Chapter 2
Transition Prediction

Abstract A selective review of methods for transition modelling and simulation is provided in this chapter. Methods are grouped into three major categories: analytical models based on the stability theory, transition models based on statistical Reynolds-averaged Navier-Stokes (RANS) equations, and Large Eddy Simulation (LES) and Direct Numerical Simulation (DNS). The advantages and disadvantages of the methods in each category are assessed for their compatibility for use in general purpose engineering CFD codes.

2.1 Overview

Transition is a complex phenomenon that involves multiple mechanisms in different applications. The nature of the transition problem is also the origin of the turbulence problem, one of the unsolved mysteries in fluid dynamics today. Because of its practical significance in engineering designs such as airplanes, ships, cars, and spacecraft, etc., significant efforts have been devoted to transition and turbulence research over the past decades. With the recent advent of high performance computing architectures and numerical solution algorithms, computational modelling and simulation has increasingly become an important tool both in scientific research and engineering designs in these fields. Efforts of different research groups have resulted in a spectrum of transition modelling approaches that can be used in different applications with acceptable accuracy. However, challenges still exist in developing robust and reliable transition models for practical engineering applications. For example, the transition process involves a wide range of scales in time and length, as well as linear and nonlinear interactions between free-stream properties and boundary layer dynamics. However, these coherent interactions may be flitted out through the Reynolds averaging of the Navier-Stokes equations in most practical CFD codes (Stock and Haase 2000). In addition to numerical limitations, it is virtually impossible to include all mechanisms into a physics-based equation framework (Menter et al.

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2015), due to a lack of complete understanding of how the underlying physics drives the transition process in various applications. Furthermore, the transition modelling cannot be isolated from the turbulence problem and flow separation, which often results in coherent interferences among different models (Savill 1993a, b).

Due to the complexity of transition phenomena, methods to predict transition have been evolved into three major categories over the past decades. The first category includes methods based on stability theory to predict the natural transition, stemmed from the Prandtl's small disturbance hypothesis (Prandtl 1904). The most noticeable one in this group is the e^N method, developed by Smith and Gamberoni (1956). Methods in the second category are based on statistical modelling of RANS equations to predict bypass and separation-induced transitions, which comprise the majority of transition modeling research in the CFD community today. The central concepts of statistical modelling for transition are stemming from Emmons's classic work (1951) of turbulent spots as well as the intermittency distributions of Dhawan and Narasimha (1958). Examples of this class include the low Reynolds number turbulence closure methods (Wilcox 1992), the intermittency method with experimental correlations (Suzen and Huang 2000, Menter et al. 2002), the laminar kinetic energy method (Walters and Leylek 2002, 2004), and many others. Methods in the last category include direct numerical simulation (DNS) (Durbin and Jacobs 2002) and large eddy simulation (LES) (Wu et al. 1999) to simulate various transition processes directly in order to avoid or minimize the usage of turbulence closure models.

The motivation of this book is to document recent advances in statistical transition modelling based on state-of-the-art parallel CFD methods that are suitable for practical engineering applications. A major method described in this book is the Local Correlation-based Transition Model, or $\gamma - \widetilde{Re}_{\theta t}$ model, developed by Menter et al. (2002, 2004, 2006) and Langtry and Menter (2006, 2009) over the last decade. Although a simplified model was recently proposed by Menter et al. (2015) to solve only the γ—equation, it is not within the scope of this book. The $\gamma - \widetilde{Re}_{\theta t}$ model (Langtry and Menter 2006, 2009) solves two transport equations: one for intermittency (γ) and another for transition momentum-thickness Reynolds number $(\widetilde{Re}_{\theta t})$. It was originally constructed under the framework of Menter's two-equation Shear Stress Transport (SST) turbulence model (Menter 1994), and was later integrated into the one-equation Spalart-Allmaras (S-A) turbulence model (Spalart and Allmaras 1994) by Medida and Baeder (2011, 2013a, b) and by Wang and Sheng (2014, 2015), respectively. A new method to correct premature flow separations, a common issue encountered in rotor CFD simulations (Sheng 2014; Sheng et al. 2016), is detailed in this book to order to improve the models' behaviour near separation points. The purpose of this book is to provide complete numerical procedures for implementing the Langtry and Menter $\gamma - \widetilde{Re}_{\theta t}$ transition model into a modern high-resolution implicit numerical scheme, and to offer advanced reading materials for university graduate students working in research areas of CFD, turbulence, and transition modeling. It also provides a practical guideline for industrial

