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LES modelling of unsteady flow around the Silsoe cube

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ABSTRACT

Large Eddy Simulation is used to model the unsteady flow over the Silsoe 6 m cube with the wind perpendicular to one face. The mean, standard deviation, maximum and minimum pressure coefficients are shown to be in reasonable agreement with published data. In regions affected by building induced pressure fluctuations the standard deviation coefficient is higher than in full-scale due to the lower turbulence intensity in the LES model. Conditional averaging is used to highlight the sequence of pressure changes that occur around strong suction spikes on both the sidewalls and roof. The LES model is shown to reproduce the pattern observed in full-scale. Flow visualisations reveal that these events are associated with the formation of a strong vortex on the windward half of the sides or roof, which is then shed and carried downstream.

1. Introduction

The Silsoe 6 m cube, see Fig. 1, was constructed in order to provide a facility for fundamental studies of the interactions between the wind and a structure. This shape was chosen since it represents a simplified building, has multiple planes of symmetry and in spite of its simplicity still exhibits many of the complex flow phenomena found on more complex building shapes. Richards et al. (2001) was the first of a series of papers which have provided full-scale data together with in-depth analysis of the pressure and flow fields. Although the 2001 paper only contained limited mean pressure data, it has been used for verification of CFD techniques including Large Eddy Simulations (LES) by Lim et al. (2009) and Detached Eddy Simulations (DES) by Haupt et al. (2011) and for evaluation of experimental facilities such as the Wall of Wind (Aly et al., 2011). More recently Richards and Hoxey (2012a, b) have provided standard deviation, maximum and minimum pressure coefficient data. The research reported in this paper uses LES to understand some of the unsteady phenomena observed at full-scale.

2. Unsteady pressure data

Fig. 2 is a typical example of the full-scale pressure data from the Silsoe cube for one of the mid-height wall taps. In each graph the symbols are the data from one 12 min run, while the solid lines are short Fourier series fitted to the data by using a least squares method. The three dashed lines represent quasi-steady expectations which are derived from the curve fitted to the mean data. For full details of the fitting techniques and quasi-steady modelling see Richards and Hoxey (2012a, b). It may be observed that the standard deviation and maximum pressure coefficients are approximately equal to that expected from the quasi-steady theory; however when the wind direction is in the range 345–45° the minimum pressure coefficient is consistently more negative than predicted. In fact the quasi-steady line almost forms a lower bound to the measured data. It may be noted that this range of angles encompasses those where the flow separates from the nearby windward vertical edge and probably reattaches to the face containing H2 at some point. Richards and Hoxey (2012b) suggest that these high suctions are due to the dynamic response of the separating and reattaching flow which periodically rolls up into an intense vortex. A similar pattern is observed with roof Tap V8 with wind directions around 90°. The form of the pressure coefficients used here follows Richards and Hoxey (2012a), who recommend

$$C_{\bar{p}}(\bar{\theta})=\frac{\bar{p}}{\bar{q}},\quad C_{\tilde{p}}(\bar{\theta})=\frac{\sigma_p}{\sigma_q},\quad C_{\widehat{p}}(\bar{\theta})=\frac{\widehat{p}}{\widehat{q}},\quad \text{and}\quad C_{\breve{p}}(\bar{\theta})=\frac{\breve{p}}{\widehat{q}} \qquad (1)$$

where p is the surface pressure and q is the reference dynamic pressures measured at cube height in the approach flow. σ_p is the standard deviation of pressure, while $\bar{p}$, $\widehat{p}$ and $\breve{p}$ are the mean, maximum and minimum values of pressure respectively, with similar meanings when applied to the reference dynamic pressure. This scaling was chosen by Richards and Hoxey (2012a) since these

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coefficients are all of comparable magnitude and are much less sensitive to changes in conditions in comparison to the more usual coefficients, where all pressure statistics are normalised by the mean dynamic pressure. Further explanation can be found in that paper.

3. Computational technique

The simulations were performed using an in-house massively parallel Large Eddy Simulation code, SnS (Armfield et al., 2002; Norris, 2001), which uses an incompressible non-staggered finite volume formulation based on a structured Cartesian mesh. Second order central differences were employed for approximating the advective and diffusive fluxes in the momentum equations, and an Adams–Bashforth fractional step solver was employed, which gives a solver that has been shown to be second order accurate in both space and time (Armfield and Street, 2002). The fractional step method negated the need for iterative coupling at each time step, allowing the efficient calculation of transient flows. Subgrid scale turbulence is modelled using the standard Smagorinsky model (Smagorinsky, 1963) with $C_s=0.18$, damped at the wall using the method of Mason and Thompson (1992), with a rough wall function (Mason and Callen, 1986) being applied at the ground boundary.

The majority of calculations were made on a 15 h × 10 h × 6.67 h computational domain (i.e.: 90 m long, 60 m wide and 40 m high), using a 246 × 123 × 186 mesh with a resolution varying from 0.02 m at the wall, to 0.5 m in the far field (see Fig. 3). The cube was modelled as being aerodynamically smooth, while the ground was modelled with a roughness of $z_0=0.01$ m. The top of the domain had a free-slip boundary condition applied, and the two side boundaries were periodic. The velocity was prescribed at the upstream boundary, with a mean velocity of 6 m/s at a height of 6 m, and a prescribed pressure outlet boundary condition was applied at the downstream boundary.

