PRESSURE FLUCTUATIONS ON THE ROOFS OF LOW-RISE BUILDINGS IN TURBULENT BOUNDARY LAYERS

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ABSTRACT

Buildings are often exposed to the highly turbulent atmospheric boundary layer flows near the earth's surface. Roofs of low-rise buildings in particular are vulnerable to the resulting aerodynamic loads, especially during the extreme wind storms. For flat-roofed, low-rise buildings with relatively large plan dimensions, the approach flow separates at the leading edge of the roof and then reattaches creating a separation bubble. This separation bubble is a turbulent recirculating flow region that is responsible for causing large-magnitude uplift on the roof surface. Such large, uplifting forces can cause damage to the roofs and roof-mounted structures. There are a limited number of studies present in literature focussing on the flow field and pressure fluctuations on the roof surface of the low-rise buildings and its dependency on the turbulence properties in the incident boundary layer flows compared to the studies performed on two-dimensional bluff bodies in uniform upstream flows. In this paper, the effects of the turbulence intensities and length scales in the boundary layer flows on surface pressure fluctuations for two low-rise building models are examined. The results indicate that roof surface pressure fluctuations strongly depend on roof height turbulence intensity and length scales in the approaching boundary layer flows. At lower levels of turbulence intensities, turbulence scales of significantly higher order of magnitudes compared to the building heights play important roles in characterizing the distribution of surface pressure fluctuations.

Keywords: Low-rise buildings, Boundary layer flows, Pressure Fluctuations, Turbulence, Particle Image Velocimetry

1. INTRODUCTION

Surface pressure fluctuations occurring on the roof surfaces of low-rise buildings are of particular importance as this may have severe effects on the roof-mounted structures (e.g, solar panels) and on the roof structure itself, especially during the extreme wind conditions. Changes in turbulence properties in the upstream have significant effects on pressure fluctuations and hence, the aerodynamic loads on the surface underneath the separating and reattaching flows for two-dimensional bluff bodies (Gartshore, 1973). There have been a number of studies addressing this issue for two-dimensional bluff bodies placed in uniform upstream flows. Experimental results provided by Hillier and Cherry (1981) show that pressure fluctuations on the surface beneath the separation bubble are strongly dependent on the free stream turbulence intensity. Similar results were found by Saathoff and Melbourne (1997). The results of Cherry et al. (1984) and Saathoff and Melbourne (1997) are regenerated as shown in Figure 1. It is observed that the fluctuating pressures under the separation bubble increase with increases to both turbulence intensities and length scales. In addition to that, increasing the turbulence intensities upstream also causes the location of maximum pressure fluctuations to move closer to the separation point (leading edge). In order to formulate the combined effects of turbulence intensity and length scale on surface pressure fluctuations, Saathoff and Melbourne (1997) found a relation of the empirical parameter (first proposed by Taylor (1936) as cited in Bearman and Morel (1983)), $\eta = (\sigma_u/U)(L_x/D)^n$, (where $\sigma_u/U = I_u$, is the turbulence intensity, n=0.15 and L_x/D is the streamwise turbulence length scale normalized by the body thickness) with surface pressure fluctuations at the separation point. Saathoff and Melbourne (1997) showed that the variation of fluctuating pressure near separation varies linearly with the empirical parameter (η). Bearman (1971) shows that for a square plate, placed normal to the upstream flow the correlation to the empirical relation is valid for the turbulent scale exponent of 2. Bearman and Morel (1983) suggest that the empirical relation is also a function of the thickness of the separated shear layer for a separated flow.

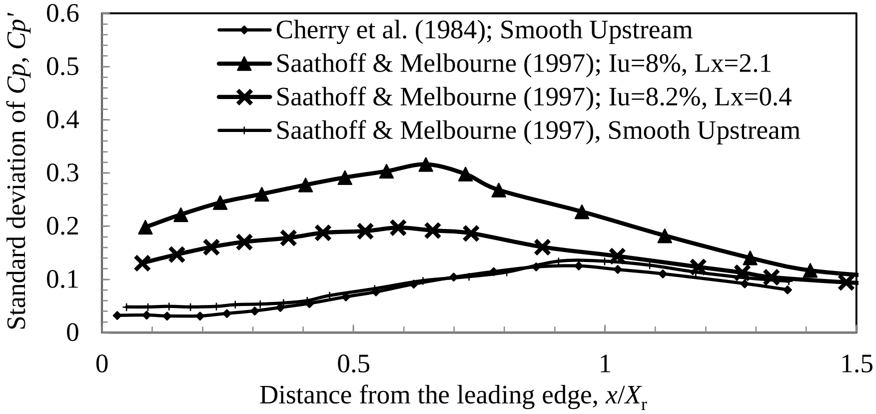


Figure 1: Distribution of fluctuating pressure coefficients under the separation bubble at smooth upstream for two-dimensional bluff bodies

