Influence of a k-type Roughness on the Behaviour of Turbulence in an Unsteady Channel Flow

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Abstract. Direct Numerical Simulations (DNS) have been carried out for a spatially fully developed turbulent channel flow with one smooth wall and one k-type rough-wall surface to study the influence of a square bar roughness on the behaviour of unsteady turbulent flow. The flow state under investigation is a uniform acceleration from an initially steady turbulent flow. Results are compared with simulations of flows in a smooth wall channel undergoing a similar acceleration, and with quasi-steady behaviour obtained using steady flow simulations. The turbulence in the wall region and the buffer layer of an accelerating flow with a rough wall shows strikingly different behaviour from that of corresponding flows with smooth walls. The characteristic long delays in the response of the streamwise turbulent velocity and the different behaviours of the three turbulent velocity components that are exhibited in smooth wall flows are not seen in the rough wall flow. This is attributed to different turbulent production mechanisms in the two types of flows. Important differences are also seen in the wall shear stress responses one wall is rough and when both walls are smooth.
1. Introduction

Unsteady flow is frequently encountered in engineering applications as well as natural systems. Studies of the detailed behaviour of turbulence in time dependent flows can assist in improving general understanding of turbulence and can have potential importance in practical engineering applications. There have been considerable experimental and computational studies on periodic channel / pipe flows. Useful reviews of the diverse literature on the subject are given in (Brereton and Mankbadi 1995; Gundogdu and Carprilioglu 1999). Flows over hydraulically smooth walls are predominant in the studies of the periodic turbulent flows; whereas, real surfaces in engineering applications are often rough. The effects of surface roughness have been a subject in fluid studies for many years. Extensive studies have been conducted theoretically, experimentally, and numerically in the subject and can be found in many papers. Examples of such studies in periodic flows include (Bhaganagar 2008; Fornarelli and Vittori 2009; Keiller and Sleath 1976; Krsitc and Fernando 2001; Sleath 1970; Sleath 1987; Sleath 1988; Vittori 2003). However, the use of DNS as a tool for studying rough-wall channel flows has a short history of less than one decade.

In contrast to pulsating flows, there are far fewer studies on non-periodic pipe/channel flow. Nevertheless some detailed studies have been conducted, most of which are experimental, but some are computational. Examples include: Ariyaratne et al. 2010; Chung 2005; Greenblatt and Moss 1999; Greenblatt and Moss 2004; He et al. 2008; He and Jackson 2000; Khaleghi et al. 2010; Seddighi et al. 2011.

To the authors’ knowledge, there have been no previous studies of non-periodic, unsteady flows over rough wall surfaces. Such studies are important because turbulent flows close to the rough surface can exhibit big differences from those close to a smooth wall. Unfortunately, neither experimental studies nor theoretical studies based on conventional computational fluid dynamics (CFD) can give sufficiently accurate, detailed information about unsteady turbulent flow behaviour close to solid surfaces.

The purpose of the present paper is to report a computational study of flow accelerating over a rough surface. DNS has been carried out for a spatially fully developed turbulent flow in a 2D channel with a smooth top surface and a rib-roughed bottom surface to study the influence of a k-type square bar roughness on the behaviour of unsteady turbulent flow. The flow is accelerated uniformly from an initially steady turbulent flow. A similar simulation of accelerating flow in a smooth-wall channel is presented to facilitate direct comparisons.

2. Numerical approach

The DNS is performed using an “in-house” code (Seddighi, He, Orlandi, & Vardy 2011). The governing equations are written in a dimensionless form normalized using the channel half height \((H/2)\) as the length scale, \(U_c\) (centreline Poiseuille velocity) as the velocity scale, and \(\rho U_c^2\) as the pressure scale:

\[
\frac{\partial u_i}{\partial t} + u_j \frac{\partial u_i}{\partial x_j} = - \frac{\partial p}{\partial x_i} + \frac{1}{Re_c} \frac{\partial^2 u_i}{\partial x_j \partial x_j} + \Pi
\]

(1)

Conservation of mass:

\[
\frac{\partial u_i}{\partial x_i} = 0
\]

(2)

The pressure gradient is split into two components, namely \(\Pi\) and \(-\partial p / \partial x_j\). The former is a spatially-uniform time-mean component of the streamwise pressure gradient required to balance (i) quasi-steady components of resistance due to friction and form drag (i.e. the values that would be needed to maintain a constant mass flow rate) and (ii), in the case of an accelerating flow, an
additional inertial force. The component $-\partial p / \partial x_i$ is a fluctuating component that varies both spatially and with time.

