TURBULENCE AND CYCLIC BURSTS IN ROTATING CHANNEL FLOW

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Abstract DNS have been performed of turbulent channel flow with spanwise rotation and bulk Reynolds number Re up to 30000. At moderate rotation rates Ro the flow on one side of the channel is approximately laminar, or has turbulent patches or oblique turbulent-laminar patterns. Intense cyclic bursts of turbulence with long time intervals are in some cases observed at sufficiently high Re and Ro. A linear analysis indicates that the turbulence bursts are initiated by a linear instability of plane waves aligned with the rotation axis. This linear instability can develop even if parts of the flow are strongly turbulent.

SETUP OF THE DNS

Spanwise rotation has an intricate effect on plane channel flows, e.g. laminar channel flow is unaffected by the induced Coriolis force, in contrast to turbulent channel flow. At low to moderate rotation rates Ro Reynolds stresses are augmented on the so-called unstable side and damped on the other so-called stable side in turbulent channel flow, which leads to asymmetric mean velocity profiles [1, 2]. Recent work has shown that at higher Ro the flow partly or completely relaminarizes [3].

However, previous work was limited to either low Re or Ro although Re effects are significant. We therefore study rotating channel flow at significantly higher Re. DNS have been performed of fully developed turbulent channel flow at $Re = U_b h/\nu = 3000$ up to 30000 and a wide range of $Ro = 2\Omega/U_b$, where U_b is the bulk velocity, h the channel half width and Ω the rotation rate. The domain size was $8\pi h \times 2h \times 3\pi h$ or larger in all cases and the governing equations were solved with a pseudo-spectral code.

RESULTS

The asymmetric mean velocity profile develops a large region where the mean gradient $\mathrm{d}U/\mathrm{d}y = 2\Omega$, as in previous DNS at lower Re [2, 3], implying that this is a universal feature independent of Re. In the DNS at $Re = 20000$ and $Ro = 0.45$ the damping by rotation is so strong that the flow partly relaminarizes and distinct oblique turbulent-laminar patterns emerge on the stable side while the flow on the unstable is still fully turbulent, see figure 1. Similar oblique turbulent-laminar patterns have also been observed in other wall-bounded flows with and without rotation [4]. As Re is lowered but Ro is kept constant, the turbulence pattern shrinks and becomes a spot and ultimately completely disappears, showing that Re effects are indeed significant.

Reynolds stresses weaken and the laminar region grows when Ro raises. However, the flow becomes highly unsteady in some DNS due to intense cyclic bursts of turbulence. These cyclic bursts can be seen, for instance, in time series of the wall shear stress and velocity fluctuations in a DNS at $Re = 20000$ and $Ro = 1.2$, see figure 2. Note that the time interval between the bursts is $O(1000h/U_b)$ and thus much longer than any turbulence time scale. Figure 3 shows the conditions, i.e. Re and Ro, when cyclic bursts of turbulence can be seen in our DNS. Roughly speaking, we observe bursts if both Re and Ro are sufficiently large, and if the computational domain is large enough to support the instabilities leading to the bursts. The latter condition is always fulfilled in our DNS.

Prior to the violent bursts, we see large plane waves aligned with the rotation axis forming on the stable side of the channel, which at very large Ro extend all the way to the unstable side. Figure 4 shows an example of such a plane wave in one of the DNS. To obtain insights into the development of plane waves and bursts we have carried out a linear stability analysis of the flow. Using the mean velocity profile of the DNS, this analysis shows that some plane spanwise waves, often called Tollmien-Schlichting (TS) waves, are linearly unstable and grow exponentially. These TS waves correspond well to the exponentially growing 2D waves observed in the DNS, indicating that the cyclic bursts are initiated by a linear instability. Curiously, this linear instability occurs in some cases in a flow that is vigorously turbulent in a part of the domain, see e.g. figure 4. Note that spanwise rotation only affects streamwise and oblique modes; the TS waves are not directly affected by rotation, only indirectly through the modification of the mean velocity profile.

A secondary instability develops due to 3D disturbances when the TS wave amplitude becomes large. In some cases we observe then the formation of classical Λ-shaped vortices. The TS waves subsequently break down into intense small-scale turbulence. This turbulence decays because of the rotation and after a while, when the turbulence is sufficiently weak, the TS waves start growing again and the whole process repeats itself, leading to the cyclic bursts.

