Wind Engineering into the 21st Century, Larsen, Larose & Livesey (eds) © 1999 Balkema, Rotterdam, ISBN 90 5809 059 0

A model of roof-top surface pressure dependence upon local flow parameters

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ABSTRACT: The overall objective of this study is to understand the flow around low-rise buildings. Particular emphasis is placed upon the nature of the separated flow above the front or leading edge of the roof, where the worst suctions on the building are known to occur. Experimental measurements were used, along with predictions from numerical simulations of delta wing vortex flows, to develop a model of the pressure field within the conical vortex separation zone. The model accounts for the change in vortex suction with wind angle, and implies that the increase in suction toward the leading roof corner or apex is the result of increased local wind speed. The model also suggests how different turbulence frequencies influence surface pressure beneath the vortex.

1 INTRODUCTION

1.1 *Extreme roof-top suction*

Many studies have shown that the worst mean and peak suctions on flat low-rise building roofs occur for cornering or oblique wind angles (Kind 1986). At such angles, conical or delta wing vortices form along the roof edges (see Figure 1). Interest in the behaviour of these vortices has been heightened by the unexpected discrepancy between the rms and peak surface pressures measured under these vortices for full-scale tests and those measured for model scale tests (Tieleman et al. 1996). Recent refinements to the wind tunnel boundary layer simulation appear to have reduced, but not eliminated, the discrepancy (Ham & Bienkiewicz 1998).

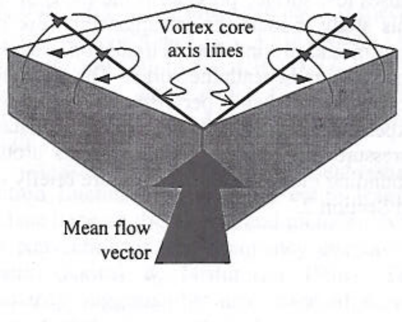

Figure 1 Dual conical vortices in cornering wind

1.2 *Correlation with upstream flow*

In attempting to explain these discrepancies, several studies have examined the variation of surface pressure with upstream flow conditions, often emphasizing the question of the effect of lateral turbulence, as suggested in Tieleman et al. (1994), and reiterated in Tieleman et al., (1998). Kawai & Nishimura (1996) simultaneously measured roof suctions and upstream velocities for a flat roof low rise model building. They concluded, based on the correlation of suction fluctuation over the entire roof, that the dual conical vortices sway in unison, and in concert with low frequency lateral turbulence. (Note that low frequency lateral velocity fluctuations could be seen as short-lived changes in wind direction.)

A connection has also been established between incident large-scale/low-frequency lateral turbulence and suction beneath the separated flow using frequency domain analyses (Hajj et al. 1997) and wavelet analysis on full-scale data from Texas Tech (TTU) (Jordan et al. 1997). However, these studies have not supplied substantiation of a connection between upstream small-scale lateral turbulence and surface pressure fluctuations.

One issue in performing such analyses is the position upstream at which the velocity measurements are recorded. Letchford & Marwood (1997) compared simultaneous upstream laser doppler anemometer (LDA) measurements of u-v-w velocity fluctuations with model surface pressures. These flow velocity measurements were taken quite close to the building, at distances upstream from 2H to

The vortex continues to appear sporadically even at $\omega = 90°$. Experimental results indicate that the flow in this apparently two dimensional case is actually very three dimensional, with circulating flows, or small, unstable vortices, being shed from the leading edge erratically. These flow structures cause the greatest surface suctions within the bubble, confirming results reported by Saathoff & Melbourne (1989). They generally travel away from the leading edge, but can also move laterally in either direction.

Figure 4 shows the Cp_S predictions with the intermittency factor included. If ω is measured $0.1H$ upstream of the leading edge, then the intermittency factor is not needed, and the maximum suction does occur at $80° < \omega < 90°$ (Letchford & Marwood 1997).

4 VALIDATION IN REAL TIME

All of the velocity and Cp terms in Section 3 were mean values. The model has to this point compared favourably to experimental time-averaged pressure and velocity data, though work remains to be done in this area (particularly in experimentally quantifying the intermittency coefficients).

