Journal of Wind Engineering & Industrial Aerodynamics 165 (2017) 58–66

Contents lists available at ScienceDirect

Journal of Wind Engineering and Industrial Aerodynamics

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

An experimental investigation of surface pressures in separated and reattaching flows: effects of freestream turbulence and leading edge geometry

Z.R. Shu[a,b], Q.S. Li[a,b,*]

[a] Architecture and Civil Engineering Research Center, Shenzhen Research Institute, City University of Hong Kong, Shenzhen, PR China
[b] Department of Architecture and Civil Engineering, City University of Hong Kong, Hong Kong

ARTICLE INFO

Keywords:
Bluff body aerodynamics
Separated and reattaching flow
Turbulence effect
Leading edge geometry
Surface pressure
Wind tunnel test

ABSTRACT

Flow separation and reattachment over bluff bodies is frequently encountered in a wide range of engineering practice. This study presents an experimental investigation on the characteristics of surface pressures over bluff bodies in separated and reattaching flows, with emphasis placed on the effects of freestream turbulence and leading edge geometry. Measurements of mean, r.m.s and peak suction pressures on blunt flat plates with different leading edge shapes are conducted in both smooth and grid-generated turbulent flows in wind tunnel test, and comparative analyses are carried out to unveil the dependence of the distributions of mean, r.m.s and peak suction pressure coefficients on turbulence intensity, turbulence integral length scale and leading edge geometry. The experimental results show that the distributions of mean pressure coefficient respond strongly to changes of turbulence intensity, but with little effect on turbulence integral length scale except in the leading edge region for the cases there are large differences of the parameter. The distributions of r.m.s and peak suction coefficients demonstrate a close correlation on both the turbulence intensity and integral length scale. In addition, the distributions of surface pressures are also related evidently on the leading edge geometry. The mean reattachment length exhibits a monotonic increase as the leading edge angle increases, while the maximum magnitudes of r.m.s and peak suction pressure coefficients are found to increase with increasing leading edge angle.

1. Introduction

The phenomenon of flow separation and reattachment may arise in a wide variety of practical engineering applications, including vehicles and atmospheric flows over hills and buildings. Nevertheless, the occurrence of flow separation generally leads to a negative impact on the performance of bluff bodies, such as the reduced maneuverability of vehicles and the increase of dynamic structural loads and peak suction pressures over buildings (Melbourne, 1980; Li and Melbourne, 1995; Jovic, 1996).

The characteristics of separated and reattaching flow over bluff bodies have attracted broad attentions over the past several decades. Flow separation over bluff bodies is instigated by an adverse pressure gradient that attributed to the local surface geometry (Holmes, 2015). Sharp-edged corners of bluff bodies are often responsible for the flow separations due to the existence of large pressure gradients near these locations (Flay, 2013). Once the flow detaches at the leading edge corners (e.g. Fig. 1), a free shear layer is generated over a certain extent of bluff body surfaces, characterizing a significant wind shear and vorticity. The shear layer is unstable in nature and may roll up towards the wake to form concentrated vortices which are subsequently shed downwind (Holmes, 2015). It is shown in numerous early works (Melbourne, 1980; Irwin, 2008; Holmes, 2015) that such an unsteady shear layer is the primary cause for a majority of structural damages, such as the damages occurred on roofs of low-rise buildings and claddings of high-rise buildings.

