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Large eddy simulation on the effect of free-stream turbulence on bypass transition

Zhengqian Xu [a], Qingjun Zhao [b,c,*], Qizhao Lin [a], Jianzhong Xu [b]

[a] Department of Thermal Science and Energy Engineering, University of Science and Technology of China, Hefei, Anhui 230026, China
[b] Institute of Engineering Thermophysics, Chinese Academy of Sciences, Beijing 100190, China
[c] Key Laboratory of Light-Duty Gas-Turbine, Chinese Academy of Sciences, Beijing 100190, China

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ABSTRACT

The effect of free-stream turbulence (FST) on bypass transition in a zero-pressure-gradient boundary layer is investigated by means of Large Eddy Simulation (LES). The broadband turbulent inflow is synthesized to validate the feasibility of LES. Both a zero-thickness plate and one with super-ellipse leading-edge are addressed. The calculated Reynolds-averaged fields are compared with experimental data and decent agreement is achieved. Instantaneous fields show the instability occurs in the lifted low-speed streaks similar to earlier DNS results, which can be ascribed to outer mode. Various inflows with bi-/tri-mode interaction are specified to analyze effects of particular frequency mode on the instability pattern and multifarious transition or non-transition scenarios are obtained. Outer instability is observed in the cases with one low-frequency mode and one high-frequency mode inflow as reported by Zaki and Durbin (2005), and with one more high-frequency mode appended. Inner instability is observed in the case with a low-frequency dominant inflow, while the high-frequency mode is indispensable to induce the secondary instability. Furthermore, the results show that the transition onset is highly sensitive to low-frequency mode while the transition rate is highly sensitive to high-frequency mode. Finally, the formational frequency of turbulent spot (FFTS) is counted and the frequency of laminar streaks is demonstrated by spectral analysis.

1. Introduction

Transition to turbulence in boundary layers with a typical high level of free stream turbulence (FST) is commonly referred to as bypass transition (Mayle, 1991). FST usually has broadband perturbations in practical flows and its properties, such as the FST intensity, characteristic wavelengths and frequencies have profound effects on transition process (Brandt et al., 2004). Experimental investigation of Roach and Brierly (1990) showed that larger FST intensity induces an earlier transition onset and a shorter transition length. Jonas et al. (2000) found that although the turbulent length scale is less relevant to transition than the intensity at the leading edge, the former controls the stream-wise decay rate of the FST intensity, as well as the transition process. This finding was also evidenced by computational results of Brandt et al. (2004) which show a smaller decay rate and earlier transition onset with a larger turbulent length scale. However, turbulent length scale and frequency (equivalent to stream-wise wavelength by invoking Taylor's hypothesis) also affect the receptivity process at the beginning of transition. More details came from the disturbance analysis by Jacobs and Durbin (1998) and Direct Numerical Simulation (DNS) by Jacobs and Durbin (2001). Most of disturbance, especially high-frequency modes cannot penetrate the boundary layer because of shear sheltering (Hunt and Durbin, 1999) (a concise interpretation of the sheltering phenomenon was provided by Zaki (2013)), and the boundary layer maintains a laminar state prior to transition. Only quite low-frequency modes can penetrate deeply into the boundary layer and initiate laminar streaks (or Klebanoff modes). Those streaks keep growing in stream-wise until the low-speed components are lifted to upper layer by upwelling. The high-frequency modes from FST induce a secondary instability of the streaks, which finally evolve into turbulent spots and fully turbulent flows. The breakdown of lifted-up low speed streaks was validated by the experimental investigation (Hernon et al., 2007) with a moderate FST (1–3%). This type of transition mechanism was reviewed by Durbin and Wu (2007).

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[*] Corresponding author at: Institute of Engineering Thermophysics, Chinese Academy of Sciences, Beijing 100190, China.

E-mail address: zhaoqingjun@iet.cn (Q. Zhao).

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With larger turbulent intensity or blunter leading-edge, another type of transition scenario caused by localized wavepacket-like oscillations in the lower portion of the boundary layer was observed by Nagarajan et al. (2007). Ovchinnikov et al. (2008) also reported a similar phenomenon with a significant large FST intensity and integral length scale, though the authors distinguished their observations from those addressed in Nagarajan et al. (2007). They found that turbulent spots form upstream of the region where streaks can be detected. This kind of transition seems to be induced by the varicose instability, which entirely differs entirely from the sinuous instability as shown in Jacobs and Durbin (2001) (for more details about the two type of instabilities, see Brandt et al. (2004)). The simulations mentioned above and particle image velocimetry measurements by Mandal et al. (2010) and Nolan and Walsh (2012) all showed that the overlap region between low- and high-speed streaks is a site of inception of turbulent spots. The observation indicates the interaction of streaks plays an important role, which is quite different from the transition scenario in Jacobs and Durbin (2001) where only low-speed streaks are involved. Goldstein (2014) concluded that the exact geometry of leading edge seems to be unimportant in the transition mechanism revealed by Jacobs and Durbin (2001) and play an important role in one revealed by Nagarajan et al. (2007). Even though the new transition processes are widely observed in both numerical and experimental results above, the inherent mechanisms are not explained manifestly. Another problem is that the FST in practical flows are not isotropic or broadband, such as in turbo-machinery flows. It is worthful to find out the effect of each mode on the transition process.

