Second Symposium on Fluid-Structure-Sound Interactions and Control (FSSIC)
Hong Kong and Macau, May 20-23, 2013

The Wake Structure of Flow over a Finite Square Cylinder Predicted by Large Eddy Simulation

N. Moazamigoodarzi, D.J. Bergstrom, M. Einian and D. Sumner
Department of Mechanical Engineering, University of Saskatchewan, Canada

Background

Turbulent flow over external bodies which is characterized by shear-layer separation is a complex phenomenon, e.g. it involves both the large-scale periodic motions associated with vortex shedding, as well as smaller-scale motions associated with the fluid turbulence. In order to predict the aerodynamic forces on the body, as well as the potential for sound generation within the flow, the instantaneous and mean structure of the wake need to be understood. In this paper, we focus on the special case of a square cylinder, which is finite in length and mounted perpendicular to a ground plane. The flow approaching the cylinder is characterized by a boundary layer of thickness, δ. An important characteristic of the flow is the aspect ratio AR = H/D (where H is the height and D is the width of the cylinder), which can be regarded as a measure of the slenderness of the cylinder. For a finite cylinder, the structure of the wake is influenced by both the flow over the top of the free end of the cylinder, as well as the boundary layer developing on the ground plane. Recent studies of finite (circular) cylinder flows [1,2] have indicated that at small aspect ratio's the wake structure becomes distinct from that at larger aspect ratio's. Wang and Zhou [3] have documented measurements which indicate both asymmetric and symmetric shedding, and they have also postulated a vortical structure for the time average wake. In contract, Bourgeois *et al.* [4] conclude that the wake structure should be understood in terms of the phase average behavior; for the case of a square prism of AR = 4, they have identified a so-called half-loop structure. The present paper reports a Large Eddy Simulation (LES) of low Reynolds number (Re = UD/ν = 500) flow over a square cylinder of aspect ratio AR = 3. Two dimensional and three-dimensional visualization of the phase average structure is used to investigate the flow and confirm the presence of asymmetric flow behavior within a single phase period, which is perhaps surprising at this low aspect ratio.

Numerical method

The mathematical model consisting of the filtered Navier-Stokes equations was discretised using the finite-volume method. A localized dynamic Smagorinsky model was used for the subgrid-scale stress terms. The resultant equation set was solved using a fractional step method, where the convective and diffusive terms were advanced in time using the Crank-Nicolson method, and a multi-grid (MG) method was used to efficiently solve the linear algebraic equation set. The initial velocity field was first developed in time to obtain a realistic flow. Thereafter, velocity data were collected to obtain time-averaged or mean values of the velocity field, the resolved-scale fluctuations and phase-average behaviour.

Preliminary Results

Sampling of the velocity field in the wake of the cylinder indicated a Strouhal number of St = 0.128. The velocity field behind the cylinder was processed in terms of five distinct phases (N = 1 to 5) to give a summary picture of the periodicity of the flow; the preliminary results were only averaged over five periods. Figure 1 shows the streamlines and associated in-plane vorticity at a height of z/H = 1/4 for period N = 1; the streamlines indicate patterns which are typical of vortex shedding. Figure 2 shows the three-dimensional structure of the wake (also for N = 1) visualized by the contours of the second invariant of the velocity gradient tensor. The flow structure is clearly asymmetric, with the initially vertical vortex tubes being reoriented in the streamwise direction. There is some evidence of a half-loop structure as described by Bourgeois *et al.* [4].

* Corresponding author (don.bergstrom@usask.ca)

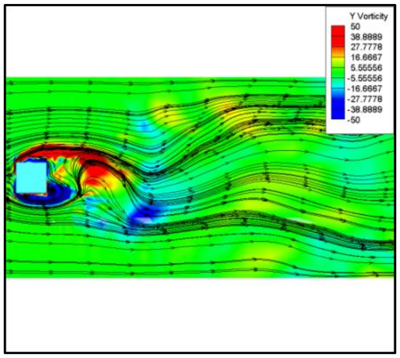


Figure 1: Phase-averaged spanwise vorticity and streamlines at z = *H/4* for phase *N* = 1.

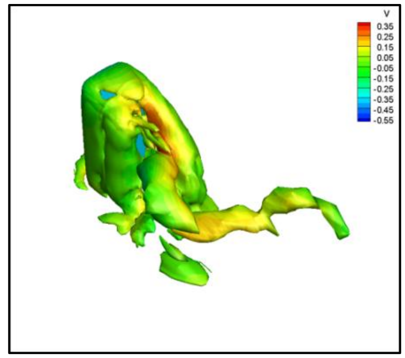
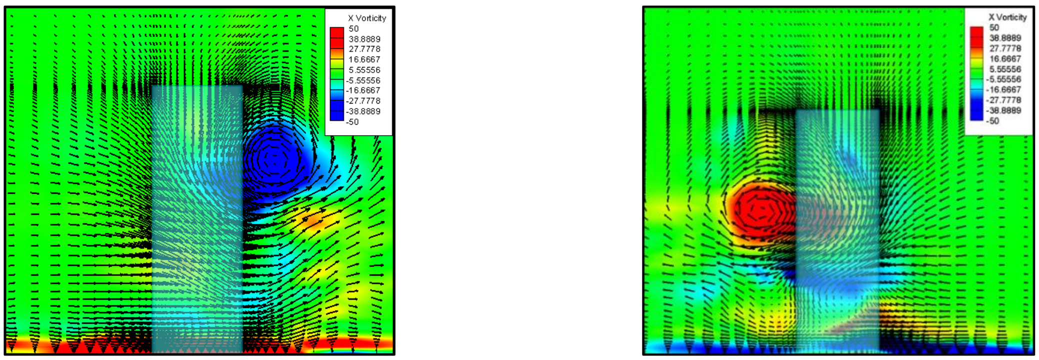


Figure 2: Visualization of the phase-averaged vorticity field using the second invariant (*Q* = 200), flooded by spanwise velocity, for phase *N* = 1.



a) Phase *N* = 2

b) Phase *N* = 5

Figure 3: Phase-averaged streamwise vorticity and velocity vectors at *x* = 3*D*.

Finally, Figure 3 shows the streamwise vorticity and velocity vectors in a vertical plane located at *x/D* = 3. Two phases are shown, *N* = 2 and *N* = 5, which show that the velocity and vorticity fields sweep across the wake creating strongly asymmetric flow patterns.

The full paper will provide a comprehensive description of the LES method and predicted velocity fields. In particular, the phase-averaged velocity and vorticity fields will be used to visualize the near-wake structure, especially the presence and mechanism of asymmetric shedding patterns.

References

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Keywords: wake, vortex structure, finite square cylinder, phase-average, Large Eddy Simulation