ENERGY GROWTH IN TRANSIENT CHANNEL FLOW

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Abstract We have recently shown that the nature of turbulence response of a transient channel flow starting from a steady turbulent flow resembles the boundary layer laminar-turbulent bypass transition [1]. In the proposed paper, we will study the effect of the initial Reynolds number on the transition process, focusing on energy growth.

INTRODUCTION

We have recently conducted a direct numerical simulation (DNS) study of a transient channel flow following a sudden increase of flow rate of an initially turbulent flow to investigate the response of turbulence [1]. In that paper, we have shown that a low-Reynolds-number turbulent flow can undergo a process of transition that resembles the laminar-turbulent transition. In response to the rapid increase of flow rate, the flow does not progressively evolve from the initial turbulent structure to a new one, but undergoes a process involving three distinct phases (pre-transition, transition and fully turbulent) that are equivalent to the three regions of the boundary layer bypass transition, namely, the buffeted laminar flow, the intermittent flow and the fully turbulent flow regions. This transient channel flow represents an alternative bypass transition scenario to the free-stream turbulence (FST) induced transition, whereby the initial flow serving as the disturbances is a low-Reynolds-number turbulent wall shear flow with pre-existing streaky structures. A thin boundary layer of high strain rate is formed adjacent to the wall following the rapid increase of flow rate, which grows into the core of the flow with time providing the main reasons for further changes of the flow. The pre-existing turbulent structures act as background perturbations to this boundary layer, much like the role the free stream turbulence plays in a bypass transition. These turbulent structures are modulated by the time-developing boundary layer and stretched to produce elongated streaks of high and low streamwise velocities, which remain stable in the pre-transitional period. At this stage, the axial fluctuating velocity increases steadily but the other two components remain effectively unchanged. In the transitional phase, localised turbulent spots are being generated which are distributed randomly in space. Such turbulent spots grow longitudinally as well as in the spanwise direction, merging with each other and eventually occupying the entire wall surfaces when the transition completes and the flow becomes fully turbulent.

In the study reported in [1], only one case was considered, whereby the initial and the final Reynolds numbers ($Re_b = U_b\delta/\nu$, where U_b is the bulk velocity of the flow and δ the channel half-height) were 2800 and 7400 respectively. The ramp period was very short (t*=0.22) and the flow variation can be viewed as a step change ($t^* = t/(\delta/U_{b1})$, where U_{b1} is the bulk velocity of the final flow at $Re_b = 7400$). In the proposed paper, we will report further studies on the effect of the initial Reynolds numbers on the characteristics of the response of turbulence, in particular focusing on the energy growth. The initial Re is increased to 3500, 4200 and 5200 respectively in the additional cases keeping the final Re and ramp rate the same.

METHODOLOGY

The simulations are performed using an "in-house" DNS code. A second order finite difference method is used to discretize the spatial derivatives of the governing equations on a rectangular grid. An explicit Runge-Kutta together with an implicit Crank-Nicholson scheme are incorporated into the fractional-step method. The Poisson equation for the pressure is solved by an efficient 2-D FFT. The equations are solved in a domain of 18(H/2), H, 5(H/2), with a mesh of (1024×240×480) in the streamwise (x), normal (y), and spanwise (z) directions, respectively. The Message-Passing Interface (MPI) is used to parallelize the code which is validated for steady channel flow results.

RESULTS AND DISCUSSION

For any simulation, the flow starts from an initially fully developed steady turbulent flow and is increased rapidly to reach the final Reynolds number (within ~t*=0.2) and the simulation then continues until a new steady flow is approached. Fig 1 shows three-dimensional iso-surface plots of u'/U_{b1}= ±0.12 and λ_2= -0.5 in (a) pre-transitional phase, (b) early stage of transition and (c) fully turbulent phases for the case Re_{b0}= 2800. In the pre-transitional stage, iso-surfaces of u'/U_{b1}= ±0.12 form long tubes which appear alternately, clearly showing elongated streaks identified in boundary layer bypass transitions. These iso-surface tubes break up alongside the generation turbulent spots as transition progresses. Hairpin vortical structures are clearly identifiable through the iso-surface of λ_2. There are fewer such structures in the early pre-transitional stage but many start to appear from the late pre-transition and transition stages. The vortices often occur around the low-speed streaks accompanying their breakup, which is similar to those shown in boundary layer transition.

Figs 2 to 3 show the friction coefficient (c_f) in the various cases versus non-dimensional times t^* and $t^{+0} = tU_{\tau 0}^2/\nu$ respectively. Focusing on case Re=2800 in Fig 2 first, it can be seen that c_f increases rapidly following the commencement of the excursion due to the inertia resulting from the rapid flow acceleration, but decreases quickly until about t_{b1}=25 where it reaches a minimum, after which it increases quickly to around the final steady value. Comparing with the flow visualisation, it is clear that the timing of the minimum c_f coincides with the onset of the transition and the decrease of c_f before this time follows closely the Blasius solution for laminar boundary layer. The period of the pre-transitional phase reduces with the increase of the initial Reynolds number (Fig 2). However when the data is plotted against t^{+0}, the onset of transition always occurs at ~ 100. It is clear (also in figures below) that the transitional process is largely dependent on the initial flow and less dependent on the final one (results not presented here).