Few studies are found in the literature addressing the effects of turbulence in the boundary layer flows on the surface pressure fluctuations on three-dimensional bluff bodies. The effects of boundary layer turbulence on surface pressure fluctuations on three-dimensional bluff bodies are important to study as this resembles the low-rise buildings exposed to highly-turbulent atmospheric surface layers. In wind tunnel testing of scaled-down models, understanding the effects of turbulence intensities and length scales separately on the characteristics of surface pressure fluctuations is crucial, and is a source of debate with respect to interpretation of test results for full-scale buildings. Due to the challenges in controlling the turbulence intensities and turbulence length scales independently in an experiment, there has not been a complete understanding of the independent effects of turbulence intensities and length scales on aerodynamic forces on low-rise buildings. For scaled-down model tests in wind tunnel, typically the high frequency ends of velocity spectra are simulated in the tunnel matching the high frequency ends of desired spectra. It is difficult to match the whole range of the model spectra simulated inside the wind tunnel with the desired full-scale spectra as simulation of larger scales are restricted by the physical size of the wind tunnels (Tieleman 2003). The effects of the low frequency (i.e., large turbulence scales) end can be approximated via the quasi-steady theory (e.g., Richards and Hoxey 2004). However, the limit up to which the mismatch of the simulated spectra and the desired spectra is acceptable has not been clearly defined in literature (Morrison and Kopp 2015). It was found by Morrison and Kopp (2015) that in order to correctly account for the aerodynamic effects of turbulence length scales on surface pressure fluctuations non-dimensional frequencies (fX_r/U, where f is the frequency, X_r (~ height of the model) is the mean reattachment length and U is the mean wind speed) in the range of 0.1-1 is required to be simulated in the wind tunnel.

In this paper, the effects of the turbulence intensities and length scales in the boundary layer flows on surface pressure fluctuations for two low-rise building models are examined. The results obtained from synchronized surface pressures and time-resolved particle image velocimetry measurements of the separation bubble for one low-rise building model and only pressure measurements for the second building model exposed to six different incident boundary layers are presented.

2. EXPERIMENTAL APPROACH

2.1 Model and Surface Pressure Measurements

Two low-rise building models were used in this experiment. One is the scaled version of the Texas Tech University "WERFL" Building (described in Levitan and Mehta 1992), labelled as Building-1 with height (H_1), width and length of 7.8cm, 27.5cm and 18.4cm, respectively. The other model is a generic low-rise building model, larger than Buiding-1, previously used in the study of Pratt & Kopp (2014). This model is labelled as Building-2 and has height (H_2), width and length of 24cm, 75.1cm and 53.3cm, respectively. On the roof surface of Building-1, a row of 9 pressure taps and on Building-2 a row of 96 pressure taps were placed along the roof centreline and connected to the pressure measurement system. Both models were placed in the high speed test section of the Boundary layer Wind Tunnel-II at the University of Western Ontario. The pressure taps were connected to the pressure scanners by tubing system (described in Ho et al. 2005). Measurements were taken at 1108 Hz for duration of approximately 180 seconds. The pressure measurement system records pressure as pressure coefficients with respect to a reference height closer to the ceiling of the wind tunnel. Pressure coefficients are then converted to obtain pressure coefficients referenced to model heights.

2.2 Boundary Layer Upstream Conditions

The experiments were conducted for six different upstream boundary layer conditions composed of three different configurations of surface roughness elements (denoted as 1, 2 and 3) raised from the wind tunnel's floor. For each of the surface roughness element configurations, two different upstream boundary layer conditions were achieved by placing a 0.38m tall barrier at the entrance of the test section (denoted as 'L'), 39m upstream of the turntable where the model were mounted, and without any barrier at the entrance of the test section (denoted as 'S'). It is observed that for one particular configuration of surface roughness elements, the model height turbulence intensities remain similar for both the barrier conditions. Placing a barrier at the entrance of the test section increases the model height turbulence length scales. However, changing from one surface roughness configuration to other changes the model height turbulence intensities. The turbulence properties of the six upstream boundary layer conditions are presented in Table 1.

Table 1: Turbulence properties of the boundary layer upstream conditions

Terrain	I_u [$y = H_1$]	I_u [$y = H_2$]	L_x/H_1	L_x/H_2	Building-1, X_r/H_1	Building-2, X_r/H_2	Legends in the figures
1L	14	10	13	4	~1.4	1.49	—■—
1S	13	9	6	2	~1.4	1.50	—□—
2L	17	13	11	5	1.05	1.12	—●—
2S	17	13	8	2	1.05	1.18	—○—
3L	27	25	12	3.5	0.88	0.62	—▲—
3S	26	22	7	3	0.88	0.67	—△—

