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Characteristics of distinct flow regimes in the wake of an infinite span normal thin flat plate

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ABSTRACT

The wake of an infinite, two-dimensional (2D), thin flat plate of height h was studied using Direct Numerical Simulation (DNS) for two Reynolds numbers, $Re = 1.2 \times 10^3$ and 2.4×10^3. The vortex shedding Strouhal number was 0.158. In addition to the high - and low - intensity shedding regimes (H and L) first reported by Najjar and Balachandar (1998), a distinct period of reorganization (M) is identified following regime H. The average flow characteristics for regime M are similar to those of the long-term mean flow. The regime-averaged recirculation length at $Re = 1.2 \times 10^3$ was 2.16h during H, 3.60h during L and 2.81h during M. Whereas the spanwise vortex rollers are well-organized during both regimes H and M, the arrangement of the streamwise ribs is much more regular and can be observed further downstream in regime H than M. The flow is highly three-dimensional during regime L, which includes less-coherent vortex rollers and spanwise randomly distributed ribs. The impact of this behavior on the roll-up, and thus the extension of the shear layer, is identified as a driving mechanism for generation and sustainability of the periodic wake behavior.

1. Introduction

Wake structures and vortex dynamics of simple bluff bodies, i.e. circular (Bearman, 1968; Kiya et al., 1982; Niemann and Holscher, 1990; Okamoto and Sunabashiri, 1992; Roshko, 1961; Williamson, 1996a) and rectangular (Bailey et al., 2002; Lyn et al., 1995; Wang et al., 2009) cylinders, have been the subject of several investigations. These studies have deepened our understanding of the vortex generation, interaction and diffusion processes in quasi-periodic turbulent wakes. In contrast, there have been few studies of the wake of thin sharp edge flat plates. These flows have a fixed separation point, similarly to square and rectangular cylinders, but differ in that there is no after-body on which the shear layer can reattach. The flow separation and reattachment for square cylinders, which have a mean drag coefficient of ≈ 2.3 (Lyn et al., 1995), and a moving separation point on the surface of circular cylinders, which have a mean drag coefficient of ≈ 1.2 (Bearman, 1968), imply differences in the wake dynamics from those of a flat plate, whose mean drag coefficient is ≈ 2.0 (Saffman, 1993). In contrast to circular and square cylinder cases, the flow around a flat plate has proven difficult to satisfactorily simulate using Reynolds-averaged turbulence models (Breuer et al., 2003; Hemmati, 2016). This characteristic of the thin flat plate suggests differences of the shear layer dynamics, when compared to the cylinder cases, and thus differences in the initial vortex roll-up and the subsequent vortex detachment process in the near wake.

Saha (2007) identified the onset of unsteady vortex shedding (Hopf bifurcation) in the near wake of a flat plate at a relatively low $Re = U_0 h/\nu$ of $30 - 35$ using Direct Numerical Simulation (DNS), where U_0 is the free-stream speed and ν is the kinematic viscosity. A second transition leading to a three-dimensional wake is expected to occur at the range of $Re = 1.05 \times 10^2$–1.10×10^2 (Hourigan et al., 2006; Narasimhamurthy and Andersson, 2009). According to Wu et al. (2005), the majority of studies of the wakes of thin plates had $Re \leq 250$ so that transition from laminar to turbulent occurred in the wake rather than in the separating shear layers as would be expected for higher Re. Comparison of the available experimental and computational studies by Hemmati (2016) showed that the shedding frequency, recirculation length, mean velocity profiles, and other flow variables change significantly in the range of $250 \leq Re \leq 1000$. Thus, the present simulations at $Re = 1.2 \times 10^3$, which are the main ones described here, are representative of high Re wakes.

The most comprehensive experimental studies on the turbulent wake of a thin flat plate have been limited to Fage and Johansen (1927), Kiya and Matsumura (1988), and Leder (1991). These studies are conducted at significantly higher Re. The experimental investigations on flat plates do not allow for a comprehen-

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sive characterization of the flow as they presented a limited set of data. Most of these studies have focused on mean flow parameters (indicated by an overbar where necessary for clarity) such as $St = fh/U_0$, $\overline{C}_p = \overline{P}/(1/2\rho U_0^2)$, $\overline{C}_d = \overline{D}/(1/2\rho U_0^2 h)$, etc. Here f is the vortex shedding frequency, $\overline{C}_d$ is the mean drag coefficient, $\overline{P}$ and $\overline{D}$ are the mean gauge surface pressure and the mean drag, respectively, and ρ is the air density. In these studies, the reported shedding Strouhal number (St) ranged from 0.146 to 0.168. Fage and Johansen (1927) presented mean pressure measurements, shedding frequency, and mean profiles downstream of the recirculation. Kiya and Matsumura (1988) provided the first data on the long-term mean and phase-averaged Reynolds stresses. Based on these hot-wire measurements at $8h$ downstream the plate at $Re = 2.3 \times 10^4$, Kiya and Matsumura (1988) proposed that all the conventional Reynolds stresses are due to random velocity fluctuation with a frequency lower than that of the shedding frequency, f_s. Specifically, the contributions at $f_s/2$ appear to dominate the shear stresses. However, Hemmati et al. (2015b) and Hemmati (2016) demonstrated that their results are in disagreement with other relevant studies on flat plates, due to using hotwire anemometers in highly turbulent flows, e.g. (Bradbury, 1976).

