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Unsteady turbulent flow with sudden pressure gradient changes

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SUMMARY

Direct numerical simulations are performed for a turbulent flow subjected to a sudden change in pressure gradient. The calculations are started from a fully developed turbulent channel flow at $Re_\tau = 180$. The pressure gradient of the channel flow is then changed abruptly. The responses of the turbulence quantities (e.g. turbulence intensities, Reynolds shear stress, and vorticity fluctuations) and the near-wall turbulence structure to the pressure gradient change are investigated. It is found that there are two different relaxations: a fast relaxation at the early stage and a slow one at the later stage. The early response of the velocity fluctuations shows an anisotropic response to the near-wall turbulence. Copyright © 2005 John Wiley & Sons, Ltd.

KEY WORDS: DNS; unsteady; pressure gradient; turbulent; channel flow

1. INTRODUCTION

Turbulent flows subject to sudden changes in boundary conditions, e.g., pressure gradient, wall temperature, roughness, curvatures and wall blowing/suction, are frequently encountered in engineering applications. When a fully developed turbulent flow is subjected to a step change in wall boundary conditions, there is an initial relaxation toward an equilibrium state after the step change of perturbation [1–4]. Many features including turbulence statistics and turbulence structure have been examined by researchers. In the recovery process, it is known that the first-order statistics, such as the mean flow, relax first, and that the second-order statistics, such as the Reynolds stresses, relax next. Recently, Chung and Sung [3] found that, using a spatially developing long channel flow DNS, the downstream relaxation was anisotropic. Hence, the relaxation process is difficult to predict using simple turbulence models [5].

A spatial or temporal relaxation occurs depending on the nature of the disturbance. For example, when boundary conditions change as the flow goes downstream, a spatial relaxation

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follows. On the other hand, if boundary conditions change in time, a temporal relaxation accompanies. Most works have focused on the *spatial* relaxation, and extensive reviews are found in Smits and Wood [1] and Bushnell and McGinley [2]. In contrast, the temporal relaxation associated with a sudden change has received less interest and the relaxation process is not yet fully understood. There are only a few studies on the temporal relaxation. Moin *et al.* [6] performed a DNS for a fully developed channel flow subjected to a spanwise pressure gradient. Strained three-dimensional wall-bounded turbulence was investigated by Coleman *et al.* [7, 8] and Le *et al.* [9]. Scotti and Piomelli [10, 11] studied a pulsating turbulent channel flow. It was found that 'standard' turbulence models gave reasonably accurate results for velocity profiles. However, the Reynolds stress could not be predicted accurately using turbulence models because non-equilibrium turbulent flows have characteristics different from the equilibrium state.

In this study, the relaxation of turbulent flow caused by a sudden pressure gradient change is considered. The direct numerical simulation technique is employed to investigate the modifications in the near-wall turbulence structures. Preliminary results have been presented in Chung and Luo [12], Chung and Sung [13] and Chung [14].

2. NUMERICAL METHODS

DNS is performed for a turbulent flow subjected to a sudden change in pressure gradient. In the DNS, a numerical code developed by Yang and Ferziger [15] is used. A low storage, third-order Runge–Kutta method is used for time integration for the non-linear convective terms, and a second-order Crank–Nicholson method for the viscous terms. The fractional-step method developed by Kim and Moin [16] is used to enforce the solenoidal condition. The resulting discrete Poisson equation for the pressure is solved using a discrete Fourier transform in homogeneous directions and a penta-diagonal direct matrix solver in the wall normal direction.

The flow is assumed to be periodic in the streamwise and spanwise directions. For spatial discretization, the second-order central differences are used. All flow variables are non-dimensionalized by the friction velocity in the unperturbed channel, u_τ and the channel half-width h. The Reynolds number is defined as $Re = u_\tau h/v$, where v is the kinematic viscosity of the fluid. The computational domain is set $(4\pi \times 2 \times 4\pi/3)$ with a grid system $(128 \times 129 \times 128)$ in the x, y, z directions, respectively. The streamwise and spanwise grid resolutions are $\Delta x^+ = 17.7$ and $\Delta z^+ = 5.89$, respectively. The first grid point away from the wall is located at $y^+ = 0.1$. Here, a superscript $+$ indicates the wall units of the unperturbed flow.