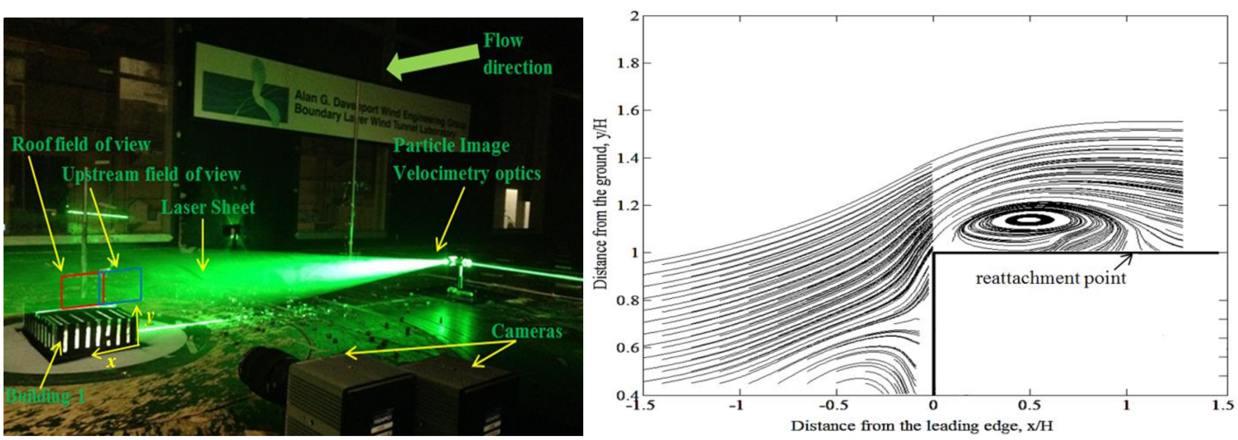


Figure 2: Photograph of Building-1 inside the wind tunnel with the coordinate systems and the PIV components (left) and mean stream lines corresponding to upstream '2L' (right).

2.3 Particle Image Velocimetry Measurements

The velocity field measurements of the separated and reattaching flows for Building-1 were taken by a Time-Resolved Particle Image Velocimetry (TR-PIV) system (described in Taylor et al. 2010) which was synchronized with the pressure measurement system. The TR-PIV system samples velocity data at 500 Hz. Atomized olive oil were illuminated by a double-head, diode-pumped Q-switched Nd:YLF laser. Two cameras (1 Mb Photron FASTCAM-1024PCI CMOS) were used to capture the images of the separation bubble and the flow upstream of Building-1. A photograph of the Building-1 placed in the wind tunnel is shown in Figure 2 (left) with the coordinate systems and the PIV components. 85μs was maintained between the two PIV images of the single image pair. PIV images were processed using FFT cross-correlation algorithm in Insight 4G, a commercial software package, with interrogation areas of size 32x32 pixels where 50% overlap was used between the interrogation areas. The post processing was done by global standard deviation filter, followed by local mean and median filters on the raw vector data. The standard cross-correlation algorithms, used for processing vectors in this experiment, have a special uncertainty of less approximately 0.1 pixels (Huang et al. 1997).

3. RESULTS

3.1 Mean Reattachment Length

As descried earlier that Particle Image Velocimetry (PIV) measurements of the flow field bounding the separation bubble were taken for Building-1. The mean reattachment length (X_r) for Building-1 was found from the mean streamlines obtained from the PIV velocity data. The mean reattachment point was obtained as the location where the flow field changes its direction from reverse flow to the forward flow near the roof surface (as shown in Figure 2 (right)). In Table 1 the mean reattachment lengths for Building-1 are presented corresponding to six upstream conditions considered in this experiment. It is observed that increasing roof height turbulence intensity causes a reduction in the mean size of the separation bubble whereas turbulence length scales in the approaching boundary layer flow do not alter the mean size of the separation bubble. It was also observed from the surface mean pressure data that when the surface mean pressures are normalized to obtain reduced pressure coefficient (Cp^*) in the manner, proposed by Roshko and Lau (1965), described as follows:

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

(where, Cp is the mean pressure coefficient and $C_{p,\min}$ is the minimum value of mean pressure coefficients), the values of Cp^* at the mean reattachment point varies with the upstream turbulence intensity systematically. This systematic variation can well be approximated by a power curve with reasonable uncertainty. Hence, the values of Cp^* at the reattachment points for Building-2 were calculated using the power curve equation and the mean reattachment lengths for Building-2 were determined. These results are also shown in Table 1. The results for Building-2 also demonstrate the shortening of the mean size of the separation bubble as turbulence intensity in the upstream is increased. These results qualitatively match with the results for two-dimensional bluff bodies placed in uniform upstream flows (e. g., Saathoff and Melbourne 1997).

3.2 Pressure Fluctuations under the Separation Bubble

In Figures 3 and 4 the distribution of the standard deviation of surface pressure fluctuations (Cp') along the roof centreline are presented for Building-1 and Building-2, respectively. It is observed that increasing both turbulence intensities and length scales in the incident flow increase the magnitude of surface pressure fluctuations and also the location of maximum pressure fluctuations moves closer to the separation point as turbulence intensity in the upstream is increased. It was described in earlier section that increasing the turbulence intensity actually reduces the size of the separation bubble. In order to investigate whether the location of maximum pressure fluctuation is formed at a particular location on the surface with respect to the scale of the separation bubble, Figure 5 and 6 are plotted for Building-1 and Building-2, respectively, where the distance from the leading edge is normalized by the mean reattachment length (X_r). It is observed from Building-1 data that peak of the pressure fluctuations are formed at distance close to $0.25X_r$ from the leading whereas for Building-2 the location of maximum pressure fluctuations varies with upstream conditions. For building-2, as turbulence is increased in the upstream, the location of maximum pressure fluctuations is also move towards the leading edge with respect to the size of the separation bubble. A closer look at the results for Building-2 also reveals that the shape of distribution of pressure fluctuations is also very different from the results of Building-1 at lower turbulence levels (upstream conditions: 1S and 1L). Hence, Building-2 data at lower turbulence levels indicate a different aerodynamic behaviour than for Building-1 data. This different aerodynamic behaviour for Building-2 is further discussed in section 3.3.

