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Temporal and spatial intermittencies within channel flow turbulence near transition

Anubhav Kushwaha

Department of Chemical and Biological Engineering University of Wisconsin–Madison Madison, WI 53706-1691 anubhav@wisc.edu

ABSTRACT

Direct numerical simulations of a pressure driven turbulent flow are performed in a large rectangular channel. Extreme and moderate drag regimes within turbulence that have earlier been found to exist temporally in minimal channels at transitional Reynolds numbers have been observed both spatially and temporally in full-size turbulent flows. These intermittent regimes, namely, "hyperactive", "active" and "hibernating" turbulence, display very different structural and statistical features. Using conditional sampling, we identify these intermittent intervals and present the differences between them in terms of simple quantities like mean velocity, all shear stress and flow structures. By conditionally sampling of the low wall shear stress events in particular, we show that the local mean velocity in large domains occasionally approaches that of one family of the exact coherent states that are characteristic of very low drag in Newtonian minimal channel flows.

INTRODUCTION

A way of understanding the chaotic dynamics of turbulent flows is to look at the exact coherent states (ECS) of the Navier-Stokes equations. Low-drag events in Newtonian flows resemble a recently-discovered family of ECS in minimal channel by Park & Graham (2015). Similar transient behaviour at low Reynolds numbers in minimal channels has also been observed in viscoelastic flows by Xi & Graham (2012). The objective of this study is to establish whether temporal intermittency in minimal-channel Newtonian flows translates to temporal and spatial intermittencies in largedomain Newtonian flows.

An important feature of spatially extended flows in the transitional Reynolds number regime is "laminar-turbulent intermittency". Manneville (2015) provides an excellent overview of this phenomenon; the basic observation is that the transitional Reynolds number regime, at a given point in the domain the flow alternates randomly between states with weak and strong fluctuations. In pipe flows, laminar-turbulent intermittency is observed by Wygnanski & Champagne (1973); Wygnanski et al. (1975) as localised turbulent patches, known as puffs, surrounded by laminar flow upstream and downstream of it. In channel flow, elongated near-wall streaks forming stripe patterns have been observed by many researchers such as Duguet & Schlatter (2013); Lemoult et al. (2012, 2013, 2014); Hashimoto et al. (2009); Rolland (2015). These patterns are oriented obliquely relative to the main flow direction. Flow is highly turbulent near the centre region of the stripes, and around the stripes are regions of streamwise streaks that are relatively less turbulent. As the Reynolds number is increased, the fluctuation intensity in the less turbulent regions increases along both streamwise and spanwise directions, the stripiness in the flow structures start to vanish and eventually, the flow becomes uniformly turbulent, *i.e.*, any apparent large-scale structures are absent.

Michael D Graham

Department of Chemical and Biological Engineering University of Wisconsin–Madison Madison, WI 53706-1691 mdgraham@wisc.edu

FORMULATION

We consider pressure driven flow of an incompressible Newtonian fluid in a rectangular, wall-bounded domain (channel) maintained at constant mass flux. The x, y and z axes correspond to the streamwise, wall-normal and spanwise directions, respectively. No-slip boundary conditions are applied at the top and bottom walls and periodic boundary conditions are adopted in the streamwise and spanwise directions. The study focusses on results for three Reynolds numbers, Re = 1490, 1820 and 2200 (corresponding to friction Reynolds numbers, $Re_{\tau} = 70,85$ and 100, respectively). The streamwise and spanwise periods in outer units are 42.86 $l \times 11.43 l$ at $\text{Re}_{\tau} = 70$, 35.36 $l \times 9.43 l$ at $\text{Re}_{\tau} = 85$ and $30.00 l \times 8.00 l$ at Re_{τ} = 100. The half-channel height, *l*, is the characteristic length scale for nondimensionalisation of all the lengths in the geometry. The dimensions in outer units correspond to a domain size of $L_x^+ \approx 3000, L_z^+ \approx 800$ in wall units at all values of $Re_{\tau}:$ 70, 85 and 100. Here, the superscript '+' indicates normalisation with the viscous length scale, $\delta_v = v/u_\tau$, where v is the kinematic viscosity of the fluid and u_{τ} is the friction velocity. We use $(N_x, N_y, N_z) = (196, 73, 164)$ grid points for $\text{Re}_{\tau} = 70$, (160, 73, 120) grid points for $\text{Re}_{\tau} = 85$ and (160, 85, 120) grid points for $\text{Re}_{\tau} = 100$ in the streamwise, wall-normal and spanwise directions, respectively. The numerical grid spacings in streamwise and spanwise directions are $\delta_x^+ \approx 15$ and $\delta_z^+ \approx 5$, respectively, for all the cases. Nonuniform Chebyshev spacing in the wall-normal direction gives $\delta_{y,min}^+ \approx 0.07$ at the wall and $\delta_{y,max}^+ \approx 3$ at the centre of the channel. A constant time step, $\delta t = 0.02$, which satisfies the CFL stability condition, is used in all simulations. The spatial and temporal resolutions are at the same level as those reported in previous studies (e.g. Alfonsi (2011)). A convergence check was also done - spatial resolution was increased and all the quantities reported in the paper were recalculated, yielding negligible changes from the results reported here.