practitioners in aerodynamic design and analysis for fixed-wing or rotary wing aircraft using modern CFD solvers based on moderate computer resources.

Following this chapter, an overview is provided for selected transition modeling methods developed in the aforementioned three categories. There are some good review articles and papers published in this subject such as Aupoix et al. (2011), Pasquale et al. (2009), Sevningsson (2006) and more. While the current work should not be considered all-inclusive for the efforts of transition modeling devoted over the past decades, it is the authors' hope that this collection of relevant work will serve as a starting point for further research in this fundamental and important field of fluid dynamics.

2.2 Methods Based on Stability Theory

Methods in this category are stemming from Prandtl's small disturbance hypothesis (Prandtl 1904), with the intention of predicting the natural transition onset occurred in low free-stream turbulence environments. Two representative methods are the e^N method developed by Smith and Gamberoni (1956) and van Ingen (1956), and the parabolized stability equations (PSE) method of Herbert and Bertolotti (1987).

2.2.1 The e^N Method

The e^N method, developed by Smith and Gamberoni (1956) and van Ingen (1956) over 50 years ago, is one of the most popular methods in this category. This method is based on the linear stability theory with a local parallel flow assumption, and calculates the growth of disturbance amplitudes from the boundary layer neutral point to the transition location. The factor N is the total growth rate of the most unstable disturbances. The application of the e^N method involves three steps: the first step is to calculate the laminar velocity and temperature profiles at different stream-wise locations for the given geometry of interest. The second step is to calculate the local growth rates of the most unstable waves among all velocity profiles. This leaves the last step being to calculate the transition onset location based on the local growth rates integrated along each streamline.

The major problem with the e^N method is that due to its local parallel flow assumption it cannot predict the transition caused by nonlinear effects such as bypass or surface roughness-induced transitions. In addition, the value of N for the transition onset is not universal and needs to be correlated with the experimental data (Warren and Hassan 1997). Hence, the e^N method is considered as a semi-empirical method at best. Finally, the e^N method is not compatible with the most engineering CFD methods in use today, because it requires solving the

boundary layer equations for global flow quantities. Arthur and Atkin (2006) developed a procedure by applying the e^N method within a conventional RANS framework. Firstly, an initial guess of the transition onset location was obtained based on the e^N criterion and a series of pressure distributions were extracted from the RANS solution. The improved boundary layer profiles were then fed back to the stability analysis to yield a new transition onset location, until the RANS solution and transition location are fully converged. Aupoix et al. (2011) implemented simplified stability methods called "database methods" at ONERA. However, these stability-based methods were difficult to apply on massively parallel computers, due to requirements of non-local quantities such as the boundary layer momentum thickness or shape factor (Aupoix et al. 2011).

2.2.2 *Parabolized Stability Equation Method*

Driven by the need to consider the nonparallel effects neglected in the linear stability theory, Herbert and Bertolotti (1987) proposed parabolized stability equations (PSE) methods. The mean flow, amplitude functions, and wave numbers were calculated based on the streamwise distance to predict the transition onset location. Savill (2002) developed the nonlinear parabolized stability equations in order to predict the subsequent transition region after the transition onset point. At first sight, these linear and nonlinear PSE methods could be considered to solve both linear and nonlinear development of disturbance waves. However, the growth of disturbance amplitude is required to evaluate along the streamlines, which is a significant difficulty for three-dimensional flow computations because the streamline direction is not always aligned with the body surface. Furthermore, development of disturbance waves highly depends on the initial amplitude of the waves, which is not universal just like the N-factor in the e^N method. These limitations make the method difficult for predicting the transition onset in three-dimensional realistic flows with complex geometries in engineering applications.