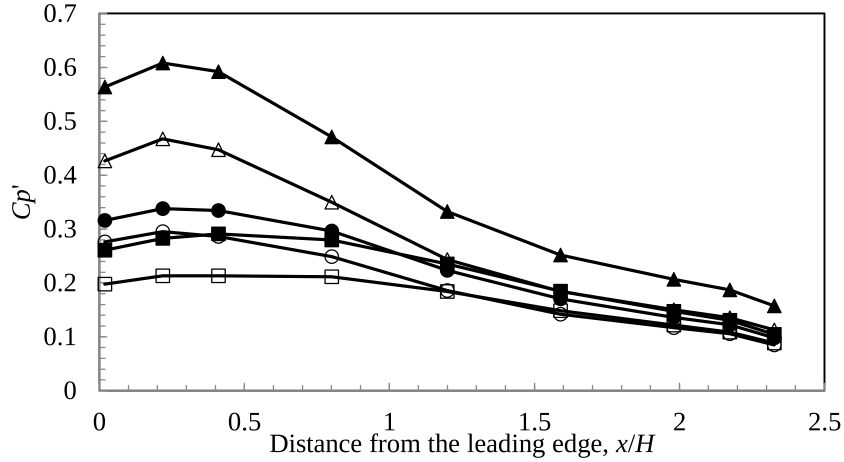


Figure 3: Distribution of fluctuating pressure coefficients (*Cp*') along roof centreline for Building-1. (Legends are shown in Table 1)

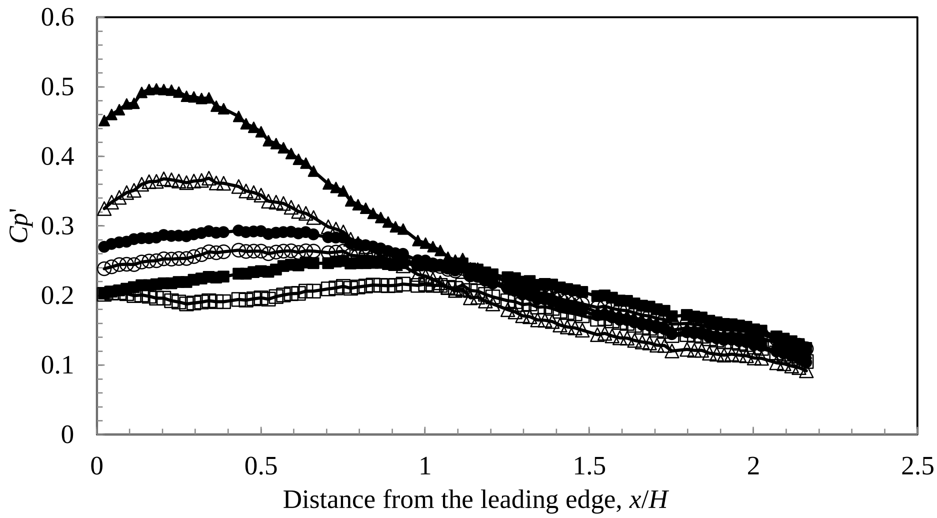


Figure 4: Distribution of fluctuating pressure coefficients (*Cp*') along roof centreline for Building-2. (Legends are shown in Table 1)

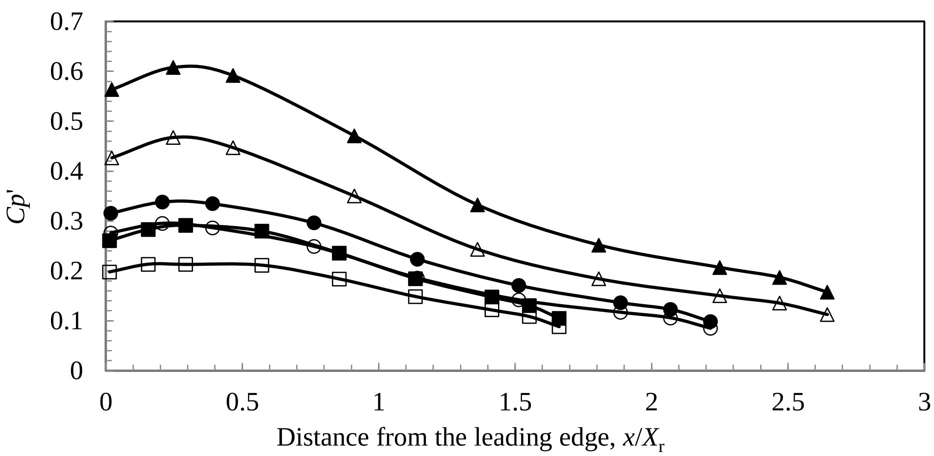


Figure 5: Distribution of fluctuating pressure coefficients (*Cp*') under the separation bubble for Building-1. (Legends are shown in Table 1)

