Flow around a Cube placed in a Simulated Turbulent Boundary Layer

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ABSTRACT: The paper presents a comparison between LES simulations of the flow around a cube placed ‘face on’ in a turbulent boundary layer and recent experimental observations of the same flow. The model flow aims to be representative of a typical urban wind environment, with a Jenson number $Je=h/z_0$, based on the cube height $h$ and roughness scale $z_0$, of 600, and Reynolds number $Re=U_h h/\nu$, based on the reference velocity $U_h$, of about 20,000. We simulate both the approaching turbulent boundary layer and the flow around cube, and compare the numerical simulations against PIV and LDA observations of both the mean and fluctuating velocity field and direct measurements of the mean and fluctuating pressure coefficients along various traverses of the cube surface.

KEYWORDS: Bluff body; large eddy simulation; wind environment.

1 INTRODUCTION

In a recent experimental study of turbulent flow past a cubic obstacle (Lim, Castro & Hoxey, 2005) it was found that while the details of the mean flow on the top of the cube, for example the mean pressure coefficients and the reattachment length, were approximately independent of the Reynolds number, as might be expected for sufficiently large values, the fluctuating pressure coefficients in contrast were not independent of the Reynolds number. This suggests that the small-scale motions, in particular the unsteady flapping and subsequent rollup of thin vortex sheets produced at the leading edge, play a much stronger role in determining the fluctuating pressure loading than was previously thought, and consequently that even at large Reynolds numbers viscous diffusion can play a significant role in determining the unsteady behavior and subsequent loading on the cube. Although there are implications for lower Reynolds number wind tunnel modeling of dynamic wind loading problems, in the present work we are interested in what effect this might have on large eddy simulations (LES) simulations, particularly as these simulations impose a necessarily limited grid resolution and account for the effects of the unresolved dynamics by adding a subgrid eddy viscosity. This additional subgrid viscosity is likely to influence the fluctuating pressures in a similar way that found in the experiments and lead to a systematic under-prediction of the fluctuating pressure loading when LES is applied to full-scale systems.

The aim of the current investigation is to conduct LES simulations alongside continuing experimental work with the intention of matching the experimental data very closely (see, for example, preliminary work reported in Lim & Thomas, 2005) so that we can first demonstrate a proper capture of the experimental behavior, and then use the numerical datasets to explore the three-dimensional unsteady structures associated with the pressure loading.
METHODOLOGY

An experimental study has been carried out alongside the numerical simulation similar to that investigated by Lim, Castro & Hoxey (2005) but taking additional velocity and pressure measurements together with PIV sections and integral measures of the approach flow structure. This more extensive dataset allows us to tune the LES parameterisation and, in particular, the rough wall treatment so that the numerical approach flow is properly representative of the experiment one.

The 3'×2' wind tunnel in the Univ. of Southampton is an open circuit facility with a 0.9m × 0.6m × 4.5m working section with a maximum wind speed of 40m/s. It is suited for generating an artificial boundary layer and is also equipped with modern hot-wire anemometry, a 2-axis LDA system and PIV system for optical measurements of the airflow. The simulation technique used classic mesh roughness, barrier, and mixing device (grids) techniques.

The computation approach is based on second order finite differences for both space and time applied to a Cartesian grid of constant spacing \( \Delta = h/32 \) and with 360×160×160 cells in the streamwise, spanwise, and vertical directions respectively. The domain extends vertically to a rigid free-slip upper boundary placed at five times the cube height, has an upstream boundary across which pre-computed time-varying turbulence is injected, and has a convective outflow boundary. A more extensive dataset allows us to tune the LES parameterisation and, in particular, the rough wall treatment so that the numerical approach flow is properly representative of the experiment one.

Table 1. Cases for the channel inflow simulation: investigating the effects wall model tuning. (Lim et al. 2005)

<table>
<thead>
<tr>
<th>Case</th>
<th>Domain size</th>
<th>Domain grid</th>
<th>Wall model</th>
</tr>
</thead>
<tbody>
<tr>
<td>CASE 01</td>
<td>10 h × 5 h × 5 h</td>
<td>320×160×160</td>
<td>Rough wall (Je=600, ( \beta = 1 ))</td>
</tr>
<tr>
<td>CASE 02</td>
<td>10 h × 5 h × 5 h</td>
<td>320×160×160</td>
<td>Rough wall (Je=600, ( \beta = 0.3 ))</td>
</tr>
<tr>
<td>CASE 03</td>
<td>( 5h \times 5h \times 5h )</td>
<td>320×160×160</td>
<td>Xie et al. (Je=600, ( \beta = 0.25, n=2 ))</td>
</tr>
</tbody>
</table>

