DIRECT NUMERICAL SIMULATION OF UNSTEADY DECELERATING FLOWS

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ABSTRACT

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 $Re_\tau = 180$ and 360. 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 of the near-wall turbulence. Four turbulence models are tested in this study: the S-A model, the $k - \varepsilon$ model, the $k - \omega$ model, the Baldwin-Lomax model.

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 (Smits and Wood, 1985; Bushnell and McGinley, 1989; Chung and Sung, 2001; Chung *et al.*, 2002). 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 (2001) found that, using a spatially-developing long channel flow DNS, the downstream relaxation was anisotropic. Hence, the relaxation process is difficult to predict using turbulence models (Bassina *et al.*, 2001).

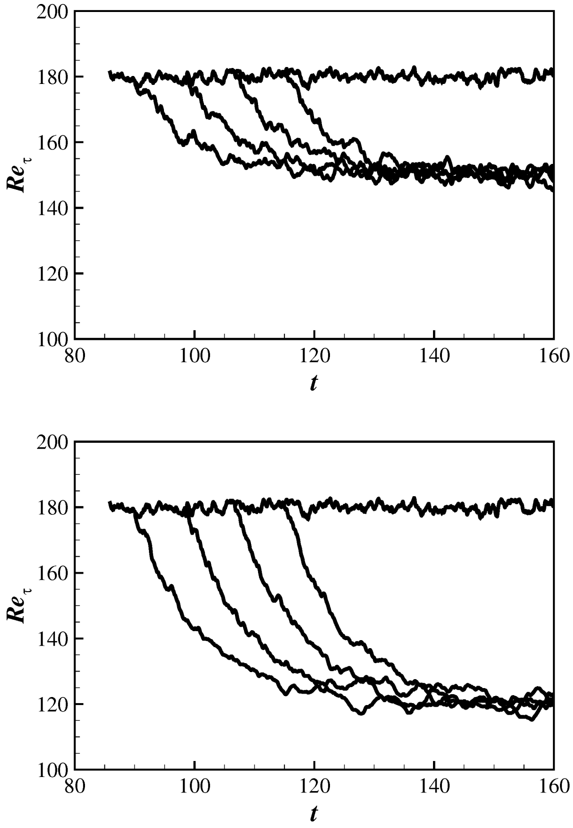

Figure 1: Time history of Reynolds number Re_τ. a) $Re_\tau = 150$ and b) $Re_\tau = 120$.

A spatial or temporal relaxation occurs depending on the nature of the disturbance. For example, when boundary conditions are changed as the flow goes downstream, a spatial relaxation follows. On the other hand, if boundary conditions are changed in time, a temporal relaxation accompanies. Most works have focused on the *spatial* relaxation, and extensive reviews are found in Smits and Wood (1985) and Bushnell and McGinley (1989). In contrast, the temporal relaxation associated with a sudden change has received less interest and the relaxation process is not fully understood yet. There are only a few studies on the temporal relaxation. Maruyama *et al.* (1976) studied transient turbulent pipe. With a stepwise increase in the flow rate, they found that the dominant feature was the generation and propagation of a new turbulence. Moin *et al.* (1990) performed a DNS for a fully developed channel flow subjected to a spanwise pressure gradient. Strained three-dimensional wall-bounded turbulence was investigated

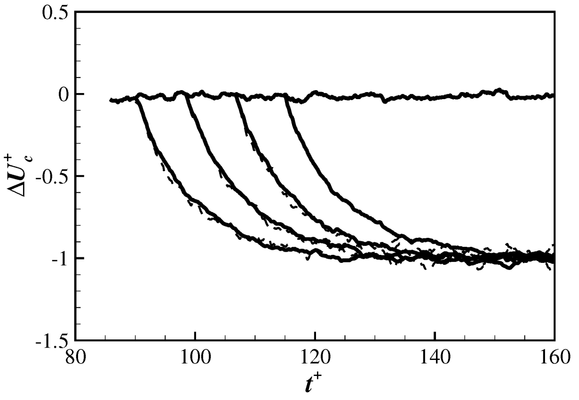

Figure 2: Time history of the centreline velocity U_c^+. Solid lines represent $Re_\tau = 120$ cases and dashed lines indicate $Re_\tau = 150$ cases.

by Coleman *et al.* (1996, 2000) and Le *et al.* (2000).

