself from others in the same category by returning correctly all the Reynolds-stress components as the wall is approached, including the wall-asymptotic limit. This is, arguably, an important property in flows in which near-wall processes play an influential role in both the transition and post-transition regions, as well as for heat-transfer predictions. When operating on its own, the model is shown to give premature transition and not to respond well to variations of free-stream turbulence and pressure gradient - not an unusual observation with most models of this type. Lardeau et al. (2004) then proceed to introduce two transition-specific elements into the turbulence model, one describing the evolution of the pre-transitional fluctuation energy, and the other an intermittency-type correlation, to control the turbulent viscosity returned by the default AJL model. Lardeau et al. (2004) show that the resulting model performs well in transitional, statistically steady, flat-plate boundary layers in variable pressure gradient and on a turbine blade. Lardeau and Leschziner (2006) have also used this model to compute unsteady wake-blade interaction in a linear cascade of low-pressure turbine blades (denoted T106), investigated experimentally by Stieger and Hodson (2003) at Cambridge University.

This summary focuses on the recent application of the extended model to two new configurations for which experimental data have only recently emerged and in which the free-stream turbulence level is much higher, namely 4%, closer to realistic operating conditions. One set of data pertains, again, to the linear cascade considered earlier; the other is for an entirely different blade geometry with a much more rounded leading edge. The experimental observations suggest significant differences in the detailed mechanisms of bypass transition and their effects.

The basic turbulence model used in the present study is not detailed herein (see references at the end for further details). Attention is restricted, rather, to highlighting major aspects of the transition model. In Lardeau et al. (2004) it is proposed that, in the transitional region, the total turbulence energy *k* should be a combination of the laminar fluctuations energy k_l and the conventional turbulence energy, k_t.the total turbulence energy is then given by:

$$k = (1-\gamma)k_l + \gamma k_t$$

The specific transition model also requires a new definition for the turbulent viscosity, given by :

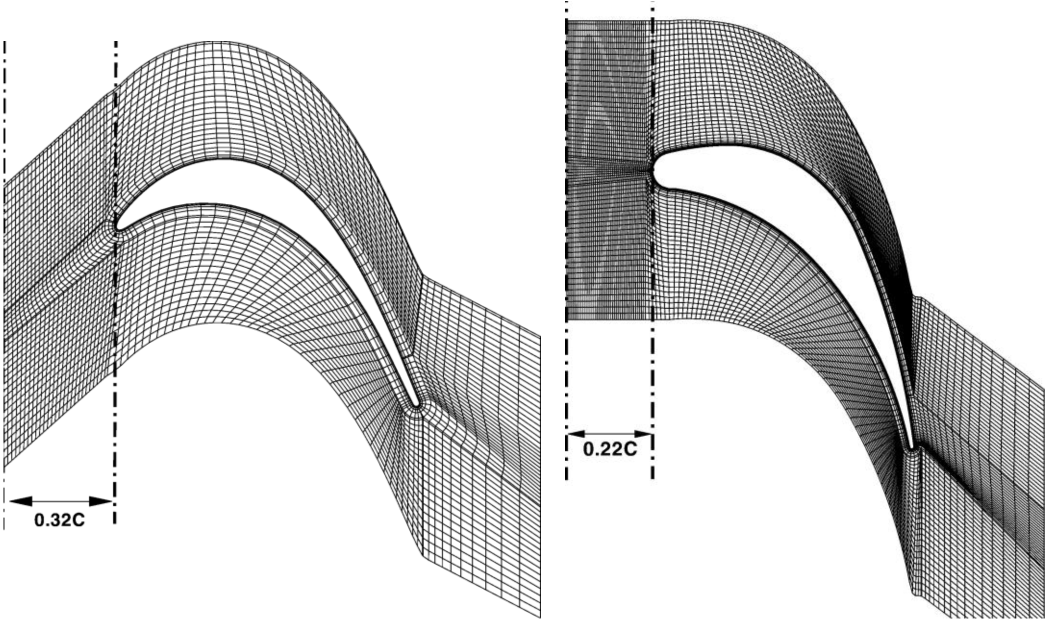
$$\nu_t = c_\mu f_\mu \frac{k(\gamma k_t)}{\varepsilon}$$

where the damping function f_μ and the manner in which the ‘intermittency’ parameter γ is determined are given in Lardeau and Leschziner (2006). The turbulence energy and the dissipation rate are determined as part of the default turbulence model (Abe et al, 2002), while the pre-transitional fluctuation energy is determined, following Mayle and Schulz (1997) from:

$$\frac{Dk_l}{Dt} = C_w \frac{U_\infty^2}{\nu}\sqrt{kk_\infty}\, e^{-y_+/13} + \nu \frac{\partial^2 k_l}{\partial n^2} - 2\nu \frac{k_l}{n^2}$$

