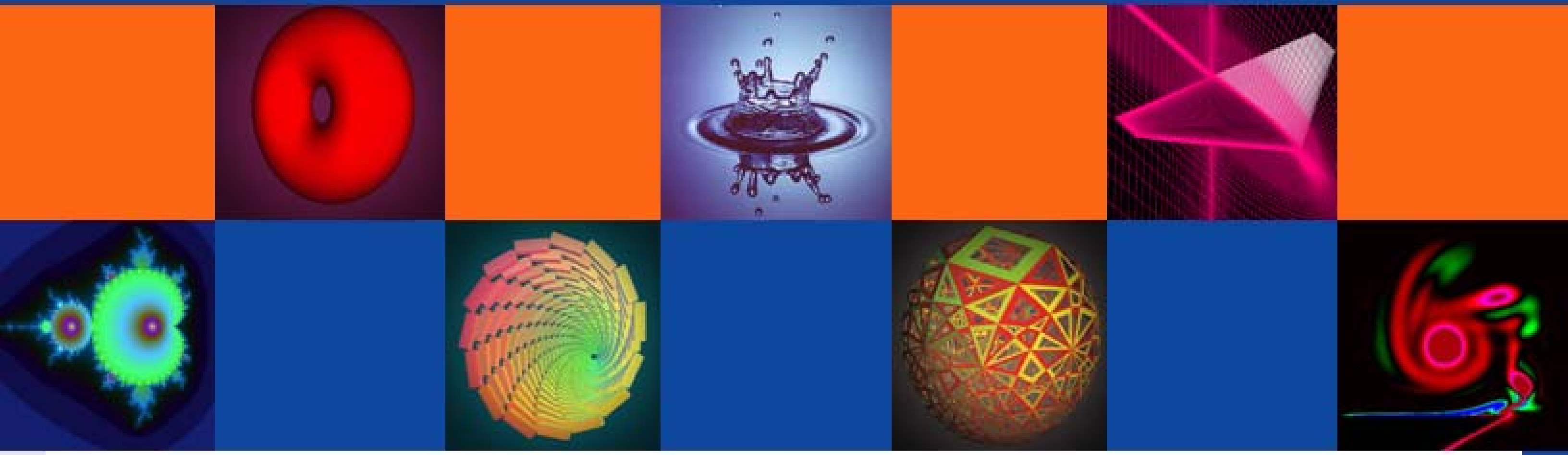

DNS for Late Stage Structure of Flow Transition on a Flat-Plate Boundary Layer

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DNS for Late Stage Structure of Flow Transition on a Flat-Plate Boundary Layer

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Direct numerical simulation of a spatially evolution flat-plate boundary layer transition process at free stream Mach number 0.5 is performed. The inflow is specified by laminar flow profile with imposed eigenmodes of two-dimensional and three dimensional Tollmien-Schlichting (T-S) waves. The parallel computation is accomplished through the Message Passing Interface (MPI) together with domain decomposition in the streamwise direction. H-type transition scenario is represented in the result of numerical simulation. Vortical structures formed by TS-waves and events at late stages of transition in wall boundary shear layers are investigated. Λ- (horseshoe-) vortices, Λ-shaped high-shear layers, and trains of ring-like (Ω -, hairpin-) vortices are studied. These vortical structures are similar with which has been found in K-type transition scenario. The purpose of this DNS study is to understand the physics of the late transition stages. Many remaining questions related to the late stages of flow transition have been answered by this DNS study.

I. Introduction

The fundamental fluid-dynamics problem of transition to turbulence has been a research focus for nearly a century, yielded its secrets sparingly and resisted simple phenomenological description (Kleiser, 1991). Physically understanding the mechanism in turbulence transition process is helpful to control the acoustic noise of aircraft and to reduce the friction coefficient over an air craft's surface. Precisely predicting the starting point of turbulence transition has significant influence on the shape design. Most of the causative coherent motions in the canonical turbulent boundary layer may be characterized as either a vortex or a shear layer (Robinson, 1991). Kinematical combinations and dynamical relationships between these two fundamental classes of structure comprise the foundation physics of the momentum-transport and mixing properties of the boundary layer. Observations show that shear layers may give birth to vortices, and that vortical structures may create shear layers. To gain the depth of understanding in order to improve practical modeling and control methodologies will require focused study of these basic three-dimensional structural features by numerical simulation and experiments. Main stages of Transition of boundary layers include receptivity, linear instability, weakly nonlinear instability, forming to vortical structures (late stage of transition) and breakdown to turbulences. At the late stages of flow transition, there are similar vortical structures in the turbulence boundary layers, which have been convinced by experiments. Recently, most direct numerical simulation of boundary layer transition is focus on Klebanoff (K-type) transition (Rist et al 2002). Experiment has show the resemblance of K- and H-type of boundary-layer transition at late stages (Kachanov 2000). Despite the significantly different nature of the initial stages of these two scenarios of transition, described usually in terms of weakly nonlinear interactions of the instability waves, the late stages of these two types of breakdown (described usually in terms of vortices attributed to the coherent structures) have approximately the same physical nature.