URANS are extensively being used in unsteady turbulent flow simulations (Wilcox, 1998). Scotti and Piomelli (2001, 2002) 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 different characteristics from the equilibrium state. Recently, Yorke and Coleman (2004) applied turbulence models to an idealised adverse pressure gradient flow.

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 (2002), Chung and Sung (2003) and Chung (2004b). Four turbulence models are tested in this study: the S-A model, the $k-\varepsilon$ model, the $k-\omega$ model, the Baldwin-Lomax model.

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 (1993) is used. A low storage, third-order Runge-Kutta method is used for time integration for the nonlinear convective terms, and a second-order Crank-Nicholson method for the viscous terms. The fractional-step method developed by Kim and Moin (1985) 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.

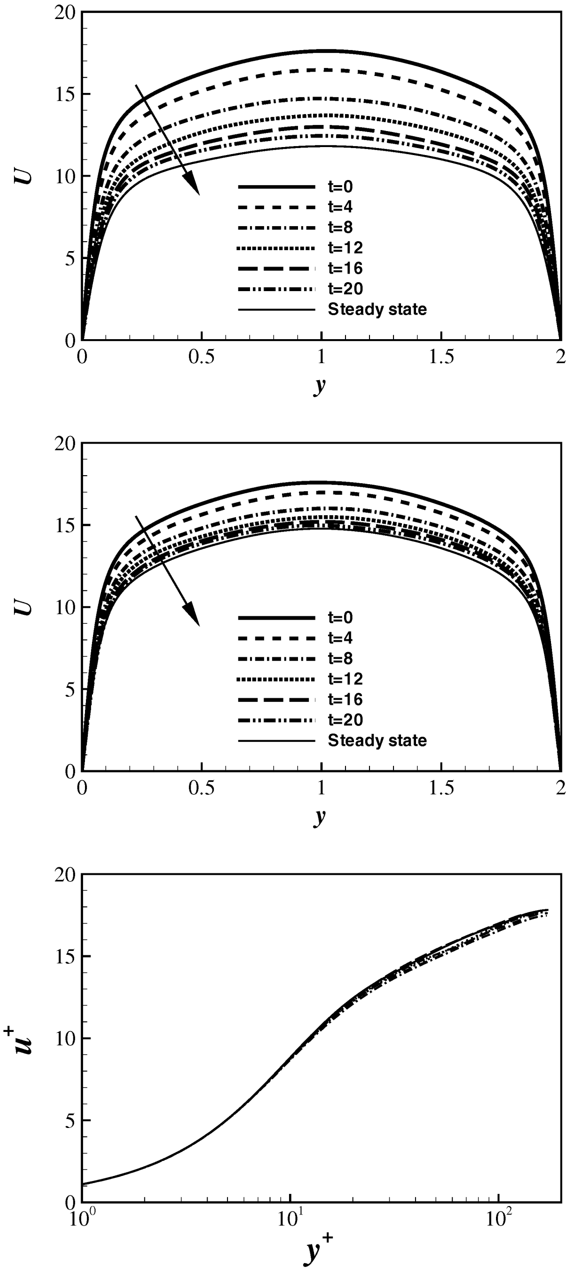

Figure 3: Streamwise velocity at several time instants.

The flow is assumed to be periodic in the streamwise and spanwise directions. For spatial discretisation, the second-order central differences are used. All flow variables are nondimensionalised by the friction velocity in the unperturbed channel, u_τ and the channel half-width h. The Reynolds number is defined as $Re = u_\tau h/\nu$, where ν 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.

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.* (1987). 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

