TURBULENT STRUCTURES IN UNSTEADY WALL-BOUNDED FLOW SUBJECT TO TEMPORAL ACCELERATION

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Abstract Direct numerical simulations (DNS) of a transient turbulent channel flow subject to constant temporal acceleration have been performed with a final Reynolds number of $Re_\tau \approx 800$. The response of turbulent structures to the temporal acceleration is investigated. A significant delay in the response of turbulent flow is observed in various turbulent properties. It is found that the response of turbulent flow to temporal acceleration consists of two stages: the destruction of the initial *old* turbulence, followed by the generation of *new* turbulence associated with a higher Re number. The *new* turbulence is much stronger than the *old* turbulence.

keywords: turbulent structure; temporal acceleration; DNS; channel/pipe flow; turbulent flow simulation

INTRODUCTION

Wall-bounded turbulent flows ($e.g.$, pipe flow, channel flow and boundary layer flow) are encountered in many engineering applications such as combustion engines, turbo-machinery, and blood in large arteries. These flows are frequently subjected to temporal acceleration, deceleration, and sudden pressure gradient change, changing the characteristics of turbulent flow significantly. However, the underlying physics of unsteady wall-bounded turbulent flow subject to temporal acceleration is yet to be fully understood. To investigate the response of turbulence to temporal acceleration, direct numerical simulations are performed for a turbulent channel flow accelerating linearly from $Re = 3500$ to $Re = 15\,000$ based on the bulk mean velocity and half channel height, using an in-house DNS code [2].

RESULTS

During acceleration, the wall shear stress shows a distinctive four-stage development as shown in Figure 1: (1) the initial transient stage with the wall shear stress overshooting the corresponding steady values, (2) the weak transient stage with the wall shear stress much lower than the steady values, (3) the strong transient stage with the wall shear stress increasing rapidly towards the steady values, and (4) the pseudo-steady stage. The first three stages were observed in this DNS. A similar response of the wall shear stress was also observed in low-Reynolds-number DNS study of transient channel flow [4], as well as in LES [3] and experimental study of transient pipe flows.

Streamwise vortices are the main flow structures of near-wall turbulent flow in equilibrium. The size of these structures scales with the Reynolds number, and becomes smaller at high Re number. When the turbulent flow is subjected to temporal acceleration, turbulent structures no longer scale with Re. As shown in Figure 2, the response to temporal acceleration of turbulent flow consists of two stages: the destruction of the initial turbulence, followed by the generation of *new* turbulence associated with a higher Re number. During the initial transient stage, the near-wall turbulent structures remain largely unchanged in terms of both strength and size, accompanied by the elongation of low-speed streaks. Then, turbulent structures become weakened with temporal acceleration, and gradually disappear from a large area (Figure 2b). As the Reynolds number increases, more than half of the channel wall is devoid of active turbulent structures before the generation of new turbulence takes place (Figure 2c). The remaining *old* turbulent structures at this Re number have a much weaker strength than in the equilibrium steady flow. During the strong transient stage of acceleration, *new* turbulent structures with smaller size and stronger strength are generated in the near-wall region. In the later stage of acceleration, the sizes of the structures become even smaller and these strong structures gradually occupy the whole near-wall region of the channel, as shown in Figure 2(d). Note that in Figure 3, the strength of the *new* turbulence (red) is more than 10 times larger than the initial *old* turbulence (blue).

The study of this type of flow is very challenging because the *old* and *new* turbulent structures have different sizes and strengths whilst they coexist. The interaction between the old and new turbulent structures is still not fully understood, and therefore, is the topic of further study. The characteristics of the *old* and *new* turbulent structures will be studied using a high quality turbulent channel flow DNS database. The area for active new turbulence will also be measured.

References

[1] R. B. Dean and P. Bradshaw. Measurements of interacting turbulent shear layers in a duct. *Journal of Fluid Mechanics*, **78**:641–676, 1976.

[2] E. Hurst, Q. Yang, and Y. M. Chung. The effect of Reynolds number on turbulent drag reduction by streamwise travelling waves. *Journal of Fluid Mechanics*, **759**:28–55, 2014.

[3] S. Y. Jung and Y. M. Chung. Large-eddy simulations of accelerated turbulent flow in a circular pipe. *International Journal of Heat and Fluid Flow*, **33**:1–8, 2012.

[4] M. Seddighi, S. He, A. E. Vardy, and P. Orlandi. Direct numerical simulation of an accelerating channel flow. *Flow, Turbulence and Combustion*, **92**:473–502, 2013.