The inlet boundary condition at the upstream boundary required the definition of an atmospheric boundary layer, including both the mean profile and the temporal and spatial fluctuations of the flow. This was generated using a precursor calculation of the flow in a 720 m × 40 m × 60 m empty domain with periodic boundary conditions in the streamwise direction, the flow being driven by a pressure gradient in the streamwise direction. The flow at the low x boundary was sampled at 0.05 s intervals for a period of 75 min. This was broken into 12.5 min blocks of data, which were used for 6 runs modelling the flow around the cube. The flow was allowed to settle for the first 30 s of each run, and then 12 min of data was recorded.

Fig. 4(a) shows the velocity profile created by the precursor calculation, which up to a height $z=4$ h is approximately equal to a simple log law with the prescribed roughness length $z_0=0.01$ m, which is typical for the full-scale site. The slightly higher velocities at

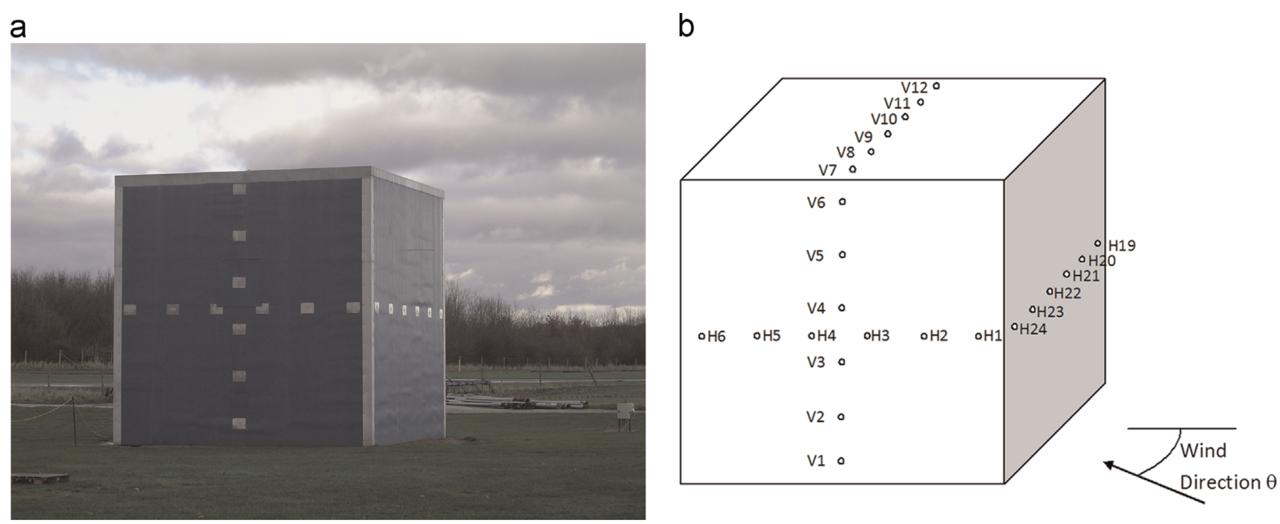

Fig. 1. (a) The Silsoe 6 m cube with the metal plates around each pressure tap clearly visible and (b) the pressure tap numbering system used in this paper.

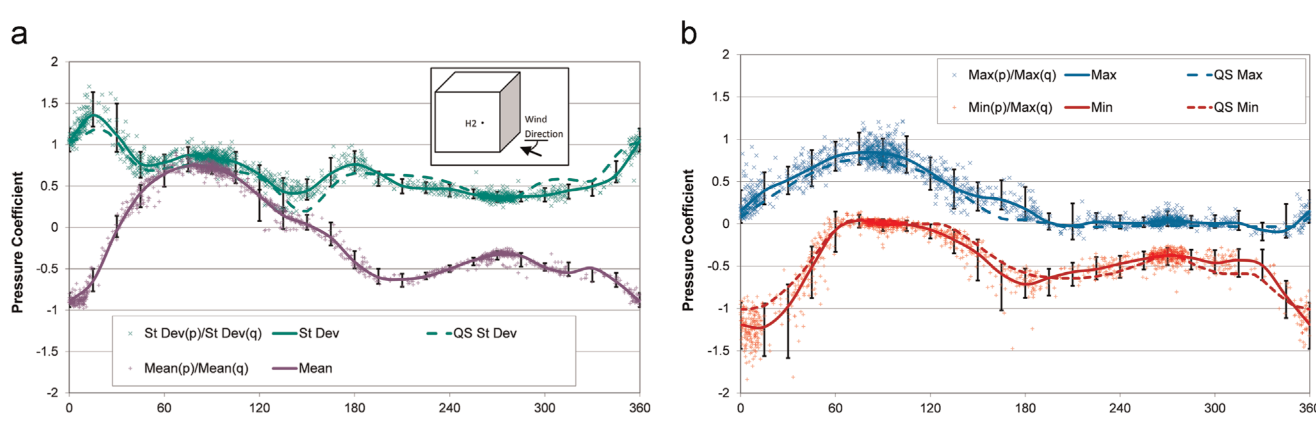

Fig. 2. Full-scale pressure coefficients for Tap H2, at mid height and 0.24 h from one vertical edge, (a) mean and standard deviation and (b) maximum and minimum.