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Turbulence structure and similarity in the separated flow above a low building in the atmospheric boundary layer

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ABSTRACT

Separated and reattaching flows over sharp-leading-edge bluff bodies are important to investigate in order to improve our understanding of practical flows such as the case of low-rise buildings in the atmospheric boundary layer. In this study, Particle Image Velocimetry measurements of the separated-reattaching flows over the roof surface of a low-rise building model were taken for six different turbulent boundary layer conditions. The results were analyzed to understand how the incident turbulence affects the flow field of the separation bubbles above the low-rise building roof. The mean flow field above the roof-surface was found to be approximately similar across the six terrain conditions using the mean reattachment length in the streamwise direction and the maximum mean thickness of the separated shear layer in the vertical direction. However, the turbulence stresses are not similar which is attributed to high levels of initial turbulence kinetic energy in the separated shear layer. This leads to fundamental differences in the initial development of the separated flow when compared to flows with lower turbulence in the incident stream. The results indicate that the Kelvin-Helmholtz instability may be altered, or perhaps even suppressed, in the initial flow development region. This leads to substantially different turbulence statistics and characteristics within the separated shear layers.

1. Introduction

Flows over sharp-edged bluff bodies have received special attention by researchers because of their numerous practical applications including atmospheric boundary layer flows around buildings and bridges. Of fundamental importance to the aerodynamic loading is the character of the separated shear layer (SSL). There have been numerous studies on the details of the development and loading effects of SSLs in uniform smooth flow. Kiya and Sasaki (1983, 1985) investigated the flow downstream of the separation at the upper edge of a two-dimensional blunt flat plate placed in uniform upstream flow with low levels of free-stream turbulence. Their investigations revealed the presence of Kelvin-Helmholtz (K-H) vortices in the separated flow region near the leading edge much like those in a classical mixing layer (see, e.g., Brown and Roshko, 1974). Downstream of the leading edge, these Kelvin-Helmholtz vortices increase in size due to pairing and, eventually breaking down into turbulence. Near the mean reattachment point, the largest surface pressure fluctuations occur due to this turbulence. These authors also observed the shedding of large-scale vortices from the separation bubble, which are associated with fluctuations of the reattachment length and flapping motions of the SSL. However, closer to the separation point, the surface pressure fluctuations, although relatively small, are related to the transient nature of the K-H instability.

For wind loads, the effects of atmospheric turbulence is critical. Emphasizing the importance of the SSL, Gartshore (1973) was the first to show that small-scale turbulence on the stagnation streamline was sufficient to produce the effects attributed to turbulence on the flow around the bluff body. Recently, Lander et al. (2016), repeating many aspects of Gartshore's experiments, showed that this small-scale turbulence causes a by-pass transition such that the normal development of turbulence in the SSL occurs much earlier, closer to the leading edge.

Saathoff and Melbourne (1997) investigated many of the effects of upstream turbulence properties on the flow field around a two-dimensional rectangular cylinder for a range of turbulence intensity and length scales. Their investigation revealed that the free-stream turbulence interacts with the separated shear layer in a variety of ways. For example, higher levels of free-stream turbulence cause greater perturbations to the separated shear layer and cause the vortices to roll-up closer to the leading edge, as confirmed by the detailed flow measurements in Lander et al. (2016). This leads to three effects. When the free-stream turbulence level is larger, (i) there is a reduction in the mean reattachment length, (ii) there are larger surface pressure fluctuations,

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(iii) which occur relatively closer to the leading edge, i.e., at a smaller x/X_r location, where X_r is the mean reattachment length. Of significance, Saathoff and Melbourne (1997) also observed that there are larger magnitude surface pressure fluctuations when there are larger integral length scales in the free-stream turbulence. However, the location of maximum surface pressure fluctuations was not observed to be affected by the integral scales over the range they studied. These authors speculate that for cases with smaller integral scales, the gusts "carry away" the vortices in the shear layer more frequently, not allowing them to grow in strength. In contrast, for turbulence with large integral scales, the gusts are relatively less frequent and allow more time for the shear layer vortices to grow in strength, which causes the surface pressures to fluctuate at a higher level. These effects on surface pressures have also been observed in the regions of separated flow on the roofs of low-rise buildings in the atmospheric boundary layer (e.g., see Fernandez-Caban and Masters, 2018, for a recent example). However, a complete understanding of how different levels of turbulence intensities and length scales in the incident flow affect the mean and fluctuating flow fields in and around the separation bubble has not been developed.

While there have been many studies examining wind loads, there have been only a limited number of studies investigating the separated and reattaching flow fields around sharp-edged, three-dimensional, surface-mounted bluff bodies (i.e., buildings) in turbulent boundary layer conditions. Castro and Robins (1977) show that for surface-mounted cubes, there is intermittent reattachment on the upper surface and that the Reynolds stress components play an important role in characterizing the aerodynamic loading. Although these results also suggest that the decay of the wake is a strong function of the upstream turbulence, velocity field measurements for a wide range of turbulence intensities and length scales have not been conducted. Hence, the nature of the mean and turbulent flow field of the roof separation bubble, and their dependence on the upstream turbulence properties, are not clearly understood.

Kim et al. (2003) took detailed velocity field measurements around a low-rise building placed in a turbulent boundary layer. Their data reveal that a short distance along the separated shear layer, turbulent kinetic energy attains its maximum value and then gradually reduces downstream. Essel et al. (2015) observe the presence of negative Reynolds shear stress and regions of negative production near the separation point on a forward-facing step. However, how the magnitudes of Reynolds stresses and the production of turbulence vary with the upstream turbulence characteristics for a low-rise building, and how these quantities affect the aerodynamics, have not been studied in detail.

