NON-EQUILIBRIUM NEAR WALL VELOCITY PROFILES IN THE FLOW AROUND A CYLINDER MOUNTED ON A FLAT PLATE

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Abstract We consider fully turbulent flow around a cylinder mounted on a flat plate. We performed a highly resolved Large Eddy Simulation using zonally refined grids around the cylinder and a fully turbulent inflow condition. The flow is characterized by strongly non-equilibrium near wall velocity profiles which deviate from the equilibrium law of the wall. We assess the prediction of wall shear stresses in those regions which has an impact on wall modeling and prediction of erosion and scour development.

INTRODUCTION

We investigate the flow around a circular cylinder mounted on a flat plate which has attracted attention due to a number of various effects. Our focus is on modeling erosion rates during scour evolution around a cylindrical bridge pier in a river bed. Current models of sediment erosion rates use the average wall shear stress acting on sediment grains. We aim at understanding how instantaneous shear stress fluctuations affect the erosion rates, how they can be used in erosion rate modeling and how instantaneous and average wall shear stresses scale with Reynolds number.

We performed a highly resolved Large Eddy Simulation of the flow around a wall-mounted cylinder applying a fully developed turbulent boundary layer as inflow condition with a Reynolds number $Re_D = 39000$ based on the bulk velocity u_b and the diameter of the cylinder D. We used our in-house code MGLET[1, 3], which is a Cartesian finite volume code. The WALE model[2] is applied to model the subgrid scales.

In the region of interest around the cylinder, the grid was refined by locally embedded grids[1], resulting in a grid spacing of $\Delta z^+ = 1$ and $\Delta x^+ = \Delta y^+ = 4$ in wall normal and in wall parallel direction (based on the wall shear stress in the undisturbed region). A grid study shows convergence of the results over grid refinement [4].

To ensure comparability with experiments in a flume, both sidewalls have noslip boundary conditions. The top wall has a slip boundary condition to simulate an open channel flow with low Froude number. Being aware of the strong influence of the inflow profile on the flow pattern around the cylinder [4], we applied a precursor grid to simulate a fully developed turbulent boundary layer of thickness $\delta = 1.5D$ as inflow condition.

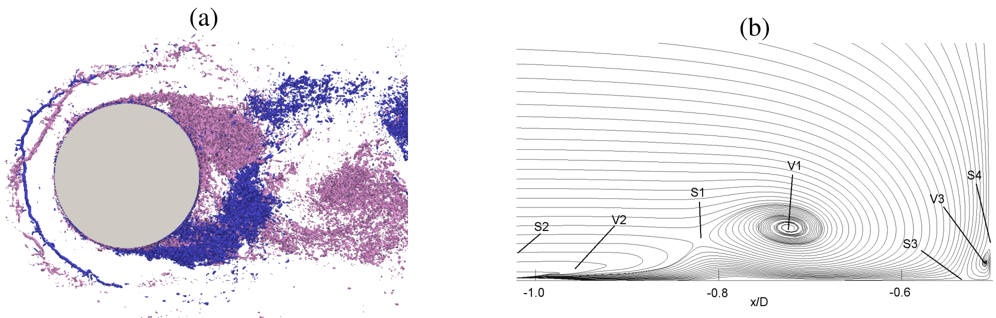

Figure 1. Overview of the flow field. Top view of isosurfaces of the Q-field at two instances in time (with different colours) (a) and streamlines of the time average velocity field in front of the cylinder (b).

In front of the cylinder a horseshoe vortex forms which follows complicated space-time dynamics as isosurfaces of the Q-field at two different instances demonstrate (Figure 1a). In the time averaged velocity field (Figure 1b), we can identify three vortices in front of the cylinder. We are interested how these vortices, especially the main horseshoe vortex, denoted as "V1" in Figure 1b, influence the velocity profiles underneath and how this will influence wall shear stress prediction from measured or simulated velocities at certain wall distances. The latter will have impact on scour development prediction and on wall modelling in simulations using wall functions.

RESULTS

Figure 2 shows velocity profiles of the stream wise velocity component in the symmetry plane in front of the cylinder at three positions: Position 1 is located upstream of the main vortex V1 at $x = -0.78D$; Position 2 is located right under V1 at $x = -0.7D$; the third profile was taken at Position 3 at $x = -0.6D$. Between the main vortex V1 and the cylinder, the flow is pointing towards the wall giving rise to a jet-like velocity profile pointing in upstream direction at

