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Scaling of the velocity profile in strongly drag reduced turbulent flows over an oscillating wall

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ABSTRACT

Scaling analysis of the velocity profiles in strongly drag reduced flows reveals that the slope of the logarithmic part depends on the amount of drag reduction (DR). Unlike DR due to polymeric fluids, the slope changes gradually and can be predicted by the analysis. Furthermore, the intercept of the profiles is found to vary linearly with the DR. Two velocity scales are utilized: the reference (undisturbed) and the actual friction velocity. The theory is based on the assumption that the near-wall linear region is only governed by the actual friction velocity, while the outer part is governed by the reference friction velocity. As a result, logarithmic part is influenced by both velocity scales and the slope of the velocity profile is directly linked to the DR. The theoretically obtained results are verified by data from six previously performed direct numerical simulations (DNSs) of boundary layers over spatial and temporal wall oscillations, with a wide range of resulting DR. The theory is further supported by data from numerous investigations (DNSs as well as experiments) of wall-bounded flows forced by various forms of oscillating wall-motion. The assumption that the outer part is unaffected by the actual friction velocity limits the validity of the proposed log-law to flows not fully adapted to the imposed wall forcing, hence the theory provides a measure of the level of adjustment. In addition, a fundamental difference in the applicability of the theory to spatially developing boundary flow and infinite channel flow is discussed.

1. Introduction

Many methods for reducing the viscous drag of turbulent flows over a wall have been proposed through the years. From a control strategy point of view, most methods are based on an open loop concept, i.e. no sensor feedback is involved. Examples include introducing polymer solution (White and Mungal, 2008; Tamano et al., 2011) or air bubbles (Elbing et al., 2013), in the case of liquid flow. For boundary layers in air, however, the most viable technique is to change the surface, either the morphology of the wall (passive control), or impose a motion of the wall or fluid (active control). One example of the former is based on riblets (García-Mayoral and Jiménez, 2011), which is a method motivated by the practicality and aims at being directly implementable. The penalty is that the drag reduction (DR) is not great, typically less than 10% for riblets. Other methods based on a dynamic manipulation of the wall which, even though not easily applicable to in a real engineering framework, have provided much greater drag reduction (Karniadakis and Choi, 2003). So far, these manipulations either consist of temporal/spatial spanwise oscillations (Quadrio, 2011) of the wall, or a morphological deformation of the surface (Nakanishi et al., 2012). Promising results have also been demonstrated by blowing and suction of fluid through the wall (Min et al., 2006).

In this paper certain aspects of the velocity profile which are detectable only at large values of DR will be discussed. In addition, the study is limited to flows where the DR is obtained via various forms of oscillating motion as the mode of wall forcing. The reason for this limitation is that methods based on altering the fluid properties, such as polymeric fluid, affects the turbulence throughout the domain, see e.g. Virk (1975), and is not limited to near-wall effects. In addition, the mechanism behind DR is much more complex due to non-Newtonian effects for these types of fluids. For the most recent theoretical development of the analysis of polymer drag reduced flow, see White et al. (2012).

A large number of DNSs and experiments of wall-bounded turbulent flows with oscillating walls exists, see e.g. Skote (2013) and references therein. However, previous studies have all focused on attempts to systematically study either energy budgets or flow structures, respectively, as means of explaining the DR mechanisms. Regarding the velocity profiles, most studies have limited themselves to observations which can be summarized in the following points:

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- Scaled with actual friction velocity:
  - the linear profile is retained,
  - the logarithmic profile is shifted upward.
- Scaled with the reference friction velocity:
  - the self-similarity in the linear region is lost,
  - the logarithmic profile is shifted slightly upward.

While most investigations have concluded this behaviour, no thorough and systematic analysis has been attempted. In the present work, the properties of the velocity profiles described above will be quantified and amended with the important feature that apart from the upward shift of the logarithmic part, also the slope is altered, when scaled with actual friction velocity. However, this behaviour is most noticeable for very high degrees of DR, and therefore DNS data from previously performed simulations of boundary layer with DR in the range of 18–46% will be used. Additional data which confirm the findings are taken from experiments by Choi and Clayton (2001) and Ricco and Wu (2004) of boundary layer flow and DNSs by Touber and Leschziner (2012) and Quadrio et al. (2009) of channel flow. The change in the slope of the logarithmic part of the velocity profile has been observed for DR generating polymeric fluids. However, the behaviour is different from the case of wall oscillation induced DR. As described by White and Mungal (2008), the log profile in the polymeric case remains parallel to the unmanipulated case until the DR reaches 40% after which the slope increases. In contrast, the slope in the case of wall oscillations is gradually increasing and is directly related to the amount of DR, which will be demonstrated in the present paper using analysis, DNS data, and experimental data.

