

TRANSITION MODELLING FOR TURBOMACHINERY FLOWS

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1. Introduction

In the past few decades a significant amount of progress has been made in the development of reliable turbulence models that can accurately simulate a wide range of fully turbulent engineering flows. The efforts by different groups have resulted in a spectrum of models that can be used in many different applications, while balancing the accuracy requirements and the computational resources available to a CFD user. However, the important effect of laminar-turbulent transition is not included in the majority of today's engineering CFD simulations. The reason for this is that transition modelling does not offer the same wide spectrum of CFD-compatible model formulations that is currently available for turbulent flows, even though a large body of publications is available on the subject. There are several reasons for this unsatisfactory situation.

The first is that transition occurs through different mechanisms in different applications. In aerodynamic flows, transition is typically the result of a flow instability (Tollmien-Schlichting waves or in the case of highly swept wings cross-flow instability), where the resulting exponential growth of two-dimensional waves eventually results in a non-linear break-down to turbulence. Transition occurring due to Tollmien-Schlichting waves is often referred to as natural transition [1]. In turbomachinery applications, the main transition mechanism is bypass transition [2] imposed on the boundary layer by high levels of turbulence in the freestream. The high freestream turbulence levels are for instance generated by upstream blade rows. Another important transition mechanism is separation-induced transition [3], where a laminar boundary layer separates under the influence of a pressure gradient and transition develops within the separated shear layer (which may or may not reattach). As well, a turbulent boundary layer can re-laminarize under the influence of a strong favorable pressure gradient [4]. While the importance of transition phenomena for aerodynamic and heat transfer simulations is widely accepted, it is difficult to include all of these effects in a single model.

The second complication arises from the fact that conventional Reynolds averaged Navier-Stokes (RANS) procedures do not lend themselves easily to the description of transitional flows, where both linear and non-linear effects are relevant. RANS averaging eliminates the effects of linear disturbance growth and is therefore difficult to apply to the transition process. While methods based on the stability equations such as the e^n method of Smith & Gamberoni [5] and van Ingen [6] avoids this limitation, they are not compatible with general-purpose CFD methods as typically applied in complex geometries. The reason is that these methods require a priori knowledge of the geometry and the grid topology. In addition, they involve numerous non-local operations (e.g. tracking the disturbance growth along each streamline) that are difficult to implement into today's CFD methods [7]. This is not to argue against the

stability approaches, as they are an essential part of the desired “spectrum” of transition models required for the vastly different application areas and accuracy requirements. However, much like in turbulence modeling, it is important to develop engineering models that can be applied in day-to-day operations by design engineers on complicated 3D geometries.

It should be noted that at least for 2D flows, the efforts of various groups has resulted in a number of engineering design tools intended to model transition for very specific applications. The most notable efforts are those of Drela and Giles [8] who developed the XFOIL code which can be used for modeling transition on 2D airfoils and the MISES code of Youngren and Drela [9], which is used for modeling transition on 2D turbomachinery blade rows. Both of these codes use a viscous – inviscid coupling approach which allows the classical boundary layer formulation tools to be used. Transition prediction is accomplished using either an e^n method or an empirical correlation and both of these codes are used widely in their respective design communities. A 3D wing or blade design is performed by stacking the 2D profiles (with the basic assumption that span wise flow is negligible) to create the geometry at which point a 3D CFD analysis is performed.

Closer inspection shows that hardly any of the current transition models are CFD-compatible. Most formulations suffer from non-local operations that cannot be carried out (with reasonable effort) in general-purpose CFD codes. This is because modern CFD codes use mixed elements and massive parallel execution and do not provide the infrastructure for computing integral boundary layer parameters or allow the integration of quantities along the direction of external streamlines. Even if structured boundary layer grids are used (typically hexahedra), the codes are based on data structures for unstructured meshes. The information on a body-normal grid direction is therefore not easily available. In addition, most industrial CFD simulations are carried out on parallel computers using a domain decomposition methodology. This means in the most general case that boundary layers can be split and computed on different processors, prohibiting any search or integration algorithms. Consequently, the main requirements for a fully CFD-compatible transition model are:

- Allow the *calibrated* prediction of the onset and the length of transition
- Allow the inclusion of different transition mechanisms
- Be formulated locally (no search or line-integration operations)
- Avoid multiple solutions (same solution for initially laminar or turbulent boundary layer)
- Do not affect the underlying turbulence model in fully turbulent regimes
- Allow a robust integration down to the wall with similar convergence as the underlying turbulence model
- Be formulated independent of the coordinate system
- Applicable to three-dimensional boundary layers

Considering the main classes of engineering transition models (stability analysis, correlation based models, low-Re models) one finds that none of these methods can meet all of the above requirements.

The only transition models that have historically been compatible with modern CFD methods are the low-Re models [10,11]. However, they typically suffer from a close interaction with