DNS Study on Turbulence Generation and Sustenance in Late Boundary Layer Transition

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Abstract: Based on our current DNS observations, the late stages of boundary layer transition consist of three steps: 1) large vortex formation; 2) small vortices generation; 3) loss of symmetry and flow randomization. Contradicting to the traditional flow transition theory, the large multiple vortex structure is not formed by "breakdown and reconnection" but "momentum deficit caused by the vortex rotation"; the small length scales are not generated by "vortex breakdown", but multiple level "shear layer instability"; The energy is transferred from the high energetic inviscid area to the lower boundary layer through multiple level sweeps. This is contradicting to Richardson's energy cascade describing that energy is transferred from large vortex to small vortex through vortex stretching and breakdown. Since the small length scales are generated by "shear layer instability" near the wall, the "Kolmogorov scale" estimation which is related to "vortex breakdown" would lose foundation and the smallest scale will be determined by analysis of "shear layer instability."

Keywords: DNS, Shear Layer Instability, Flow Transition, Vortex Breakdown, Energy cascade, Turbulence

1. Introduction

The transition process from laminar to turbulent flow in boundary layers is a basic scientific problem in modern fluid mechanics. After over a hundred of years of study on flow transition, the linear and weakly non-linear stages of flow transition are pretty well understood. However, for late non-linear transition stages, there are still many questions remaining for research. Adrian (2007) described hairpin vortex organization in wall turbulence. Wu and Moin (2009) reported a new DNS for flow transition on a flat plate and obtained fully developed turbulent flow with structure of forest of ring-like vortices by flow transition at zero pressure gradients. Recently, Guo et al (2010) conducted an experimental study for late boundary layer transition in more details. However, turbulence is still covered by a mystical veil in nature after over a century of intensive study. Following comments are made by wekipedia web page at http://en.wikipedia.org/wiki/Turbulence "Nobel Laureate Richard Feynman described turbulence as "the most important unsolved problem of classical physics". According to an apocryphal story, Werner Heisenberg was asked what he would ask God, given the opportunity. His reply was: "When I meet God, I am going to ask him two questions: Why relativity? And why turbulence? I really believe he will have an answer for the first." Horace Lamb was quoted as saying in a speech to the British Association for the Advancement of Science, "I am an old man now, and when I die and go to heaven there are two matters on which I hope for enlightenment. One is quantum electrodynamics, and the other is the turbulent motion of fluids. And about the former I am rather optimistic".

In order to get deep understanding the mechanism of the late flow transition in a boundary layer and physics of turbulence, we recently conducted a high order direct numerical simulation (DNS) with 1920×241×128 gird points and about 600,000 time steps to study the mechanism of the late stages of flow transition in a boundary layer at a free stream Mach number 0.5. The code was very well validated by comparison with linear theory, experiment, and other DNS results.

2 Problem Statement

2.1 Classical theories on turbulence

A turbulent flow is characterized by a hierarchy of scales through which the energy cascade takes place. According to Richardson, turbulence is random interactions of "eddies" as "**big whorls have little whorls, little whorls have smaller whorls, that feed on their velocity, and so on to viscosity**" (Figure 1 by Feynman, 1955). On the other hand, vortex stretching is the core mechanism on which the turbulence energy cascade relies to establish the structure function. According to Richardson (1928) and Kolmogorov (1941), the radial length scale of the vortices decreases and the larger flow structures break down into smaller structures (Figure 2 by Frisch et al, 1978). The process continues until the small scale structures are small enough to the extent where their kinetic energy is overwhelmed by the fluid's molecular viscosity and dissipated into heat.

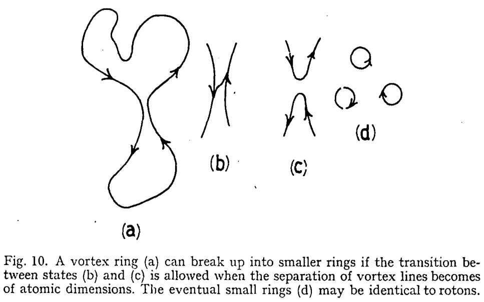

Figure 1: Sketch of vortex breakdown (Feynman, 1955; Tsubota et al, 2009)

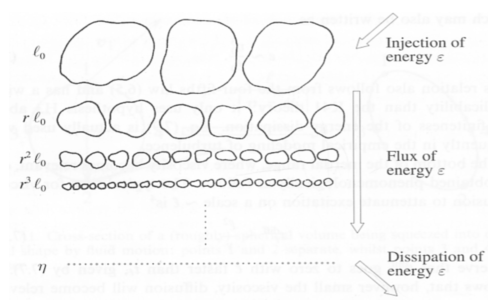

Figure 2: Sketch of Richardson cascade process (Frisch et al, 1978)

