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Effects of an adverse pressure gradient on a turbulent boundary layer

Joung-Ho Lee, Hyung Jin Sung *

Department of Mechanical Engineering, KAIST, 373-1, Guseong-dong Yuseong-gu, Daejeon 305-701, Republic of Korea

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Abstract

Direct numerical simulations were performed to investigate the effects of an adverse pressure gradient (APG) on a turbulent boundary layer. A fully implicit fractional step method was employed to simulate the flows. Equilibrium APG flows were established using a power-law free-stream distribution, $U_\infty \sim x^m$. The streamwise length from the inlet was made sufficiently long that the change in free-stream velocity associated with the APG did not influence the main stream. The flow with zero pressure gradient (ZPG) was also simulated and compared with the APG flows. The spatially developing characteristics of the turbulence stresses in the non-equilibrium APG flows were carefully examined. The instantaneous flow fields and vorticity fluctuations were analyzed to characterize the response of the outer turbulence to an APG. The present numerical results showed that the mean flows are greatly affected by an APG, and the coherent structures in the outer layer of the APG flows were more activated than those in the ZPG flow which may be attributed to increased turbulence intensities, shear stresses and pressure fluctuations in the APG systems. Examination of the Reynolds stress budget revealed that the energy redistribution was enhanced in the outer layer of the APG flows compared to the ZPG flow.

Keywords: Adverse pressure gradient; Turbulent boundary layer; Direct numerical simulation; Budget of Reynolds stress; Vortex identification

1. Introduction

Flows subjected to an adverse pressure gradient (APG) occur in numerous engineering applications, including diffusers, turbine blades and the trailing edges of airfoils. The performance of such flow devices is greatly affected by the presence of an APG. If a turbulent boundary layer flow encounters a large APG, the flow becomes unstable and, if the APG is sufficiently large, separates from the surface. Such separation almost always has negative consequences such as drag reduction and loss of heat transfer. Thus, it is of practical importance to investigate the effects of APGs on turbulent boundary layers.

Many important features of APG flows are quite well understood. In general, as the magnitude of an APG increases, the mean velocity profile develops a large wake region and the turbulent kinetic energy decreases in the near-wall region. Nagano et al. (1993) suggested that this near-wall reduction in turbulent kinetic energy is due to a decrease in the production of turbulent kinetic energy. On the other hand, it is not certain that the standard logarithmic law of the wall holds in APG flows. Skåre and Krogstad (1994) and Bernard et al. (2003) observed that the law of the wall is valid for higher Reynolds number APG flows and for the decelerating flow around an airfoil, respectively. In contrast, Nagano et al. (1993) showed that the logarithmic region is shifted below the standard logarithmic law profile for turbulent boundary layer flows where the pressure gradient is maintained at a nearly constant positive value. This shift was also observed in the APG recovery section of a backward-facing step flow

* Corresponding author. Tel.: +82 42 869 3027; fax: +82 42 869 5027.
E-mail address: hjsung@kaist.ac.kr (H.J. Sung).

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(Le et al., 1997) and in other decelerating flows (Spalart and Watmuff, 1993; Debisschop and Nieuwstadt, 1996). Nagano et al. (1993) found that the turbulence intensity profiles in the outer region of APG flows collapse onto a single curve when normalized by the inlet free-stream velocity. Coleman et al. (2003) also examined the outer layer turbulence of a temporally developing flow; however, their findings cast doubt on whether the velocity fluctuations along the streamlines in the outer region are conserved. The effects of an APG on the mean velocity and the outer layer dynamics depend on both the characteristics of the APG and the geometrical shape of the surface. Hence, to isolate the effect of an APG, it is necessary to consider a flat plate surface.