Finally, there is also little available information on the scaling parameters which control or normalize the SSL and, more generally, the separated-reattaching flow at bluff-body edges. For low-rise buildings in the atmospheric boundary layer (ABL), Lin et al. (1995) argued that the distance from the wall stagnation point to the roof edge (i.e., the separation point), H_s, was the critical geometric scale. These authors then suggested that building height, H, could be a proxy for H_s. Akon and Kopp (2016) found that, for a single building shape in six distinct terrain conditions, H_s was a fixed proportion of H, making this a useful geometric parameter. The other obvious scaling parameters are related to the flow field, such as the distance from the separation point to the mean reattachment point, X_r, or the maximum value of the mean thickness of the separation bubble, T_b. For buildings, Akon and Kopp (2016) showed that X_r depends strongly on turbulence intensity, I_u, but approaches an asymptotic limit for relatively high values of I_u. Castro and Haque (1988), in their examination of a SSL in smooth flow used T_b, but it is not clear how this parameter varies with the stream turbulence characteristics or body geometry since it has not been systematically investigated.

The objective of this paper is to examine the flow similarity in the separated-reattaching flow on the upper surface of a low-rise building, as a function of the approaching ABL conditions. In particular, the roles of possible scaling parameters are examined using Time-Resolved Particle Image Velocimetry measurements in six distinct terrain conditions. The mean and fluctuating velocity fields in and around the roof separation bubbles are examined in detail in order to meet this objective.

2. Experimental details

A 1/50 scaled model of Texas Tech University (TTU) Wind Engineering Research Field Laboratory (WERFL) Building (Levitan and Mehta, 1992) was used in these experiments. This building geometry was chosen because it has been widely studied and has aspect ratios common to many low-rise buildings. The model building has plan dimensions of length, L, by width, W, of $18.3\,\text{cm} \times 27.5\,\text{cm}$, and roof height, $H = 7.8\,\text{cm}$. Thus, the wall aspect ratios were $L/H = 2.35$ and $W/H = 3.53$. The roof-height mean wind speed was 6.7 m/s, yielding a Reynolds number of 35,000. A single wind direction is used in this study, which is perpendicular to the wide face of the building. The blockage ratio for this configuration is 0.3%.

A schematic of the coordinate system and set-up is shown in Fig. 1. A Cartesian coordinate system is used in the current analysis such that streamwise and vertical directions are labelled as the x and y axes, respectively. The midplane of the windward wall at the roof edge considered to be the origin, $(x,y) = (0,0)$, which is convenient for describing the flow above the roof. For the velocity profiles describing the upstream boundary layer, we use Y for the vertical coordinate, with $Y = 0$ defining the ground plane, i.e., $y/H = Y/H - 1$.

Six different terrain conditions were used in Boundary Layer Wind Tunnel II at UWO, the properties of which are provided in Table 1. The high-speed test section for this wind tunnel has a length of 39 m from the inlet to the centre of the turntable, a cross-section that is 3.4 m wide and a nominal height of 2.4 m at the location of the turntable. The six terrain conditions were made up of three different ground roughness configurations, each of which was repeated with and without a 0.38 m tall barrier at the test section inlet. As in Akon and Kopp (2016), the three terrain conditions with the barrier are labelled as 1L, 2L, and 3L, while the three without the barrier are 1S, 2S, and 3S. The number in these labels indicates the terrain roughness, while the label L indicates the presence of the barrier, which has a Larger integral scale, and the label S indicates that the no barrier was used, which results in a Smaller integral scale.

Fig. 2 shows the vertical distributions of turbulence intensities for upstream conditions considered in this experiment measured at the location of the building model, but with the building removed. These boundary layers are identical to those reported by Akon and Kopp (2016) and Wu et al. (2017), where many further experimental details, including the mean velocity profiles, can be found. These are not repeated here due to length considerations, although it is noted that the mean velocity profiles normalized by the mean wind speed at the roof height are similar for $Y/H < \sim 2$. The turbulence intensities, I_u, and integral scales, L_x, range from $I_u = 13\%$ with $L_x/H = 6$ to $I_u = 27\%$ with $L_x/H = 12$. Thus, there is a factor of two change in both intensity and scale in these data. Velocity spectra can be found in Wu et al. (2017). Further details of the

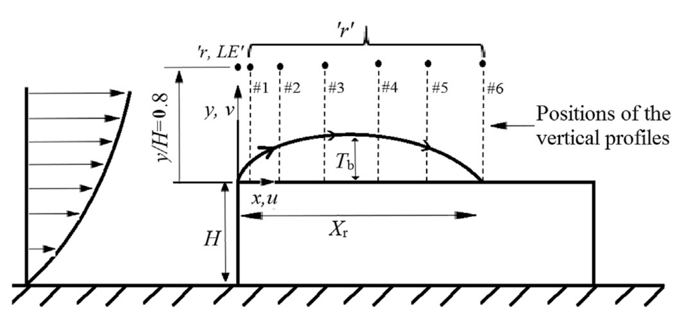

Fig. 1. Schematic representation of the flow field, building set-up, and coordinate system. Detailed analysis positions are numbered, with precise locations provided in Table 2. The locations used for variable normalization are also provided.