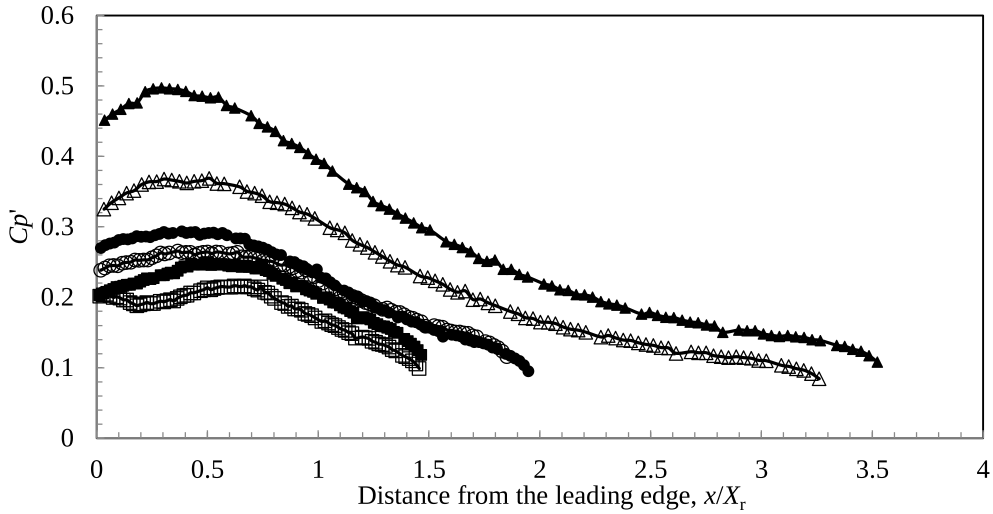


Figure 6: Distribution of fluctuating pressure coefficients (*Cp*') under the separation bubble for Building-2. (Legends are shown in Table 1)

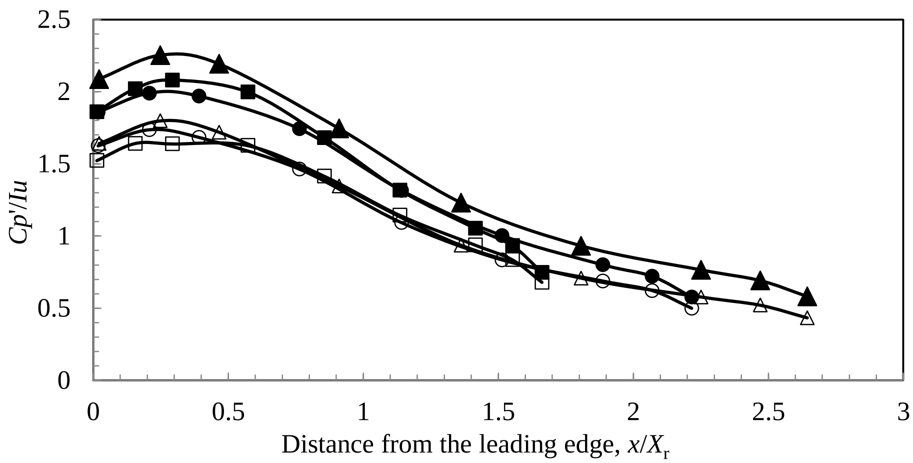


Figure 7: Distribution of fluctuating pressure coefficients (*Cp*') under the separation bubble normalized by roof height turbulence intensity (I_u) for Building-1. (Legends are shown in Table 1)

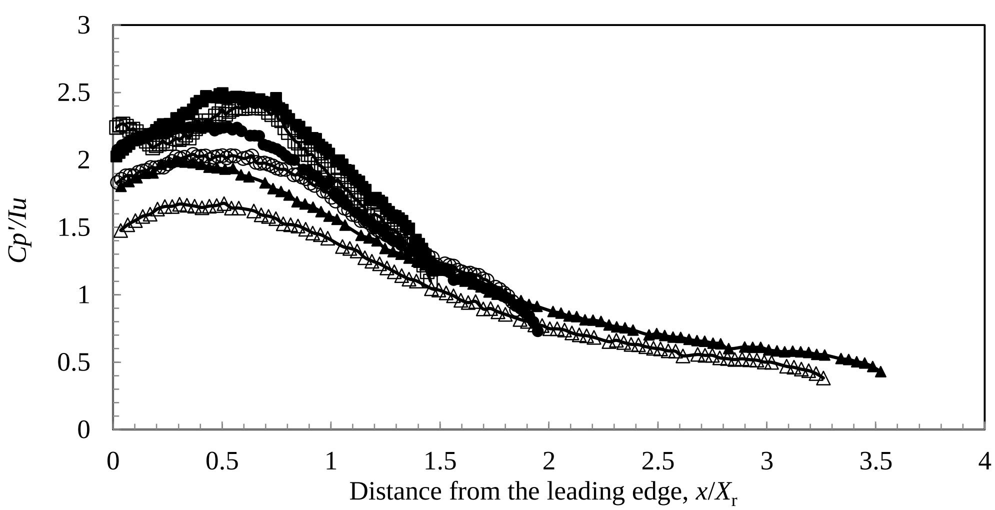


Figure 8: Distribution of fluctuating pressure coefficients (*Cp*') under the separation bubble normalized by roof height turbulence intensity (I_u) for Building-2. (Legends are shown in Table 1)