A second order central finite difference method is used to discretize the spatial derivatives of the governing equations on a rectangular grid, where a three-dimensional staggered mesh is employed with a non-uniform spacing in the direction normal to the wall. For the time advancement, a low storage third-order Runge-Kutta scheme is used for the non-linear terms and a second order Crank-Nicholson scheme is used for the viscous terms, which are combined with a fractional-step method described by (Kim and Moin 1985; Orlandi 2001). The Poisson equation for the pressure is solved by an efficient 2-D FFT (Orlandi 2001). The equations are solved in a domain of $(4H, H, \pi H/2)$, where $H$ is the channel height, with a mesh of $(640 \times 240 \times 240)$ in the streamwise ($x$), normal ($y$), and spanwise ($z$) directions respectively. The roughness is treated using an immersed boundary method (IBM) described in detail by Orlandi et al. (Fadlun et al. 2000; Leonardi et al. 2003; Leonardi et al. 2006; Leonardi et al. 2007; Leonardi and Orlandi 2003). The Message-Passing Interface (MPI) is used to parallelize the code for use on a distributed-memory computer cluster.

3. Results and discussion

Simulations have been performed for an accelerating flow in a 2D channel, (i) with smooth walls at the top and bottom and (ii) with a smooth wall at the top and a rough wall at the bottom, as shown in Figure 1. Herein they are referred to as the smooth-wall case and the rough-wall case respectively. Steady flows at several Reynolds numbers have also been conducted for both surface conditions. For the rough-wall, a $k$-type transverse square bar roughness ($H/h=10$, $h=k$ and $s/h=7$, see Fig 1) is used. For the unsteady flow simulations, the flow starts from an initially fully developed steady turbulent flow at $Re_b = 2333$ and the mass flow rate is increased uniformly to $Re_b = 7595$ (Figure 2), where $Re_b$ is based on the bulk velocity ($U_b$) and the channel half height ($H/2$).

For each case, five simulations (each starts from an independent initial steady flow) have been performed to facilitate the calculations of turbulence statistics based on ensemble averaging. Statistics presented are based on spatial averages in the span and stream directions, and also over five repeated runs. Results obtained from five runs are reasonably converged. The smooth-wall flow is discussed in detail in (Seddighi et al. 2009; Seddighi et al. 2010) and the focus of this paper is on the rough-wall flow, although some smooth-wall results are presented for comparison.

Figure 3 shows a comparison of the developments of the turbulent velocity fluctuations at several locations in the all-smooth wall and smooth-rough wall simulations. The quantities are normalised using the bulk velocity at the start of the excursion (that is a constant during the excursion) so that the
actual variations with time can be studied.

![Figure 2: Prescribed velocity history for the accelerating flows.](image)

The behaviour of the flow in a smooth-wall channel is discussed in detail elsewhere (Seddighi, He, Vardy & Orlandi 2009), but a brief summary is given here to facilitate comparison. It can be seen from Fig 3(a), (c) & (e) that all three turbulent velocities show a clear delay everywhere in the flow in responding to the acceleration of the mean flow, although the detailed behaviour is different at different locations and for different components. The $u'_1$ responds first at around $y = 0.1$ ($y^+ \sim 15$ for the smooth-wall case), and the response then progressively spreads to the core (and also to the wall). The $u'_2$ and $u'_3$ show much greater delays in the wall/buffer regions where they appear to respond simultaneously - without diffusion in wall-normal direction. The timing of the response in the core is similar to that of $u'_1$. These behaviours are reflections of the inherent turbulence characteristics of shear flows over a smooth wall. In such flows, turbulence is produced directly only through shearing in the stream direction and this is then redistributed into the other two directions through pressure-strain interactions. Spatially, turbulence is generated mostly in the buffer layer and is transmitted into other regions through molecular diffusion and turbulent mixing.

The behaviour of the turbulent velocities in the rough-wall flow contrasts strongly with the behaviour outlined above for the smooth wall flow. The responses of $u'_1$ and $u'_2$ in the wall and the ‘buffer’ layer ($y < 0.1$) show no obvious delays and that of $u'_3$ shows only a very small delay. In the core, the three velocities behave similarly, exhibiting similar, but progressively longer delays with increasing distance from the wall. The delays are shorter than those in the smooth wall flow at corresponding locations.

Useful conclusions can be drawn from comparisons of the predictions for the smooth- and rough-wall cases:
Figure 3: Development of velocity fluctuations; left: smooth-wall case; right: rough-wall case.
There is effectively no delay in turbulence production near the rough wall. Unlike the flow over a smooth wall where turbulence is produced by shearing, the main mechanisms of turbulence production over the rough wall considered herein are flow separation, and vortices in the wakes caused by the roughness. The turbulence is directly proportional to the velocity magnitude rather than its gradient. In an unsteady flow, the velocity tends to increase simultaneously across the channel/pipe up to the wall, resulting in an almost immediate increase in turbulence production.

There is effectively no delay between the response of \( u_1' \) and that of \( u_2' \) & \( u_3' \). The significant delay between \( u_1' \) and \( u_2' \) & \( u_3' \) responses over a smooth wall is associated with the time scale of the response of pressure-strain activities which redistribute turbulent energy from \( u_1' \) to \( u_2' \) & \( u_3' \). Over a rough surface, the flow over the roughness elements is highly three dimensional and turbulence is produced directly in all three directions. The redistribution between the three components is much less important under such a condition. The predicted small delay in the response of \( u_3' \) may be a consequence of the two dimensional nature of the particular roughness type (ribs) considered.