2.3 Statistical Methods of Transition Modelling

All statistical modeling methods are stemming from the classic work of Emmons (1951) on the formation of turbulent spots and the intermittency distributions of Dhawan and Narasimha (1958). Differentiations in these methods exist in the way of obtaining the intermittency distributions. This is either done by using algebraic correlations with experimental data, solving transport equations, or could also be a combination of both. Other modeling methods include the low Reynolds number turbulence models (Wilcox 1992) and the laminar kinetic energy methods (Walters and Leylek 2002, 2004).

2.3.1 Low Reynolds Number Turbulence Models

The concept of using low Reynolds number turbulence models to predict transition is based on the models' wall damping capability in the boundary layer (Jones and Launder 1973) to simulate the transition process, such as bypass transition that is dominated by a diffusion effect from the freestream. These models typically suffer from a close interaction between the transition capability and the viscous sublayer modeling, which prevents independent calibration of both phenomena (Savill 1993a, b). There are several low Reynolds number models where transition prediction was specifically considered during the model calibration, such as the Wilcox low Reynolds $k-\omega$ model (Wilcox 1992), the Langtry and Sjolander's low Reynolds number $k-\varepsilon$ model (Langtry and Sjolander 2002), and Walters and Leylek's transition model (Walters and Leylek 2002, 2004). Regardless, these models still exhibit a close connection between the sublayer behavior and the transition calibration. Re-calibration of one model would change the performance of the other (Menter and Langtry 2006). Models like Launder and Sharma model (1974), where the near-wall behavior is described by the turbulent Reynolds number, perform better than those that use the local wall distance. However, no model in this group provides reliable transition predictions for any combination of Reynolds numbers, free-stream turbulence levels, and pressure gradients (Pasquale et al. 2009).

2.3.2 Correlation-Based Intermittency Models

Models in this group use the concept of intermittency (γ) of Dhawan and Narasimha (1958) to blend the laminar and turbulent flow regimes. Intermittency γ is a measure of the probability that a given point in space is located inside the turbulent region. In other words, it is the fraction of time that the flow is turbulent during transition. By setting the intermittency factor as ranging from zero to one, the value of zero then represents the pre-transitional laminar flow and the value of one being the fully turbulent flow. In practice, this intermittency factor is multiplied to the production source term of turbulent eddy viscosity, which is calculated by Reynolds-averaged Navier-Stokes equations (RANS) codes. This approach neglects the interaction between the non-turbulent and turbulent parts of the flow during the transition, but the loss of some physical information is acceptable in the content of statistical modeling using the RANS codes (Pasquale et al. 2009).

Two selections need making in order to utilize the intermittency-based approaches for transition prediction. One is how to determine the intermittency factor distributions, and the second is how to define the transition onset criterion. Various methodologies have been proposed over the past decades, which form the main body of transition modeling methods in this category. The intermittency factor

can generally be determined by algebraic models (Gostelow et al. 1994) or by transport equation (Suzen and Huang 2000; Suzen et al. 2002; Menter et al. 2002). The transition onset criterion can be determined based on empirical or experimental correlations (Abu-Ghannam and Shaw 1980) or based on the transport equation with correlation (Langtry 2006; Langtry and Menter 2009).

