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An efficient setup for freestream turbulence on transition prediction over aerospace configurations

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ABSTRACT

Inflow turbulence variables play a key role in the performance of correlation-based transition models. In order to consider this important effect, a wing-body configuration in transonic flow is simulated using the $\gamma - Re_\theta$ Langtry–Menter transition model. The influences of the freestream turbulence intensity, Tu_i, and freestream eddy viscosity ratio, μ_t/μ, over the simulation results are addressed, and an efficient setup for these variables is suggested. Two distinct turbulence conservation boxes, regions in which the turbulence source terms are turned off and in which no turbulence decay occurs, are addressed in the paper. This strategy is an option to the approach of specifying higher values for the freestream turbulence variables and allowing them to decay up to the geometry near field. Discussions on the decay of the turbulent kinetic energy (k) outside of the conservation boxes support the results presented in the paper and provide relevant guidelines regarding the specification of boundary values for turbulence variables.

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1. Introduction

The ability to predict the transition to turbulence is relevant in fluid mechanics. It is widely recognized that laminar and turbulent flows are very distinct and, therefore, different behaviors are associated to each of these flow regimes. In aerospace engineering, viscous effects are arguably the most relevant drag source in cruise conditions for a typical jetliner aircraft, as indicated in Ref. [1]. Since laminar boundary layers are characterized by smaller skin friction than turbulent ones, one of the objectives of aerodynamicists is to extend laminar regions in the airframe. In order to design laminar flow geometries by taking advantage of Computational Fluid Dynamics (CFD) techniques, the solver must be able to predict the transition initial position and length. Once the latter is accomplished, optimization techniques can be used to extend the laminar flow portion of the airframe, leading to lower drag aircraft.

From a physical point of view, it is well known that there are several mechanisms that can trigger transition to turbulence. The amplification of Tollmien–Schlichting waves is one of the most common mechanisms that causes natural transition in airplanes, while crossflow vortices are usually found to originate turbulence in swept wings at high Reynolds and Mach numbers. The attachment line contamination can occur when the turbulence originated at the fuselage triggers transition to turbulence at the wing. Laminar separation bubbles (LSB) may cause transition to turbulence when the unstable detached flow transitions and re-attaches.

The Reynolds-averaged Navier–Stokes (RANS) formulation, which is the formulation largely used in industrial applications, can be seen as the result of a Favre time-averaging of the original Navier–Stokes equations. As a result of this process, turbulent effects are removed from the main variables for which the equations are being resolved for. On the other hand, the Favre-averaged equations acquire a few extra terms which contain the effects of added transport for a turbulent flow. These new terms must be adequately represented, or calculated, which is usually done by means of a turbulence model. In industrial applications, the use of eddy-viscosity turbulence models is the norm. Such formulation, however, cannot describe the physical mechanisms that lead to the flow transition from a laminar to a turbulent state as, for instance, the amplification of Tollmien–Schlichting waves [2]. Due to the

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importance of correctly predicting the laminar-turbulent transition in practical applications, modifications are performed to existing turbulence models such that they would be able to predict the transition onset and extent [3]. In order to account for transitional effects, additional transport equations based on empirical data can be added to an underlying turbulence model. The model presented by Langtry and Menter [4] is adopted in this work and further studied against experimental data. In this sense, the present work provides an extension of the effort described in Ref. [2], in which several test cases were used to validate the implementation of the Langtry–Menter transition model in the CFD++ solver.

Langtry and Menter [4–7] propose a new model where two additional transport equations are used to estimate transition onset and extent. Transition onset is triggered by the momentum thickness Reynolds number transport equation. A second transport equation, based on the intermittency, allows for an estimation of the extent of the transition region. The shear stress transport (SST) turbulence model [8] is coupled to the intermittency transport equation, which turns on the term responsible for producing the turbulent kinetic energy downstream of the transition onset point. This coupling takes place throughout a modification of the turbulent kinetic energy production term in the SST model.

The use of empirical correlations was first performed by Abu-Ghannam and Shaw [9], Mayle [10] and Suzen et al. [11]. Essentially, the computed Re_θ is compared to a threshold value in order to specify the transition onset. The main shortcoming of using Re_θ as an indicator of the transition position is the fact that its calculation demands an integration in the wall-normal direction, along the boundary layer profile, in order to obtain the momentum thickness, θ. This is a main issue when CFD calculations over complex computational domains and large data sets are considered, since the parallel computing techniques are not compatible with such non-local operations. One should observe that computational grids are typically divided into smaller partitions in order to allow efficient, distributed-memory, parallel computations. Therefore, models directly based in the estimation of Re_θ are not the best approach to treat large scale, complex industrial problems. The correlation-based transition model presented in Ref. [4] does not require non-local information, except for the classical distance to the wall variable, which is computed in a pre-processing stage. The strain-rate Reynolds number [12], Re_v, is a key factor for assuring that non-local information will not be required during the computations. The strain-rate Reynolds number can be directly correlated to Re_θ, in such a way that no wall-normal boundary layer integration is required during the computations. Additional details can be found in Refs. [13,14].