In some cases the growth rate of the TS waves in the DNS agrees reasonably well to results of the linear stability analysis while in other cases the growth rate is much lower in the DNS or the waves and bursts are not seen in the DNS although the TS waves are linearly unstable according to the analysis. Visualizations show in the latter cases relatively slow oblique or streamwise waves in the flow, which apparently damp or suppress the TS waves through non-linear interactions. The next step is to further examine the correspondence between the linear stability analysis and DNS for different Re and Ro.

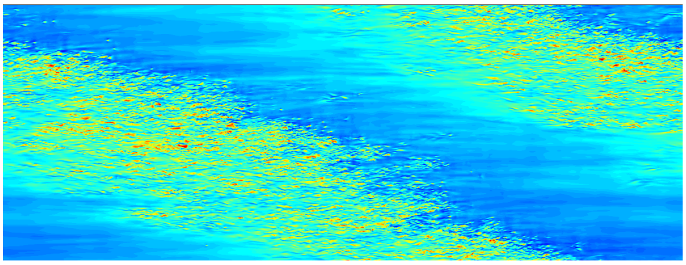

Figure 1. Instantaneous streamwise velocity in a wall-parallel plane on the stable side at $Re = 20000$ and $Ro = 0.45$.

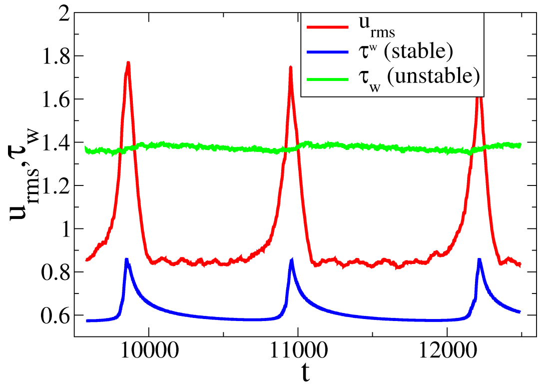

Figure 2. Time series of the wall shear stresses and rms of the streamwise velocity fluctuations at $Re = 20000$ and $Ro = 1.2$.

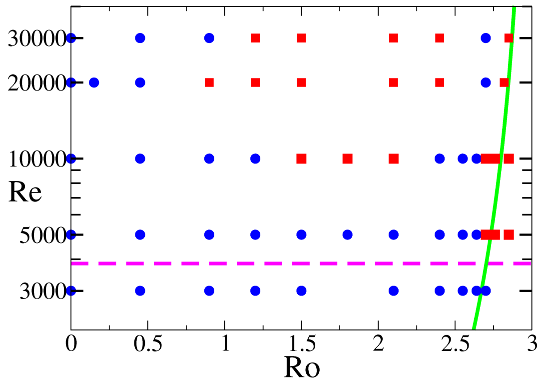

Figure 3. Conditions when cyclic instabilities (red squares) and when no instabilities are observed (blue circles).

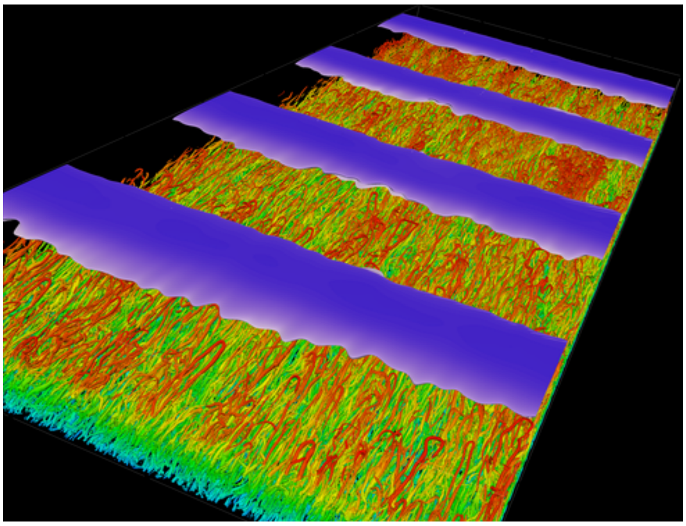

Figure 4. Visualisation of the turbulence on the unstable (bottom) side and a developing instability on the stable (top) side of a channel flow at $Re_b = 20000$ and $Ro_b = 1.2$.

References

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