Direct numerical simulation of a spatially evolution flat-plate boundary layer transition process at free stream Mach number 0.5 is performed, and typical H type transition scenario is shown. The numerical simulation results represent the typical coherent vortcial structures. The properties of coherent vortical

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structures are investigated. The same physical nature at the late stage of transition is confirmed as the K-type transition.

After more than a century study, the linear and weakly nonlinear stability have been understood well, but there are still a lot of questions on the late stages of flow transition which need to be understood. The purpose of this DNS study is to try to understand the physics of the late transition stages which includes:

1. Is the flow transition structure in late stages same for both K-type and H-type transitions?
2. Why the Λ - vortex is lifted and stretched?
3. How the ring type vortex is formed?
4. Why the legs of first and second ring are longer than others?
5. The flow crosses the ring and goes up, but why it then goes down with large magnitude?
6. What is the consequence of the downward jets?
7. What is the role of upward jets?
8. Why the turbulence profile is fuller than laminar flow?
9. Why the viscosity did not dissipate small vortexes? Where the turbulence is continuously generated and why it can be sustained?
10. Why the positive spike has the same speed as the negative spike (Λ vortex) while the flow speed is much smaller near the wall.

II. Numerical Method and Computation Model

Governing system is the three-dimensional compressible Navier-Stokes equations in generalized curvilinear coordinates (Jiang et al, 1999). Sixth-order compact scheme (Lele, 1992) is used for spatial derivatives in the streamwise and wall-normal directions. In the spanwise direction, the spectral method is used in the place of the compact scheme in favor of periodic condition. Fourier transform are used to calculate the derivatives in the spanwise direction. A third-order TVD Runge-Kutta method (Shu, 1988) is used for time-integration.

We perform the DNS of spatially evolution compressible flat-plate boundary layer transition process at a free stream Mach number of 0.5. The inlet boundary condition is two dimensional laminar flat-plate boundary layer flow profile with enforced disturbances. The disturbance includes a two-dimensional Tollmien-Schlichting (T-S) wave and a pair of conjugate three-dimensional T-S waves. The T-S wave parameters are obtained by solving the compressible boundary layer stability equations (Malik, 1990). The adiabatic and the non-slipping conditions are enforced at the wall boundary on the flat plate. On the far field and the outflow boundaries, the non-reflecting boundary conditions (Jiang et al 1999b) are applied. The computation domain is displayed in Fig1. The parallel computation is accomplished through the Message Passing Interface (MPI) together with a domain decomposition approach in the stremewise direction. The computation domain is partitioned into n equal-sized sub-domains along the streamwise direction (Fig2).

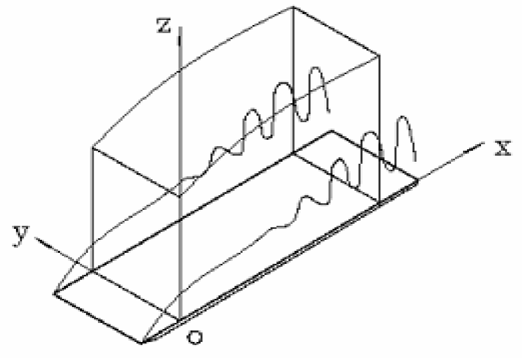


Fig1 Computation domain

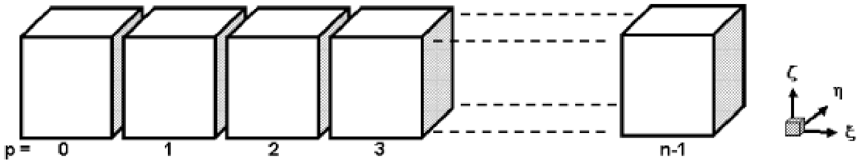


Fig2 The domain decomposition along streamwise direction in the computational space

III. Computational Results and Discussions

3.1 Code Validation

The skin friction coefficient calculated form the time-and spanwise-averaged profile is displayed in Fig3. The spatial evolution of skin coefficient of laminar flow is also plotted out for comparison. It is observed form this figure that the sharp growth of the skin-friction coefficient occurs after $x \approx 450\delta_{in}$, which is defined as the 'transition point'. The skin friction coefficient after transition is in good agreement with the flat-plate theory of turbulent boundary layer by Cousteix in1989 (Ducros, 1996).