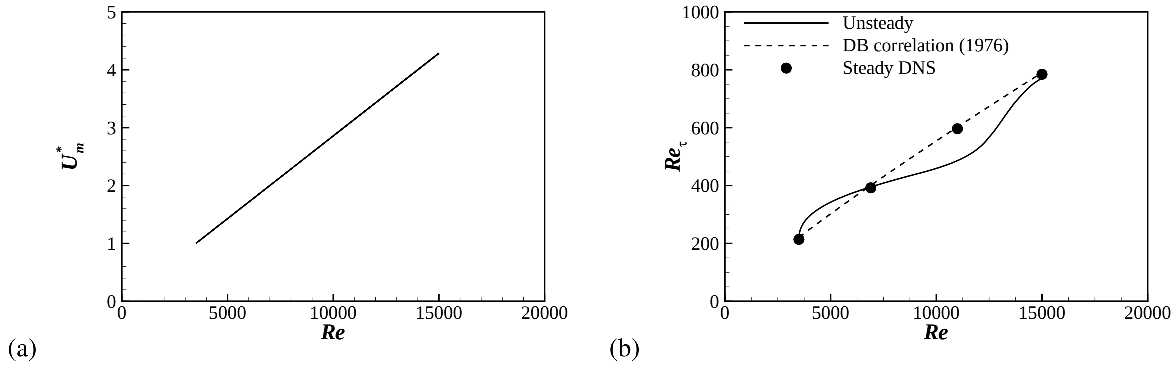
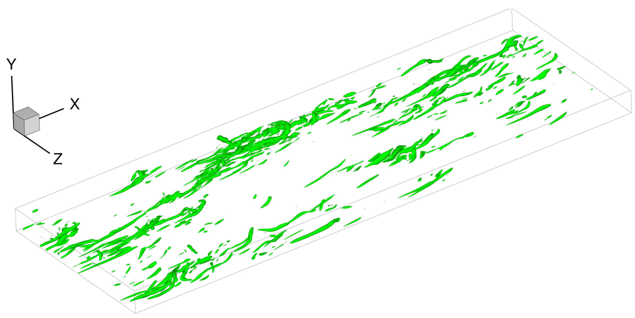
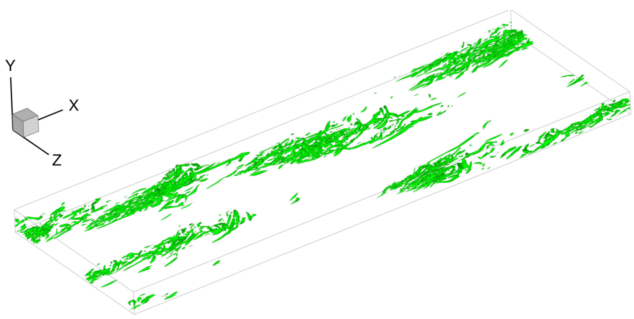


Figure 1. (a) Time history of bulk mean velocity during the acceleration. (b) Development of mean wall shear stress during the acceleration. Steady DNS data and experimental correlation of Dean and Bradshaw [1] are included for comparison.

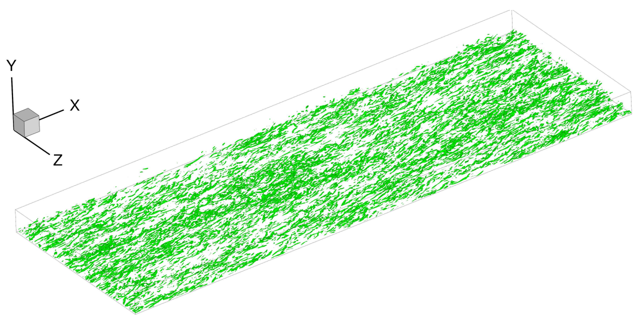
(a) $Re = 3500$



(b) $Re = 9000$



(c) $Re = 11\,000$



(d) $Re = 15\,000$

Figure 2. λ_2 structures in the near-wall region at different stages during the temporal acceleration.

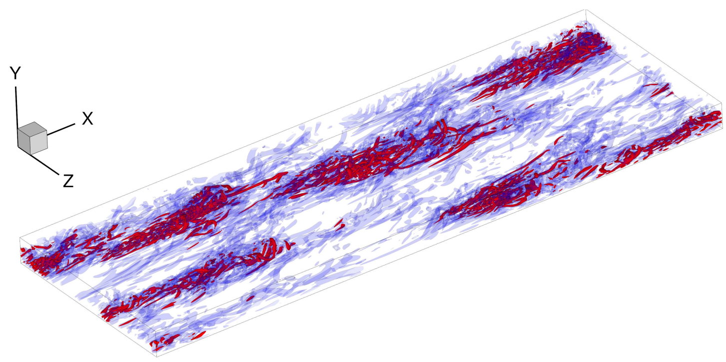


Figure 3. λ_2 structures in the near-wall region at $Re = 11\,000$ during the acceleration. New turbulence in red; old turbulence in blue.