The results presented here may be important from two points of view. First, the various groups currently working on the drag reduction techniques will be able to compare their velocity profiles with the theory provided. Second, researchers developing tools based on turbulence modelling for predicting the efficiency of various drag reduction techniques will find the theoretical aspects presented here valuable. Although such tools have recently started to emerge, see e.g. the work by Duque-Daza et al. (2012) or Moarref and Jovanović (2012), it is my hope that the findings described in this paper will speed-up the model development process.

The remaining part of the paper is structured as follows. In Section 2 the analysis of the logarithmic and inner part of the boundary layer velocity profiles is presented. The results are compared with a set of six DNSs of boundary layer flow with DR produced by temporal and spatial wall oscillations in Section 3. In Section 4 further confirmation by utilizing data from boundary layer experiments as well as DNS of channel flow at various Reynolds numbers (Re) and with different mode of DR techniques is provided. The range of applicability of the theory is discussed in Section 5 before the conclusions are summarized in Section 6.

2. Analysis

In the following, two velocity scales will be used, namely the friction velocity of the unmanipulated boundary layer (the reference case), denoted u_τ^0, and the actual friction velocity (u_τ). The friction velocity is defined as

$$u_\tau \equiv \sqrt{\nu \frac{\partial u}{\partial y}\bigg|_{y=0}}, \tag{1}$$

where ν is the kinematic viscosity.

The DR will in this paper be quantified according to:

$$\mathcal{D} = \frac{C_f^0 - C_f}{C_f^0}, \tag{2}$$

where $C_f^0 = 2(u_\tau^0/u_\infty)^2$ is the skin friction of the reference case. Hence, we may write $\mathcal{D} = 1 - r^2$, where r is the ratio between the two velocity scales, $r = u_\tau/u_\tau^0$.

The logarithmic behaviour of the turbulent boundary layer is obtained from the asymptotic matching of the velocity gradient in the inner and outer regions of the boundary layer. In the following we will utilize the knowledge that the velocity profile in the inner part is completely governed by u_τ while the wake function or velocity defect (and hence also the velocity gradient) in the outer part is completely governed by u_τ^0. The argument for the latter scaling proposition is that the outer part is not affected by the change of velocity scale near the wall where the wall manipulations generate the DR. Hence the classical theory (Clauser, 1956) of wall manipulated boundary layer flow is followed in the sense that the wake function is assumed to be unaffected. As will be shown below, the classical theory is however expanded with the permission of a change of the von Kármán coefficient (or rather, the slope of the logarithmic velocity profile). This is also the reason why the theory can only be applied to flows where the control is imposed through wall manipulation, since changing the fluid properties by polymers or by other means clearly affects the flow also far away from the wall. In the procedure below, the analytical steps demonstrated by Skote and Henningson (2002) are followed.

At this point it is necessary to define the notation for the scaling by two different velocity scales. For the vertical coordinate (y) we will use $y^+ \equiv yu_\tau/\nu$ and $y_0^+ \equiv yu_\tau^0/\nu$, while the streamwise velocity (u) is written as $u^+ \equiv u/u_\tau$ and $u_0^+ \equiv u/u_\tau^0$.

For the matching of the inner and outer equations, it is enough to observe that the velocity gradient can be written in the following form in the inner part:

$$\frac{\partial u}{\partial y} = f' u_\tau^2/\nu, \tag{3}$$

where f' is a function of a similarity variable (y^+).

In the outer part it is assumed that the velocity gradient can be written,

$$\frac{\partial u}{\partial y} = F' u_\tau^0/\Delta, \tag{4}$$

where F' is a function of a similarity variable ($\eta \equiv y/\Delta$) and Δ is the outer length scale.

The crucial step here is the use of u_τ for the inner part, and u_τ^0 for the outer part. If the assumptions (3) and (4) are valid, then the matching of the velocity gradient gives the equation,

$$f' y^+ r = F' \eta, \tag{5}$$

where r is the ratio between the two velocity scales,

$$r = \frac{u_\tau}{u_\tau^0} = \sqrt{1 - \mathcal{D}}. \tag{6}$$

Noting that the two sides of (5) depend on different variables, we set the first part equal to a constant and formulate it as,

$$y^+ \frac{du^+}{dy^+} = \frac{1}{\kappa r}. \tag{7}$$

In the reference case, $r = 1$ and Eq. (7) yields the usual logarithmic velocity profile when integrated:

$$u^+ = \frac{1}{\kappa} \ln y^+ + B_0. \tag{8}$$

with $\kappa = 0.41$ and $B_0 = 5.2$. For the case with DR, r is not equal to unity, and integrating Eq. (7) gives:

$$u^+ = \frac{1}{\kappa\sqrt{1-\mathcal{D}}} \ln y^+ + B(\mathcal{D}). \tag{9}$$