Given the above discussion, it is evident that the investigation of the separated and reattaching flows is of substantial importance in wind engineering, in particular associated with bluff body aerodynamics. Hence, the objective of the present study is to examine the characteristics of surface pressures over bluff body surfaces in the separated and reattaching flows, which provides insight into the features of flow separation and reattachment. The effects of freestream turbulence on the distributions of mean, r.m.s (root-mean-square) and peak suction pressures on typical bluff bodies will be investigated respectively. Moreover, the effects of leading edge geometry on the streamwise

* Corresponding author at: Architecture and Civil Engineering Research Center, Shenzhen Research Institute, City University of Hong Kong, Shenzhen, PR China.
E-mail address: bcqsli@cityu.edu.hk (Q.S. Li).

http://dx.doi.org/10.1016/j.jweia.2017.03.004
Received 5 December 2016; Received in revised form 14 February 2017; Accepted 11 March 2017
Available online 17 March 2017
0167-6105/

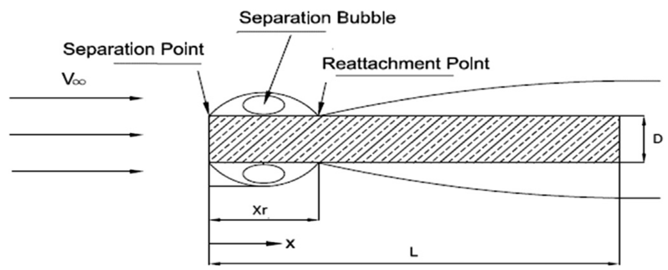

Fig. 1. Schematic drawing of separated and reattaching flow over a blunt flat plate. *Xr* denotes the reattachment length, *L* and *D* are the chord and thickness of the plate.

surface pressures will be examined as well. The rest of this paper is divided into the following sections: Section 2 provides a brief review on previous studies associated with the separated and reattaching flows over bluff bodies; Section 3 introduces the details of the experimental setups for wind tunnel test; Section 4 presents the experimental results and discussions and Section 5 summarizes the major outcomes and conclusions of this study.

2. Early works on separated and reattaching flow

Owing to the significance of the separated and reattaching flow, there have been numerous studies that aimed to enhance the understanding of its characteristics. In particular, a large body of knowledge associated with the separated and reattaching flows over bluff bodies has been obtained by undertaking experimental investigations in wind tunnels (Lee, 1975; Ota et al., 1981; Hillier and Cherry, 1981; Kiya and Sasaki, 1983; Cherry et al., 1983; Saathoff and Melbourne, 1987, 1997; Nakamura and Ozono, 1987; Nakamura et al., 1988; Li and Melbourne, 1995, 1999; Li et al., 1999; Matsumoto et al., 2003; Taylor et al., 2014).

