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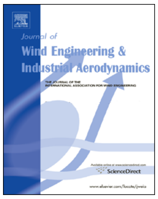

Mean pressure distributions and reattachment lengths for roof-separation bubbles on low-rise buildings

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ABSTRACT

Investigations of separated and reattaching flows near the leading edge of three-dimensional bluff bodies placed in turbulent boundary layers are important because of the large aerodynamic loads that these flows cause. Roofs of low-rise buildings are vulnerable to this kind of wind loading. Turbulence properties in the approaching boundary layer flow affect the pressure distributions and the mean size of the separation bubble formed on building surfaces. In this study, the effects of turbulence intensities and length scales in the incident boundary layer on the mean reattachment lengths and surface mean pressure distributions for low-rise building roofs are investigated. Particle Image Velocimetry measurements of the roof separation bubble, along with surface measurements, for a low-rise building model were taken for six different, upstream, boundary-layer conditions. Surface pressure measurements were taken for a second building model in similar upstream conditions. Along with these data, pressure data from the NIST aerodynamic database were used in the analysis. The mean size of the roof separation bubble is found to be unaffected by the turbulence length scales over the range tested, whereas turbulence intensity has a significant effect on reattachment lengths. The mean pressure distribution was found to be a function of both the mean reattachment length and the upstream turbulence intensity. A method of estimating the mean reattachment length on the roof of low-rise buildings from measured surface pressures and roof height turbulence intensity is proposed.

1. Introduction

Separating and reattaching flows on the surface of sharp-edged, elongated bluff bodies are of fundamental importance to the aerodynamic loads for these shapes. The flow near the leading edge of such bodies has received special attention by researchers since there are large pressure fluctuations on the surface beneath the separating–reattaching flow (Lyn and Rodi, 1994; Saathoff and Melbourbe, 1997). These cause large uplifting loads (e.g., on the roofs of low-rise buildings (Tieleman et al., 1996) or can interact with the trailing edge, leading to the flow instabilities such as vortex streets in the wake (e.g., on long-span bridges, Taylor et al., 2014). In the present paper, the focus is on the mean pressure field beneath separation bubbles on surface-mounted prisms in turbulent boundary layers. Fig. 1 shows a schematic representation of the terminologies used to describe separating–reattaching flows over sharp-edged, elongated, bluff bodies. In particular, the point on the bluff-body surface where the mean flow reattaches is known as the reattachment point, the distance between the separation point and the reattachment point is defined as the reattachment length.

1.1. Two-dimensional bluff bodies

Ruderich and Fernholz (1986) investigated the nature of the mean pressure field beneath separating–reattaching flows and found similarity of the distribution when the mean pressure coefficients are normalized by the minimum pressure such that the reduced pressure coefficient is

$$C_p^* = \frac{(C_p - C_{p,\,\min})}{1 - C_{p,\,\min}} \tag{1}$$

where C_p is the mean pressure coefficient, $C_{p,\,\min}$ is the minimum value of the mean pressure coefficient on the surface under the separation bubble, while streamwise distance, x, is normalized by the reattachment length, X_r. Eq. (1) was first proposed by Roshko and Lau (1965). The experimental results of Hudy et al. (2003) were found to be similar to the results of Ruderich and Fernholz (1986). These authors found that, for a smooth (i.e., low turbulence) free stream, irrespective of Reynolds numbers, body shape, blockage ratio, over a large range of reattachment lengths, the distribution of reduced pressure coefficients fall on the same curve. However, the reasons for the particular shape of the curve, or how surface pressures arise, were not explained.

Researchers have shown that the flow structure of separation

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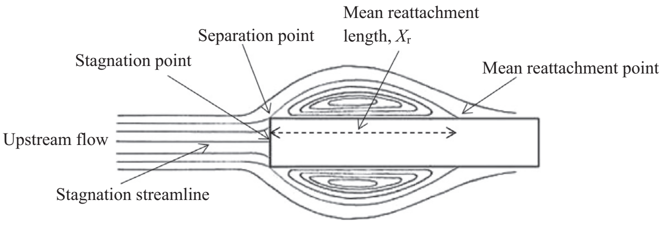

Fig. 1. Schematic diagram of a separating and reattaching flow over a sharp-edged, elongated, two-dimensional bluff body placed in uniform upstream flow.

bubbles, the surface pressure and aerodynamic forces on the body beneath the separation bubble, and the reattachment length are strongly dependent on the turbulence parameters in the upstream flow (e.g., Gartshore, 1973; Hillier and Cherry, 1981). Upstream properties affecting the separation bubble properties are turbulence intensities, $I_u = \frac{\sigma}{U}$ (where, σ is the standard deviation of the velocity fluctuations and U is the streamwise mean velocity), and the turbulent scales, particularly the integral scales, $L = \int_0^\infty r(\xi)d\xi$, relative to the dimensions of the body, where $r(\xi)$ is the correlation coefficient of the velocities separated by some distance, ξ. Usually the integral scale, L_x, formed by the streamwise velocities separated in the streamwise direction, x, is considered to be the most important integral scale.

