Large Eddy Simulation of Surface Pressure on the Silsoe Cube

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Abstract

Large Eddy Simulations (LES) of flow around the Silsoe Cube \((h = 6 \text{ m})\) for perpendicular approach flow were performed for \(\text{Re}_h = 4 \times 10^6\). The aim was to assess the ability of LES to estimate mean surface pressure at the cube outer walls. Simulations on 3 structured grids with grid refinement close to the cube were performed. The LES predicted pressure coefficients showed on average a relative absolute deviation of 13\% from the full-scale measurements with relative deviations between -31\% and +41\% with the smallest deviations at the roof and the largest deviations at the back wall.

1 Introduction

The numerical simulation of the mean surface pressure on buildings with Computational Fluid Dynamics (CFD) is still a challenging task. In particular close to sharp building edges and corners, e.g. wall and roof edges, where flow separation occurs and strong gradients or discontinuities in the surface pressure distribution are present, the class of the frequently used Reynolds-averaged Navier-Stokes (RANS) equation based turbulence models often provides only limited reliable results. A further problematic issue with RANS turbulence models is the flow reattachment at “long” building walls. The commonly employed standard \(k-\varepsilon\) turbulence model for example predicts in general too small recirculation regions at obstacle top faces with too early, i.e. upwind shifted, reattachment positions which is a consequence of the stagnation point anomaly (e.g. Rodi 1997; Tsuchiya et al., 1997).

A clear improvement of the numerical prediction of surface pressures on building walls is expected from Large Eddy Simulations (LES). Moreover, since LES is time resolved, it is also expected to provide more accurate data of the temporal variations in the flow and surface pressure both in statistical (e.g. higher order moments) and time series terms. This suggests LES in particular as a potential tool for estimating peak wind loads.

The aim of this study is to assess the performance of LES to calculate the mean surface pressure on a generic shape building. To this end, LES of the Silsoe 6 m Cube (e.g. Richards et al., 2000; Richards et al., 2001; Richards & Hoxey, 2008; Richards & Hoxey, 2012) were performed. To the best of the author’s knowledge, LES of the Silsoe Cube were only performed by Köse & Dick (2010) so far. This study differs from the former one in that it (i) employs a dynamic subgrid-scale model instead of static or implicit modeling, (ii) it uses a totally conformal instead of a non-conformal mesh, and (iii) it provides a grid sensitivity analysis based on 3 meshes.
which are all coarser than that used by Köse & Dick (2010). The Silsoe Cube was chosen as an object of study since it represents a generic geometry of the basic shape of many buildings. Its generic character allows investigating the resulting flow and surface pressure without a superposition of the disturbances caused by decorative or smaller scale architectural features. In addition, since the cube is a full-scale object subjected to a fairly well developed atmospheric boundary layer flow and has been investigated for more than 10 years with continuous documentation, it is a very suitable object for this study.

2 Numerical Simulation Setup

The simulations were done with the general-purpose CFD code ANSYS FLUENT 12.1.4 (ANSYS Inc., 2009) employing LES with the dynamic Smagorinsky-Lilly subgrid-scale (SGS) model. The dimensions of the computational domain, the location of the cube and the boundary conditions are shown in Figure 1 (left). They were chosen according to the recommendations compiled in the COST Action 732 (Franke et al., 2007; Franke et al., 2011) and comply with the AIJ guidelines for CFD pedestrian wind environment studies (Tominaga et al., 2008). Simulations on 3 structured grids with a total number of 694500, 839100 and 941500 cells differing in the grid resolution around the cube were performed. The cube sides were discretized by 25, 30 and 35 cells in each direction with the finest cell size at the cube edges being 0.1 m (Figure 1, right) and stretching ratios of 1.14, 1.09 and 1.06, respectively. At the inlet boundary, vertical profiles for mean wind speed $U$ (Eqn. 1), turbulence kinetic energy $k$ (Eqn. 2), and turbulence dissipation rate $\varepsilon$ (Eqn. 3) were prescribed:

$$U(z) = \frac{u_t}{\kappa} \ln \left( \frac{z}{z_0} \right)$$  \hspace{1cm} (1)