In addition to broadband FST used in above simulations, single or two modes have also been introduced to investigate the receptivity and transition process by many researchers. With specified amplitude of fluctuation (3% wall-normal velocity fluctuation), Zaki and Durbin (2005) designed two Orr–Sommerfeld modes as the inflow condition. They found neither two low receptivity (or high frequency) nor two high receptivity (or low frequency) modes, but a low and a high receptivity mode can trigger transition. The transition scenario is quite similar to that of Jacobs and Durbin (2001). Durbin et al. (2009) studied the interaction of a discrete mode which represents Tollmien–Schlichting (T–S) wave and a continuous mode which represents FST. A pattern of Λ-structures with transition was observed in their simulation. Mode interaction was also studied in favorable and adverse pressure gradients by Zaki and Durbin (2006) and Schrader et al. (2011). Hoepffner and Brandt (2008) proposed a stochastic approach to predict the optimal growth mode prior to transition. Johnson (2011) found that the boundary layer is most receptive to fluctuations that lie in a plane perpendicular to the stream-wise direction. Mode interaction has been used to validate the new transition mechanism. Based on the results of secondary instability analysis, Vaughan and Zaki (2011) classified two most unstable modes as inner and outer instabilities, corresponding to transition scenarios described by Nagarajan et al. (2007) and Jacobs and Durbin (2001), respectively. Nolan and Zaki (2013) proposed a laminar-turbulent discrimination technique which allows the tracking of individual streaks to identify the inception location of turbulent spots. More recently, Hack and Zaki (2014) identified the inner and outer instabilities in realistic flow configurations with the base flow extracted from DNS fields. Zaki (2013) reviewed the progress of bypass transition to turbulence, and discussed the complementarity of theory, simulations and experiments.

The instability analysis with mode interaction has largely enhanced our knowledge of transition mechanism. Although the instability mechanisms were clearly revealed by Vaughan and Zaki (2011), the secondary disturbance was added to the base flow manually and the receptivity of the boundary layer to FST was not considered. For example, it is speculative how the leading edge affects the inner instability. Besides, the roles of various frequency modes are worthy of further investigation. A question about the inner instability is whether the high frequency mode is indispensable, considering that the interaction of streaks occurs at the bottom of boundary layer without random forcing from FST. The purpose of the current work is to discuss the influence of particular modes, the high frequency mode and/or low frequency mode on the transition process with a leading edge.

The feasibility of Large Eddy Simulation (LES) for bypass transition has been investigated for practical benefits. Voke and Yang (1995) believed that the underlying physics of bypass transition is similar to that of full turbulent flow, and is therefore amenable to LES. Lardeau et al. (2007) successfully performed LES over a flat plate and confirmed that it is conventional shear-stress/shear-strain interaction, rather than pressure diffusion which lead to the amplification of laminar streaks. The finding assisted in improving the performance of Reynolds Averaged Navier–Stokes (RANS) type transition model. Monokrousos et al. (2008) proved that LES can capture bypass transition efficiently with a precise sub-grid scale (SGS) model by comparing results of DNS and LES. Lardeau et al. (2012) found that LES is quite reluctant to capture fluctuation amplification without FST. Unlike RANS-based transition models which mainly concern statistical properties concluded by experimental databases, LES directly resolves the unsteady stream-wise evolution of large fluctuations in the boundary layer. In this regard, LES captures the transition process in the same way as DNS and the effect of SGS model must be well controlled. The belief which bypass transition can be captured by LES is supported by the fact that laminar streaks derived from low frequency disturbance of FST overwhelm the viscous, slow and exponential amplified of T–S waves. LES will be performed herein to investigate the bypass transition induced by FST.

2. Computational details

2.1. General settings

The three-dimensional, spatially filtered incompressible Navier–Stokes equations can be expressed as

$$\frac{\partial \bar{u}_i}{\partial x_i} = 0 \tag{1}$$

$$\frac{\partial \bar{u}_i}{\partial t} + \bar{u}_j \frac{\partial \bar{u}_i}{\partial x_j} = -\frac{\partial}{\partial x_j}\left(\frac{\bar{p}}{\rho}\delta_{ij} + \tau_{ij}\right) + \nu \frac{\partial^2 \bar{u}_i}{\partial x_j \partial x_j} \tag{2}$$

where $\bar{u}_i$, $\bar{p}$, ρ, δ_{ij} and ν are the filtered velocity field, the filtered static pressure, the density, the Kronecker delta and the kinematic viscosity, respectively. The SGS-stress tensor τ_{ij} is originally expressed as $\tau_{ij} = (\overline{u_i u_j} - \bar{u}_i \bar{u}_j)$ and modeled as

$$\tau_{ij} = -2C_\tau \bar{\Delta} k_{SGS}^{1/2} \bar{S}_{ij} + \frac{2}{3}\delta_{ij} k_{SGS} \tag{3}$$

where C_τ, Δ and $\bar{S}_{ij}$ are the coefficient, the filter width and the resolved strain rate tensor $(\partial \bar{u}_i/\partial x_j + \partial \bar{u}_j/\partial x_i)/2$, respectively. The SGS kinetic energy k_{SGS} is originally expressed as $k_{SGS} = (\overline{u_k u_k} - \bar{u}_k \bar{u}_k)/2$ and determined by the following transport equation (Kim and Menon, 1999)

$$\frac{\partial k_{SGS}}{\partial t} + \bar{u}_i \frac{\partial k_{SGS}}{\partial x_i} = -\tau_{ij}\frac{\partial \bar{u}_i}{\partial x_j} - \epsilon_{SGS} + \frac{\partial}{\partial x_i}\left(\nu_T \frac{\partial k_{SGS}}{\partial x_i}\right) \tag{4}$$

where ϵ_{SGS} and ν_T are the SGS dissipation rate modeled as $C_\epsilon k_{SGS}^{3/2}/\bar{\Delta}$ and the eddy viscosity modeled as $C_\tau \bar{\Delta} k_{SGS}^{1/2}$, respectively. The coefficients C_τ and C_ϵ are usually determined by the dynamic procedure