Time-and spanwise-averaged streamwise velocity profile for various streamwise locations are show in Fig4. The inflow velocity profile at $x = 300.79\delta_{in}$ is of a typical laminar flow .At $x = 632.33\delta_{in}$ the mean velocity profiles resemble that turbulent flow.

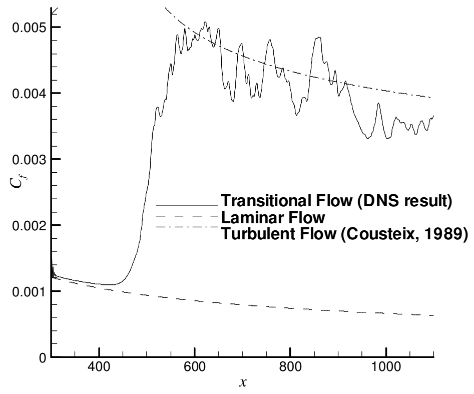


Fig3 Streamwise evolution of the time-and spanwise-averaged skin-friction coefficient

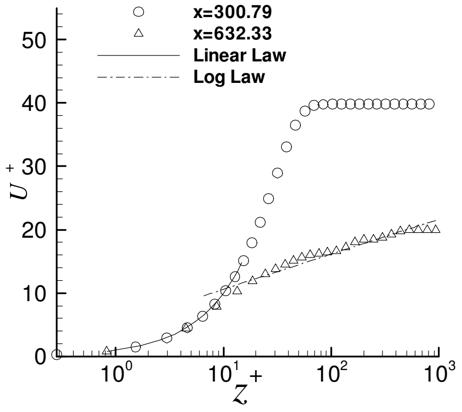


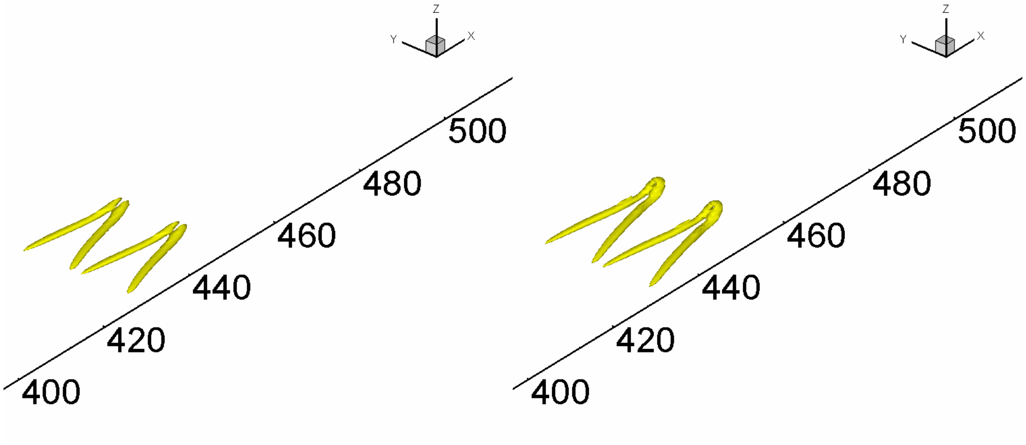
Figure4. Log-linear plots of the time-and spanwise-averaged velocity profile in wall unit.

The validation shows our computation is correct compare with existing literature.