The algebraic intermittency models were widely used in earlier structured grid CFD codes (Arnel 1988) where the transition onset location was usually based on the empirical correlation of Abu-Ghannam and Shaw (1980). Suzen and Huang (2000) proposed a new approach based on the transport equation to solve the intermittency factor, where the source terms were designed to mimic the behavior of some algebraic intermittency models. Similar efforts were made by Menter et al. (2002) and Steeland and Dick (2001). The transition onset criterion was determined by the local Reynolds number and the transition onset Reynolds number. Both numbers were functions of the free-stream turbulence intensity and the acceleration parameter. These non-local quantities were compared with the experimental correlation of Huang and Xiong (1998) to determine the transition onset location. These models were validated for flows with zero-pressure and adverse-pressure gradients at different free-stream turbulence intensities, and received good agreements with the experimental data of Savill (1993a, b). The major problem of this transition model is the requirement of non-local quantities, which makes it difficult to be applied for three-dimensional flows or using unstructured grid parallel CFD solvers.

The transition model, proposed by Papp and Dash (2005), was based on a concept analogous to the Warren, Harris and Hassan one-equation model (Warren et al. 1995). An additional transport equation was solved for the non-turbulent fluctuations that include the cross-flow instabilities and second mode instabilities. The transition onset location was predicted as the minimum distance along the surface. This distance was determined by the turbulent viscosity coefficient, kinematic viscosity and eddy viscosity due to the non-turbulent fluctuations. The Papp and Dash transition model was implemented into the RANS solver by multiplying the turbulent eddy viscosity with the intermittency. Simulations showed that the transition onset location was properly obtained, but the peak value in heat transfer did not match correctly in some cases. This discrepancy was attributed to the algebraic nature of the intermittency function use.

Probably the most notable model in this category is the so-called Local Correlation-based Transition Model, or $\gamma - \widetilde{Re}_{\theta t}$ model, proposed by Menter and Langtry about a decade ago (Menter et al. 2002, 2004, 2006; Langtry and Menter 2009). This model solves two transport equations: one for intermittency (γ) and another for the momentum thickness Reynolds number ($\widetilde{Re}_{\theta t}$). In this formulation, only local information is used to activate the production term in the intermittency equation. The link between the intermittency equation and the correlation is achieved through the use of vorticity Reynolds number ($Re_{\theta t}$), which only depends on local variables such as density, viscosity, vorticity, and local wall distance.

Initially, only the conceptual framework of this model was published by Menter et al. (2002, 2004, 2006). A full disclosure of the $\gamma - \widetilde{Re}_{\theta t}$ model was later published by Langtry and Menter (2009), including all experimental correlations used to determine the transition onset location for different boundary layer velocity profiles. The $\gamma - \widetilde{Re}_{\theta t}$ model, however, is not considered to satisfy the Galilean invariance (Menter et al. 2015), which limits the model from being applied to surfaces moving relative to the coordinate system. Menter et al. (2015) recently proposed a simplified one-equation γ model in order to overcome the deficiency in the original $\gamma - \widetilde{Re}_{\theta t}$ model. While the $\gamma - \widetilde{Re}_{\theta t}$ transition model was originally solved under the framework of the Menter two-equation SST turbulence model (Menter 1994), extensions were made by incorporating it into a widely used one-equation Spalart-Allmaras (S-A) turbulence model by Medida and Baeder (2011, 2013a, b) under a structured grid RANS framework, and by Wang and Sheng (2014) under an unstructured grid RANS framework. In addition, extensions to include crossflow instability in the $\gamma - \widetilde{Re}_{\theta t}$ model were recently proposed by several researchers such as Seyfert and Krumbein (2012), Medida and Baeder (2013a, b), Grabe and Krumbein (2014), and Grabe et al. (2016). All these extensities show the versatility of the $\gamma - \widetilde{Re}_{\theta t}$ model in any correlation based formulations.

