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An intermittency factor weighted laminar kinetic energy transition model for heat transfer overshoot prediction

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ABSTRACT

An intermittency factor weighted laminar kinetic energy transition model appropriate for the prediction of overshoot in the transition region is proposed. Based on the hypersonic laminar kinetic energy transition model, study finds that the model predicts the overshoot when the transition onset is near the front of the configuration with a short transition zone, and greater gradients of relevant variables account for this circumstance. Therefore, the thought that accelerating the forming process of turbulent boundary layer in the late transition region to make greater variable gradients comes into being. Considering the convective and diffusive timescales of disturbances, an algebraic intermittency factor is presented and involved in the small-scale viscosity. In order to achieve the acceleration, compared with the DNS data as well, the intermittency factor is revised for a further step. Finally, the large-scale and small-scale viscosities are weighted by the revised intermittency factor. The revised model has been applied to flat plate boundary layer and boundary layer transitions over a blunt cone at different Reynolds numbers test cases. The results demonstrate the capacity of the model to reproduce overshoot with a reasonable degree of accuracy and reflect the effect of Reynolds number successfully. The revision originates from the perspective of transition model construction. A more sophisticated physics-based description of transition would be more preferable.

1. Introduction

The stability and laminar-turbulent transition of boundary layers at supersonic and hypersonic speeds have been studied for more than 50 years [1] and have become advanced research hotspots as well as formidable challenges. The physics underlying this phenomenon indicates that the transition is a multifold process that evolves in many different ways depending on numerous parameters of the mean flow and disturbances [1]. Hypersonic boundary layer transition phenomena have several unique features and the topics must be treated independently. In low speed boundary layers, one is accustomed to thinking of the vorticity instability mode which produces low frequency, low amplitude velocity fluctuations. A unique feature of a hypersonic boundary layer is the presence of the higher instability modes, the Mack mode [2]. These instabilities produce high frequency, large amplitude density fluctuations which can dominate the transition process [3].

From an application perspective, as boundary layer transits from laminar flow to turbulent flow, the fractional drag and aerodynamic heat of the aircrafts operating at sustained supersonic or hypersonic speeds increase prominently, which threatens the flight safety immensely. As a result, predicting boundary layer transition accurately is of great significance to the design of aerodynamic configurations, thermal protection systems and so on.

In the computational fluid dynamics (CFD) range, primitive boundary layer transition prediction methods mainly consists of experimental or empirical correlations [4,5]. The classical attempts of these approaches are to correlate transition onsets with one or two parameters from multitudinous influencing factors such as Reynolds number, Mach number and so on. For specific conditions, these correlations achieve great success, while for general cases, lacking in universality brings about large dispersion of the prediction results.

To be reliable for a broad range of circumstances, flow mechanisms based methods dominant boundary layer transition prediction approaches by degrees. Hierarchically, these methods involve, in the order of descending requirement in computational resources, direct numerical simulation (DNS) [6], large eddy simulation (LES) [7], nonlinear parabolized stability equations (NPSE) [8], e^N methods [9] based on Linear Stability Theory (LST) and linear parabolized stability equations (PSE), and Reynolds Averaged Navier-Stokes (RANS) approaches.

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Nomenclature

x_j	Cartesian coordinates
U_j	velocity vector
ρ	fluid density
p	pressure
E	total energy
T	temperature
δ_{ij}	Kronecker delta function
S	strain rate, $\|S_{ij}\|$
Ω	vorticity, $\|\Omega_{ij}\|$
k_T	turbulence kinetic energy
k_L	laminar kinetic energy
ω	specific turbulence dissipation rate
$k_{T,s}$	effective small-scale turbulence
$k_{T,l}$	effective large-scale turbulence
P_{kT}	production term of k_T equation
D_{kT}	dissipation term of k_T equation
P_{kL}	production term of k_L equation
D_{kL}	dissipation term of k_L equation
μ	molecular viscosity
$\mu_{T,l}$	large-scale dynamic viscosity coefficient
$\mu_{T,s}$	small-scale dynamic viscosity coefficient
$\nu_{T,l}$	large-scale kinematic viscosity coefficient
$\nu_{T,s}$	small-scale kinematic viscosity coefficient
ν_T	turbulent kinematic viscosity coefficient
λ_{eff}	effective length scale
$\tau_{T,l}$	characteristic timescale
$\tau_{T,l1}$	first mode characteristic timescale
$\tau_{T,l2}$	second mode characteristic timescale
$\mu_{T,l1}$	first mode viscosity
$\mu_{T,l2}$	second mode viscosity
f_v	viscous damping function
f_{int}	intermittency factor
f_{ss}	shear-sheltering damping function
C_μ	turbulent viscosity coefficient
α_T	effective diffusivity
f_ω	kinematic damping function
R_{BP}	model term for bypass transition
R_{NAT}	model term for natural transition
F_2	blend function
Tu	free stream turbulence intensity
h_{FR}	Reference heat transfer rate
Re_T	effective turbulence Reynolds number
Ma_{rel}	local relative Mach number
q	heat transfer rate
Ma	Mach number
Re_∞	free stream Reynolds number
P_0	stagnation pressure
T_0	stagnation temperature
H_{aw}	adiabatic wall enthalpy
H_{iw}	isothermal wall enthalpy