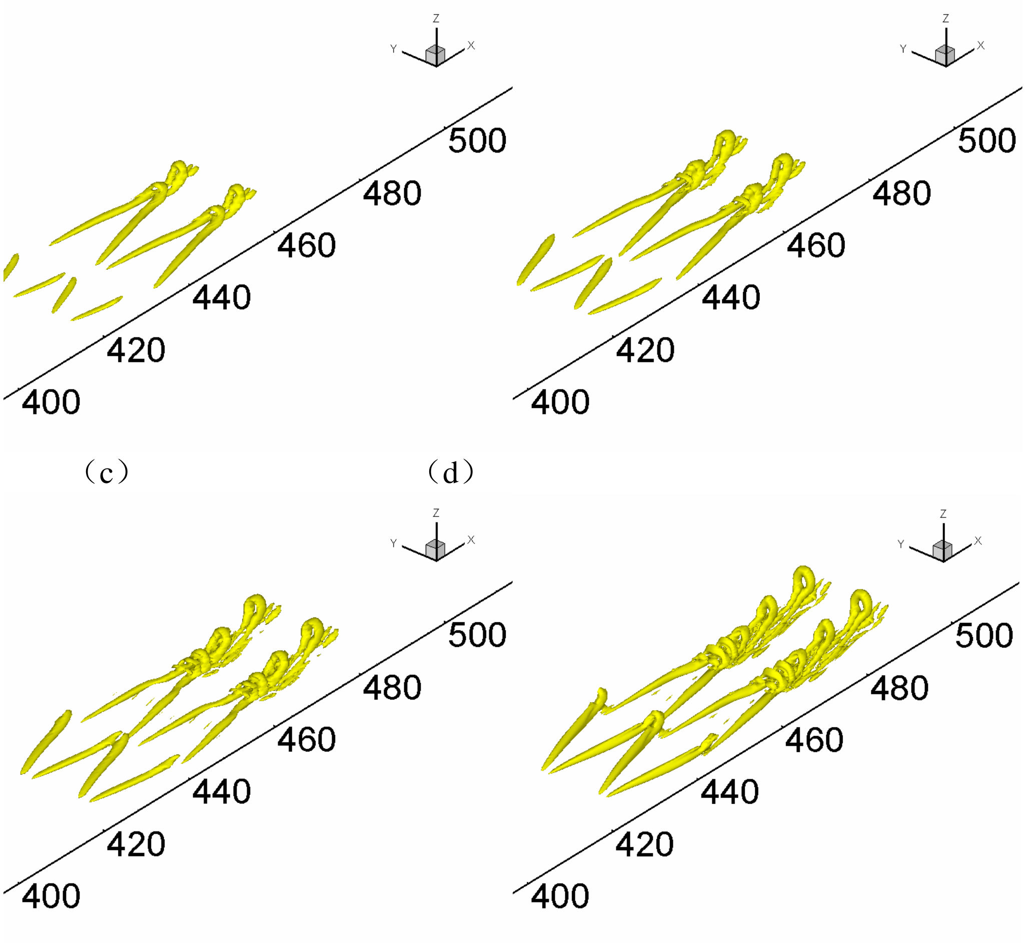
3.2 DNS for Late Stages of Flow Transition

Focus is placed on DNS for late stages of flow transition. At the late stages of flow transition, vorticical structures are formed by growing TS-waves with nonlinear interaction. First Λ- (Horseshoe-) vortices which are shown in Fig.5a are formed from peak and valley structures of TS-waves. The Λ- vortices structures are staggered along the streamwise. That is a typical H-type transition caused by sub-harmonic secondly instability. Between the legs of - Λ (Horseshoe-) vortices, there is ejection which forms the negative spike. The vortical structures are stretched and uplifted by the mean flow. At the top of the horseshoe the velocity is higher than that at the leg, which is a typical mean flow profile inside the boundary layer. The two legs are in rotation. That's the reason why the horseshoe is stretched and uplifted. Later the head of horseshoe vortices is enclosed and became forming the hairpin vortices (Fig.5b). Based on the Crow instability (Moin, 1986), the head of hairpin vortices will change into ring-like vortex. A curved filament concentrated vorticity evolves into a vortex ring as a result of self-induction effects. Ring-like vortex has close relationship with the positive spike. This process will be repeated and a chain of ring-like vortices are formed (Fig5c-Fig5f), which are similar to previous experiment work (Cunbiao Lee, 2005). All these vortical structures are similar to those founded in K-type transition (U.Rist et al 2002). It shows both K-type and H-type transition have same structure in the late transition stages. The new finding is that the positive strike is produced by jets crossing the ring like vortex.