2.2 Our new obsevations on turbulence generation and sustenance.

1. Stremwise vortex is stretched but never breaks down (Figure 3).
2. In the middle of two vortex legs, there is a low speed zone formed by ejection from boundary layer bottom to bring momentum deficit up to this area. This momentum deficit forms a long shear layer (Figure 4).
3. This shear is unstable and multiple rings with spanwise vorticity will form one by one to generate multiple rings near the inviscid region due to the shear layer instability (Figure 4). In this process, Helmholtz vorticity conservation must be satisfied.
4. In the two sides of the vortex legs, high speed zones are formed by sweeps which bring high energy (energy increment) from inviscid area to the near wall región (Figure 4). The energy increment will form shear layers near the wall
5. The shear layers near the wall are unstable (shear layer instability) and will form multiple smaller ring-like vórtices (Figure 4)
6. These newly generated large and smaller vortices will continue similar process to generate smaller ring-like vortices (Figure 6) until the vortex size is too small and the new shear layer become stable.
7. Energy is transferred from the large size vortices to small size vortices through multiple level sweeps (Figure 5 and Figure 7). Dissipation is inevitable during the energy transfer.
8. All smaller vortices are newly generated by shear layer instability, but not by original vortex "breakdown"
9. Smallest length scales are all generated by the wall surface which must related to the surface configuration and cannot be "isotropic."