Visualization of the vortex indicates that while the vortex rapidly and erratically changes its position and size, the shape of the vortex re-circulation is generally self-similar, provided the vortex is not completely "washed out", so that it is reasonable to assume that the normalized velocity and curvature profiles remain constant. If this is the case, the model's surface pressure predictions can be compared to a measured Cp time series. The cross-vortex pressure drop can be made time dependent by using time varying velocities:

$$P_S = P_M - \tfrac{1}{2}\rho U_{My}^2(t) \cdot 2 \int_M^S \frac{U^2(a,t)}{U_{My}^2(t) \cdot Rc(a)} da$$

As mentioned above, it is assumed that the integral does not change with wind magnitude or direction, so that g is constant.

At the point M, the quasi-steady theory should apply, which requires that

$$\frac{U_{ref}^2(t)}{\overline{U}_{ref}^2} = \frac{U_M^2(t)}{\overline{U}_M^2} = \frac{U_{all}^2(t)}{\overline{U}_{all}^2}$$

where U_{all} = flow at any point in the flow field. Applying Equation 1 to the point M gives

$$Cp_M = \frac{U_{all}^2}{\overline{U}_{all}^2}\left(1 - \frac{\overline{U}_M^2}{\overline{U}_{ref}^2}\right)$$

Combining these equations gives

$$Cp_S(t) = Cp_M - \left(\frac{\overline{U_M}}{\overline{U_{ref}}}\right)^2 \left(\frac{U_M(t)}{\overline{U_M}}\right)^2 \left[\sin^2(\omega(t)) \cdot I_\delta(\omega(t)) \cdot g\right]$$

$$= \frac{U_{all}^2(t)}{\overline{U}_{all}^2}\left(1 - \left(\frac{\overline{U_M}}{\overline{U_{ref}}}\right)^2 \left[1 + \sin^2(\omega(t)) \cdot I_\delta(\omega(t)) \cdot g\right]\right) \qquad (6)$$

where the subscript S indicates the moving point beneath the vortex core. Since this point changes, $Cp_S(t)$ does not correspond to the pressure at a single tap. Instead, the pressure predicted by Equation 6 is compared to the maximum suction measured at any time for a series of taps in the 'x/H = constant' plane of interest.

Note that Equation 6 obeys the quasi-steady theory for the moving point 'S', with the exception of the intermittency term. For a time series, the intermittency is a "two-level" delta function; if the vortex is present, $I_\delta = 1$. Current data indicate that I_δ is expected to be ~0.5 for longer duration wind angle shifts to $\omega > 70°$ (the vortex is absent, but the flow still re-attaches). For longer duration wind angle shifts above $\omega > 80°$, I_δ is generally 0, as the flow seldom re-attaches with much curvature. This is similar to the "wash-out" phenomenon, where $I_\delta = 0$. As mentioned above, even at $\omega = 90°$, the vortex can form momentarily, in which case $I_\delta = 1$.

Recall that the quasi-steady theory is known to hold for the surface under the vortex only if velocities are measured close to the roof's leading edge. In this validation experiment, the normalized time varying velocity ($U_{all}(t)/U_{all}$) was measured at the point 'C', directly above the leading edge at the mean vortex core height. The resulting measured and predicted Cp_s time series are shown for the 1:50 model of the TTU field site in Figure 5. The data are low-pass filtered at 15Hz for this plot, and $I_\delta(t)$ was set to 1, since $\omega(t) < 65°$ for the entire segment. The value of g, based on the velocity profile shown in

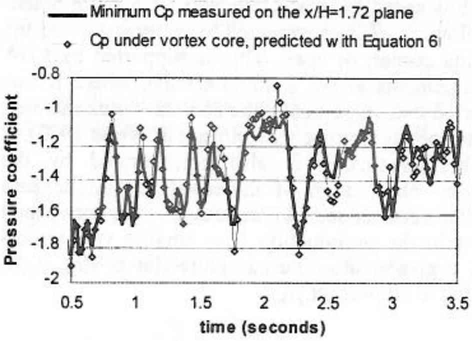

Figure 5 Measured and predicted pressure coefficient time series for roof surface beneath the vortex core, filtered at 15Hz.

Figure 3 and the *Rc(a)* formulae in Section 3.2, is 1.5. The correlation coefficient for the filtered data is over 0.9. The calculated and measured Cp_{rms} and mean Cp values for the unfiltered time series are within 2% of each other.

