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Aerodynamic forces on generic buildings subject to transient, downburst-type winds

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ABSTRACT

Having been identified as the cause of design load winds in many parts of the world, transient winds such as gust fronts and thunderstorm downbursts have been increasingly researched over recent years. The difficulties in simulating the flow structure of downbursts in the laboratory, particularly their rapid radial acceleration and associated ring vortices, have complicated measuring wind loads on structures subject to these conditions. The University of Birmingham Transient Wind Simulator (UoB-TWS, a 1 m diameter impinging jet with aperture control) has been used to simulate the transient aspects of downburst-like flow, allowing the pressure distributions they create over cube and portal framed structures to be measured for the first time, at model-scale (1:1600). Analysis of the velocity and pressure fields show that the simulator is capable of creating velocity fields which are similar to those observed in nature. Development of the ring vortex is demonstrated through phase-plot analysis. Two methods of calculating the turbulence intensity of the unsteady flow field have been used, giving mean values of between 3% and 10% depending on the method. Force coefficient time series have been estimated with the buildings angled at 0°, 45° and 90° to the radial wind direction. These are presented along with the instantaneous pressure coefficient distribution at the time of maximum roof suction. This novel research also highlights the difficulties of undertaking transient flow at model scale and drawing conclusions which are applicable to full-scale, i.e., where no two events are the same.

1. Introduction

Over the last few years there has been renewed interest in evaluating the impact of transient winds caused by convection in thunderstorm cells, i.e. gust fronts, downbursts and tornadoes. This has been driven by the acknowledgement that in many parts of the world it is such transient winds (rather than synoptic, boundary layer winds) which are the cause of design wind speeds (Chay and Letchford, 2002a). Research has been undertaken to physically simulate tornadoes (e.g. Chang, 1971; Haan et al., 2008; Jischke and Light, 1983; Mishra et al., 2008) and downbursts. The latter, which are the main subject of this paper, have been simulated in a number of ways: very small-scale density driven flows (e.g. Lundgren et al., 1992); slot jets (e.g. Butler and Kareem, 2007; Lin et al., 2007); multi-fan wind tunnels (e.g. Butler et al., 2010); steady impinging jets (e.g. Chay and Letchford, 2002a,b; Choi, 2004; Wood et al., 2001; Zhang et al., 2013) and pulsed impinging jets (e.g. Haines et al., 2013; Mason, 2003; Mason et al., 2009a; McConville et al., 2009). Complementary research has been undertaken in terms of numerical simulation of downbursts (e.g. Butler and Kareem, 2007; Chay et al., 2006; Kim and Hangan, 2007; Mason, 2003; Mason et al., 2009b). In many of these studies, the emphasis has been on re-creating the familiar "nose" of a downburst outflow, in which the maximum horizontal streamwise velocity is seen to occur close to the ground, unlike the monotonically increasing, logarithmic distribution of atmospheric boundary layer (ABL) winds.

The pressure field on structures subject to downburst winds have been investigated in a number of the works mentioned above. Chay and Letchford (2002a) and Sengupta et al. (2008) measured pressure distributions over a cube exposed to a steady, translating, impinging jet at a relatively small scale (jet diameter $D=0.51$ m, $D=0.20$ m, $D=0.20$ m respectively). Mason et al. (2009a) attempted to simulate the ring vortex of a downburst using a pulsed version of Chay and Letchford's impinging jet, while Butler et al. (2010) examined the pressures on prismatic buildings in a 2-D downburst simulator. Butler et al. investigated the effects of varying the building height with respect to the height of the maximum outflow velocity. Zhang et al. (2013) examined the forces acting on gable-ended (portal) buildings under steady-state, impinging jet flow, with two roof angles examined. The above work have tended to express the

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pressure and force data in terms of a generalised coefficients (C_p) and drag coefficients (C_d), defined as

$$C_p = \frac{p - p_{ref}}{\frac{1}{2}\rho V^2} \quad (1)$$

$$C_d = \frac{1}{A_s}\int_{A_s} C_p \, dA \quad (2)$$

where p is the absolute pressure, p_{ref} is a reference pressure, ρ is the air density, A_s is the total area of the surface under consideration, and V is the velocity used to calculate a reference dynamic pressure for normalisation. When considering "closed" or sealed buildings, with negligible permeability, the internal pressure will tend to remain constant over the short duration of a transient wind event, and as such the static (atmospheric) pressure (p_{atm}) may be used for p_{ref}. For porous buildings where the internal pressure follows closely changes in the local static pressure which occur during the event, a reference pressure is more problematic and the local time varying static (atmospheric) pressure could be used when calculating forces. The choice of V varies by application – for ABL winds, the eaves height wind-speed is the standard for normalisation (see, for example, Richards et al., 2001), and is the maximum wind-speed to which the windward surface is exposed; for transient flows the choice is complicated by spatial (varying vertical velocity profile) and temporal (transient nature of the flow) considerations. Full-scale data indicate that the maximum velocity occurs at a height 30 m $< z_m <$ 100 m (Fujita and Wakimoto, 1981; Hjelmfelt, 1988). For low-rise buildings (for which eaves height will be below z_m), the eaves height wind-speed has the same significance as for ABL winds. For high-rise buildings (for which eaves height is above z_m), the eaves height wind-speed is not the maximum on the windward face; the peak maximum speed takes this role. It may be argued that the peak maximum speed is the better choice when comparing pressure fields on buildings of different heights subject to downbursts, or when comparing high-rise buildings subject to downbursts with those in ABL winds; conversely the eaves height wind-speed is arguably better for comparison of pressure fields on low-rise buildings exposed to downbursts and ABL winds. An alternative for downbursts is to use the downdraft velocity (herein referred to as V_j due to its being the equivalent of the jet velocity in impinging jet simulations), though this is problematic for full-scale events as it is not directly measured and must be estimated. The normalising velocity used by each group of researchers is stated where their results are mentioned in Section 4.

