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Review

Improved k-ω-γ model for crossflow-induced transition prediction in hypersonic flow

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ABSTRACT

Accurate prediction of boundary layer transition is extremely important for the aerodynamic and aerothermodynamic design of a hypersonic vehicle. Crossflow instability plays a crucial role in inducing transition in three-dimensional (3D) boundary layer. In this paper, a crossflow timescale τ_{cross} based on crossflow velocity and crossflow Reynolds number is proposed and incorporated into the k-ω-γ transition model. Additionally, a grid pretreating method that can calculate boundary layer parameters with massive parallel execution is also proposed. HIFiRE-5, circular cone at angle of attack and X-33 vehicle are considered as test cases to assess the performance of the improved k-ω-γ transition model. Simulation results demonstrate that the boundary layer edge of complex hypersonic 3D flow can be obtained accurately with the help of grid pretreating method. It has been shown that if crossflow is taken into consideration, the shapes and locations of the transition onsets predicted by the improved k-ω-γ transition model are more consistent with experimental and direct numerical simulation results compared to the original transition model. This indicates that the improved k-ω-γ transition model provides significant improvement when crossflow-induced transition in hypersonic 3D boundary layer flow is predicted. Furthermore, application of the improved k-ω-γ transition model to X-33 vehicle flow shows that this model can be successfully used to predict crossflow-induced transition on complex full aircraft hypersonic configuration.

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Nomenclature

μ	molecular viscosity	$U(y_s)$	local mean velocity at y_s
μ_t	eddy viscosity	y_s	generalized inflection point
k	turbulence kinetic energy	U_e	boundary layer edge velocity
ω	specific turbulence dissipation rate	w	crossflow velocity
γ	intermittency factor	Re_{CF}	crossflow Reynolds number
P_k	production terms of k transport equation	w_{max}	the maximum crossflow velocity
D_k	dissipation terms of k transport equation	γ_g	heat capacity ratio
P_ω	production terms of ω transport equation	Pr	Prandtl number
D_ω	dissipation terms of ω transport equation	θ	boundary layer momentum thickness
Cd_ω	cross-diffusion term of ω transport equation	$\delta_{0.1}$	location along wall-normal direction where w=0.1w_{max}
P_γ	production term of γ transport equation	δ	boundary layer thickness
D_γ	dissipation term of γ transport equation	Ma_e	boundary layer edge Mach number
Tu_∞	freestream turbulence intensity	Re_θ	boundary layer momentum thickness Reynolds number
S	absolute value of strain rate, $\lvert S_{ij}\rvert$	h_0	total enthalpy
Re_v	strain rate Reynolds number	Ma_∞	freestream Mach number
F_{onset}	transition onset function	α	angle of attack
μ_{eff}	effective eddy viscosity	T_w	wall temperature
μ_{nt}	non-turbulent viscosity	Re_∞	freestream Reynolds number
τ_{nt}	characteristic timescale	y^+	non-dimensional distance to the wall
τ_{nt1}	first mode disturbance characteristic timescale	φ	azimuthal angle
τ_{nt2}	second mode disturbance characteristic timescale	C_f	wall skin friction coefficient
Ma_{rel}	local relative Mach number	H	heat transfer coefficient, $q/(h_{aw} - h_{nw})$
ζ	length scale	q	heat transfer rate
ζ_{eff}	effective length scale	h_{aw}	adiabatic wall enthalpy
d	wall distance	h_{nw}	non-adiabatic wall enthalpy
E_u	kinetic energy of the mean flow, $0.5\lvert U\rvert^2$	x_t	transition onset
ζ_T	turbulence length scale, $k^{0.5}/\omega$	R_n	nose bluntness
ζ_{th}	bound of the length scale, $k^{0.5}/(C_\mu\lvert S\rvert)$		
τ_{cross}	crossflow timescale		

1. Introduction

It is extremely important to predict boundary layer transition accurately when thermal protection system, drag reduction, propulsive efficiency and stability of hypersonic vehicles are estimated [1]. Excellent reviews of hypersonic boundary layer transition have been given by Stentson and Kimmel [2], Malik [3], Morkovin and Reshotko [4], Fedorov [5] and so on. The hypersonic boundary layer flow is always three-dimensional (3D) due to the swept wing, the angle of attack and the non-axisymmetric configuration. Crossflow instability plays a crucial role in inducing a transition in this case. Bippes [6], Arnal and Casalis [7], Saric et al. [8] have provided comprehensive reviews of crossflow-induced transition on subsonic swept wing. Fig. 1 shows a scheme of crossflow-induced transition on an infinite swept wing [9]. In swept wing flows, with the combined effects of sweep angle Λ and spanwise pressure gradient, the external streamlines at the boundary-layer edge develop curvature in the planes parallel to the wing surface. Thus, centrifugal force occurs as a result of curved streamlines and radial pressure gradient occurs to over-balance this centrifugal force. As static pressure is assumed to be constant in the wall-normal direction within a boundary layer, the secondary flow in the spanwise direction is generated by radial pressure gradient at the boundary layer edge. Thus, a crossflow velocity component is produced [9]. Crossflow velocity at both the no-slip wall and the boundary layer edge is equal to zero and its profile has an inflection point as shown in Fig. 1. Thus, the crossflow is subject to inviscid instability which can induce the transition process in 3D boundary layer. Neglecting the crossflow instability effects in 3D boundary layer flow simulations can lead to inaccurate transition prediction. Therefore, it is essential to take into account this important mechanism when predicting 3D boundary layer transition.

There are a variety of transition prediction methods such as e^N method, transition models, engineering correlations, direct numerical simulation (DNS) and large eddy simulation (LES). Transition

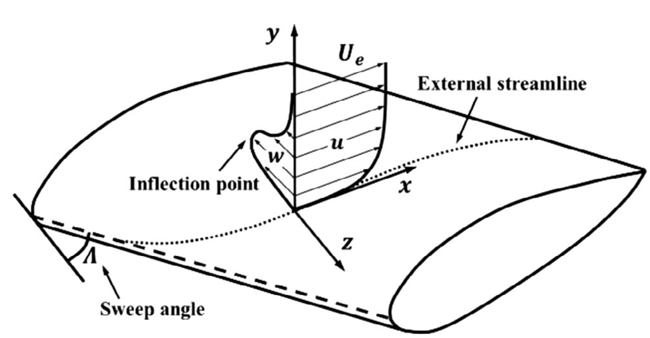

Fig. 1. Crossflow-induced transition on an infinite swept wing [9].