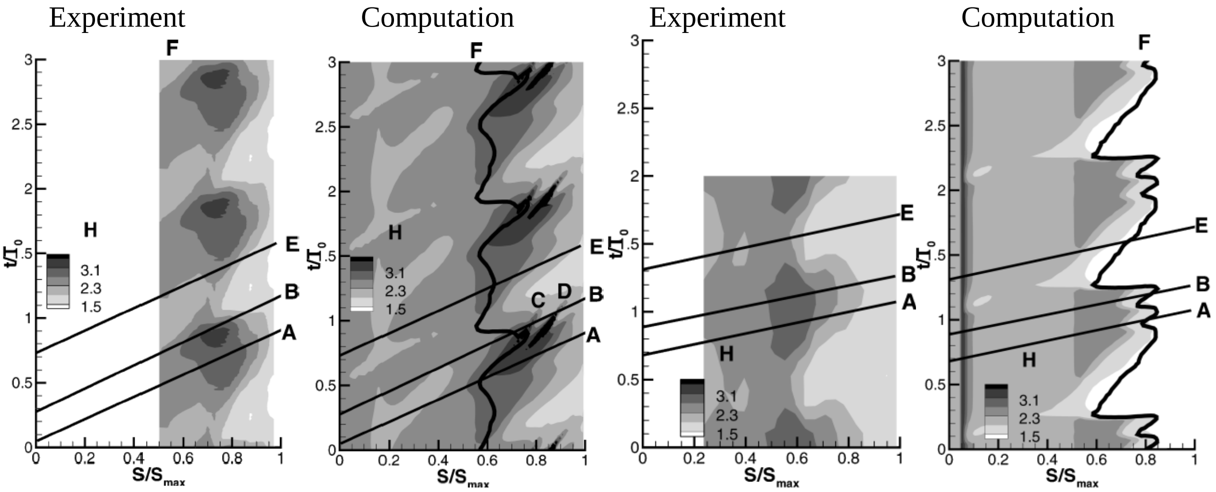
where n is the coordinate normal to the blade surface and k_∞ is the free-stream turbulence intensity. This model is based on the supposition that the fluctuation energy is not generated by shear, as is the case for the turbulence energy. In fact, LES studies by Lardeau et al (2007) demonstrate that this is incorrect and that the pre-transitional fluctuation energy is produced by the interaction between weak fluctuation-related shear stress $\overline{uv}_l$ and the shear strain.

Computational modelling was performed with the multi-block in-house code STREAM, with grids of the type shown in Fig. 2.



(a) (b)

Fig. 2: Multiblock grid arrangement used to compute wake-blade interaction for (a) T106A low-pressure turbine blade and (b) TC4 LP-turbine blade.



(a) (b)

Fig. 3: time-space contours of shape factor on suction side of (a) T106 low-pressure-turbine blade at 4% free-stream turbulence intensity and (b) TC4 LP turbine blade at 4% FSTI (solid line represents computed onset of transition).

Space–time plots of the shape factor for the T106A blade, Fig. 3(a), show that the transition modification has a major influence on the detailed response of the boundary layer to the wake. First, the transition model tends to delay the transition onset, the flow effectively remaining laminar between the wakes (line A). Second, the separation zone, occurring between lines A and B from *S/Smax* ≈0.7, is extended. Whereas both the original model and its transition-modified form predict wake-induced transition under the passing wakes (between lines B and E), the latter produces a downstream shift, to around *S/Smax* ≈0.8, in good agreement with the experimental observation. A significant point of difference between the prediction and the experiment relates, however, to features C and D. These identify short-lived and small separation zones that precede transition.

For the second TC4 blade (Fig 3(b)), the main effect of the transition modification is to substantially delay the transition onset, resulting in a behaviour that is much closer to the experimental conditions. In contrast to the previous blade, no separation occurs here, either in the experiment or the calculation. However, regions of elevated shape factor are predicted downstream of S/S_{max} =0.5 in the largely laminar region between lines A and B, as a consequence of the wake's dynamics.

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