Fig6 represents the flow structure around the ring-like vortices. The vectors shown in the Fig6 are disturbance velocity. There obviously exists upward injection between the two rotation vortices legs that represents a mixing near the bottom of the boundary layer. Beside the vortices leg there are downward sweeping. These injecting and sweeping events have close relationship with the negative and positive spike formation in the near wall region, which is shown in Fig7. They are similar as the result of Borodulin et al (2002), which simulated the K-type transition. The positive spike has the same speed as the negative spike (Λ vortex) while the flow speed is much smaller near the wall. It certificates the positive spike caused by sweeping events induced by ring-like vortices. Injecting and sweeping events change the shape of the velocity profile and convert laminar flow to turbulent flow, so turbulent velocity profile is much full than laminar velocity profile.



（a）　　　　　　　　（b）



（c） （d）

Fig5 The evolution of vortical structures at the late stage of transition based on eigenvalue λ_2 (JEONG, 1995)

IV. Conclusions

Vortical structures formed by TS-waves and events at late stages of H-type transition in wall boundary layers are investigated. Λ- (horseshoe-) vortices, Λ-shaped high-shear layers, and trains of ring-like (Ω-, hairpin-) vortices are studied. Two scenarios of transition (H-type and K-type) form the same vortical structures at the late of transition in flat plate boundary layer. These typical coherent structures play an important role in the late stages of the flow transition. Momentum and energy transfer produced by sweep and ejection events will convert laminar flow to turbulence flow. The late stages of flow transition including the ring like vortex formation, downward and upward jest formation and their roles, positive spike formation, boundary layer mixing, and turbulence self sustain are all revealed by this DNS simulation.

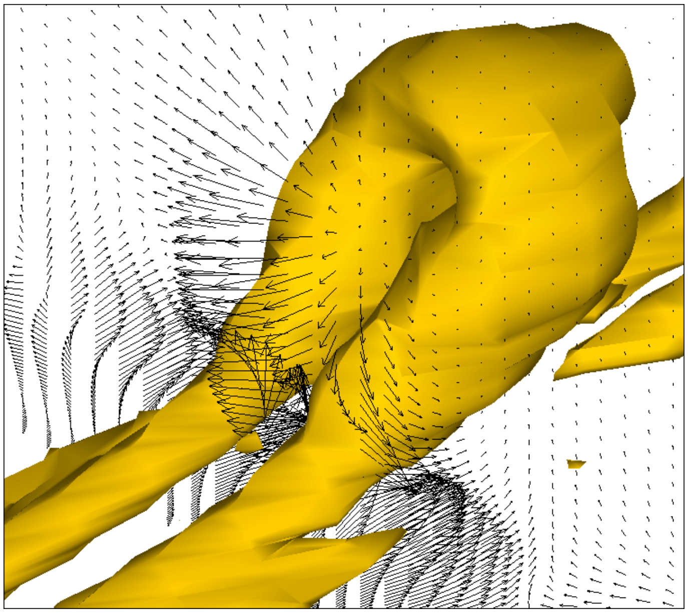


Fig6 Flow structure around the ring-like vortices

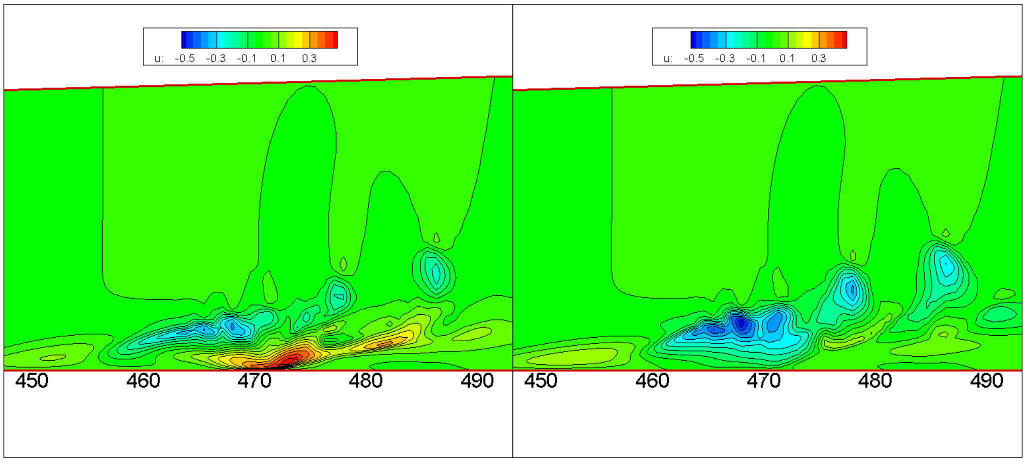


Fig7 Negative and positive spikes in near wall region

Acknowledgments

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