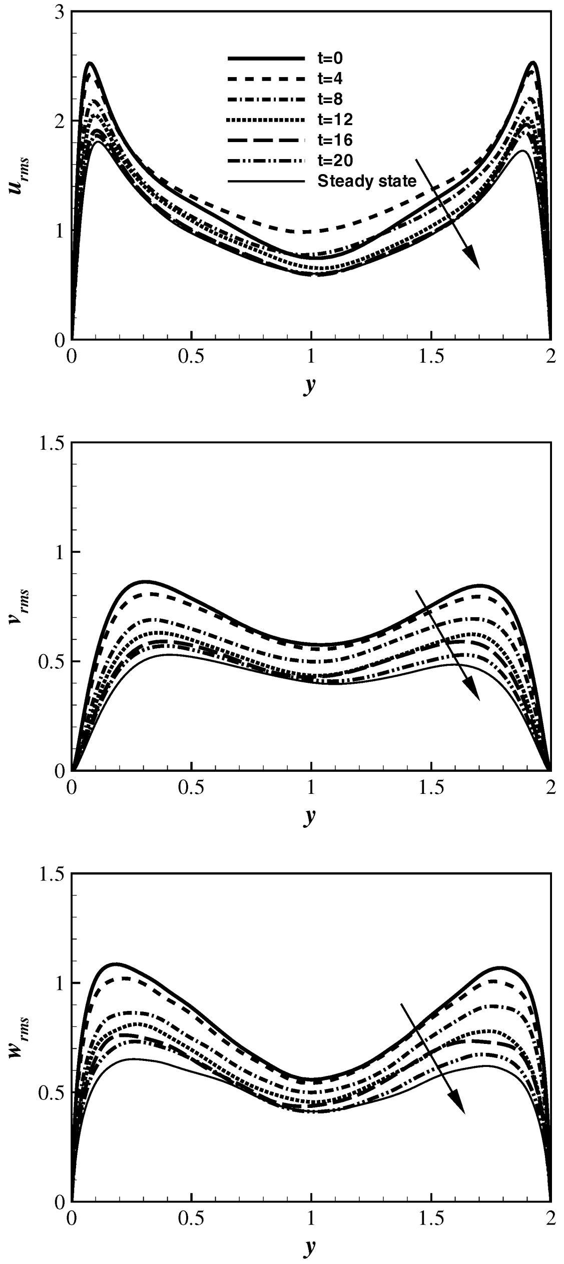

Figure 4: Turbulence intensities at several time instants.

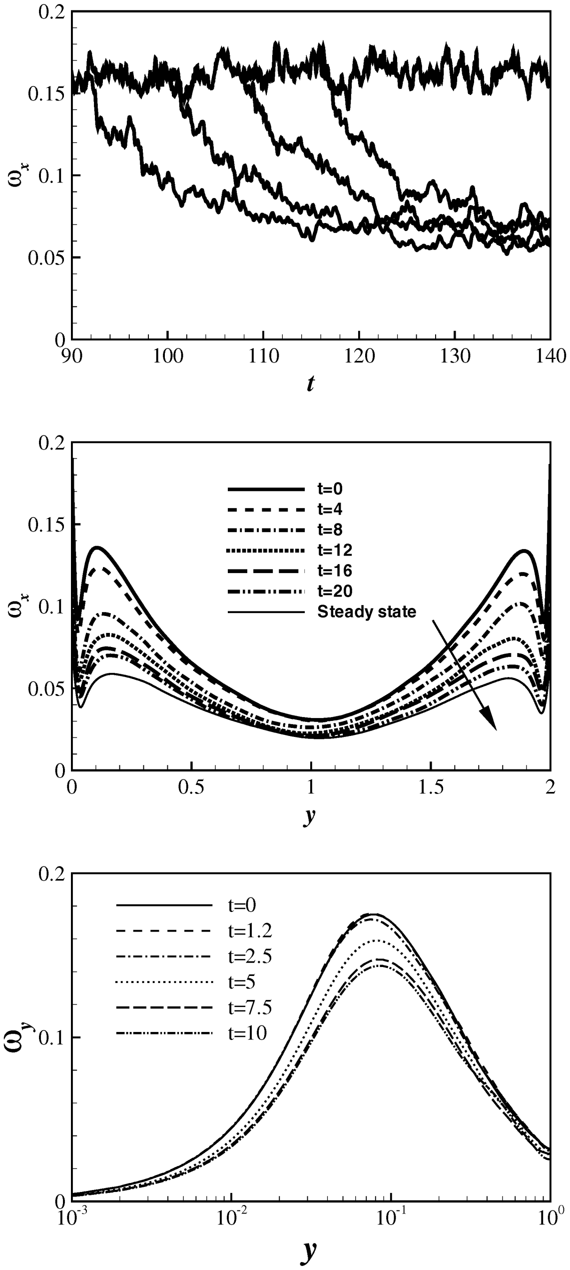

Figure 5: ω_x profiles at several time instants.

gradient is $\partial P/\partial x = -\tau_w/\delta$, 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 ($A = 4/9$ and $25/36$), 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 (2004) and Chung (2004a)

