International Journal of Heat and Fluid Flow 61 (2016) 197–212

Contents lists available at ScienceDirect

International Journal of Heat and Fluid Flow

journal homepage: www.elsevier.com/locate/ijhff

# Effect of side-edge vortices and secondary induced flow on the wake of normal thin flat plates

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ARTICLE INFO

*Article history:*
Available online 29 June 2016

*Keywords:*
Thin normal flat plate
Direct numerical simulation
Finite aspect ratio
Turbulence
Shear layer
Wake dynamics
Cyclic wake

ABSTRACT

The wake of a normal thin flat plate of aspect ratio 3.2 was studied in comparison to that of an infinite span (2D) plate at Reynolds number of 1200 (based on the common dimension of the two plates) using Direct Numerical Simulations. The presence of side-edge shear layers suppressed the spanwise instabilities responsible for the three distinct flow regimes in the wake of 2D plates. There was a vortex “peeling” mechanism that detached the vortices in the shear layers on the shorter sides. It increased the Strouhal number to 0.317 from 0.158 for 2D plates. It is also associated with increased entrainment of freestream fluid and a reduction in the mean recirculation length by 40% to 1.6*h*. Moreover, the peeling mechanism led to formation of interlocked vortex loops outside the base region. The maximum turbulence kinetic energy along the wake centreline for the 3D case was 76% lower than for the 2D flow. Vortex detachment was constrained to the plate sharp corners in contrast to the most common example of thin flat bodies (circular flat disks). This difference lead to a relatively higher vortex shedding frequency for flat plates. The *side-edge vortices* are associated with a secondary induced flow behind the plate, which formed two interlocked vortex loops and resulted in formation of separating vortex streets in the wake (*wake split*). Two opposing *in-wash* flows (in the chordwise direction) were observed accompanied by a similar system of *out-wash* flows (normal to the plate chord), which increased the freestream fluid entrainment. The *in-wash* flow contracted the wake in the plane of the chord. The *out-wash* flow expanded the wake in the spanwise direction and resulted in two counter-rotating vortex streets.

## 1. Introduction

The flow topology and vortex dynamics in the wake of circular cylinders (Bearman, 1968; Kiya et al., 1982; Niemann and Holscher, 1990; Okamoto and Sunabashiri, 1992; Roshko, 1961; Williamson, 1996), rectangular cylinders (Bailey et al., 2002; Lyn et al., 1995; Wang et al., 2009), and flat disks (Berger et al., 1990; Cannon et al., 1993; Fuchs et al., 1979; Huang and Tsai, 2001; Lee and Bearman, 1992; Marshall and Stanton, 1931; Miau et al., 1997; Zhong et al., 2011) have been the subject of many investigations. There have also been a limited number of studies on the wake of infinite span (2D) thin flat plates using Direct Numerical Simulations (Hemmati et al., 2014; 2015a; 2015b; Najjar, 1994; Najjar and Balachandar, 1998; Narasimhamurthy and Andersson, 2009), Large Eddy Simulations (Hemmati et al., 2015c; Joshi, 1994) and experimental measurements (Fage and Johansen, 1927; Kiya and Matsumura, 1988; Wu et al., 2005). Despite numerous studies on the structures formed in the wake of finite-aspect-ratio (3D) flat plates at low angles of attack (Taira and Colonius, 2009) and wall-mounted plates (Ringuette et al., 2007), there have been no comprehensive studies of the wake of 3D plates at high (i.e. normal) angles of attack (Hemmati et al., 2015b). However, despite their simplicity, these flows are of significant fundamental and practical interest. Understanding the wake dynamics, controlling the size of shed structures, and reducing the aerodynamic forces are of interest in solar panel installations, automobile design, and propulsor fin performance.