Hot-wire measurements in the separation bubble by Hillier and Cherry (1981) for different turbulence intensities and integral length scales show that higher levels of the free-stream turbulence intensity causes a reduction in the reattachment length, but that the reattachment length tends to be insensitive to the integral scales. Kiya and Sasaki (1983) and Saathoff and Melbourbe (1997) also found similar trends in the reduction of the reattachment length with turbulence intensity. These authors suspected that the higher levels of entrainment in the turbulent flow cases are responsible for the smaller reattachment lengths. These studies were performed on two-dimensional bluff bodies of thickness, D, in uniform flow over a range of turbulence intensities up to 15% and length scales, L_x/D, up to 2.1. However, the effects of length scales on mean reattachment lengths for larger ranges of turbulence length scales have not yet been investigated. Nakamura and Ozono (1987) investigated the surface mean pressures under the separated and reattaching flows for an extended range of integral length scales ($L_x/D = 0.4–24$), focussing on the maximum turbulence-intensity levels investigated by Hillier and Cherry (1981) and Kiya and Sasaki (1983). Their investigation indicated an independence of the surface mean pressure distribution at smaller ratios of integral scale to body thickness. However, for higher ratios of integral scales to body thickness, they observed dependence of the mean surface pressures to the integral scales. These results indicate that larger integral scales may have some effect on the mean reattachment length.

Perhaps the most investigated property of separation bubbles is the surface pressure field because of the practical importance. The properties of free-stream turbulence are known to significantly affect the mean pressure field. For example, Hillier and Cherry (1981) have shown that for smooth flow in the free stream, the maximum value of the mean suction coefficient is smaller in magnitude and occurs further away from the leading edge. Increased levels of free-stream turbulence tend to increase the maximum values of the mean suction coefficients near the leading edge to a significant extent, while moving the location of the maximum closer to the leading edge. However, pressure recovery for the smooth upstream case is slower than for the turbulent case because of the larger reattachment lengths in smooth flow.

Integral scale effects on the mean pressure appear to be more complex. For example, Hillier and Cherry (1981) do not observe any effects of the turbulent integral scales, at fixed levels of turbulence intensity, up to values of $L_x/D = 1.95$. Kiya and Sasaki (1983) and Saathoff and Melbourne (1989) make similar observations. However, the study by Nakamura and Ozono (1987) found that there is dependence of mean pressures over a large range of integral length scales (i.e., over the range of their study with $L_x/D = 0.4–24$. For values of L_x/D up to 2, these authors found similar results to those obtained by Hillier and Cherry (1981). However, at larger integral length scales, the mean pressure distribution begins to behave more like those with smooth upstream flow conditions. The reason for this is that the free-stream fluctuations become relatively slower, with reduced fluctuating energy at the smaller-scales. Thus, these relatively slow fluctuations in the upstream flow are unable to influence the mean flow and the mean pressure over the bodies (Bearman and Morel, 1983; Nakamura and Ozono, 1987) and the combination of both scale and intensity are important parameters for the character of the separation bubble.

1.2. Surface-mounted, three-dimensional bluff bodies

Many of the engineering applications of bluff body aerodynamics are for buildings, i.e., surface-mounted, three-dimensional prisms, placed in the atmospheric boundary layer. In this case, there are both relatively high turbulence levels along with high levels of mean shear. However, similar flow patterns occur with flow separations, mean flow reattachment and separation bubbles. Despite the similarities in these flow patterns, there are also some significant differences. The main difference arises due to the streamwise vorticity generated in the separated shear layer from the sides of the body (Martinuzzi and Tropea, 1993). For example, Martinuzzi and Tropea (1993) show that, in addition to a recirculation region on the top surface, there is also a recirculation region formed in front of the body (a cube in their particular case). This recirculation region in front of the body extends around the sides of the body, forming a "horseshoe" vortex (Castro and Robins, 1977; Martinuzzi and Tropea, 1993). The aspect ratio of the body is also observed to alter the reattachment lengths. Martinuzzi and Tropea (1993) and Kim et al. (2003) both report shorter reattachment lengths for three-dimensional, surface-mounted prisms than those observed for two-dimensional bodies. This is attributed to a mean flow that has a higher acceleration at separation for two-dimensional bodies than for three-dimensional bodies of similar thickness.

So, in contrast to two-dimensional, sharp-edged bluff bodies, the effects of turbulence on surface-mounted bodies have not been systematically investigated. The objective of the present work is to examine the relationships between upstream turbulence conditions on the mean surface-pressure distributions and mean reattachment lengths for relatively low (i.e., with heights less than the plan dimensions), surface-mounted prisms. In order to do so, pressure measurements on two prisms were taken for six different upstream, boundary-layer flows. For one of the prisms (which we will call Building-1), Particle Image Velocimetry (PIV) measurements were made, synchronized with surface pressure measurements. In addition, pressure data from the NIST Low-Rise Building Aerodynamic Database (Ho et al., 2005) are utilized.

2. Experimental set-up

2.1. Building models and pressure measurements

The dimensions of the two models used in the current study are presented in Table 1. Building-1 is a scaled version of the Texas Tech University "WERFL" Building, which is described in Levitan