Available online at www.sciencedirect.com
ScienceDirect
Progress in Natural Science 18 (2008) 873–878
Progress in Natural Science
www.elsevier.com/locate/pnsc

Large eddies induced by local impulse at wall of boundary layer with pressure gradients

Changgen Lu [a,b,*], Weidong Cao [b], Yanmei Zhang [b], Jintao Peng [b]

[a] College of Atmospheric Science, Nanjing University of Information Science & Technology, Nanjing 210044, China
[b] College of Environmental Science and Engineering, Hohai University, Nanjing 210098, China

Received 2 January 2008; received in revised form 1 February 2008; accepted 1 February 2008

Abstract

Large eddies induced by local impulse at the wall with pressure gradients in the boundary layer was studied by direct numerical simulations. The results show that the amplitude evolution, the high and low speed stripes, the formation of streamwise vortices, the ejection and sweeping, inflexions and distortion at the mean velocity profiles, as well as other characteristics, are consistent with the experimental and other numerical results. It is also found that large eddies are easy to be excited with adverse pressure gradient in the boundary layer, and the growth of amplitudes, formation of streamwise vortices and the influencing area etc., are much larger than those with favorable pressure gradient in the boundary layer. In contrast, large eddies are hardly to be induced through local impulse disturbance at the wall with favorable pressure gradients in the boundary layer.

Keywords: Boundary layer; Pressure gradients; Impulse; Large eddies

1. Introduction

Transition is always an important topic in the field of fluid mechanics, which often occurs in ships, cars, planes, gas engines, etc. It is significant to forecast and control transition for ameliorating drive engines' motility and efficiency. Schubauer and Skramstad have experimentally proved secondary and higher order instability on the basis of linear disturbance wave's growth. Based on the weak nonlinear theory, Herbert conducted numerical simulations on the experiments of Saric et al., and successfully constructed the theory of secondary instability. Since the experiment of Klebanoff and Kanchanov et al. and the direct numerical simulation of Orszag and Fasel et al., it has been a classical and frequent method for transition by disturbance wave's instability growth [1]. Numerical simulation was conducted on the evolution of large eddies by Breuerl and Landahl, and many forms of eddy structure were obtained by using two pairs of inviscid reverse eddy structure as the large eddy initial models in the boundary layer [2]. The characteristics of large eddies are obtained by Jeong and Hussain numerically with steamwise eddies' model, and the results agree well with the experimental results [3]. Using hairpin vortices as initial disturbance, semi-streamwise vortices, semi-spanwise vortices and strong high shear layer are excited by Zhou et al. [4]. According to the structure of large eddies and the instable wave characteristics of transition in the experiment, resonant triad of hydrodynamic stability was adopted as large eddies' model by Jang et al. [5], and it was found that the asymmetrical disturbance could be excited and magnified easily. In channel flow, the growth of 3D spanwise disturbance wave was studied by Schoppa and Hussain with low speed stripe and the cause of inducing streamwise

* Corresponding author. Tel.: +86 13770755281; fax: +86 25 83786606.
E-mail address: lu678q@163.com (C. Lu).

1002-0071/$ - see front matter
doi:10.1016/j.pnsc.2008.02.007

vortices and high shear layer, and the results were similar to the experimental results close to the wall [6]. The formation characteristics of large eddies in the Poiseuille flow and boundary layer have been numerically simulated by Spalart et al. [7] using the localized disturbance close to the wall as the initial flow. Katz et al. experimentally found that large eddies would be gradually diminishing in a boundary layer with favorable pressure gradients [8]. The occurrence and evolution of the large eddies induced by impulse at the wall of Blasius boundary layer had been numerically simulated by Singer [9]. Numerical simulation was conducted by Lu et al. on the evolution of large eddies in a turbulence boundary layer with pressure gradients with a period of instable wave as the initial model [10], and some useful results are obtained.

The cause of inducing large eddies is closely related to the Reynolds, wall temperature, shape, wall roughness, compressibility, pressure gradients and so on. Theoretical analysis was performed by Bertolotti on the effect of pressure gradients on the critical Reynolds in a boundary layer [11]. However, in the condition of large Reynolds, about the formation of large eddies, scale, shape and inside structure, there does not exist a clear conclusion. Recently, research on large eddies has been focused on the boundary layer with zero pressure gradients. However, in practice, most of the problems in the boundary layer are with adverse pressure gradients. Therefore, it is not only a theoretical problem but also a practical urgent problem to study the cause of large eddies induced by local impulse at the wall of boundary layer with different pressure gradients. Here, the cause and evolution of large eddies induced by local impulse at the wall of boundary layer with different pressure gradients have been studied by using direct numerical simulation.

