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Transition of transient turbulent channel flow

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Abstract

The paper reports a series of DNS, LES and experimental studies of unsteady flows following a sudden increase in flow rate from an initial turbulent flow in a channel with smooth or rough surfaces and shows that the transient flow is laminar-turbulent transition even though the initial flow is turbulent.

Keywords: Transition; Transient Channel Flow; DNS; LES

1. Introduction

Direct numerical simulation (DNS) of a transient channel flow following an increase of flow rate of an initially turbulent flow has previously been conducted by the present authors to investigate the response of turbulence [1,2,3]. It has been shown that transient flow undergoes a process of laminar-turbulent transition even though the initial flow is turbulent, and the process resembles boundary layer bypass 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 turbulence) 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 a bypass transition scenario alternative to the free-stream turbulence (FST) induced transition, whereby the initial flow serving as the disturbances is a 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

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reasons for further changes of the flow. The pre-existing turbulent structures act as background disturbances to this boundary layer, much like the role that 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 this paper, we discuss some recent work aimed at expanding the ideas of [1,2,3] to study (i) the effect of high Reynolds number ratios using LES and (ii) transient flows over rough surfaces using DNS. (iii) We also show some laboratory evidence measured by PIV and LDV supporting the findings of the numerical studies.

![Fig. 1. (a) Variation of flow rate in a transient channel flow. (b) Variation of friction coefficient with time in LES_Re2825_25000](image)

2. Numerical methods

Direct numerical simulations (DNS) and large eddy simulations (LES) of transient turbulent channel flow are performed using an “in-house” code based on a second order central finite difference method [1,2,5]. An explicit, third-order Runge–Kutta scheme and a second order implicit Crank–Nicholson scheme are used for the nonlinear and the viscous terms, respectively. These are combined with the fractional-step method to enforce the continuity. The Poisson equation is solved using FFT. The Wall Adaptive Local Eddy-Viscosity (WALE) model is used for LES. Additionally, the code is capable of simulating rough surfaces using an immersed boundary method (IBM).

The computational domain is a rectangular box. A periodic boundary condition is applied to the streamwise and spanwise directions, and no-slip boundary condition is used for the top and bottom walls. A transient flow is started from a fully developed stationary flow, and is accelerated rapidly and linearly to the final Reynolds number, after which it is run at a constant mass flow until the flow becomes fully developed again. Ensemble-averaged turbulence statistics are obtained by averaging over the stream and span-wise directions and also over several repeated runs.

3. Large eddy simulations

LES of transient turbulent channel flows has been carried out to extend the Reynolds number range that was covered by [3]. Figs. 1(a&b) show the variation of the flow and the response of the friction coefficient (\(C_f\)). Fig 2 shows the contours of the fluctuating streamwise velocity at a horizontal plane \(y^{+} = 5\) for a particular run. It can be seen that before \(t^* \sim 60\) (\(t^* = t/\bar{U}_b/\sqrt{\nu}\)), where \(\bar{U}_b\) is the bulk velocity of the final flow), elongated streaks of positive and negative fluctuating velocities are formed. Isolated turbulent spots are generated at around \(t^* = 60\). Such spots grow and merge with each other. By around \(t^* = 100\), the entire surface is covered by new turbulence. The above process is very similar to that of the bypass transition of spatially developing boundary layer induced by free stream turbulence (FST). Fig 1(b) shows separately the time variations of the friction coefficient for four separated runs (each starting from a different steady flow field) and also that on the top and bottom walls. According to [1], the minimum \(C_f\) approximately corresponds to the time when turbulent spots are first generated, referred to as the critical time (or critical Reynolds number). The time when \(C_f\) reaches its peak is referred to as the end of the transition and the difference between the two times is known as the period of transition. It is clear that the transition
time can be significantly different from run to run. It can also be very different on the top and bottom walls. The spread of transitional Reynolds number is higher for a higher final Reynolds number.

![Contours of streamwise fluctuating velocity to show streaks and turbulent spots (LES_Re2825_25000).](image)

Fig. 2 Contours of streamwise fluctuating velocity to show streaks and turbulent spots (LES_Re2825_25000).

![Time-development of profiles of r.m.s. of fluctuating velocities in Case LES1 (Re=2825-35000).](image)

Fig. 3. Time-development of profiles of r.m.s. of fluctuating velocities in Case LES1 (Re=2825-35000).

![Dependency of critical Reynolds number on FST.](image)

Fig. 4 (a) Dependency of critical Reynolds number on FST. (b) Correlation between period of transition and critical Reynolds number.

Fig. 3 shows the development of the profiles of the r.m.s. of fluctuating velocities in LES_2825_35000 (the initial and final Reynolds numbers are 2825 & 35000 where $Re = U\bar{b}/\nu$ and $\delta$ is channel half-height). For this case, the critical time and completion time are approximately $t^* = 80$ and 100 respectively according to $c_f$ and flow visualization. It can be seen from the figure that $u'$ increases progressively in the wall region soon after the perturbation of the flow and maintains this trend to the onset of transition. The other two components however remain largely unchanged during this period (in fact, reduces slightly). During the transition period (approximately, $80 < t^* < 110$), $u'$ increases further and interestingly, resulting in two peaks: one very close to the wall and one further away from it. The former is formed rapidly during the transitional period, increasing from very low initial values. The latter is only slightly higher than that at the point of onset of transition and is slightly further away from the wall. Similar trend was observed in the experiment of [4]. At the end of transition ($t^* \approx 110$), $u'$ reduces and approaching its steady flow value. During the transitional period, $v'$ and $w'$ increase rapidly and monotonically to a peaks, showing no overshooting or double peaks. At the point of completion of transition, the turbulence in the core is still very low, but increases gradually with time, firstly in the wall region then the centre.