As understood from earlier discussions that the magnitude of pressure fluctuations depend on both turbulence intensities and length scales. In order to separate the effects of only turbulence intensity on the surface pressure fluctuations from the effects of other parameters Figure 7 and 8 are plotted where the standard deviation of pressure fluctuations are normalized by the corresponding turbulence intensities. After normalization by corresponding roof height turbulence intensities, even though the differences in the values of pressure fluctuations corresponding to different upstream conditions are minimized the values are still significantly different. These results show more clearly that the turbulence intensity is not the only parameter affecting surface pressure fluctuations.

An attempt, similar to Saathoff and Melbourne (1997), was made to investigate the relation of the surface pressure fluctuations with the empirical parameter (η) for the present datasets. The variation of surface pressure fluctuations at six different axial locations (x/X_r=0.02, 0.2, 0.4, 0.6, 0.8 and 0.98) for Building-1 and Building-2 are presented in Figures 9 and 10, respectively. It is observed that at each location considered within the separation bubble the magnitude of surface pressure fluctuations show satisfactory linear relationship with the empirical parameter (η) for both the buildings. For the present experimental cases, the value of the length scale exponent, *n* was found to be 0.35. Even though these variations are linear, as the axial locations move from the leading edge towards the reattachment point, the slopes of the linear fits varies in a non-systematic manner. Also, normalizing the surface pressure fluctuations with corresponding values of the empirical parameter (shown in Figures 11 and 12) does not account for all the differences in magnitudes of pressure fluctuations for the different upstream conditions considered in this experiment, particularly for Building-2. In addition to this, the shape of the surface pressure fluctuations cannot be also be accounted by this empirical parameter. This gives an indication that the shape and magnitude of the distribution of surface pressure fluctuation under the separation bubble cannot be only explained by the turbulence intensities and length scales. There are some other dynamic mechanisms present in the establishing the surface pressure which is more active for Building-2, the larger model used in this experiment.

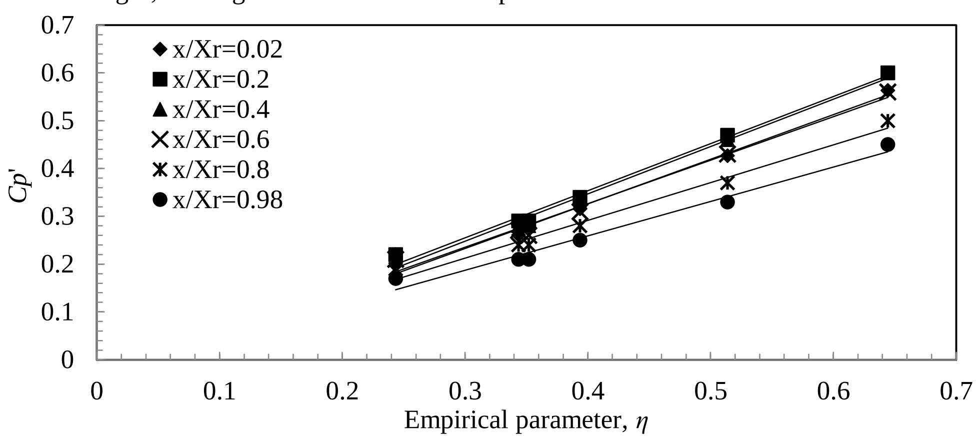


Figure 9: Variation of *Cp*’ with the empirical parameter (*η*) at different axial locations under the separation bubble for Building-1.

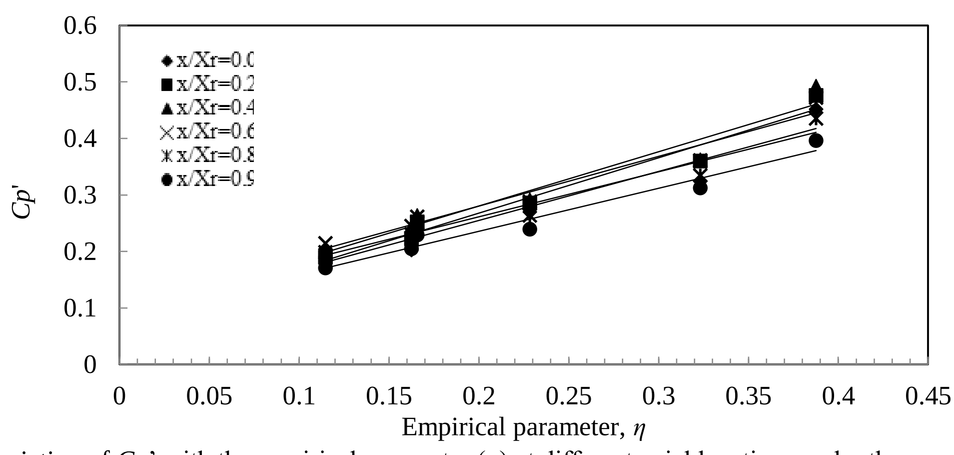


Figure 10: Variation of *Cp*’ with the empirical parameter (η) at different axial locations under the separation bubble for Building-2.