The choice of the boundary values for turbulence variables is an important factor when a RANS framework is used to predict transition by means of correlation-based models. Previous investigations addressed the importance of using appropriate values for the turbulence intensity in the freestream, Tu_i, in order to obtain good numerical results [2,15]. According to Spalart and Rumsey [16], Tu_i values near 0.08% should be used for general external aerodynamics simulations when RANS turbulence models are used without considering transition to turbulence. This value must be specified not exactly in the domain limits, but in the geometry near field. This leads to the use of the so-called turbulence conservation boxes, which aim at conserving inflow turbulence variables up to the geometry near field. More details of this approach will be given in the forthcoming sections, in which distinct values for Tu_i are considered in addition to the settings proposed by Spalart and Rumsey [16]. Our past investigation [2] added interesting knowledge regarding the specification of boundary values for turbulence variables. However, in that work, the results were not really conclusive, due to the fact that only a simple conservation box was used to assess the Langtry–Menter model behavior when a transonic flow test case was simulated. In the present work, we show additional results for the simple turbulence conservation box, which is here termed *conservation box 1*, but also propose a new turbulence conservation approach, in which a conservation box adapts to the wing leading edge. We also indicate here effective values for the near field turbulent kinetic energy that lead to numerical results in agreement with wind tunnel data. By doing so, the present work proposes conclusive guidelines for specifying freestream turbulent quantities that lead to a correct transition front for typical aeronautical configurations when using the Langtry–Menter transition model. One should observe that this transition model is now available in several commercial CFD packages and, therefore, we believe that the knowledge introduced in this paper is of interest of practitioner engineers, as well as in research environments.

The numerical simulations included in the present work are performed with the CFD++ finite volume solver, version 11.1 [17]. A compressible, preconditioned RANS formulation is used in the CFD++ code, with the nodal-based reconstruction polynomials and with the *minmod* limiter. The present paper is organized as follows. Section 2 presents a brief overview of the issues associated to turbulence decay that are relevant in the context of the present work. The details of the theoretical and numerical formulations used in this work are not included here for the sake of brevity. However, the interested reader can find such details in Ref. [2]. Section 3 discusses results for a wing-body configuration and depicts the influence of inflow variables in the transition onset. Finally, section 4 concludes the present paper with some final remarks.

2. Turbulence decay

As previously indicated, one of the main issues addressed in the present paper is the specification of boundary conditions for turbulent properties for typical CFD simulations of aeronautical configurations. It is well-known that the turbulence levels specified at far field boundaries present a fast decay in the flow direction, in a numerical framework, depending on the values of the eddy viscosity ratio, μ_t/μ, specified in the flow boundaries [14]. It is also observed that the Langtry–Menter transition model is sensitive to the freestream turbulence intensity if Tollmien–Schlichting waves or bypass instability are the leading transition mode. As a result, it is necessary to choose one of the following approaches. It is possible to establish a turbulence conservation box, which advects the inflow turbulence values until the near field. This particular method is adopted in this paper and additional details will be given in Sec. 3. The second possibility is to specify sufficiently high inlet values and allow them to decay until the near field region such that, in this region, the values are those required for the numerical analysis at hand.

In order to choose inflow turbulence parameters and allow them to decay, the following analytical solution [14] can be adopted:

$$k_{NF} = k_i \left(1 + \omega_i \beta t\right)^{-\frac{\beta^*}{\beta}} , \tag{1}$$

where k_{NF} is the turbulent kinetic energy in the near field, k_i the turbulent kinetic energy at the inlet and ω_i the rate of turbulence dissipation at the domain inlet. For the SST turbulence model, the constants in Eq. (1) are, in the freestream, $\beta = 0.09$ and $\beta^* = 0.0828$, as recommended in Ref. [14]. The time scale, t, can be defined as

$$t = \frac{d}{V} , \tag{2}$$

where d is the streamwise distance downstream of the inlet and V is the mean convective velocity. In addition, the eddy viscosity, μ_t, for a k–ω type model, is given by

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