Figure 1 shows some instantaneous snapshots of wall shear stress fluctuations from our channel flow DNS in extended domain at friction Reynolds numbers 70, 85 and 100. The flow structures are significantly three-dimensional at all the Reynolds numbers and fluctuations can be seen throughout the domain: the intermittency observed is purely within turbulence. It is interesting to note that at $\operatorname{Re}_{\tau} = 70$, which is the lowest Re_{τ} we consider, a large-scale stucture of weak and strong turbulent fluctuations appears in the form of stripes that are oriented obliquely relative to the mean flow. Similar stripy patterns have also been observed experimentally in channel flow by Hashimoto et al. (2009) as well as in Couette flow computations (e.g. Barkley & Tuckerman (2005)). As the Reynolds number increases, the stripiness start to disappear (see Figure 1 (b) and (c)) and eventually the turbulence becomes uniform. A natural question is how closely minimal channel observations are related to the phenomenon of laminar-turbulent intermittency in the transitional Reynolds number regime for spatially extended flows.



Figure 1. Spatial patterns of instantaneous wall shear stress fluctuations in the streamwise (x)-spanwise (z) plane of a turbulent channel flow. Flow is from left to right. Red is high, blue is low.

RESULTS AND DISCUSSION

To detect and sample low and high drag events happening locally with time, we measure the instantaneous wall shear stress at a point on a wall. At the same time, we keep track of all the three velocity components at various discrete distances from the wall. Our criteria for an event is that the wall shear stress (τ_w) at the point must surpass a threshold value and it must stay on the same side of the threshold for a specified minimum time duration. Specifically, for an event to be called hibernation, the wall shear stress must fall below the specified threshold and must last for a duration $t^* > 3$, and for an event to be hyperactive, τ_w must become higher than the corresponding threshold value and, as before, must stay high for $t^* > 3$. Here, $t^* = tu_{\tau}/l$, *i.e.*, time measured in units of eddy turnover times. Choosing a different value for t^* , e.g., 2.5 or 3.5 gives essentially identical results. Figure 2(a) shows many low wall shear stress events measured at $Re_{\tau} = 85$ that satisfy the criteria for hibernation. The beginning of each event shifted to $t^* = 0$, *i.e.*, $t^* = 0$ is the time when the wall shear stress falls below a threshold of 90% of the mean wall shear stress and stays below it for at least 3 eddy turnover time units. We are calling such low-drag events hibernating turbulence. The ensemble average of all the instantaneous hibernation events is shown as a thick green line. On average the wall shear stress during hibernation falls to a plateau in the time interval $0.7 \le t^* \le 2.8$ and is preceded by a sharp peak in the wall shear stress (higher than the mean, $\overline{\tau_w}$) during $-0.8 \le t^* \le 0$. These characteristics of hibernation are observed for a range of Reynolds numbers and threshold criterion. Similarly, for hyperactive intervals we select instances when the wall shear stress becomes more than 110% of the mean and remains higher than the specified threshold for $t^* > 3$ (Figure 2(b)).







Figure 2. Instantaneous (thin grey lines) and ensemble-averaged (thick green solid line) wall shear stress before, during and after the intervals of hibernation and hyperactivity at $\text{Re}_{\tau} = 85$. Here, t^* is the time measured in units of eddy turnover times.

detector function, which is a function of flow properties at the wall or in the fluid region. The detector function is lowpass-filtered and thresholded that results in demarcation of weakly and strongly turbulent areas. The sum of the absolute values of the streamwise wall shear stress and the spanwise derivative of the streamwise velocity is chosen as the detector function, *i.e.*,

$$D \equiv \left| \frac{\partial U}{\partial y} \right|_{w} + \left| \frac{\partial U}{\partial z} \right|_{y^{+}=15}$$
(1)

The filtered signal is then thresholded using Otsu's method (Otsu (1979)) — an image-processing technique used to automati-



Figure 3. Edges between high- and intermediate-drag regions (solid) and between intermediate- and low-drag regions (dashed). Flow is from left to right.