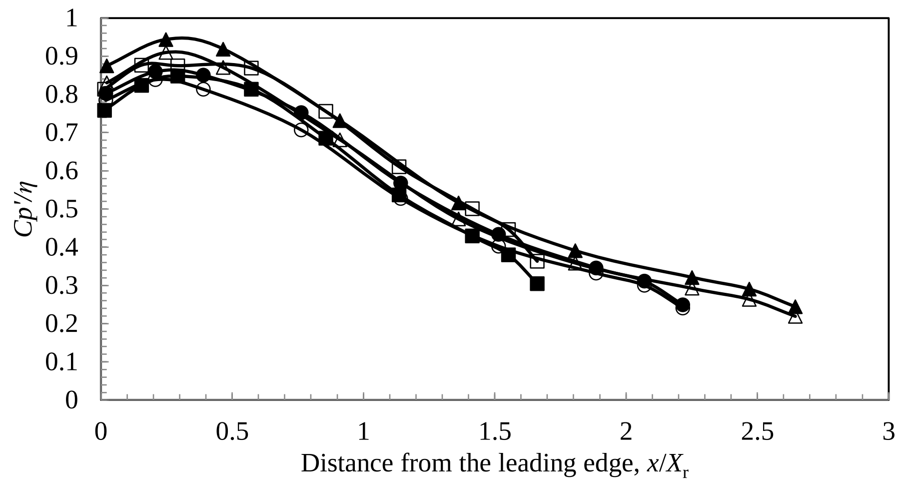


Figure 11: Distribution of fluctuating pressure coefficients (*Cp*') under the separation bubble normalized by the empirical parameter (η) for Building-1. (Legends are shown in Table 1)