Chay and Letchford (2002a) examined the differences between the centreline pressure coefficients on a cube (calculated using $p_{ref}=p_{atm}$, and the jet velocity for normalisation) at 0° yaw angle for downburst (steady impinging jet) and ABL winds, illustrated in Fig. 1 (where $C_{pe} \equiv C_p$ and X is the radial distance from the centre of the downburst). Windward wall pressure coefficients are higher for downburst winds, and more uniform. For $X/D = 0.75$ (relative distance from the downburst impact), suction is approximately 30% smaller on the roof at the leading eave compared to ABL flow. Chay and Letchford partly ascribe the differences over the roof to the difference in turbulence intensity, with the uniform, downburst and ABL flow cases having turbulence intensities of $<5\%$, 20% and 27%.

The advances made through this and similar research, encouraged reflection on how transient winds should be analysed. Downburst outflow is radial, with the radial velocity represented herein by U. Traditional analysis methods and parameters (e.g., turbulence intensity, spectral power density, etc.) assume a stationary time series which, by definition, is not the case for a transient event. In order to make use of these parameters, methods have been employed which split the time-series into at least two parts, one representing the underlying velocity trend, $U(t)$, and the other the turbulent fluctuations about this trend, $u'(t)$. The former may be approximated by using a running mean (e.g. Holmes et al., 2008) or the low-frequency levels of a discrete wavelet transform (e.g. Wang and Kareem, 2004; Wang et al., 2013) and removed from the time-series to leave only the fluctuations. Alternatively, a "detrended" time-series may be derived by splitting the time-series into sub-sections, each of which has an identifiable trend which may be removed (Orwig and Schroeder, 2007). The method used in the current research is similar to that of Wang and Kareem, and so this will now be discussed in more detail. In place of the standard definition of turbulence intensity for a stationary signal, I_u

$$I_u = \frac{\sigma_u}{U} \quad (3)$$

in which σ_u is the standard deviation of U, Wang and Kareem proposed a windowed version

$$I_{u,T}(t) = E\left[\frac{\sigma_{u,T}}{U_T(t)}\right] \quad (4)$$

giving an instantaneous value of $I_{u,T}$ at time t. $I_{u,T}(t)$ is the expected value of the instantaneous turbulence intensity calculated using a time-varying mean, $U_T(t)$, over a window of width T. This gives a turbulence intensity time-series – if applied to a stationary signal, the standard definition of I_u is simply the expected value of this time-series; i.e. it is $I_{u,T}$ with a single window spanning the entire time-series. Whether a running mean or wavelet approach is used to determine $U_T(t)$, there is an element of subjectivity in deciding the boundary between the turbulent and mean components, though Wang and Kareem did attempt to avoid this by comparing the probability density function (pdf) of the turbulent component to a Gaussian distribution.

Despite the large effort expended in simulating downburst-type events, there has been little explicit acknowledgement in the wind engineering literature of the variability that exists with such phenomena, and the corresponding implication that this can have on the near ground wind speeds. This may perhaps be attributed to the dearth of appropriate full-scale measurement with data captured at Andrews Air Force Base (AAFB) (Fujita, 1985), the Texas Rear Flank Downdraft (TRFD) (Gast and Schroeder, 2003; Orwig and Schroeder, 2007) and Tuas, Singapore (Choi, 2004) and by Lombardo (2011) being the exception. Interestingly, the Lombardo work clearly highlights such variability. McConville et al. (2009) illustrated the variability which can occur between different experimental runs of an impinging jet, transient wind simulator. Their work focused on generating an ensemble average which was then compared with the AAFB data, and this ensemble approach is maintained in the current research. While an averaging method such as this may seem inappropriate for the investigation of forces on structures, in which maximum aerodynamic forces may be deemed of greatest importance, it is shown later that, due to the velocity scaling, the force coefficients calculated from the ensemble approach are comparable to those from a single run "maximum". The ensemble approach then permits amalgamation of results, as will be explored in more detail later.

Despite the advances made to date in this field, there is still work required in order to understand not only the structure of transient winds but also their interaction with engineering structures and the corresponding implications of these interactions. The current paper will address these issues (at model scale) for two engineering structures, i.e., a typical portal-framed structure and a cube. However, before such interactions are examined, Section 2 will briefly outline the experimental facility used while Section 3 will examine the profiles of the generated wind velocities. Section 4 outlines the aerodynamic pressure and forces coefficients on both structures while appropriate conclusions are drawn in Section 5.