For example, measurements of mean pressures on several square prisms were conducted by Lee (1975) to examine the effect of turbulence scale on mean drag force. The results indicated that the drag force demonstrate a strong correlation on the changes in turbulence integral length scale (*Lx*), which characterizes a distinct maximum at a scale size approximately equal to the body size. Ota et al. (1981) presented a visualization investigation with concentration on the reattachment length and transition of the separated and reattaching flow over blunt flat plates with various nose shapes, and Reynolds numbers examined in the tests were in the range of 40–2000. The variations of reattachment length with Reynolds number demonstrated a good agreement among cases with difference types of leading edge shapes, in which the reattachment length was found to increase at low Reynolds numbers, reaching a maximum at a specific Reynolds number, and then decrease monotonically to a minimum. The study given by Hillier and Cherry (1981) focused on the effects of freestream turbulence on the surface pressure measurements over a two-dimensional flat plate, in which the considered turbulence intensity ranged from 1.83% to 9.35%, and the turbulence integral length scale was about (13.7–74.3) mm. It was shown that the mean pressure responded strongly to turbulence intensity, but with little effect on turbulence integral length scale. The size of the separation bubble contracted aggressively as turbulence intensity increases. The surface r.m.s pressure, on the other hand, demonstrated a clear dependence on both freestream turbulence intensity and scale. Kiya and Sasaki (1983) found that the negative peak in mean pressure measurements increased in respond to the increase of turbulence intensity, and the location where it occurs moved towards the upstream direction due to the earlier recovery of the surface pressure. Cherry et al. (1983) delivered an extended work following Hillier and Cherry (1981), in which 5 types of leading edge geometries were considered in relation to the distributions of mean pressure, the low wave-number flagging motion of the shear layer, as well as the appearance of a characteristic frequency for the shedding of vorticity at reattachment. Saathoff and Melbourne (1987) carried out a series of wind tunnel tests based on axisymmetric cylinders to assess the effects of blockage and freestream turbulence on measurements of streamwise surface pressures in a separation bubble. Their results with respect to the effects of turbulence intensity and scale agreed well with the observations described by Hillier and Cherry (1981), while the blockage effects in wind tunnel tests also indicated a significant influence on the measurements of mean and r.m.s pressures. The work presented by Nakamura and Ozono (1987) concentrated on the distributions of mean pressures with different turbulence intensities (7% and 11%) and integral length scales (Lx/D=0.5–24). It was shown that the size of separation bubble tends to reduce with increasing turbulence intensity. However, the mean pressure distribution along the separation bubble was found to be independent on the changes in turbulence scale up to a scale-to-thickness ratio (*Lx*/D) of 2. The effects of turbulence scale on separated and reattaching flow were further examined by Nakamura et al. (1988), who concluded that the turbulence scale affects the mean flow over bluff bodies in two different manners: small-scale turbulence leads to earlier reattachment of separated shear layer through enhanced mixing, while large-scale turbulence interacts with vortex shedding from a bluff body, and therefore changes the mean flow significantly. Likewise, Li and Melbourne (1995, 1999) drew their attention on the assessment of the effects of large scale turbulence (*Lx*/D up to 30) on the distributions of mean, r.m.s and peak suction pressures, as well as the spanwise cross-correlation of fluctuating pressures. The results suggested that, the mean pressures depend strongly on turbulence intensity, but were not significantly influenced by turbulence scale with a value of Lx/D ranging from 0.4 to 3.6. However, with further increase in turbulence scale ($Lx/D > 6.0$), the distributions of mean pressures, especially in the upstream part near the leading edge corner, became scale-dependent. The r.m.s and peak suction pressures were a function on both turbulence intensity and scale, their magnitudes increased as the freestream turbulence increased. Meanwhile, the spanwise cross-correlation of r.m.s pressures near separation was found to increase as the turbulence integral length scale increases.

In addition to the characteristics of surface pressures on sharp-edged bluff bodies, there are some other properties associated with the separated and reattaching flows have also been extensively examined in previous researches (Melbourne, 1980, 1993; Saathoff and Melbourne, 1989, 1997; Li et al., 1999; Matsumoto et al., 2003; Taylor et al., 2014). For example, large negative peak pressures that frequently arise near leading edge corners of bluff bodies have been generally considered as the major cause of many wind-induced damages on buildings. The mechanism of generation of such negative peaks, however, has not been thoroughly revealed. Melbourne (1980, 1993) reported that the generation of these large peak suction pressures was primarily resulted from the movement of the reattachment line due to the enhanced entrainment rate of the shear layer, and the studies presented by Saathoff and Melbourne (1989, 1997) found that the occurrence of large negative peak pressures was related to an unstable process involving the intermittent roll-up of separated shear layer in both smooth and turbulent flows. These peak suction pressures were often observed at 0.25*Xr* from the leading edge where *Xr* is the mean reattachment length, and their magnitudes are a function on both turbulence intensity and integral length scale. Aside from that, probabilistic characteristics of pressure fluctuations underneath the separated shear layer were examined respectively by Melbourne (1980) and Li et al. (1999). It was indicated that the pressure fluctuations within the separated and reattaching flows was characterized with distinct non-Gaussianity. Alternatively, the log-normal density function was found capable of providing favorable description of the probability distribution of pressure fluctuations in the separated and reattaching flows (Li et al., 1999). Matsumoto et al. (2003) concentrated on the spanwise coherence of pressures on bluff body surfaces in both smooth and turbulent flows, in which a higher coherence level was found at slightly upstream of the reattachment point. More recently, Taylor et al.