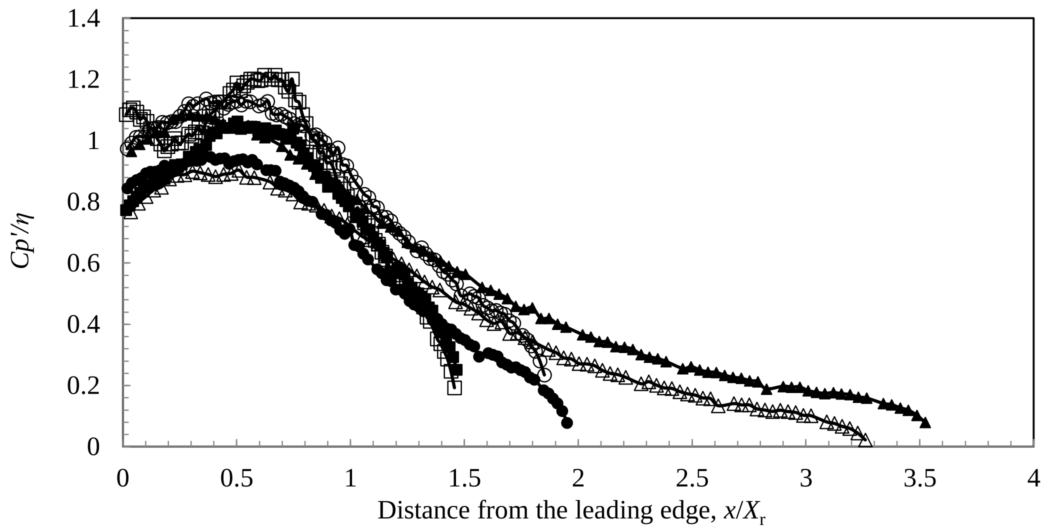


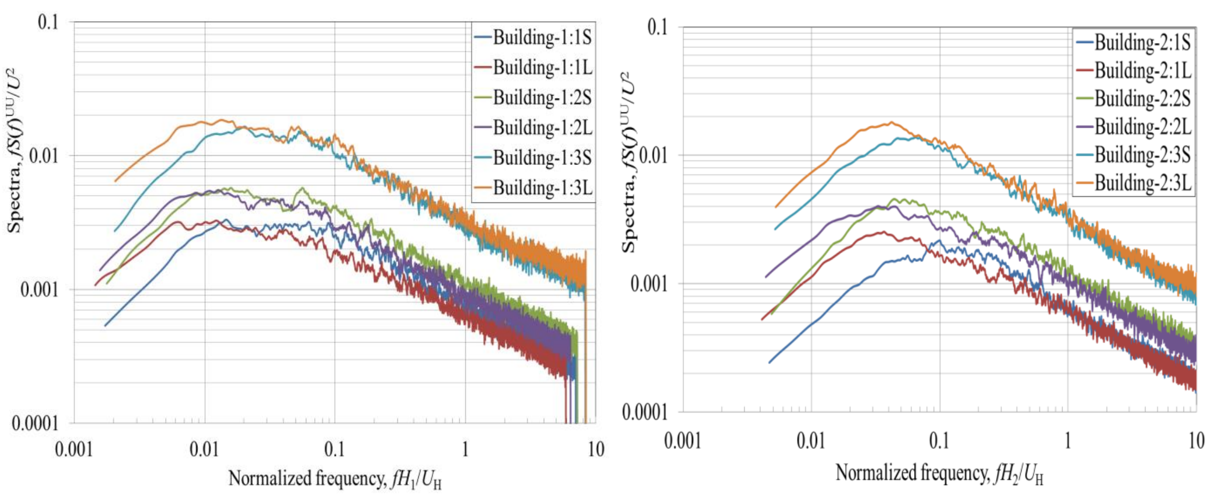
Figure 12: Distribution of fluctuating pressure coefficients (*Cp*') under the separation bubble normalized by the empirical parameter (η) for Building-2. (Legends are shown in Table 1)

3.3 Roof height Velocity Spectra and Surface Pressure Fluctuations

A closer look at Figures 5 and 6 indicate that the shape of the distributions of pressure fluctuations under the separation bubble of Building-1 is similar for all of the six upstream conditions. For all six upstream conditions the fluctuating pressure distributions for Building-1 attain the maximum value at a short distance downstream from the leading edge (separation point) and the magnitude of fluctuation is reduced gradually towards the reattachment point. However, for one particular level of roof height turbulence intensity in the upstream, increasing the integral length scales increases the magnitude of surface pressure fluctuations. Similar is true for Building-2 only at higher levels of roof height turbulence intensities (e.g., upstream conditions 3S and 3L). However, at lower levels of roof height turbulence intensities for Building-2 the shape of distribution of pressure fluctuations are significantly different from Building-1 and Building-2 at higher levels of turbulence intensities. For Building-2, at lower levels of roof height turbulence intensities (e.g., upstream conditions 1S and 1L), the maximum surface pressure fluctuations occur closer to the mean reattachment point. In order to understand the differences in magnitude in pressure fluctuations at similar levels of roof height turbulence intensities and the shape of distribution of surface pressure fluctuations, the streamwise velocity spectra at the two model heights are investigated. These streamwise velocity spectra for Building-1 and Building-2 are shown in Figure 13(a) and Figure 13(b) respectively.

It is observed from Figure 13(a) and Figure 13(b) that at one particular surface roughness configuration (upstream conditions 1, 2 or 3), for both the upstream conditions (upstream conditions 'S' and 'L') the high frequency ends of the streamwise velocity spectra match reasonably well with each other showing a mismatch between the spectral distributions at lower values of normalized frequencies (fH/U). This indicates that the energy in the flow associated with the turbulence scales of significantly higher order of magnitudes compared to the building heights are different from each other even though the configuration of the surface roughness elements are same and the roof height turbulence intensities are similar. Hence, even though the high frequency ends of the spectral distribution are similar to each other, because of the different levels of flow energy associated with lower frequencies, the surface pressure fluctuations show significant differences. The effects of the low-frequency turbulence scales are more significant at lower levels of roof height turbulence intensities as these affect the dynamics of the surface pressure fluctuations, where in addition to the magnitude, the shape of the distribution of surface pressure fluctuations are also altered (e.g., Building-2 at upstream conditions '1S' and '1L' in Figure 4 and Figure 6).

These results have an important application to the wind tunnel testing of scale models. In wind tunnel testing of scale models, typically the higher ends of the velocity spectra are simulated and matched with the desired spectra assuming these high frequency ends (smaller turbulence scales) are important in characterizing the loads on the models. In these tests, it is also assumed that the effects of the higher length scales are not significant and can be approximated by the quasi-steady theory. However, it is observed from the present experimental results that properly simulating the turbulence scales of significantly higher order of magnitude compared to the building heights are also important as the turbulent scales of these orders of magnitude play an important role in characterizing the wind loads exerted on the buildings by altering the behaviour of surface pressure fluctuations.



(a) (b)

Figure 13: Streamwise velocity spectra at roof height, (a) Building-1 and (b) Building-2.

4. CONCLUSIONS

Surface pressure measurements and velocity measurements of the separating and reattaching flows were performed for Building-1, whereas only surface pressure measurements were taken for Building-2. Results indicate that the surface pressure fluctuations increase with both turbulence intensity and length scales in the boundary layer upstream. Especially at lower levels of roof height turbulence intensities, turbulence scales of significantly higher order of magnitude compared to the building heights play important roles in characterizing the shape of the distribution of surface pressure fluctuations. These results have important applications to the wind tunnel testing of scale models.

ACKNOWLEDGEMENTS

This work was funded by the NSERC Discovery Grants program.

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