It was shown in [3] that the critical Reynolds number ($Re_{t,cr}$) and the free-stream turbulence ($Tu_0$) is related via $Re_{t,cr} = 1.34 \times 10^3 Tu_0^{-1.71}$, where $Re_{t,cr} = \tau_{cr} U_{b1}/\nu$, $Tu_0 = (u'_{rms1})_{max}/U_{b1}$, $U_{b1}$ is the bulk velocity of the final flow and $(u'_{rms1})_{max}$ is the peak r.m.s. velocity of the initial flow. The results of the various LES runs are shown together with the above in Fig 4(a). Note that the highest Reynolds number in [3] was 12600. It can be seen that the
data start to deviate from the correlation when the FST is lower than 0.02. It is also noted that the values of the critical Reynolds number may be quite different for different runs of the same case. Fig 4(b) shows the correlation of the period of transition in form of Reynolds number ($\Delta Re_{cr}$) with the critical Reynolds number. The data are reasonably well represented by $\Delta Re_{cr} = 16.43 \times Re_{cr}^{0.781}$.

Fig. 5 Contours of streamwise fluctuating velocity ($u'$) in EXPT_Re2900_7925

4. Experiments

Experiments have been carried out to demonstrate the transition phenomenon established in DNS and LES simulations. The flow is driven by gravity and the flow rate is altered by a computer controlled, pneumatically driven valve. The cross section of the test section is 50mm x 350mm and the developing length is 7m. Measurements of the velocity and turbulence statistics were carried out using PIV and LDV.

Fig 5 shows the contours of the streamwise fluctuating velocity at a horizontal plane at $y^+ = 5$ in Case EXPT_Re2900_7925. Strong elongated streaks are clearly present at the early stages of the flow transient and breakdown to turbulence is seen at $t=4.57s$. Fig 6 shows the correlation of the critical Reynolds number with $u_{e0}/U_{p1}$, which is closely related to FST. It can be seen that the data can be closely represented by a power law expression. However, for the same $Tu_0$, the critical Reynolds number in the experiments is higher than in DNS. A significant reason is that the acceleration period in experiments is much longer than in the DNS/LES. The former is in the order of a couple of seconds whereas it is at the order of 10’s of milliseconds in DNS/LES.

Fig. 6 Dependence of critical Re on FST – DNS & experiments

Fig 7 Flow channel with a rough wall

Fig 8 (a) Vortical structures ($\lambda_2$) coloured by wall-distance. (b) Vortical structures ($\lambda_2$) and streaks ($u'$-contours, positive: green & negative: blue)
5. DNS of transient channel flow with a rough wall

DNS has been carried out for a channel with the bottom wall replaced by a rough surface made of closely packed pyramids as shown in Fig 7. It can be seen from Fig 8 that soon after the commencement of the transient, a vortical structure is formed along the ridge of each of the roughness elements ($t^* = 0.12$), which later splits into a standing vertex and a hairpin vortex ($t^* = 0.35$). In this section, $t^* = t / (\delta / U_{c_0})$, where $U_{c_0}$ is the centreline velocity of laminar Poiseuille flow at $t = 0$. The former remains largely stationary and inactive, whereas the latter is advected downstream, moves away from the wall with time and eventually breaks down. Additionally, at an early time ($t^* = 0.35$), high speed streaks are formed running through the entire domain length. At $t^* = 0.58$, long low speed streaks are also formed which sit below the primary hairpin vortices. The streaks break up while vortices break. The above observation shows that a transient channel flow with a rough wall is basically a roughness induced turbulent transition, characterized by a single cycle of birth, growth and breakup of primary vortices (see [5] for details). Fig 9 shows that the variation of the friction coefficient on the smooth wall of this case agrees closely with that in a fully smooth wall channel and in particular, the transition is not influenced by the opposite rough wall. The friction coefficient on the rough wall never reduces below the final steady value since the transition is completed early (before $t^* = 5$) when the effect of the flow acceleration is still strong. Fig 10 shows that turbulent shear stress over the rough wall increases rapidly at the early stage of the transient, significantly overshooting its steady values. This is due to the early vortical activities. At around $t^* = 5$, the near-wall distribution of turbulent shear stress assumes the steady flow profile but it takes some time before the early response propagates into the center of the channel.

6. Conclusions

DNS, LES and experimental studies have shown that the transient process following an increase of Reynolds number of an initially turbulent flow is effectively a laminar-turbulent bypass transition. The critical Reynolds number can be correlated with the free-stream turbulence intensity. When the surface of the wall is made of distributed roughness elements, the transition is induced by these roughness elements, which occurs much faster than over a smooth wall. The transition over the smooth wall is however not influenced by the opposite rough wall.

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