Computers & Fluids 91 (2014) 68–76

Contents lists available at ScienceDirect

Computers & Fluids

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

Numerical investigation on chaos in late boundary layer transition to turbulence

Ping Lu, Manoj Thapa, Chaoqun Liu *

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

A R T I C L E I N F O

Article history:
Received 26 March 2013
Received in revised form 1 October 2013
Accepted 25 November 2013
Available online 11 December 2013

Keywords:
Chaos
DNS
Flow transition
Turbulence

A B S T R A C T

The mechanism of chaos in late boundary layer transition is a key issue of the laminar-turbulent transition process in a flat plate boundary layer. A careful study on the characteristic of chaos is carried out by high order direct numerical simulation (DNS). The process of flow chaos was originally considered as a result of large background noise and non-periodic spanwise boundary conditions. It was addressed that the large ring structures are affected by background noises first, and then the change of large ring structures affect the small scale vortices quickly, which directly lead to chaos and formation of turbulent flow. However, according to our DNS observation, the loss of symmetry starts from the middle level vortex rings while the top and bottom rings are still symmetric. The non-symmetric structure of second level vortex rings will influence the small scale vortices at the boundary layer bottom quickly. The loss of symmetry at the bottom of the boundary layer quickly spreads to upper level through ejections. This will lead to chaos of the whole flow field. Therefore, the internal instability of multiple level ring structures, especially the middle ring cycles, is the main reason for the process of flow chaos, but not the large background noise.

1. Introduction

Turbulence is still covered by a mystical veil in nature after over a century of intensive study. Following comments are made by Wikipedia web page at <http://en.wikipedia.org/wiki/Turbulence>: Nobel Laureate Richard Feynman described turbulence as "the most important unsolved problem of classical physics" (USA Today 2006) [1]. 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" [2,3].

These comments clearly show that the mechanism of turbulence formation and sustenance is still a mystery for research [4–9]. Note that both Heisenberg and Lamb were not optimistic for the turbulence study.

The transition process from laminar to turbulent flow in boundary layers is a basic scientific problem in modern fluid mechanics [10–14]. 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 [15,16]. However, for late non-linear transition stages, there are still many questions remaining for research [17–22]. Adrian [23] described hairpin vortex organization in wall turbulence, but did not discuss the sweep and ejection events and the role of the shear layer instability. Wu and Moin [24,25] reported a new DNS for flow transition on a flat plate. They did obtain fully developed turbulent flow with structure of forest of ring-like vortices by flow transition at zero pressure gradients. However, they did not give the detailed mechanism of the late flow transition. Recently, Guo et al. [26] conducted an experimental study for late boundary layer transition in more details. They concluded 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 of 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 $1920 \times 128 \times 241$ 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 [27,28,29–41]. The work was supported by AFOSR, UTA, TACC and NSF Teragrid. A number of new observations are made and new mechanisms are revealed in late boundary layer transition.

Chaos is a key issue of late boundary layer transition and turbulence formation [42]. This work is devoted to the investigation of

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

0045-7930/$ - see front matter © 2013 Elsevier Ltd. All rights reserved.
http://dx.doi.org/10.1016/j.compfluid.2013.11.027

Nomenclature

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

the late stages of the laminar-turbulent transition process in a flat-plate boundary layer. As well known, in order to get a fully developed turbulent flow, the following two characteristics should be obtained: (1) small scale vortices; (2) chaos. There are not many existing literatures investigating the mechanism of chaos. Here, we only take those conclusions into account, which were made by Meyer and his co-workers (see Meyer et al. [43]). They believe that "the inclined high-shear layer between the legs of the Λ-vortex exhibits increasing phase jitter (i.e. chaos) starting from its tip towards the wall region." However, by carefully checking our DNS data, we observed a phenomenon which is different from the hypothesis given by Meyer and his co-workers.

A λ_2 technology developed by Jeong and Hussain [44] is used for visualization.

2. Case setup and code 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 ($Z^+ = 0.43$). The parallel computation is accomplished through the Message Passing Interface (MPI) together with domain decomposition in the streamwise direction (Fig. 2). The flow parameters, including Mach number, Reynolds number, etc. are listed in Table 1. Here, $x_{in} = 300.79\delta_{in}$ represents the distance between leading edge and inlet, $Lx = 798.03\delta_{in}$, $Ly = 22\delta_{in}$, $Lz_{in} = 40\delta_{in}$ are the lengths of the computational domain in x-, y-, and z-directions, respectively, and $T_w = 273.15K$ is the wall temperature.

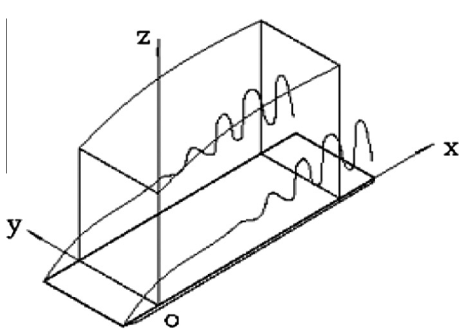

Fig. 1. Computation domain.

2.2. Code validation

The DNS code – "DNSUTA" has been validated by NASA Langley and UTA researchers [45,29,37] carefully to make sure the DNS results are correct and reliable. For verification purpose, we only show the skin-friction coefficient and velocity profiles in turbulent wall flow with coarse and fine grids. Detailed comparisons between DNS results with linear theory, experimental and other DNS results can be found from previous publications [32,35].

The skin friction coefficient calculated from the time-averaged and spanwise-averaged profile on a coarse and fine grid is displayed in Fig. 5. The spatial evolution of skin friction coefficients of laminar flow is also plotted out for comparison. It is observed from these figures that the sharp growth of the skin-friction coefficient occurs after $x \approx 450\delta_{in}$, which is defined as the "onset point". The skin friction coefficient after transition is in good agreement with the flat-plate theory of turbulent boundary layer by Ducros [46]. Fig. 3(a and b) also show that we get grid convergence in skin friction coefficients.

Time-averaged and spanwise-averaged streamwise velocity profiles for various streamwise locations in two different grid levels are shown in Fig. 4. The inflow velocity profiles at $x = 300.79\delta_{in}$ is a typical laminar flow velocity profile. At $x = 632.33\delta_{in}$, the mean velocity profile approaches to a turbulent flow velocity profile (Log law) [47]. This comparison shows that the velocity profile from the DNS results is turbulent flow velocity profile and the grid convergence has been realized.

Table 1
Flow parameters.

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

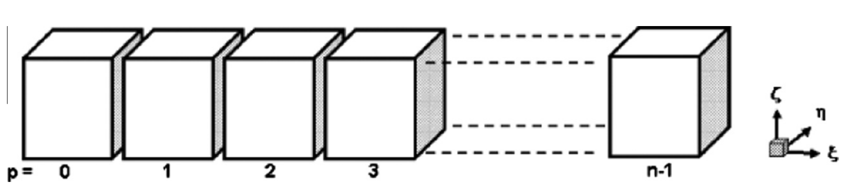

Fig. 2. Domain decomposition along the streamwise direction in the computational space.