Computers & Fluids 55 (2012) 36–47

Contents lists available at SciVerse ScienceDirect

Computers & Fluids

journal homepage: www.elsevier.com/locate/compfluid

Numerical study on U-shaped vortex formation in late boundary layer transition

Ping Lu, Zhengjie Wang, Lin Chen, Chaoqun Liu *

University of Texas at Arlington, Alrington, TX 76019, USA

ARTICLE INFO

Article history:
Received 21 February 2011
Received in revised form 3 October 2011
Accepted 28 October 2011
Available online 9 November 2011

Keywords:
Boundary layer
Transition
U-shaped
Vortex

ABSTRACT

This paper illustrates the mechanism of the U-shaped vortex formation, which has been found by both experiments and DNS in boundary-layer transition. The main goal of this paper is to find how the U-shaped vortex is formed and further developed. According to the results obtained by our direct numerical simulation (DNS) with high order accuracy, the U-shaped vortex is part of the large coherent vortex structure. This new finding is quite different from existing theories which describe that the U-shaped vortex is a secondary vortex induced by second sweeps, and it is newly formed as the head of young turbulence spot and finally breaks down to small pieces. However, it is found that the U-shaped vortex is neither generated by the second sweeps nor the consequent positive spikes. Actually, the U-shaped vortex is induced by the secondary vortices and the solid wall. The new finding also shows the U-shaped vortex is a vortex tube but not the heading wave. In addition, it is found that the U-shaped vortex has the same vorticity sign as the original Λ-shaped vortex legs, which means the U-shaped vortex is not secondary but tertiary. It serves as an additional channel to provide vorticity to support the multiple ring-like vortices when the original vortex tube is stretched and multiple rings are generated.

1. Introduction

The transition process from laminar to turbulent flow in a boundary layer is a basic scientific problem in modern fluid mechanics and has been studied for over a century. For explaining the mechanism of turbulence generation, many different concepts have been developed based on numerous experimental, theoretical, and numerical investigations. After over a century of study on turbulence, the linear and early 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 [1,2,9,10,18]. One of the problems which people do not fully understood is the mechanism of U-shaped (or Barrel shaped) vortex formation and its roles. U-shaped vortex was found by both experiment [2] as "barrel shaped wave", and DNS [19] as newly formed vortex. Singer and Joslin [19] described that the U-shaped vortex is the head of young turbulence spot and eventually breaks down to small pieces. Boroduln et al. believed the U-shaped is really a barrel-shaped head wave, since its speed is almost the same as the original vortex ring head while its location is much lower than the ring head in the boundary layer. Recently, Guo et al. [7] conducted an experimental study for late boundary layer transition in more details. They found that the U-shaped vortex is a barrel-shaped head wave, secondary vortex and is induced by second sweeps and positive spikes. In order to get deep understanding on the late flow transition in a boundary layer, we recently conducted a high order DNS with 1920 × 241 × 128 gird points and about 600,000 time steps to study the mechanism of the late stage of flow transition in a boundary layer. A number of new findings have been made and new mechanisms have been revealed [3,4,5,11,12,13,14,15,16]. These new findings on late flow transition in a boundary layer include: (1) the widely spread concept, "hairpin vortex breakdown to small pieces", which was considered as the last step of flow transition, is not observed in our DNS (Fig. 16); (2) the ring-like vortex with or without legs is found to be the only form existing inside the flow field; (3) the ring-like vortex formation, which is perfectly circular, perpendicularly standing and never pinched off, is the result of the interaction between two pairs of counter-rotating primary and secondary streamwise vortices; (4) the formation of the multiple ring structure follows the first Helmholtz vortex conservation law. The primary vortex tube rolls up and is stretched due to the velocity gradient. In order to maintain vorticity conservation, a bridge must be formed to link two Λ-vortex legs. The bridge finally develops as a new ring. This process keeps going onto form a multiple ring structure (Fig. 7a); (5) neither the hairpin vortex nor U-shaped vortex breaks down (Fig. 16). The existing articles, which reported vortex breakdown, were either based on 2-D visualization or using low pressure center as the vortex tube (Fig. 14); (6) the small vortices can be found on the bottom of the boundary layer near the wall surface (bottom of the boundary layer). It is justified that the small vortices, and thus turbulence, are all generated by high shear layers and the wall surface instead of by "large vortex breakdown".

* Corresponding author.
E-mail address: cliu@uta.edu (C. Liu).