cally perform image segmentation by determining threshold(s) between distinct regions such that each region shares certain characteristics. It can also be used for multilevel thresholding; in general, the number of classes is one more than the number of thresholds. Another simple technique of conditionally partitioning data sets into distinct groups or *clusters* such that properties in the same cluster are more similar to each other than those in other clusters is k-means clustering. Even though the k-means and Otsu algorithms are different, it can be shown that they both extremise the same objective function (Liu & Yu (2009)). For a given snapshot, we find boundaries between regions of varying levels of turbulence. We emphasise that there are no explicit thresholds of either time or stress level in Otsu's method - all we specify is the number of classes we want the data at each time instant to be classified into. Otsu's method picks out the optimum threshold(s) by minimising the intra-class variance, or maximising the inter-class variance. We specify that three classes be sought - low, medium and high. The boundaries (or edges) between any two classes results in demarcation of weakly, intermediately and strongly fluctuating regions (hibernating, active and hyperactive). An example of the result of Otsu's algorithm is shown in Figure 3. The contours represent the wall shear stress patterns from an instantaneous flow-field at $\text{Re}_{\tau} = 85$. The solid black line represents the demarcation line between high-drag and intermediate-drag regions and the dashed black line separates the intermediate-drag areas from the low-drag



Figure 4. For caption see the right column.



Figure 4. (a) Unconditional (solid lines) and conditional (symbols) streamwise mean velocity profiles at $\text{Re}_{\tau} = 85$. (b) Conditionally averaged velocity profiles for low-, intermediate- and high-drag regions occurring spatially at different Reynolds numbers. (c) Mean velocity profiles of lower and upper branches ECS (shown in orange) in Newtonian flows in the minimal channel (Park & Graham (2015)). Velocity profiles numbered (i)-(iii) are instantaneous profiles in the minimal channel at time instances when the turbulent trajectory approaches the branches LB1, UB and LB2, respectively.

areas. A distinct difference between the three regions is observed — areas enclosed by solid lines show high wall shear stress and strong fluctuations whereas the areas enclosed by dashed lines are smooth, local wall shear stress values are low and the variations are small. Regions between solid and dashed lines lie in the intermediate-drag regime. The average size of the low-drag patches in the streamwise and spanwise directions, respectively, are 318×46 for Re_{τ} = 70,

 288×32 for Re_{τ} = 85 and 278×29 for Re_{τ} = 100. Clearly, the area of the region experiencing low-drag depends on the Reynolds number — as the Reynolds number is increased, the area occupied by low-drag regions decreases. In general, the occurrence of low-drag events, both temporally and spatially, decreases as Reynolds number increases (Kushwaha *et al.* (2017); Whalley *et al.* (2017)).

Conditional mean velocity profiles for hibernating and hyperactive turbulence at $\text{Re}_{\tau} = 85$ occurring both in time and in space are presented in Figure 4(a). It is observed that low-stress conditional averages from edge-detection scheme (spatial) nearly matches pointwise thresholding results (temporal) - both profiles are shifted upward of the unconditional mean profile and lie close to the lower branch ECS mean profile. Similarly, the mean velocity profiles during hyperactivity, both temporal and spatial, lie below the unconditional time-averaged profile. The hibernation profiles in a large domain Newtonian flow also lie close to the lower branch ECS profile near the wall (up to $y^+ \approx 30$) observed in a minimal channel. Figure 4(b) shows conditional mean velocity profiles for low-, intermediate- and high-drag regions at friction Reynolds numbers of 70, 85 and 100. Only a weak dependence of conditional profiles on Re_{τ} is observed. Just like the data presented in Figure 4(a) for $\text{Re}_{\tau} = 85$, all the spatially averaged profiles at different Reynolds numbers plotted in Figure 4(b) show a very good correspondence with the corresponding temporally averaged profiles; the temporally averaged profiles are not shown to avoid overcrowding. Illustrated in Figure 4(c) are the velocity profiles of one family of exact coherent states obtained by Park & Graham (2015) in the minimal channel: we have compared our low-drag results with the LB2 branch of this family. Also shown as (i), (ii) and (iii) are three instantaneous velocity profiles in the minimal channel at time instances when the turbulent trajectory approaches the branches LB1, UB and LB2, respectively.

Similar observations have also been made experimentally by Whalley *et al.* (2017). They observed intermittency of low-drag pointwise measurements of wall shear stress within Newtonian turbulent channel flow at transitional Reynolds numbers. The mean velocity profile for low-drag events is shifted upward and matches the conditional profile obtained from the DNS at same friction Reynolds number, which in turn, matches the lower branch ECS mean profile in the near-wall region ($y^+ \leq 30$).

CONCLUSIONS

Intermittent excursions towards low and high drag states, which have earlier been found to exist temporally in minimal channels, have also been observed to occur both temporally and spatially in large-domain Newtonian flows. Using conditional sampling and edge-detection techniques, we identified these transient intervals and it was found that the local near-wall properties and structures of the low drag events in particular resemble one family of the lower branch exact coherent states in the minimal domain.

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