$$k(z) = \frac{u_t^2}{\sqrt{C_\mu}} \hspace{1cm} (2)$$

$$\varepsilon(z) = \frac{u_t^2}{\kappa(z+z_0)} \hspace{1cm} (3)$$

with $u_t (= 0.63 \text{m s}^{-1})$ the friction velocity, $\kappa (= 0.4)$ the von Karman constant, $z$ the height coordinate, $z_0 (= 0.01 \text{m})$ the aerodynamic roughness length (Richards et al., 2000), and $C_\mu = 0.09$, resulting in an undisturbed approach flow velocity at cube height $h$ of $u(h = 6 \text{m}) = 10.08 \text{m s}^{-1}$ and a corresponding building Reynolds number of $Re_h = 4\times10^6$. At the inlet boundary, fluctuations were superimposed on the mean velocity profile (Eqn. 1). These fluctuations were generated with the Vortex Method (Mathey et al., 2006).

![Figure 1: Computational domain with boundary conditions (left), and grid around cube (right).](image-url)
The fractional step algorithm for pressure-velocity coupling was used together with the ANSYS FLUENT implementations of the Bounded-Central-Differencing scheme for momentum and the Standard scheme for pressure (spatial discretization), and a Second-Order-Implicit scheme with non-iterative time advancement (temporal discretization).

The initialization run was performed over 25 s comprising 2.2 flow-through times based on the streamwise bulk velocity. The results presented here originate from statistics over 225 s with a time step of 0.005 s. Since this time step ensures a CFL < 1 for each cell, a time step analysis was set aside. Deploying the Strouhal relation \( S = f_s h U_c^{-1} \) with \( S = 0.12 \) and the characteristic velocity \( U_c = U(z = 0.5 h) \), the cube-induced vortex shedding frequency \( f_s \) is estimated to 0.18 Hz. Hence, the 225 s sampling period can be considered as an averaging over 40 of the largest cube-induced vortex structures and is assumed to provide reliable statistics of the flow and pressure quantities at the cube roof, side and back walls.

3 LES Results and Comparison with Measurement Data

Figure 2 shows the pressure coefficient \( C_p \), with the dynamic pressure at cube height \( h \) as reference, along the vertical center-plane transect (left) and the horizontal center-plane transect (right). In comparison to the measurements, the LES in general overestimate the \( C_p \)-values at the cube front and side walls, and underestimate them at the roof and back wall. Overall, relative deviations between -31 and +41% are found, with best agreement at the roof and worst agreement at the back wall. In average, the relative absolute deviations amount to 12, 13 and 12% on the coarse, medium and fine mesh, respectively. The overestimation at the front wall is primarily attributed to the acceleration of the streamwise approach flow close to the ground between the inlet plane and the cube (Blocken et al., 2007; Hargreaves & Wright, 2007). This is due to an inadequate representation of the surface roughness since a smooth wall condition was applied here. Results based on the implementation of rough wall functions will be presented in the full paper.

The results of the grid sensitivity study have to be handled with care and allow only limited conclusions. Neither do the simulations show strict monotonic behavior nor do they always come closer to the full-scale measurements with increasing grid refinement. However, the differences between the 3 grids are rather modest with 28% maximum and 11% average mutual deviations.

![Figure 2: Pressure coefficients \( C_p \) at the cube surface along the vertical (left) and horizontal (right) center-plane transect.](image-url)
4 Conclusions / Outlook to Full Paper

Since the grid sensitivity study did not provide an overall monotonic behavior in the mean $C_p$ values it is concluded that the underlying meshes with 25, 30 and 35 cells along each cube side are strictly not sufficient but further refinement is needed in order to guarantee profound and reliable LES of the surface pressure on the Silsoe cube. The full paper will cover this deficiency by simulations on finer meshes. The mesh will be systematically refined until strict monotonic behavior will be achieved and allows for a meaningful grid sensitivity analysis. Furthermore, the preservation of the inlet flow will be addressed with the aim to improve the LES pressure calculation at the front wall. To this end, e.g. roughness modifications, different wall functions or additional shear stress at the top boundary layer will be implemented as recommended by Blocken et al. (2007) and Hargreaves & Wright (2007).

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References