2. Governing equations and numerical method

2.1. Governing equations and numerical method

The governing equations are the non-dimensionalized 3D incompressible Navier–Stokes equation and continuity equation:

$$\frac{\partial}{\partial t}\boldsymbol{u} + (\boldsymbol{u}\cdot\nabla)\boldsymbol{u} + (\boldsymbol{u}\cdot\nabla)\boldsymbol{u}_0 + (\boldsymbol{u}_0\cdot\nabla)\boldsymbol{u} = -\nabla p + 1/Re\cdot\nabla^2\boldsymbol{u} \tag{1}$$

$$\nabla\cdot\boldsymbol{u} = 0 \tag{2}$$

Here, ∇ is the gradient operators; ∇^2 is the Laplacian operators; $\boldsymbol{u}$, p are the disturbance wave's velocity and pressure, respectively; $\boldsymbol{u}_0$ is the basic solution of Falkner–Skan equation; $Re = U_e\cdot\delta/\upsilon = 3250$, where δ is the thickness of the inlet boundary layer, U_e is the velocity of inlet potential flow, and υ is the kinematic viscosity.

The procedures of direct numerical simulation of Eqs. (1) and (2) are as follows: a third-order mixed explicit–implicit scheme is employed for time discretization, and the space discretization is combined the higher accuracy compact finite differences of non-uniform meshes with the Fourier spectral expansion. Detailed information can be seen in Ref. [12]. The normalized time is 0.02.

2.2. Calculation region and boundary conditions

The calculation region is defined as follows:

- The streamwise: $0 \leqslant x \leqslant 120$; the spanwise: $-7.2 \leqslant z \leqslant 7.2$; the vertical: $0 \leqslant y \leqslant 6$; calculating grid: $\{x, y, z\} = \{200, 200, 32\}$.
- Inlet boundary condition: $x = 0$, $u = v = w = 0$, $\partial p/\partial x = 0$.
- Outlet boundary condition: $x = 120$, non-reflecting boundary condition.
- Boundary condition at the upper boundary; $y = 6$ $\partial u/\partial y = 0$ $\partial v/\partial y = 0$, $\partial w/\partial y = 0$, $p = 0$.

Boundary condition at the wall: $y = 0$, normalized impulse time $t \leqslant 10$, $v = A_0\sin[\pi(x-2.5)/1.5]\cos[\pi z/3.6]$, which are distributed in the streamwise grid ($1 \leqslant x \leqslant 4$) and the spanwise grid ($-1.8 \leqslant z \leqslant 1.8$), where A_0 is the disturbance intensity of initial impulse, $A_0 = 0.014$, and the rest of the grids: $u = v = w = 0$; $\partial p/\partial y = 0$; the impulse at the wall is removed when $t > 10$. All of the grids are $u = v = w = 0$. Fig. 1 shows the initial distribution of vertical disturbance velocity without local impulse at the wall.

3. Results and analysis

The evolution of large eddies' amplitude induced by local impulse at the wall is shown in Fig. 2, in the condition of different pressure gradients ($\beta = -0.1$, -0.05, 0, +0.05, +0.1). The large eddies' amplitude is defined as:

$$A = \sqrt{|u|^2_{\max} + |v|^2_{\max} + |w|^2_{\max}} \tag{3}$$

Fig. 2 shows the evolution of amplitude with different pressure gradients. With the same settings of the given location, area and intensity of the initial local impulse at the wall, the evolution of the amplitudes of induced large eddies with different pressure gradients is not the same. With either favorable pressure gradients or zero pressure gradients at the wall of boundary layer, the evolution of amplitudes induced by local impulse usually increases at

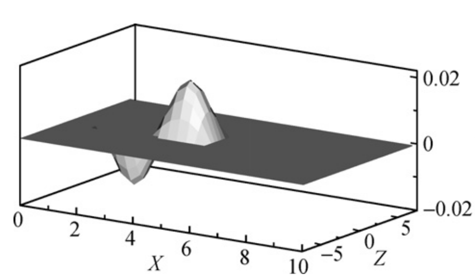

Fig. 1. Vertical disturbance velocity at the wall.