Figure 1 shows the time history of the friction velocity u_τ and centre-line 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 (2003). The acceleration (or deceleration) rate (dU/dt) during the early relaxation depends on the magnitude A. It is clearly seen in Fig. 1(b), where the relaxation of the centre-line velocity is plotted. When normalised, the $Re_\tau = 120$ and 150 cases show a similar trend during the relaxation. The value A appears to play an important role in the early fast relaxation, while the

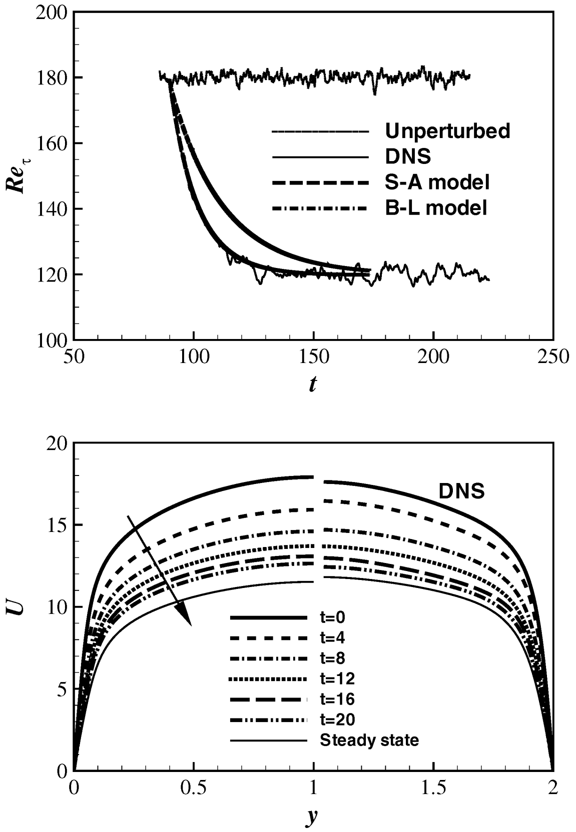

Figure 6: Time history of the friction velocity u_τ^+ and the centreline velocity U_c^+. Solid lines represent $Re_\tau = 120$ cases and dashed lines indicate $Re_\tau = 150$ cases.

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 Fig. 3, 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 change. Since mean results have been obtained by averaging over four realisations, 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 Figs. 4 and 5. 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_{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, $-\overline{uv}\frac{\partial U}{\partial y}$. In contrast, v_{rms} and w_{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,

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

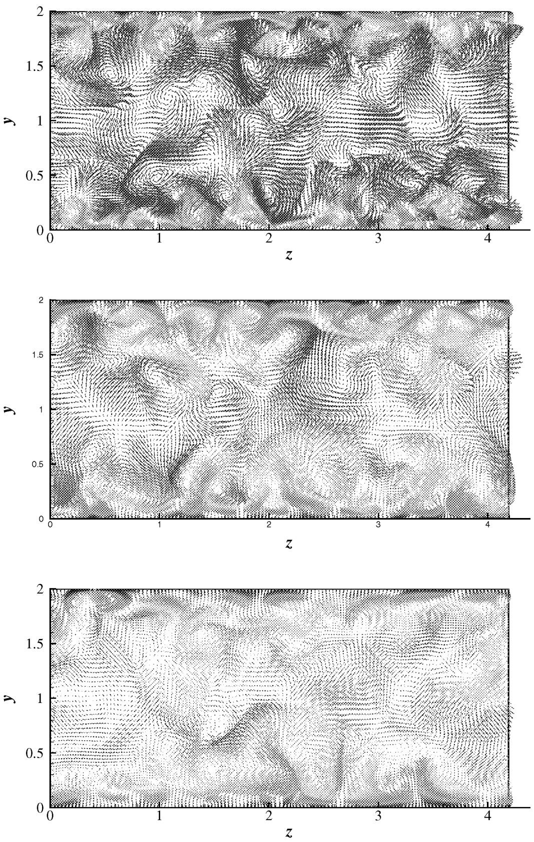

Figure 7: Velocity vector plots in $y - z$ plane. top) unperturbed flow, middle) mild deceleration, and bottom) strong deceleration.