Fail et al. (1959) measured the shedding frequency, mean recirculation length, and mean drag for normal 3D flat plates for a range of aspect ratios ($AR = 1 - 20$). More recently, Aly and Bitsuamlak (2013) conducted a rare and limited set of surface pressure measurements, coupled with a Reynolds Stress Model (RSM) simulation, on a 3D plate of $AR = 6.8$ at two angles of attack (25° and 40°). The mean and fluctuating pressure loads were analyzed and compared between different dimensional-scales (1:5 to 1:400) of the plate, representing ground-mounted solar panels at different wind conditions. Comparing the results of Taira and Colonius (2009) and Aly and Bitsuamlak (2013) with

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http://dx.doi.org/10.1016/j.ijheatfluidflow.2016.05.012
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those of Fail et al. (1959) and more recent experiments of Ortiz et al. (2015), which determined the mean lift and drag variation with respect to the plate aspect ratio over the range of $1 \le AR \le 20$, confirmed that the flow topology differs significantly between the wake of low and high angles of attack. Radi et al. (2013) performed Laser Droplet Velocimetry (LDV) experiments on a series of elliptical cylinders ranging from circular cylinders to flat plates to quantify the influence of Reynolds number ($Re$) on shedding frequency. However, Radi et al. (2013) limited these studies to low $Re$ ranges of 100−300. Despite these limited studies, there has been no attempts (that the authors know of) to characterize the wake of 3D plates, study their vortex formation mechanisms, identify changes in their flow topology, and evaluate the importance of aspect ratio on their wake dynamics. This paper aims at addressing these topics by comparing the wake of a 2D plate to that of a 3D plate, both positioned normal to uniform flow. The plates have a common chord ($h$) which is at right angles to the span ($w$).

Numerical study of the wake behind thin flat plates have proven difficult and inaccurate using Reynolds Averaging Navier Stokes (RANS), Unsteady-RANS (URANS), Detached Eddy Simulations (DES) and Large Eddy Simulations (Breuer et al., 2003; Hemmati et al., 2015c). Experimentally, it is difficult to avoid flow interference in experiments on 3D thin flat plates due to their small thickness (Ortiz et al., 2015). Thus, the current study aims at simulating the flow around 3D plates using Direct Numerical Simulations (DNS) by expanding on the proven simulations on the wake of 2D plates (Hemmati et al., 2014; 2015a; 2015b; 2015c). Reynolds number of 1200 was selected for this study to allow the direct comparison with the wake of 2D plates at the same $Re$, and to avoid unnecessary computational complexities. Furthermore, DNS is the best method to relate fluctuating aerodynamic forces to the evolution of the vortex structures (Hemmati et al., 2015a).

Recent numerical studies on the wake of 2D plates (Hemmati et al., 2014; 2015a; 2015c) have confirmed the low frequency flow pattern (denoted by $L$ and $H$ based on the shedding mechanisms) originally found by Najjar and Balachandar (1998) and Wu et al. (2005). Initially, two flow regimes ($H$ for high-intensity and $L$ for low-intensity shedding) were observed in the wake of 2D plates by Najjar and Balachandar (1998) at $Re$ of 250 using DNS. Experimentally, Wu et al. (2005) confirmed this observation at $Re = 1800$, while describing them as short and long vortex formation regimes. This paper will use the original definition of $H$ and $L$ regimes. According to Hemmati et al. (2015a), the shear layers extended during $L$ upto $\approx 2h$ (where $h$ is the plate height) behind the plate, which formed a region of high pressure behind the plate. Lower pressure drop across the plate led to lower drag in comparison to regime $H$. Moreover, dislocation of vortices during this period resulted in the disappearance of spanwise rollers at approximately $3h$. Streamwise ribs were stretched and subsequently detached from their counterpart rollers, which elongated the base region and reduced the shedding frequency. The collapse of this mechanism, which extended the shear layers prior to their roll-up, led to a period of intensified shedding (regime $H$). The positioning of the roll-up and vortex formation closer to the plate increased the lift fluctuations, while the base pressure, and thus drag, decreased due to the close proximity of the base vortex to the plate. Furthermore, Hemmati et al. (2015a) identified an additional distinct flow regime ($M$ for moderate intensity shedding), which has regular Karman shedding. According to Hemmati et al. (2015a), a secondary spanwise instability identified by a spatially-periodic spanwise pressure variations (Hemmati et al., 2014) suppressed the regular Karman shedding ($M$) and initiated a re-stabilizing process leading to regimes $H$ and $L$. The current hypothesis is that the addition of spanwise shear layers on the 3D plate suppresses the secondary spanwise instability observed for 2D plates (Hemmati et al., 2013), eliminating the three shedding regimes. Previous studies on 2D and 3D cylinders have identified a similar variation on the flow topology and vortex dynamics due to additional vortex formations (Ohya, 1994; Wang et al., 2009).