2.3.3 The Laminar Kinetic Energy Method

In contrast to the models using the intermittency factor, a different approach was proposed by Walters and Leylek (2002) that solves the transport equation for laminar kinetic energy. This method is based on the concept that bypass transition is caused by very high amplitude streamwise fluctuations, which are very different from turbulent fluctuations. Mayle and Schulz (1997) proposed a second kinetic energy equation to describe these streamwise fluctuations, called laminar kinetic energy (K_L). In the near wall region, the turbulent kinetic energy (K_T) is split into small-scale energy and large-scale energy. The small-scale energy contributes directly to the turbulence production and the large-scale energy contributes to the production of non-turbulent fluctuations (K_L). Volino (1998) believed that the amplification of laminar kinetic energy (K_L) is caused by redirection of normal velocity fluctuation into streamwise direction, which generates local pressure gradients in the boundary layer and leads to breakdown of laminar fluctuations into full turbulent flows. The transition onset in the Walters and Leylek model was determined by a parameter that is based on the turbulent kinetic energy, the kinetic eddy viscosity, and the wall distance. The validations of the model were performed based on low Reynolds number $\kappa - \varepsilon$ model, which yielded a reasonable prediction of the transition onset. This is also a single-point transition model that only needs local flow quantities. The major issue of this model is that the calibration of the transition

model will affect the solution in fully turbulent flows, and the model is not flexible enough for a wide range of transition mechanisms in realistic applications.

Similarly, Lodefier et al. (2006) also proposed a model based on the concept of streamwise fluctuations, but introduced the intermittency equation to describe the transition region. The intermittency equation was based on the work of Steelant and Dick (2001), which was multiplied to the production term to start the transition process. Like Langtry and Menter's model, the vorticity Reynolds number was used to trigger the transition. However, the model used the free-stream turbulence intensity to evaluate the transition-momentum thickness Reynolds number, and the empirical correlation used for the transition momentum thickness Reynolds number does not include a pressure gradient. This model was incorporated into the SST $k-\omega$ model by multiplying the eddy viscosity with the intermittency and the modification of production terms in the turbulent kinetic energy and dissipation rate equations. Unlike the Langtry and Menter's model, this model used the free-stream turbulence intensity to determine the transition onset and was not a single point model.

2.4 Transition Simulation Methods

Direct Numerical Simulation (DNS) solves the fully unsteady Navier-Stokes equations directly, and does not need any turbulence models to close the equations. Theoretically, it can simulate the whole transition process including the development of disturbance waves, interaction between waves and boundary layers, ignition of turbulent spots, laminar flow breakdown, and development into fully turbulent flow (Durbin and Jacobs 2002). However, the grid for the DNS computations has to be extremely fine in order to capture the small scales of turbulent flows. The total number of grid points is in the scale of $O(Re_L^3)$ for a "modelling free" simulation (Aupoix et al. 2011). With the increasing speed of modern CPU's and the advent of cluster computing, DNS computations have moved beyond simple flat plates and it is now possible to perform DNS computations of a three-dimensional low-pressure turbine blade at Reynolds numbers up to 1.5×10^5 (Wu and Durbin 2001). However, from a computing resource standpoint it is still prohibitive to use DNS to simulate practical engineering problems, such as full vehicle configurations operating at high Reynolds numbers.

Due to significant computational costs associated with DNS, Large Eddy Simulation (LES) (Wu et al. 1999) is an alternative method for many researchers who have tried to solve transitional flows. LES uses the concept of solving the large-scale eddies directly, and modeling the small eddies using the Smagorinsky eddy viscosity approach (Smagorinsky 1963). This may create a major problem, as the transition onset location predicted by LES is sensitive to the value of Smagorinsky constant. This constant is needed to calibrate the local sub-grid eddy viscosity. The dynamic sub-grid-scale model developed by Germano (1992) was

more appropriate for predicting the transition onset, because the sub-grid eddy viscosity was automatically reduced to zero in a laminar boundary layer.

Because DNS methods solve all scale levels of turbulence to the smallest grid sizes, they are capable of simulating various transition processes including natural transition, bypass transition, and separation-induced transitions, etc. However, the computational costs for DNS or LES methods are prohibitively high in solving problems for realistic geometries at high Reynolds numbers. Therefore, these methods for transition simulations are largely used as research tools in academies or as substitutes for controlled experiments.

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