Figure 1. – Inflow conditions computed at the test position \( x=4 \) in the absence of an obstacle: (a) mean stream-wise velocity \( \langle u \rangle /u_* \); (b) Reynolds shear stress profiles \( \langle u v \rangle /u_*^2 \); (c) turbulence intensity profile \( \langle u' \rangle /u_* \).
condition located sufficiently far downstream to allow much of the wake region to be captured. A separate periodic simulation is used to compute the inflow turbulences. The subgrid model is based on the traditional Smagorinsky model but with modifications to restrict its intervention locally when the turbulence is fully resolved by a Kolmogorov type measure. We tested three different rough wall boundary treatments on the lower surface: standard Schumann synthetic; modified Schumann that splits the stress into separate mean and fluctuating components (see, Thomas & Williams, 1999); and a further extension that adds a second-order fluctuating term (see, Xie et. al., 2004). We found that for this moderately rough flow, $Je = 600$, the additional terms correcting terms made relatively little difference although we would expect them to be more important if the roughness length were larger. The computational approach and LES modeling details are similar to those of Thomas & Williams (1997, 1999) and the computations were carried out on a parallel MPI platform consisting of a cluster of dual-CPU Intel nodes.

3 RESULTS (TURBULENT INFLOW SIMULATION & FLOW AROUND THE CUBE)

The results from the separate inflow simulation were sampled after conditioning for approximately $100h/\nu^*$, where $\nu^*$ denotes the bed shear velocity and $h$ the cube height, and significantly longer than that in Lim & Thomas (2005) thus allowing for better discrimination between the different wall treatments; the velocity and turbulence profiles normalized using $\nu^*$, and the spectrum normalized by the turbulence integral length $L_x$, are shown in Figures 1 and 2. The samples are averaged spatially over the periodic domain and over the period $50h/\nu^*$.

Note that the mean velocity profile in Figure 1(a) obtained from the wind tunnel is actually for a Reynolds number ($Re=U_hh/\nu$) range $1.86 \times 10^4 \leq Re \leq 7.31 \times 10^4$ in comparison with the current computed profile at $Re=1.86 \times 10^4$; however there appears to be no implied profile variation with $Re$. The mean velocity fits a standard log-profile up to at least $z=3h$, so that the cube is fully submerged within the log-law region. Figure 1(b) and (c) show the corresponding Reynolds stress, $<u'w'>$ , and intensity, streamwise $<u'>$ profile. The stress profiles indicate that the simulations are sufficiently converged and that the results for all wall models appear similar and in agreement with the wind tunnel measurements. The constant pressure gradient forcing used in the computations implies a nearly linear variation of shear stress with height, whereas in
the wind tunnel it reduces more rapidly above \(z=1.5h\). The computed streamwise turbulence intensity \(<u'/u^*>\) broadly matches that found in the experiments, but we note that the vertical intensity (not shown) is 20\% lower than the wind tunnel measurements.

The spectra plotted in terms of the turbulence integral length scale are all in good agreement, although we note that the turbulent forcing from the upstream grid arrangements in the wind tunnel implies that the integral length in the experiment is somewhat larger than in the computations and consistent with the elevated levels of vertical intensity.

Figure 3 shows the distribution of the mean surface pressure coefficient. The circle and triangle symbols represent the data from wind tunnel and field measurements respectively, and the solid line is from the computations; the agreement amongst all the datasets is good and is consistent with the experimental finding that there appears to be little variation with the Reynolds number. In addition, we have examined the velocity distribution around the cube and compared it against measured PIV cross-section data, also with good detailed agreement for both the mean and unsteady data. The agreement between the fluctuating \(C_p\) values (not presented) along traverses of the cube surface is quite encouraging but is consistent with the variation expected from an increased diffusion implied by the subgrid model, i.e. a lower “effective” Reynolds number. We intend to present 3D visualisations of the unsteady flow structure.

4 CONCLUSIONS

A large eddy simulation of a turbulent flow past a cubic obstacle has been carried out alongside an experimental study of the same flow. We have presented simulated results that are consistent with the experimental observation. We feel that the current grid resolution, although limited to a spacing of \(h/32\), is just sufficient to capture the shedding and evolution of the unsteady vortex shedding from the body, and although we have not presented a detailed numerical convergence study here, we know from previous experience of similar simulations that we can expect good agreement of the unsteady dynamics with the corresponding experimental data. We are currently investigating how the fluctuating pressure coefficients produced from LES simulations could be influenced by the subgrid modeling process.

5 REFERENCES