Turbulent flows with an APG have been regarded as being among the most difficult flows to predict using turbulence models (Wilcox, 1993). The Reynolds stress equations, which are the basis for closure of the Reynolds averaged Navier–Stokes equations, include several terms that must be modeled (e.g., pressure–strain tensor and dissipation). Since direct numerical simulation (DNS) can provide accurate information directly, DNS findings would be instructive for the improvement of turbulence models. The major difficulty in simulating a spatially evolving turbulent boundary layer with an APG is imposing the conditions of free-stream flows and realistic turbulent inflows. Since there is no systematic way to choose boundary conditions that result in a specific pressure distribution, an iterative procedure is required (Na and Moin, 1998). For these reasons, only a limited number of DNS studies of APG flows over a flat plate have been conducted. Moreover, previous DNSs have failed to reproduce some of the experimental findings for APG flows, such as the existence of inward turbulent energy transport which is the opposite of that observed in systems with a zero pressure gradient (ZPG), and the development of a distinct outer peak in the streamwise turbulence intensity (Bradshaw, 1967; Cutler and Johnston, 1989; Nagano et al., 1993; Skåre and Krogstad, 1994). Clauser (1954) suggested a new class of equilibrium boundary layer with an APG, in which the ratio of the pressure gradient force to the wall shear force remains constant. The mean velocity profiles in an equilibrium boundary layer at different streamwise locations show similarity when properly scaled. Townsend (1961) and Mellor and Gibson (1966) showed that an approximate equilibrium flow is obtained when the variation of free-stream velocity in the streamwise direction has the form of a power-law relation $U_\infty \sim x^m$, analogous to Falkner–Skan laminar flow. Hence a power-law relation is employed in the present study. This is valuable from the viewpoint of numerical simulation since the free-stream boundary condition can be applied directly and the strength of the APG can be controlled simply by adjusting the magnitude of m.

In the present study, DNSs of spatially developing turbulent boundary layer flows subjected to several APGs were performed to elucidate the effects of an APG on a turbulent boundary layer. A schematic diagram of the flow configuration is shown in Fig. 1. The Reynolds number was varied in the range $Re_\theta = 300$–1500. To investigate the effects of an APG, simulations were performed using three values of $m = -0.075$, -0.15 and -0.2, representing mild, moderate and strong APGs, respectively. For comparison, the ZPG flow ($m = 0$) was also simulated. The evolutions of turbulence intensity and Reynolds stress in a non-equilibrium turbulent boundary layer were examined. Instantaneous flow fields and vorticity fluctuations were analyzed to characterize the response of the outer layer turbulence to the APG. Finally, the budgets of the Reynolds stress equations were examined to improve turbulence models.

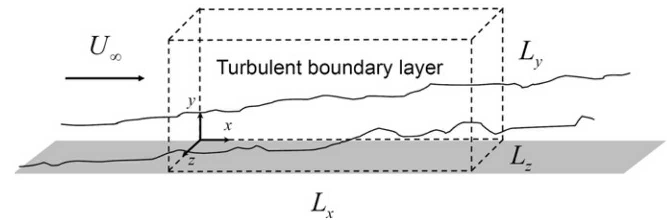

Fig. 1. Schematic diagram of computational domain.

2. Computational details

For an incompressible flow, the non-dimensional governing equations are

$$\frac{\partial u_i}{\partial x_i} = 0, \tag{1}$$

$$\frac{\partial u_i}{\partial t} + \frac{\partial}{\partial x_j} u_i u_j = -\frac{\partial p}{\partial x_i} + \frac{1}{Re}\frac{\partial}{\partial x_j}\frac{\partial u_i}{\partial x_j}, \quad i = 1, 2, 3, \tag{2}$$

where x_i are the Cartesian coordinates, p is the pressure, u_i are the corresponding velocity components, and Re is the Reynolds number. All variables are non-dimensionalized by the momentum thickness θ_{in} and free-stream velocity U_0 at the inlet.

The numerical schemes used in the present work were similar to those of Lee and Sung (2005). The governing equations were integrated in time using the fractional step method with the implicit velocity decoupling procedure proposed by Kim et al. (2002). The computational time step is $\Delta t^+ \approx 0.2$ in wall units. Under this approach, the terms are first discretized in time using the Crank–Nicolson method, and then the coupled velocity components in the convection terms are decoupled using the implicit velocity decoupling procedure. The decoupled velocity components are solved without iteration. Because the implicit decoupling procedure relieves the Courant–Friedrichs–Lewy restriction, the computation time is reduced significantly. The overall accuracy in time is second-order. All of the terms are resolved with a second-order central difference scheme in space with a staggered mesh. Details regarding the numerical algorithm can be found in the paper of Kim et al. (2002).