Leder (1991), using phase-locked Laser-Doppler Anemometry (LDV), showed that the maximum amplitude of phase-averaged Reynolds stresses occurred in the region directly upstream of the mean location of the saddle points marking the end of the mean recirculation region. In this study, however, the time history of the signal was not considered and no attempts were made to characterize the instantaneous wake structure or its dynamics. The length of the mean recirculation region was $2.5h$, compared to $1.65D$ (McKillop and Durst, 1986) and $1.4D$ (Lyn et al., 1995) for circular ($Re \approx 2 \times 10^4$) and square ($Re = 2.19 \times 10^4$) cylinders, respectively, where D is the cylinder diameter.

Detailed investigations of the wake dynamics have been considered in numerical simulations but at very low Re compared to the experimental studies. Numerical simulations at appropriate Re are necessary to obtain additional important information on the three-dimensional and time-dependent forces on the plate and their relation to the structure of the vortex shedding and development. Numerical studies on thin flat plates were by Najjar (1994), Joshi (1994), Najjar and Vanka (1995b), Najjar and Balachandar (1998), Narasimhamurthy and Andersson (2009), Afgan et al. (2013) and Hemmati et al. (2015b). Most computational studies have been limited to either 2D simulation or low Re cases in the range of 3.0×10^1–1.0×10^3, mainly due to the high demand on computational resource to adequately resolve these complex flows at high Re. Hemmati et al. (2015b) discussed some of the important discrepancies observed in the literature and distinguish between the influence of the numerical implementation (especially the prescription for the boundary conditions) and Reynolds number effects.

Najjar and Vanka (1995b) and Najjar and Vanka (1995a) demonstrated that dynamics of streamwise and spanwise vortices play a dominant role in the wake of a thin flat plate. Najjar and Vanka (1995a) performed the first three dimensional (3D) study on the wake unsteadiness behind a flat plate using DNS at $Re = 10^3$. The wake unsteady characteristics were described in terms of a low-frequency signature coupled with 3D effects observed in the wake. According to Najjar and Balachandar (1998), the low-frequency signature is as low as one tenth of the nominal vortex shedding frequency. A link between generation and distortion of spanwise vortex “rollers” and streamwise vortex “ribs” was also suggested as a source for the low-frequency behavior, as a consequence of the three dimensional effects.

Najjar and Balachandar (1998) performed a more quantitative evaluation of this phenomenon by looking at behavior of the plate forces and relating them to the coherent wake structures, i.e. spanwise vortex “rollers” and streamwise vortex “ribs”. They identified two distinct flow regimes (H and L) based on a qualitative observation of the unsteady forces. The low-frequency signature was also identified from the spectra of instantaneous forces by Hemmati et al. (2015b) and Hemmati (2016). Instances of high and low drag, coupled with large and small fluctuations of lift, were observed in the long-term flow results of Najjar and Balachandar (1998) at $Re = 2.5 \times 10^2$ and Hemmati et al. (2015b) at $Re = 1.2 \times 10^3$. These illustrate a relationship between wake structure interactions, causing variations in the pressure and vorticity fields, and the identified low-frequency regimes. However, an objective criterion for defining these regimes and quantitative description of their characteristics is still missing.

Many aspects of the vortex interaction phenomenon and non-linearity of the wake remain unknown. Narasimhamurthy and Andersson (2009) reported the only numerically obtained Reynolds stresses at $Re = 7.5 \times 10^2$ using DNS. However, this Re is lower than the threshold of 10^3 identified by Wu et al. (2005) and Hemmati et al. (2015b), below which there are strong Re-effects in the results. These effects may help explain the disagreement between the Reynolds stresses reported by Narasimhamurthy and Andersson (2009) and those from other experimental and numerical studies.

In this DNS study, the wake structures, the resultant transient turbulent regimes, and their effect on the plate forces are investigated. The goal is to characterize the wake dynamics for different regimes identified previously by Najjar and Balachandar (1998) and Wu et al. (2005). The Reynolds stresses and mean flow variables are discussed in relation to the wake dynamics. This study is a base-case for investigating the wake of finite aspect ratio plates with applications in solar panel installations, fluid-structure interaction, etc. The next section describes the numerical details, followed by the Results. Section 5 contains the discussion and the main conclusions are given in Section 6.

2. Problem description

The 3D incompressible Navier–Stokes equations were solved using DNS. All quantities are normalized using the plate height, h, and the freestream velocity, U_0. Simulations were conducted at $Re = U_0 h/\nu = 1.2 \times 10^3$ (DNS 1) and 2.4×10^3 (DNS 2). The governing equations,

$$\frac{\partial u_i}{\partial x_i} = 0 \tag{1}$$

$$\frac{\partial u_i}{\partial t} + u_j \frac{\partial u_i}{\partial x_j} = -\frac{1}{\rho}\frac{\partial p}{\partial x_i} + \nu \frac{\partial^2 u_i}{\partial x_j x_j}, \tag{2}$$

where $\{i, j\} = 1, 2, 3$, u is the velocity, t is the time, ρ is the air density, ν is the air kinematic viscosity, and x is the spatial coordinate identifier, were solved using the second-order central-difference method for spatial discretization in all directions (x: streamwise, y: chordwise and z: spanwise) and second-order backward Euler method for temporal discretization. An iterative SIP (Strongly Implicit Procedure) was used to solve the Poisson equation. Further detail on the numerical schemes and the base solver can be found in Hemmati (2016).

The computational domain shown in Fig. 1 was chosen on the basis of Rodi et al. (1997), Najjar (1994), Joshi (1994), Najjar and Vanka (1995a), Najjar and Balachandar (1998), and Narasimhamurthy and Andersson (2009), and its suitability verified by Hemmati (2016). The domain extends from $-5h$ upstream to $20h$ downstream the plate in the streamwise (x) direction. The domain in the chordwise (y) direction extends from $-8h$ to $8h$ with the plate positioned symmetrically relative to the top and bottom