Advances in Applied Mathematics and Mechanics
Adv. Appl. Math. Mech., Vol. **6**, No. 4, pp. 523-538
DOI: 10.4208/aamm.2013.m266
August 2014

A Four-Equation Eddy-Viscosity Approach for Modeling Bypass Transition

Guoliang Xu[1,2] and Song Fu[2,*]

[1] *China Aerodynamics Research and Development Center, Mianyang 621000, China*
[2] *School of Aerospace, Tsinghua University, Beijing 100084, China*

Received 1 July 2013; Accepted (in revised version) 26 February 2014

Available online 30 May 2014

Abstract. It is very important to predict the bypass transition in the simulation of flows through turbomachinery. This paper presents a four-equation eddy-viscosity turbulence transition model for prediction of bypass transition. It is based on the SST turbulence model and the laminar kinetic energy concept. A transport equation for the non-turbulent viscosity is proposed to predict the development of the laminar kinetic energy in the pre-transitional boundary layer flow which has been observed in experiments. The turbulence breakdown process is then captured with an intermittency transport equation in the transitional region. The performance of this new transition model is validated through the experimental cases of T3AM, T3A and T3B. Results in this paper show that the new transition model can reach good agreement in predicting bypass transition, and is compatible with modern CFD software by using local variables.

AMS subject classifications: 76F06, 76F55

Key words: Bypass transition, non-turbulent viscosity, free stream turbulence, turbulence model.

1 Introduction

Laminar to turbulence transition is an important issue in modern fluid mechanics. Numerous theoretical and experimental studies on the incompressible boundary layer flow over a smooth flat plate are available in the literature. In general, two different transition routes are identified for the zero pressure gradient flat plate: natural and bypass transitions. The Tollmien-Schlichting (T-S) instability waves will lead to turbulence on flat pate in the very low levels of free-stream turbulent environment. But the T-S waves will be bypassed and a rapid transition process occurs when free-stream turbulence intensity

*Corresponding author.
Email: fs-dem@tsinghua.edu.cn (S. Fu)

 ©2014 Global Science Press

exceeds 1% of the free-stream velocity. In the past, bypass transition has been extensively studied for its importance in engineering design. Dryden [1] and Taylor [2] were probably the first in conducting the experimental studies of transition under the influence of intense free-stream turbulence. They observed span-wise alternating low and high-speed regions in the pre-transitional boundary layer flow. Klebanoff [3] showed that disturbances in the low and high-speed regions grow more or less linearly with the boundary layer thickness. Kendall [4, 5] showed that disturbances are low-frequency and streaky fluctuations and originate from the leading edge, and Kendall figured out that the disturbances are not turbulence. Similar to the work of Klebanoff [3], Westin et al. [6] found that the stream-wise velocity disturbance varies linearly with the square root of the distance from the beginning of the leading edge. Matsubare & Alfredsson [7], in their experimental studies, showed that free-stream turbulence penetrates the boundary layer and then induces the stream-wise velocities in the pre-transition region of the boundary layer flow. They also pointed out that the span-wise wavelength of streaky fluctuation is of the order of the boundary layer thickness. Fransson, Matsubare & Alfredsson [8] studied bypass transition which focused on the modeling of the transition zone under different conditions. All the results above confirm that disturbances in the region of boundary layer flow are low-frequency non-turbulent fluctuation whose streamwise velocity has a much larger magnitude than both the normal and spanwise velocities.

Bypass transition has also been studied by direct numerical simulation (DNS) and Large eddy simulation (LES). In the process, the mathematical modeling of the non-turbulent fluctuation is added to DNS or LES as the inlet condition. The free stream turbulence is commonly modeled with the continuous spectra of the Orr-Sommerfeld (OS) and Squire operators in most of the research work (Jacobs & Durbin [9], Zaki & Durbin [10] and Yang Liu, Tamer A. Zaki & Paul A. Durbin [11]). Butler & Farrell [12], Andersson, Berggren & Henningson [13] and Luchini [14] derived a different model based on non-modal growth analyses approach. These mathematical models and DNS/LES methods are very useful for academic simulations, but are very costly and expensive for engineering applications.

Almost all experimental results reveal that the flow becomes intermittent in the transition region when the bypass transition occurs. Dhawan & Narasimha [15] first considered transition as an eruption of turbulent spot. The physical nature of the transition flow can be described with the intermittent factor. There are many algebraic models for intermittency based on this idea and experimental data in previous works [16]. But most algebraic models are valid only for the flow with zero pressure gradient and TS wave transition.

A further approach into intermittency modeling is obtained as a solution of the intermittency transport equation [17–24]. The main advantage of this approach is that the modeling of the transition process is not only in the flow direction but also across the boundary layer, and hence provides a more realistic prediction method [22]. But most intermittency transport equations require non-local information which is not easy to obtain in CFD solvers, such as the boundary layer thickness and the free-stream velocity. And