The model was also applied to full-scale data obtained from the TTU Wind Engineering Field Laboratory (WERFL). The Cp values measured at tap 50501 were compared with those predicted by Equation 6 using wind velocities measured above the roof apex with a 3 component sonic anemoter. (The facilities are described in Zhao et al. (in prep. b)). A value of $g = 1.5$ was again used, and $I_S(t)$ was assumed to follow the two level behaviour described above. The calculated and measured Cp_{rms} and mean Cp values were within 5% of each other.

4.1 *Effects of instantaneous flow structure*

By normalizing the measured $Cp_s(t)$ profiles by the $Cp_s(t)$ minima predicted by Equation 6, the effect of instantaneous velocity fluctuations can be removed:

$$Cp_S^N(t) = \frac{Cp_S^M(t)}{Cp_S^C(t)}$$

where the superscripts denote 'Normalized', 'Measured', and 'Calculated' (Eqn. 6).

Close examination of the corresponding image sequences shows that vortices with normalized $Cp^N{}_S > 1$ generally corresponded to vortices with well-defined re-attachment points, while images with $Cp^N{}_S < 0.8$ often corresponded to "wash-out" phenomena, where the vortex is momentarily not present and reattachment is not evident. These changes in vortex reattachment occur very quickly ($fH/U > 25$), so that they are difficult to observe on a 1:50 scale model with a camera frame rate of $f =$ 60Hz ($fH/U = 6$). Using a camera shutter speed of 250 Hz (fH/U=25) helps, but future tests will be conducted on a larger model to slow down the phenomenon.

5 A THREE FREQUENCY RANGE MODEL

A normalized frequency of $fH/U > 25$ implies a length scale smaller than the circumference of the vortex. Data presented for bubble separation in Li & Melbourne (1995) shows that for constant levels of turbulence intensity (ranging from 8% to 15%), increasing the integral scale (Lx) had no effect on mean suction until Lx exceeded the re-attachment length, which is approximately equal to the vortex circumference. At this point, the mean suction decreased. Melbourne (1993) has pointed out that the smaller separation zones, which feature greater curvature and higher surface suction, are instigated by small-scale turbulence, which increases the entrainment in the shear layer. Turbulence or velocity fluctuations larger than the separation zone would be expected to increase the speed of the vortex rotation, rather than affect the entrainment. This would in turn increase the peak and rms suction, since each gust is amplified by the curving separated flow, but would reduce entrainment, and so reduce curvature, thus reducing the mean suction. This is in fact what has been observed (Li & Melbourne 1995).

As a result, the simulation of all scales of turbulence could be important in reproducing suction beneath the conical vortex. Vertical fluctuations of a size smaller than the vortex circumference are expected to influence entrainment, and so control the shape of the re-attachment zone, though some portion of turbulence at this scale is generated by the leading edge itself. Lateral fluctuations larger than the vortex circumference, but smaller than the building length, are expected to accelerate the vortex spin, without changing its position or size. (This would explain why "fast and large" wind direction changes (short duration, large angle change), in which the wind briefly flows normal to the leading edge, have been observed to produce suction peaks (Zhao et al. in prep. a)). Lateral fluctuations larger than the building will cause the vortex to move its position, and vortex motion significantly affects Cp rms values near the vortex, especially at the point of flow re-attachment. Longitudinal or stream-wise gusts of all scales larger than the vortex circumference will influence vortex rotation speed. Larger scales could also be associated with vortex "wash-out".

Note that the vortex circumference increases with distance from the apex. This suggests that as the apex is approached, it becomes increasingly important to simulate smaller and smaller scales of turbulence in order to reproduce peak pressures. A fairly small gust in u or v will last long enough to spin the vortex around faster and transfer a momentary low core suction to the surface.

6 CONCLUSIONS

A curvature based model for the relationship between local flow speed and roof surface pressure has been developed and evaluated. The model links the components of flow velocity, measured near the roof's leading edge, to the pressure fluctuations beneath the conical vortices which form on the flat roofs of low-rise buildings subjected to cornering winds. The model's predictions agree well with time series measurements, both for the time averages and the low frequency components, though some further validation is required.

7 ACKNOWLEDGEMENTS

The essential contributions of Dr. David E. Neff and Dr. Bernd Leitl in developing the experimental facilities at CSU are gratefully acknowledged. This work is supported by the US National Science Foundation, Grant No. CMS-9411147.

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