0045-7930/$ - see front matter © 2011 Elsevier Ltd. All rights reserved.
doi:10.1016/j.compfluid.2011.10.014

Nomenclature

M_∞	Mach number	ω	frequency of inlet disturbance
δ_{in}	inflow displacement thickness	α_{2d}, α_{3d}	two and three dimensional streamwise wave number of inlet disturbance
T_∞	free stream temperature	β	spanwise wave number of inlet disturbance
Lz_{out}	height at outflow boundary	γ	ratio of specific heats
Lx	length of computational domain along x direction	Re	Reynolds number
Ly	length of computational domain along y direction	T_w	wall temperature
x_{in}	distance between leading edge of flat plate and upstream boundary of computational domain	Lz_{in}	height at inflow boundary
A_{2d}	amplitude of 2D inlet disturbance	R	ideal gas constant
A_{3d}	amplitude of 3D inlet disturbance	μ_∞	viscosity

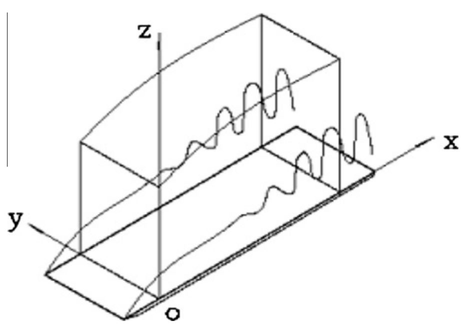

Fig. 1. Computation domain.

2. Case setup and DNS validation

2.1. Case setup

The computational domain is displayed in Fig. 1. The grid level is 1920 × 128 × 241, representing the number of grids in streamwise (x), spanwise (y), and wall normal (z) directions. The grid is stretched in the normal direction and uniform in the streamwise and spanwise directions. The length of the first grid interval in the normal direction at the entrance is found to be 0.43 in wall units ($y^+ = 0.43$). The T-S wave parameters are obtained by solving the compressible boundary layer stability equations [17].

The parallel computation is accomplished through the Message Passing Interface (MPI) together with domain decomposition in the streamwise direction Fig. 2. The computational domain is

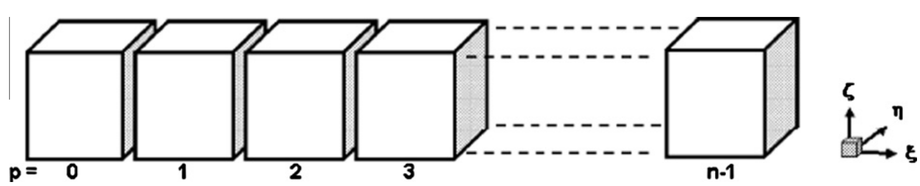

Fig. 2. Domain decomposition along streamwise direction in the computational space.

Table 1
Flow parameters.

M_∞	Re = 1000	$x_{in} = 300.79\delta_{in}$	$Lx = 798.03\delta_{in}$	$Ly = 22\delta_{in}$	$Lz_{in} = 40\delta_{in}$	$T_w = 273.15K$	$T_\infty = 273.15$
0.5	1000	$300.79\delta_{in}$	$798.03\delta_{in}$	$22\delta_{in}$	$40\delta_{in}$	273.15 K	273.15 K

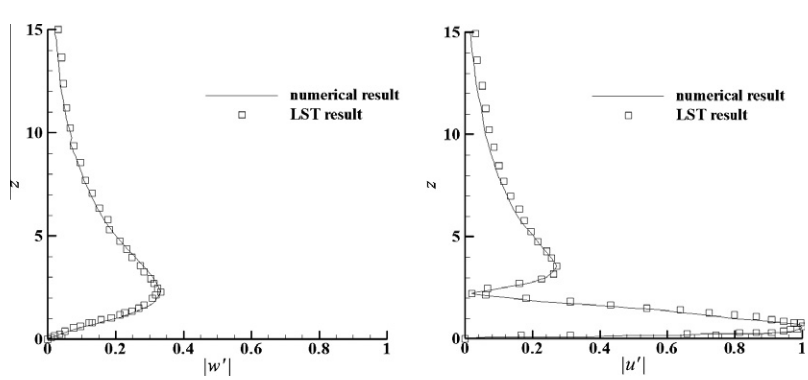

Fig. 3. Comparison of the numerical and LST velocity profiles at Rex = 394,300.