The propagation of the responses of all turbulence components in the core region of the flow over a rough surface is similar to that over a smooth one. The faster response in the rough-wall case seems likely to be associated with the higher turbulence in this flow.

The wall shear stress is an important parameter in applications. For a rough wall, it can be interpreted in several ways. In this paper, the (effective) wall shear stress is defined as the total flow force divided by the nominal surface area of the wall over which the force acts on. Here the flow force is the sum of the drag and frictional force and the nominal area is the area of the corresponding smooth surface in the absence of the rough elements. The location of the ‘wall’ is deemed to be at the root of the roughness.

Figure 4 shows variations of the wall shear stress in the all-smooth-wall flow \( (\tau_s^*) \) and in the flow with one smooth wall and one rough wall \( (\tau_{sr}^* \) and \( \tau_{rr}^* \)). The trend of the variation of \( \tau_{sr}^* \) is the same as that of \( \tau_s^* \) except that it shows a slightly faster response. The shear stress in the unsteady flow overshoots the quasi-steady curve briefly before falling below it and remaining below for a relatively long period during which the difference increases. At a later stage, the shear stress increases rapidly and approaches quasi-steady values. In contrast, the wall shear stress on the rough wall \( (\tau_{rr}^*) \) exhibits a stronger overshoot which persists for a longer period. Probably, it never falls below the steady values (although more steady runs are needed to confirm this trend, which is inferred from a visual extrapolation of the limited steady flow data).

![Figure 4: Predicted wall shear stress histories.](Image)
For the smooth-wall case, the initial overshooting is known to be caused by a rapid increase of velocity gradient very close to the wall at the commencement of the excursion. Also, the subsequent undershooting is a result of a delayed response of turbulence (He, Ariyaratne, & Vardy 2008).

For the rough-wall case, the wall shear stress on the rough wall is dominated by drag forces. These are directly proportional to the velocity near the wall which tends to overshoot the quasi-steady values at the early stage of the excursion. This is so called inertia effect which is also the reason of the overshooting of wall shear on the smooth wall. A second reason is the presence of the inertial component of the pressure gradient. This component causes an Archimedes-like drag on the roughness elements. A further factor to note is that the absence of a significant delay in turbulence response near a rough wall automatically removes the cause of the undershooting of the wall shear stress that is seen on a smooth wall after the early overshoots.

4. Conclusions

Direct numerical simulations of an accelerating channel flow with a uniform increase of mass flow rate have been successfully performed for a channel with two smooth walls and for a channel with one smooth and one rough wall. The wall shear stress and the turbulence in the wall and the buffer layers in an accelerating flow in the two channels differ markedly. It has been attributed to the differences in the turbulence production mechanisms, namely (i) production due to shearing over a smooth surface and (ii) production due to flow separation and wakes caused by the roughness elements of a rough surface.

Nomenclature

| Symbol | Definition |
|--------|------------|
| H | Channel height |
| $\rho$ | Pressure normalized by $\rho U_c^2$ |
| $\frac{\partial p}{\partial x}$ | Mean pressure gradient |
| $Re = \frac{(H/2)U_c}{v}$ | Reynolds number based on $U_c$ and channel half height |
| $Re = \frac{(H/2)U_b}{v}$ | Reynolds number $U_b$ and channel half height |
| $Re = \frac{(H/2)u_r}{v}$ | Reynolds number based on $U_r$ and channel half height |
| $t^*$ | Time normalized by H/2 & $U_c$ |
| $u_{r,j} = j=0,1$ | Friction velocity for the low ($j=0$) and high ($j=1$) flow rate of the ramps |
| $u_i', i=1,2,3$ | RMS velocity fluctuations |
| $u_m$ | Local mean velocity |
| $U_b^*$ | Bulk velocity normalized by $U_c$ |
| $U_{b,j} = j=0,1$ | Bulk velocity for the low ($j=0$) and high ($j=1$) flow rate of the ramps |
| $U_{c,j} = j=0,1$ | Centreline Poiseuille velocity for the low ($j=0$) and high ($j=1$) flow rate of the ramps |
| $x, y, z$ | Streamwise, wall-normal and spanwise co-ordinates normalized by H/2 |
| $y^*$ | Wall-normal distance normalized by $u_c$ |

Special characters

| Symbol | Definition |
|--------|------------|
| $\tau^*$ | Wall shear stress normalized by $\rho U_c^2$ |
| $\rho$ | Fluid density |

Subscripts

| Symbol | Definition |
|--------|------------|
| $i=1,2,3$ | 1, streamwise; 2, wall-normal; 3, spanwise directions |


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