3. RESULTS AND DISCUSSION

Direct numerical simulation is performed for a fully developed planar channel flow that was subjected to a sudden pressure gradient change. The calculations are started from a fully developed turbulent channel flow. The initial fields, at $Re_\tau = 180$, are similar to those of Kim *et al.* [17]. We use a constant pressure gradient boundary condition to accommodate the sudden pressure gradient change. The results of simulations starting from four independent initial fields are averaged into the statistics shown here. The initial pressure gradient is $\partial P/\partial x = -\tau_w/\delta$,

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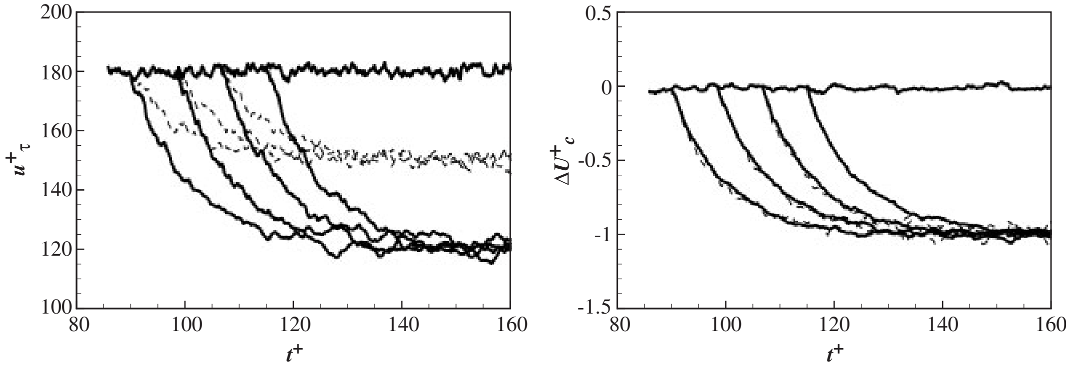

Figure 1. Time history of the friction velocity u_τ^+ and the centreline velocity U_c^+. Solid lines represent $Re_\tau = 120$ cases and dashed lines indicate $Re_\tau = 150$ cases.

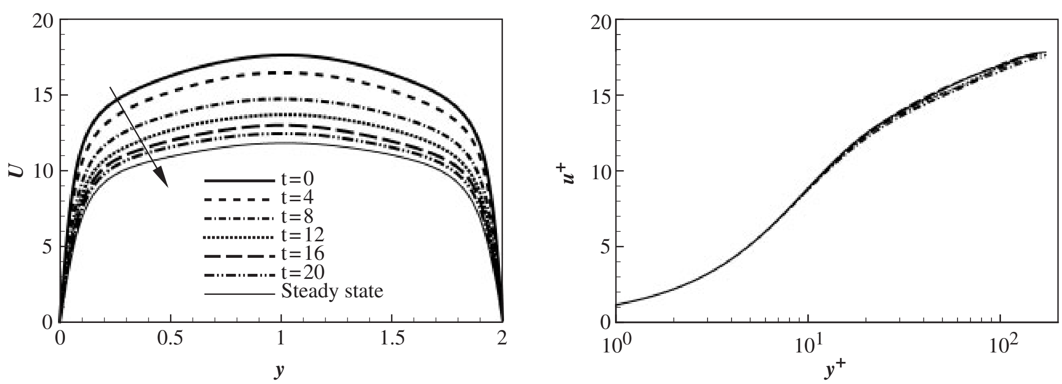

Figure 2. Streamwise velocity at several time instants.

where τ_w is the mean wall shear stress in the unperturbed channel and δ the channel half-width. The subsequent calculations are performed with a new pressure gradient $\partial P/\partial x = -A\tau_w/\delta$. Two values of A are considered ($A = \frac{4}{9}$ and $\frac{25}{36}$), which correspond to $Re_\tau = 120$ and 150, respectively. Results are averaged in the homogeneous directions (x and z). More details about the numerical method can be found in Chung and Choe [18] and Chung [19].

Figure 1 shows the time history of the friction velocity u_τ and centreline velocity change ΔU_c^+. Time traces from four separate simulations are included and the time intervals between different simulations are roughly 10 (tu_τ/h) in wall units. u_τ for the unperturbed case is also included for comparison purposes. Although the pressure gradient change is abrupt, the adjustment of the near-wall turbulence is gradual. From the figure, it is found that there are two different relaxations: a fast relaxation at the early stage and a slow one at the later stage. Recently, two relaxations have also been observed in the spatial relaxation by Fukagata and Kasagi [20]. The acceleration (or deceleration) rate ($\mathrm{d}U/\mathrm{d}t$) during the early relaxation depends on the magnitude A. It is clearly seen in Figure 1(b), where the relaxation of the centreline velocity is plotted. When normalized, the $Re_\tau = 120$ and 150 cases show a similar