An important concept of transient flow transition is that it responds to a time-developing boundary layer. Fig 4 shows that the momentum-thickness Reynolds number correlates closely with t^{+0} for three cases. But c_f of the highest Re shows a very different feature, potentially indicating a different transition mechanism which will be investigated closely. Fig 5 shows that the starting turbulence intensity increases with Re_0 but around the point of transition, the energy of 'disturbances' reach a similar level of ~15%. Fig 6 shows the time-developing boundary layer based on 0.99%U_{centre} (solid/blue horizontal lines) and momentum displacement thickness (dashed/black horizontal lines), superimposed with (a) the mean velocity (U), (b) r.m.s. of streamwise velocity (u') and (c) r.m.s. of wall-normal velocity (v'). These show the development of (a) the time-developing boundary layer in terms of U profile, (b) energy growth of u' in pre-transitional period and (c) the profile of v', which remains largely unchanged for t^{+0}<100.

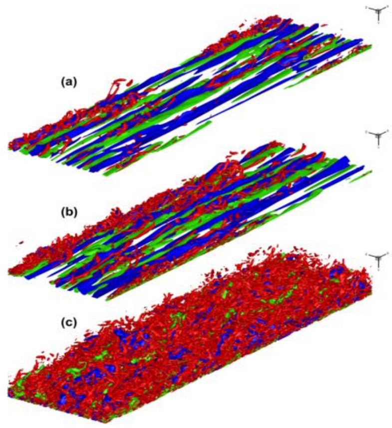

Figure 1 Flow structures in 3D iso-surface plots (Green: u'=+0.12; Blue: u'=-0.12; λ_2=-0.5)

References

[1] S. He and M. Seddighi (2012) Turbulence in transient channel flow, *Journal of Fluid Mechanics*, accepted for publication.

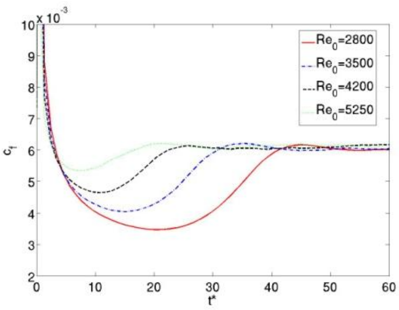

Figure 2 Effect of initial Reynolds number

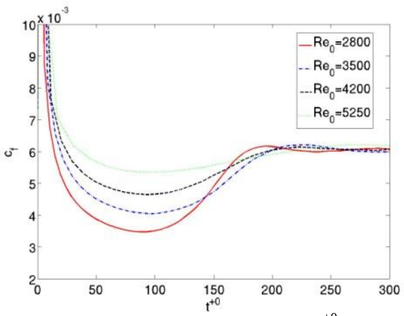

Figure 3 Friction factor versus t^{+0}

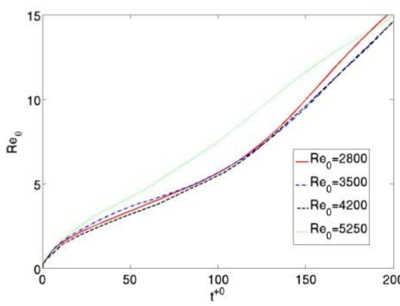

Figure 4 Momentum displacement Re

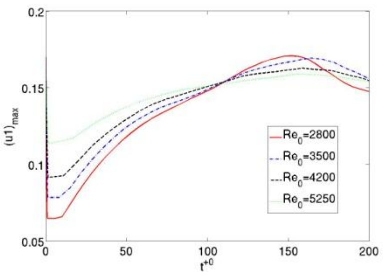

Figure 5 Energy growth in the various cases

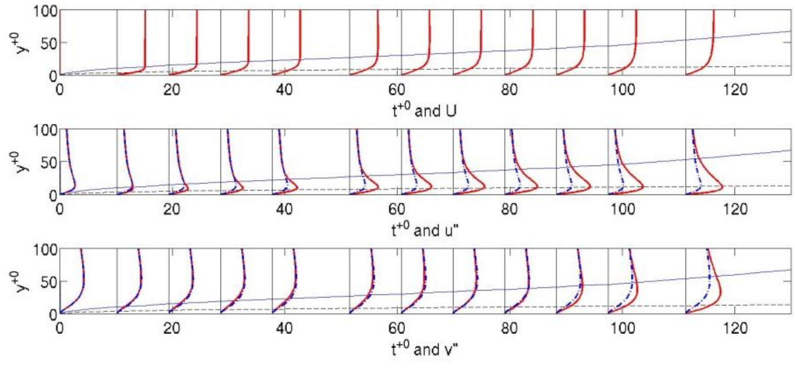

Figure 6 Time developing boundary layer & energy growth (red: instantaneous; blue: initial)