Modelling and control of separation bubbles in transitional turbomachinery flows

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1 Introduction

In turbomachinery flows, the boundary-layer can remain laminar up to 70% of the chord length, due to a relatively low local Reynolds number on the blade. The high free-stream turbulence intensity penetrates into the laminar boundary-layer by the combined action of turbulence diffusion and pressure fluctuations, and triggers the transition process to a turbulent state. This transition process is said to be of *bypass* type, in contrast to the *natural* transition occuring at low free-stream turbulence intensity, in which case transition is preceded by the linear growth of Tollmien-Schlichting waves, well described by the linear stability theory.

In an industrial context, statistical Reynolds-Averaged Navier-Stokes models are commonly used to describe the effects of turbulence, because of their low computational cost compared to other approaches such Direct Numerical Simulation, Large Eddy Simulation or hybrid methods. Low-Reynolds-number turbulence models are able to mimic the transition process via the diffusion of turbulence into the boundary layer, but the position and rate of growth of the transition is often poorly predicted. Consequently, the modelling of the transition process must be explicitly aided by using empirical correlations to describe the transition point and an *intermittency factor* γ, which defines the laminar ($\gamma = 0$) and turbulent ($\gamma = 1$) regions.

In the present work, EVM (Eddy-Viscosity Models) are being used. The classical approach consists of multiplying the eddy-viscosity by the intermittency factor to define the effective eddy-viscosity in the transitional flow. An approach, proposed by Mayle & Schulz [2], is to use a transport equation for the *laminar fluctuating kinetic energy* to model the growth of non-turbulent fluctuating energy before the transition onset. This is a modelling element that is being developed further and integrated into a turbulence-modelling framework based on a non-linear eddy-viscosity formulation. The above approach is oriented towards modelling transition in attached flow. However, in highly-loaded conditions on blades, the adverse pressure gradient acting on the boundary-layer can result in the laminar or transitional boundary layer separating and possibly reattaching on the blade, in which case a recirculation zone forms above the blade surface. Such separated regions are the source of high losses and should be avoided. As regards transition, the new feature introduced by separation is that transition tends to occur in the detached shear layer, rather than in the near-wall layers. The physics of the latter differ significantly from those in the former, and the modelling needs to account for these differences. One aim of the work is thus to formulate a modelling framework, appropriate to a practical design environment, to predict transition in separated shear layers. At a later stage, the effectiveness of synthetic jets for the control of separation from blades will be studied.

2 Preliminary results

A first test case considered here corresponds to Direct Numerical Simulations performed by Wissink & Rodi [3]: a laminar flow at $Re = U_0 L/\nu = 60000$ evolves on a flat plate of length L, with a uniform velocity U_0. An adverse pressure gradient is imposed via a contoured upper surface so as to simulate the pressure distribution on the suction surface of blades in turbomachines. Calculations are being performed using an in-house finite-volume code, with a TVD scheme for the convective terms and the AJL non-linear eddy-viscosity model proposed by Abe *et al.* [1]. Fig. 1 shows that the model exhibits, if implemented without an explicit transition model, a separation bubble of length $1.7L$, a value much larger than the DNS result $0.77L$. This is due to a seriously delayed response of the separated shear layer to the free-stream turbulence.

A first attempt to correct this behaviour is to add a sink term S_ε in the dissipation equation in order to increase the turbulent intensity. This term is modelled by:

$$S_\varepsilon \quad = \quad \max\left(0, C_\varepsilon F(R_T)\frac{P\varepsilon}{k} S^*(S^*_{eq} - S^*)\right) \tag{1}$$

where $S = \sqrt{2S_{ij}S_{ij}}$ is the mean shear, $S^* = Sk/\varepsilon$, $S^*_{eq} = 4.3$ its equilibrium value in homogeneous shear flows, and $F(R_T)$ an increasing function of the turbulent Reynolds number. The mean flow and the statistics of turbulence (see Fig. 2) are substantially improved, and the separation bubble is much more realistic. Although this model mimics well the transition process, it has no strong physical basis.

Based on stronger physical basis, another modified model involves a transport modelled equation for the *laminar fluctuating kinetic energy* k_l, written as [2]:

$$U_j \frac{\partial k_l}{\partial x_j} = \underbrace{C_\omega \frac{U_\infty^2}{\nu}\sqrt{k_l k_\infty} e^{-y^+/C^+}}_{\text{production}} - \underbrace{2\nu\frac{k_l}{y^2}}_{\text{dissipation}} + \underbrace{\nu\nabla^2 k_l}_{\text{diffusion}} \tag{2}$$

The total fluctuating kinetic energy, shown on Fig. 3, is defined by $k_{tot} = k_l + k$, the sum of the laminar and turbulent fluctuating energy. The eddy viscosity is modified as:

$$\nu_t = \gamma \nu_{\mathrm{AJL}} \frac{k_{tot}}{k} \tag{3}$$

where ν_{AJL} is the eddy viscosity given by the AJL model. This new proposal does not improve the bubble length, because the increase of the eddy viscosity is too close to the wall, instead of being in the shear layer. Moreover, the contribution of the turbulent energy to the total energy is negligible. A transfer term must be added in the equations to redistribute the energy from the laminar part k_l to the turbulent part k, such that the turblent AJL model does its job. Further investigations are in progress to correct these shortcomings.

References

[1] K. Abe, Y.-J. Jang, and M. A. Leschziner. An investigation of wall-anisotropy expressions and length scale equations for non-linear eddy viscosity models. *Int. J. Heat & Fluid Flow*, 24:181–198, 2003.