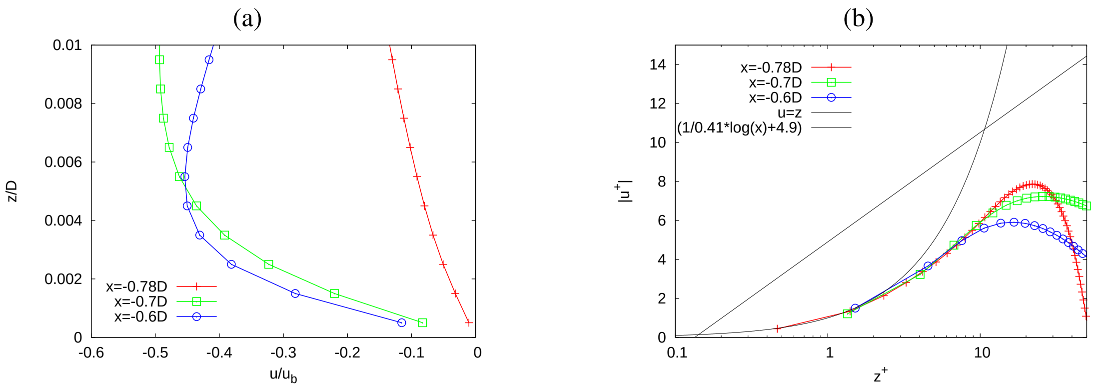

Figure 2. Velocity profile in the symmetry plane in front of the cylinder at three different positions of x in outer scaling (a) and in inner scaling (b).

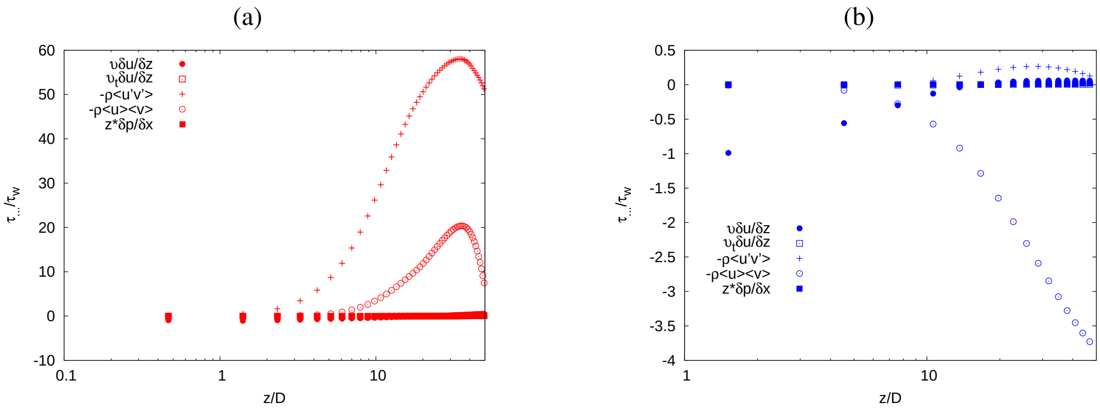

Figure 3. Momentum balance at (a) Position 1 ($x = -0.78D$) and (b) Position 3 ($x = -0.6D$).

$x = -0.6D$. Under the vortex center ($x = -0.7D$), the outer velocity is accelerated by the vortex while at the wall, it is decelerated, presumably by the wall shear stress and convection from the symmetry plane outwards. Upstream of the vortex ($x = -0.78D$), the flow slows down due to the upward motion induced by the vortex. Figure 2b shows the velocity profiles in inner scaling. Since τ_w is smallest for $x = -0.78D$, the grid resolution in wall units is the finest here. The viscous law of the wall is valid only up to $z^+ < 3$ for all profiles. The logarithmic law of the wall is not obtained at any position. The wall shear stress under the main vortex is therefore much larger than what would be estimated by assuming an equilibrium boundary layer and applying the law of the wall.

This behaviour is illustrated by the individual contributions of shear stresses to the momentum balance, plottet in Figure 3 for $x = -0.78D$ and $x = -0.6D$. The modeled SGS-stresses $< \nu_t > \frac{\partial <u>}{\partial z}$ and the pressure gradient contribution $z \frac{\partial p}{\partial x}$ are of minor influence at both positions. At the first two grid points, the flow is dominated by the wall shear stress. But, the Reynolds stress $-\rho < u'w' >$ dominates the momentum balance already at $z^+ = 3$ at $x = -0.78D$ (see Figure 3a), and reaches values as large as $50\tau_w$. In addition, the momentum flux by the time averaged flow field $-\rho < u >< w >$ reaches values as large as $20\tau_w$. It has to be noted that Reynolds stresses and time averaged convection have different signs than the viscous term at the wall and could lead to largely false wall shear stress predictions if a constant stress layer would have been assumed. In absence of such large Reynolds stresses, the flow at $x = -0.6D$ (see Figure 3b) is dominated by the time averaged convection $-\rho < u >< w >$ which dominates the momentum balance starting above $z^+ \approx 8$ and reaches multiples of the wall shear stress. This study shows that wall shear stresses would be difficult to predict by equilibrium models if the primary vortex and the layer underneath were not resolved properly by the grid.

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