The delayed response of turbulence to a sudden pressure change is also observed for ω_x in Fig. 5, indicating that the (strength of the) low-speed streaks are not affected immediately by the pressure gradient change. Four turbulence models are tested and results are shown in Fig. 6. The S-A, $k - \varepsilon$ and $k - \omega$ models give reasonable results in the near wall region, while the Baldwin-Lomax model is not suitable for unsteady flow calculations. The time-mean velocity profile predicted by the S-A model shows fairly good agreement with the DNS data.

Figure 7 shows instantaneous vector plots. It is clearly seen that the near-wall layer becomes thicker as the flow rate decreases. The spacings between streamwise vortices also increase. Figures 8 and 9 show contour plots of instantaneous velocities at $y - z$ and $x - y$ planes, respectively.

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

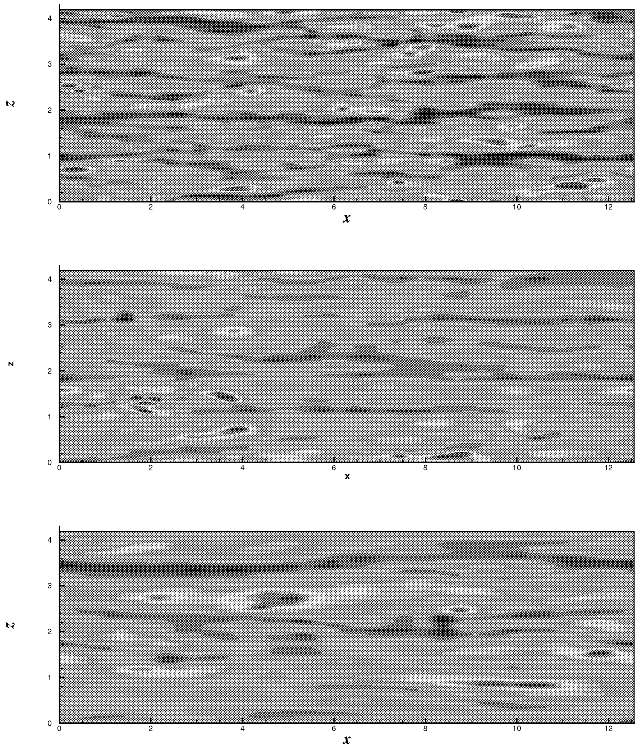

Figure 8: Turbulent flow structures in $x - z$ plane. top) unperturbed flow, middle) mild deceleration, and bottom) strong deceleration.

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

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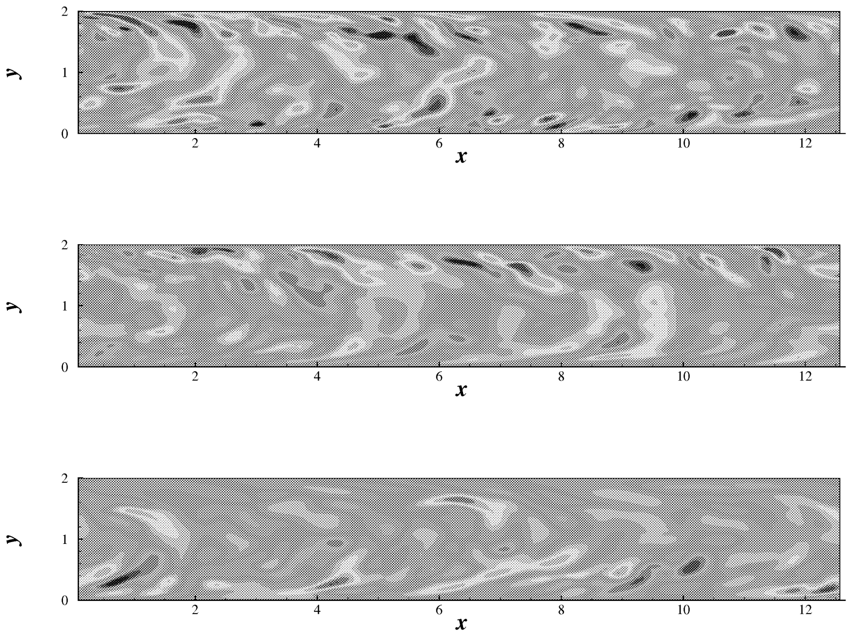

Figure 9: Turbulent flow structures in $x - y$ plane. top) unperturbed flow, middle) mild deceleration, and bottom) strong deceleration.

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