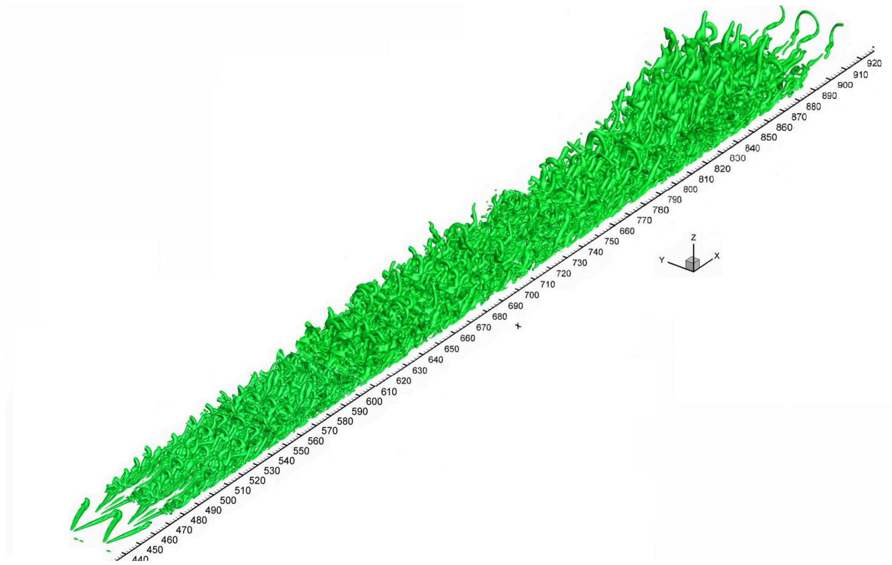

Figure 3: Multiple vortex ring generation in late boundary layer transition

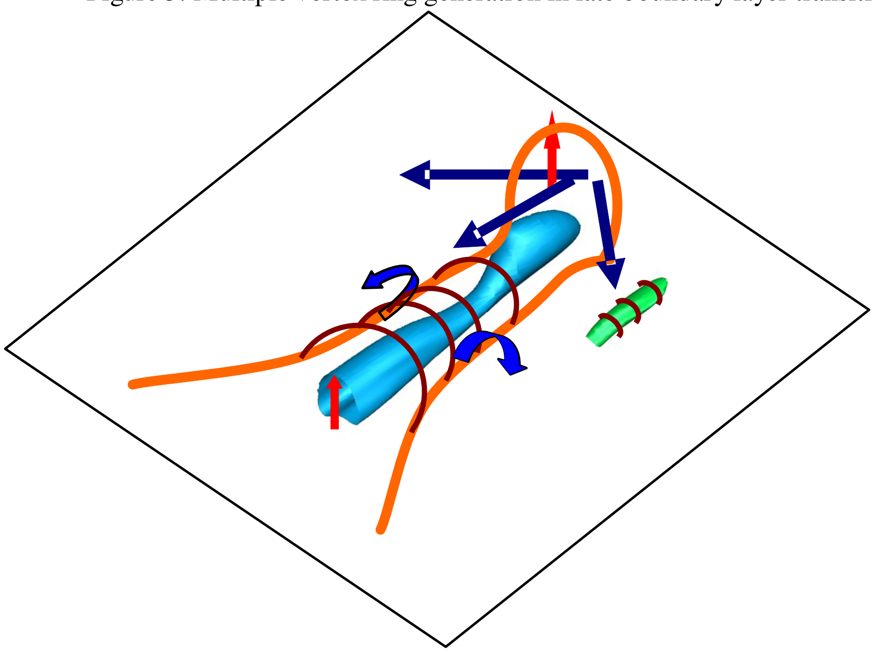

Figure 4: Sketch of large vortex structure and small length scale formation

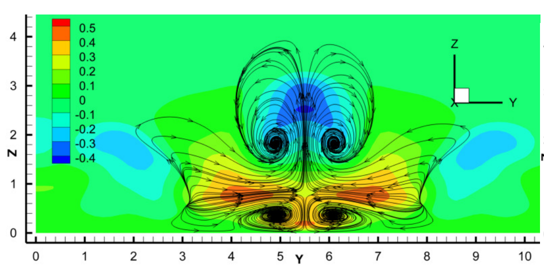

Figure 5: Multiple level sweeps

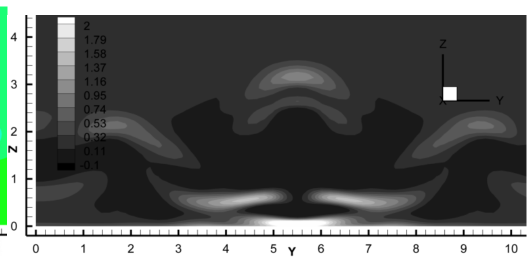

Figure 6: Multiple level shear layers

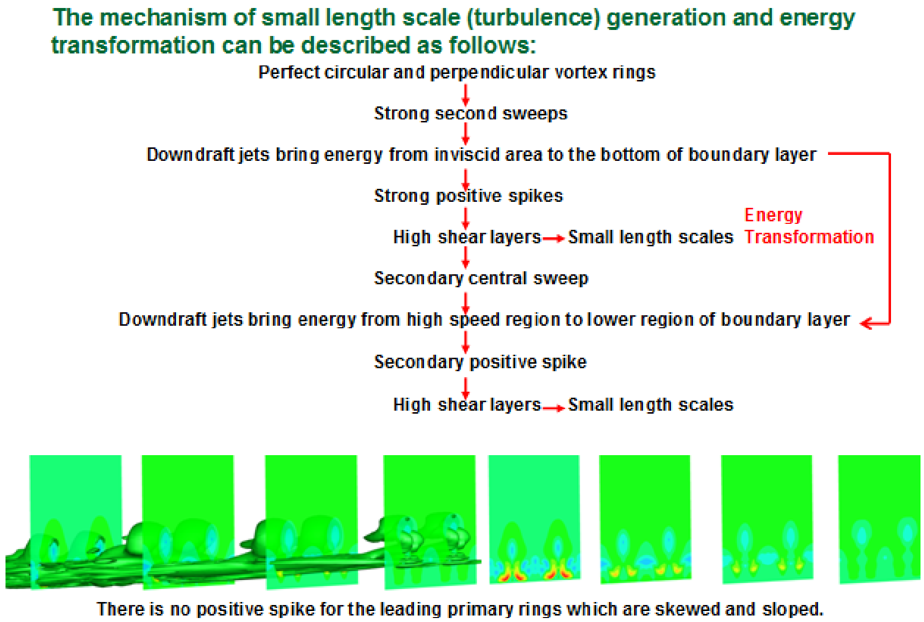

Figure 7: New energy cascade by mitiple level sweeps

3 Conclusion and Future Work

3.1 New observations on boundary layer transition

Classical theory on boundary layer transition can be described by four stages: 1) Boundary layer receptivity; 2) Linear instability; 3) Non-linear growth; 4) Vortex breakdown to turbulence. Apparently, we disagree with the classical theory. The new observation can be described by five stages: 1) Boundary layer receptivity; 2) Linear instability; 3) Large vortex structure formation; 4) Small vortices generation; 5) Symmetry loss and flow randomization.

3.2 New observations on turbulence generation and sustenance

The vortex cascade in turbulence given by Richardson, Kolmogorov and others is not observed. “Turbulence” is not generated by “vortex breakdown” but “shear layer instability”. “Kolmogorov scale” is not observed.

Future work includes a deep study and revisit of “Richardson energy cascade” and “Kolmogorov langth scale” in a detailed analysis.

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