The study of wall-mounted (finite height) rectangular cylinders (Bailey et al., 2002; Bourgeois et al., 2011; Hosseini et al., 2013; Lyn et al., 1995; Wang et al., 2009; 2006) has identified a major change in flow topology with addition of side-edge vortices compared to the wake of 2D cylinders. Similar observations have also been reported for the wake of circular cylinders (Bearman, 1968; Okamoto and Sunabashiri, 1992; Roshko, 1961; Williamson, 1996). The downwash effects due to the vortex on the cylinder free-end modified the wake topology by suppressing the regular shear layer roll-up on the other two edges of the cylinder (Bourgeois et al., 2011; Hosseini et al., 2013; Okamoto and Sunabashiri, 1992; Sumner et al., 2004; Wang et al., 2009; 2006; Zdravkovich, 1997). Side-edge vortices entrained high-speed flow into the wake, resulting in increased mean streamwise velocity at higher cylinder elevations closer to the cylinder free-end. This led to separation of two opposite sign vortices in the wake, which was evident by a double-peak distribution of mean streamwise velocity ($\overline{u}$) and appearance of minor peaks in distribution of the mean streamwise velocity gradient in the direction cylinder height ($\partial\overline{u}/\partial y$). Furthermore, tip and base vortices resulted in a highly three-dimensional near wake and complex vortex dynamics (Okamoto and Sunabashiri, 1992; Sumner et al., 2004; Wang et al., 2009; 2006; Zdravkovich, 1997). These studies suggest the possible difference between the wake of 2D and 3D plates, which support the need to perform a comprehensive study of the flow behind 3D plates.

The flow around circular flat disks (Berger et al., 1990; Cannon et al., 1993; Fuchs et al., 1979; Huang and Tsai, 2001; Lee and Bearman, 1992; Marshall and Stanton, 1931; Miau et al., 1997; Zhong et al., 2011) may be comparable to that of 3D flat plates. Marshall and Stanton (1931) performed the first study on circular flat disks at $Re = 100$, in which they identified interconnected three-dimensional loop structures formed in short distances downstream the disk. Willmarth et al. (1964) observed similar structures in the wake of a free falling disk at a range of $Re$s. Furthermore, Pao and Kao (1977), Taneda (1978), Sakamoto and Haniu (1990), Perry and Lim (1978), Huang and Tsai (2001) and Zhong et al. (2011) reported vortex loops in the wake of axisymmetric bodies including spheres, round disks, and other slender bodies. Miau et al. (1997) performed a detailed study of individual vortex structures in the wake of circular flat disks at $Re$ between $10^3$ and $10^5$. They showed that the individual vortices shed behind a circular disk, which are azimuthally 90° apart, exhibit very different characteristics. These measurements demonstrated that the phase-relation of the structures are not deterministic. This implies that a vortex structure shed from a given circumferential point on the disk may not form at the same location after one shedding period. Different flow regimes were developed due to the variation in the structure and interaction of shed vortices at different circumferential locations. Therefore, a comparison of two consecutive shed structures can not be conclusive with respect to the arrangement of vortices. Perry and Lim (1978) had previously verified that the large-scale structures formed in 3D wakes retain their identity for long streamwise distances, while making the largest contribution to Reynolds stresses. Despite similarities between flat disks and plates, the presence of sharp corners on the latter can result in a different wake system. The hypothesis is that sharp corners restrict the location of vortex detachments in the wake of flat plates, and thus, eliminate the randomness observed in the wake of circular disks. Interaction of adjacent shear layers, however, can result in either an elongated base vortex and delayed shedding, or an accelerated shedding process coupled with formation of vortex loops in the wake. The difference between the two depends on the mechanism of vortex interaction and the impact of $AR$.