[2] R. E. Mayle and A. Schulz. The path to predicting bypass transition. *J. Turbomachinery*, 119:405–411, 1997.

[3] J. G. Wissink and W. Rodi. DNS of transition in a laminar separation bubble. In *Advances in Turb. IX, Proc. 9th European Turb. Conf.*, pages 1–4, 2002.

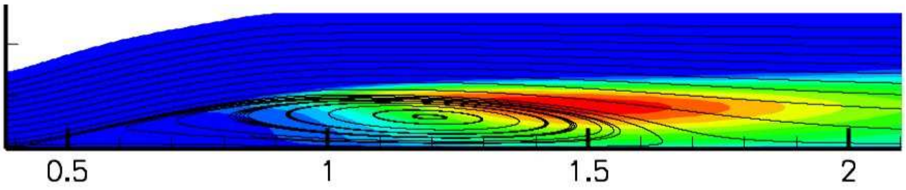

Figure 1: Streamlines and turbulent kinetic energy isocontours. AJL model without transition modification.

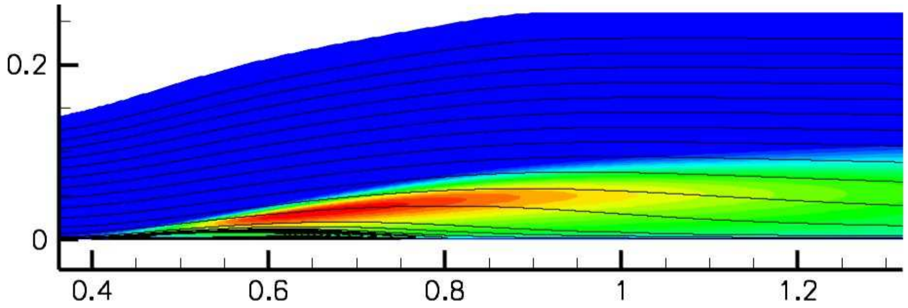

Figure 2: Streamlines and turbulent kinetic energy isocontours. Modified AJL model (Eq. (1)).

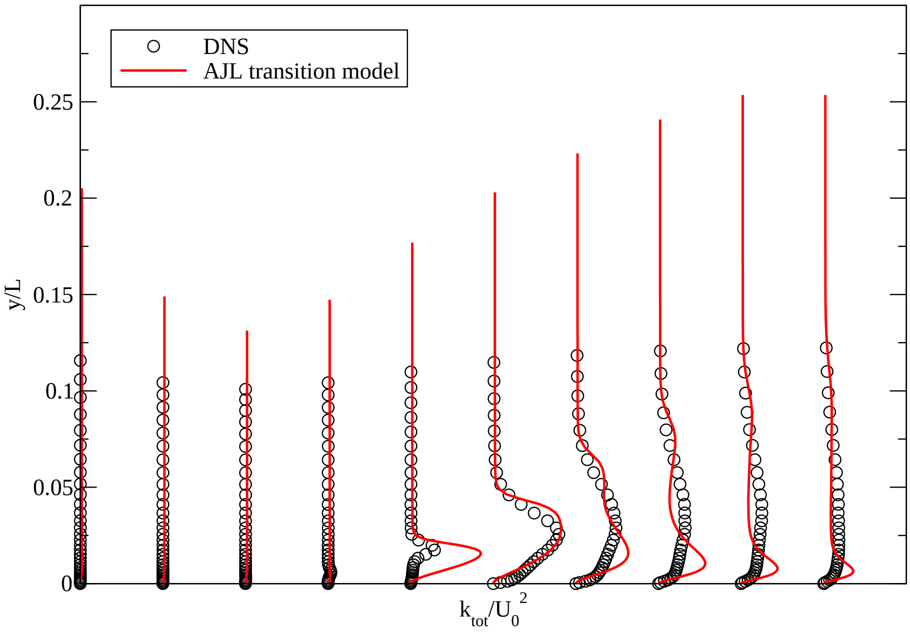

Figure 3: Total fluctuating kinetic energy profiles. Comparison with DNS [3].

3 Publications and communications

Publications in International Journals

A. Fadai-Ghotbi, R. Manceau and J. Borée. "A temporal filtering approach for a seamless hybrid RANS/LES model in inhomogeneous flows". Article in preparation.

A. Fadai-Ghotbi, R. Manceau and J. Borée. "A seamless hybrid RANS/LES model based on transport equations for the subgrid stresses and elliptic blending". Article in preparation for submission to *Physics of Fluids*.

A. Fadai-Ghotbi, R. Manceau and J. Borée. "Revisiting URANS computations of the backward-facing step flow using second moment closures. Influence of the numerics". To be published in *Flow, Turbulence & Combustion*, 2008.

Articles in International Conferences with proceedings

August 2007: Turbulent Shear Flow Phenomena 5, Munich, Germany. "A seamless hybrid RANS-LES model based on transport equations for the subgrid stresses and elliptic blending".

July 2006: International Conference on Computational Fluid Dynamics 4, Ghent, Belgium. "Revisiting URANS computations of the flow behind a backward-facing step using second moment closures".

International Conferences

October 2007 : German Association for Computational Mechanics 2, Munich, Germany. "A seamless hybrid RANS-LES model based on transport equations for the subgrid stresses".

June 2004: 5^{th} International Conference on Multiphase Flow, Yokohama, Japan." Simulation and kinetic modelling of inertial droplet coalescence in homogeneous turbulent gas flows".

Other Conferences

April 2006 : Spring School of the Institut of Physics of Cargèse, Corsica, France. "Phenomenology and Modeling Issues in Turbulence".