Recently, as a main method of the refined flow simulations, the rapid developing DNS has made remarkable contributions to the reveal of transition mechanisms. However, regarding the large computational consumption, DNS remains to be a pure research tool rather than an engineering prediction method. Comparatively, based on the universal assumption following Kolmogorov's Universal Equilibrium Theory, LES reduces the computational requirements by modelling the turbulence below the inertial sub-range, while the calculation is still quite beyond affordability for engineering applications, especially for complex geometries. In addition, for hypersonic flows, on account of the massive difficulties in reliable transition experiments, DNS and LES are somewhat far ahead of experimental database.

As for flows dominated by initial small disturbances with linear growth of instability modes, the e^N methods based on the integrated amplification of wave amplitude can reproduce the early transition behaviors. While for transition scenarios resulting from nonlinear disturbances growth with strong amplification of high-frequency secondary instabilities, more sophisticated NPSE methods would be preferable [8].

From the perspective of engineering, RANS based methods represents a reasonable compromise between accuracy and expense. Coupled with RANS equations, transition models are the most practical methods to predict boundary layer transition. For a further step, the most effective practices of transition models are to extend turbulent models by including additional transport equations to reproduce transition behaviors.

The intermittent behavior was discovered in the transition process after Emmons recorded that transition was induced by the eruption of turbulent spots [10]. Based on the correlation of intermittency factor γ summarized by Dhawan and Narasimha [11], a γ transport equation was firstly proposed by Steelant and Dick [12]. Employing a γ equation, a k-ε-γ model was proposed by Cho and Chung [13] to simulate the transition behaviors in the free shear flows. Concentrating on the intermittency distribution in both streamwise and crosswise direction, Suzen and Huang [14] developed a new γ transport equation. While the non-local variables, such as boundary layer thickness and boundary layer momentum thickness in Suzen and Huang's model [14] result in extremely tough work to implement the model with massively parallel execution and unstructured grids. The variables localization thought reversed the situation when Langtry, Menter and Volker [15] proposed the correlation based transition model γ-Re_θ. Test cases [15,16] manifest great correspondence with the experimental results for low-speed flows. Hao et al. [17] developed the γ-Re_θ transition model to be appropriate for hypersonic flows by introducing a new correlation of momentum thickness Reynolds number using local variables.

According to LST analysis, for hypersonic flows at Mach number lower than four, the first-mode disturbances master the transition process, while the second-mode disturbances master the situation when Mach number is greater than four. To take account of these two unstable modes, Warren and Hassan [18] put forward the non-turbulent viscosity μ_{nt}, a function of non-turbulent timescale related to the unstable modes. Similarly, pondering different unstable modes, Wang and Fu [19–21] proposed a k-ω-γ transition model applicable to both subsonic flows and supersonic/hypersonic flows. Hao et al.'s research [22] on the performance of the k-ω-γ transition model under different free-stream conditions demonstrates that the model can predict reasonable transition trends without accurate transition onsets at different Reynolds numbers, even worse for the effect of nose bluntness. Reformulating the γ transport equation and modifying the timescale of the second-mode, Zhou et al. [23] made further efforts to improve the k-ω-γ transition model to reflect the Reynolds number effect and nose bluntness influence more accurately.

Forsaking transition estimation correlations, phenomenological or physics-based models [24,25] are more preferable because the transition mechanisms are taken into consideration directly. However, regarding the fact that the mechanisms of transition are not