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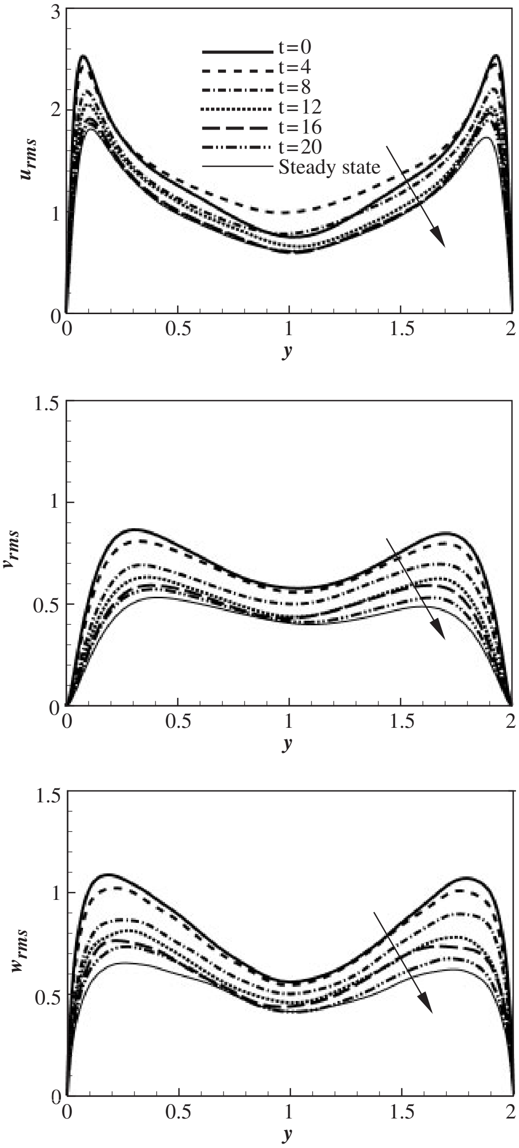

Figure 3. Turbulence intensities at several time instants.

trend during the relaxation. The value A appears to play an important role in the early fast relaxation, while the second relaxation is almost independent of A. After the sudden changes in the pressure gradient, u_τ decreases gradually. The centreline velocity U_c also shows a similar trend.

In Figure 2, the streamwise velocity profiles are shown at several instants during the relaxation. The times shown in the figure are the time measured from the start of the pressure

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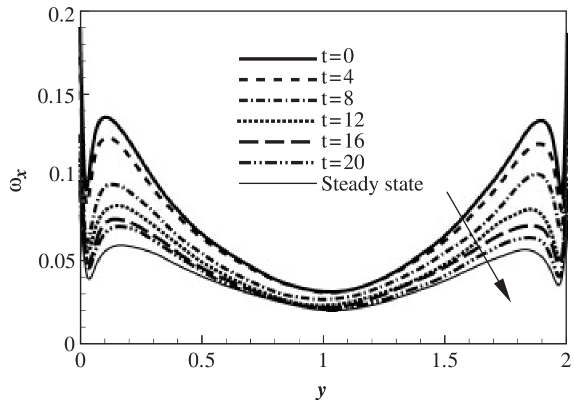

Figure 4. ω_x profiles at several time instants.

change. Since mean results have been obtained by averaging over four realizations, it seems more appropriate to use the time measured from the start of the pressure change rather than the real time used in Figure 1. The mean velocity begins to decrease as soon as the pressure gradient is changed. It is interesting that the log-law is not affected during the relaxation, while the velocity profiles are changed significantly in global units.

Turbulence intensities are also analysed for $Re_\tau = 120$ cases in Figure 3. The response of turbulence intensity is first observed in the near-wall region where turbulence production dominates the turbulence budget. The early response of the streamwise velocity fluctuations $u_{\rm rms}$ is found to be faster than that of other components, indicating an anisotropic response of the near-wall turbulence. This feature is attributed to the decrease in the production term, $-\overline{uv}\partial U/\partial y$. In contrast, $v_{\rm rms}$ and $w_{\rm rms}$ do not decrease immediately and show a little delayed response after the pressure gradient change. The slow response of the transverse velocity fluctuations is explained by the fact that the main energy source for these components of turbulence intensity is the redistribution terms in the Reynolds stress transport equations

$$\phi_{ij} = \frac{1}{\rho}\overline{p\left(\frac{\partial u_i}{\partial x_j} + \frac{\partial u_j}{\partial x_i}\right)}$$

The delayed response of turbulence to a sudden pressure change is also observed for ω_x in Figure 4, indicating that the (strength of the) low-speed streaks are not affected immediately by the pressure gradient change.

4. CONCLUDING REMARKS

Turbulent flows subjected to a sudden change in pressure gradient are investigated using direct numerical simulations. The calculations are started from a fully developed turbulent channel flow at $Re_\tau = 180$. The pressure gradient of the channel flow is then changed abruptly. The temporal relaxation of the turbulence quantities after a sudden pressure gradient change is analysed. It is found that there are two different relaxations: a fast relaxation at the early

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stage and a slow one at the later stage. The early response of the velocity fluctuations shows an anisotropic response to the near-wall turbulence.

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