LARGE AND DETACHED EDDY SIMULATION OF SEPARATED FLOW OVER 3D HILL GEOMETRIES WITH SURFACE ROUGHNESS TO MIMIC FLOWS OVER COMPLEX TERRAINS

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Abstract With the push to making wind power a significant contributor to the energy portfolio in the U.S. and Europe, there is considerable effort to deploy the currently available peta-scale computational resources to assess and improve well known simulation techniques, such as the large eddy simulation (LES) and detached eddy simulation (DES) techniques, to model the complex flows in wind farms, taken as a whole, as opposed to individual wind turbines. Simulating turbulent flows in wind farms, consisting of arrays of wind turbines, begins with the modeling and simulation of the atmospheric boundary layer (ABL) over complex terrain that is characterized by regions of separated flow with a high degree of turbulence anisotropy. Over the years there has been considerable work on applying LES and Reynolds Averaged Navier–Stokes (RANS) simulations over terrain geometries, such as the Askervein Hill, to understand turbulence closure models for flow over complex terrain. Such studies, however, have had limited success due to difficulties associated with the closure models in the near wall region of the flow. At the same time, turbulence simulations over *canonical* geometries, such as the periodic and axisymmetric hills, have been shown to compare well with data obtained from laboratory scale experiments, where the inflow turbulence and boundary conditions are better characterized and defined respectively. In an effort to extend these canonical flows to be more representative of flows over complex terrain, this paper aims to present results of large and detached eddy simulations of separated flow over three dimensional hill geometries with roughness parametrization, with the objective of developing better closure models for flow over complex terrain.

INTRODUCTION

In their recent work, Balogh *et al.* [1] present the results of RANS simulations of the incompressible Navier–Stokes equations applied to the atmospheric boundary layer with an improved $k-\epsilon$ model with wall function formulation. They point out that modifications to the $k-\epsilon$ model to overcome the inconsistencies between the wall function formulation and the inflow conditions for the fully developed ABL, while improving the velocity profile, lead to non-homogeneity of the turbulent flow variables throughout the computational domain. They conjectured that the inconsistencies could be addressed by accounting for the effects of roughness by specifying the velocity, turbulent kinetic energy, and its dissipation rate in the source terms in the $k-\epsilon$ equation in the cell adjacent to the wall in the computational domain. While this formulation was shown to be successful for the unperturbed ABL, it was found that the results showed no improvement when applied to separated flows. In a related work, O'Sullivan *et al.* [4] address the inability of the $k-\epsilon$ model to predict flow separation and account for turbulence anisotropy by using a v^2-f model for the former and an algebraic structure function based model (ASBM) for the latter. They applied their formulation to a three dimensional hill geometry, that was representative of a complex terrain, and obtained good comparisons with experimental results for the turbulence quantities, such as the Reynolds stress components. They further developed wall functions for the ASBM and v^2-f closures to enable flow simulations at higher Reynolds number by incorporating the effects of surface roughness. The results of their 2D simulations indicate that for low Reynolds number while the separated region and reattachment points are captured accurately, the most energy carrying turbulent stress component $\langle u'u'\rangle$ is under predicted in the region ahead of the region of flow separation. Further, while both closures appear to give results that agree well in the region immediately following flow separation, there are significant differences further downstream, and there appears to be an expectation that such differences could be amplified in a fully three dimensional turbulent flow. For high Reynolds number flows, on the other hand, the wall function formulations appear to have done reasonably well in the vicinity of the separated region as well as the downstream regions.

In an effort to improve on the findings of [1, 4], and provide a detailed reference solution to serve as a benchmark, with extensions to mesoscale simulation, for wall bounded and separated flows on complex terrain, it was decided to revisit the large eddy simulations of three dimensional separated flow over periodic hills [2] and over an axisymmetric hill [3] with added surface roughness. Since LES calls for a much finer grid resolution than RANS, a way to extend LES to high Reynolds number flows is to adopt the use of log-law or power-law based wall functions that are similar to those used in RANS calculations. While these wall functions allow for coarser near wall resolution in high Re flows, these approximations are designed to satisfy the log-law in a time averaged manner, and provide an inadequate representation for non-equilibrium and separated flows where the near wall flows do not have a well defined log-law region. Hence, for high-Re flows, it was decided to pursue a hybrid RANS-LES technique where a RANS model for the turbulence in the near wall region affords a method to evolve the flow dynamics at grid resolutions that are coarser than wall resolved LES. This is due to the fact that under steady state conditions, the statistical properties in the direction parallel to the wall have a lower rate of change than those in normal direction to the wall. This approximation, while tenable for flows such as channel flows, is not valid for flows where there is marked surface curvature and flow unsteadiness due to separation. Hence, in an effort to extend these simulations to high-Re numbers, it was decided to simulate the flows over the same geometries with the improved delayed detached eddy simulation (IDDES) as described in Shur *et al.* [5].

SIMULATION METHODOLOGY & PRELIMINARY RESULTS

Results of the LES and detached eddy simulations are shown below for the flow conditions [2, 3]. Computations on the same geometries with surface roughness are underway and will be the subject of the presentation.

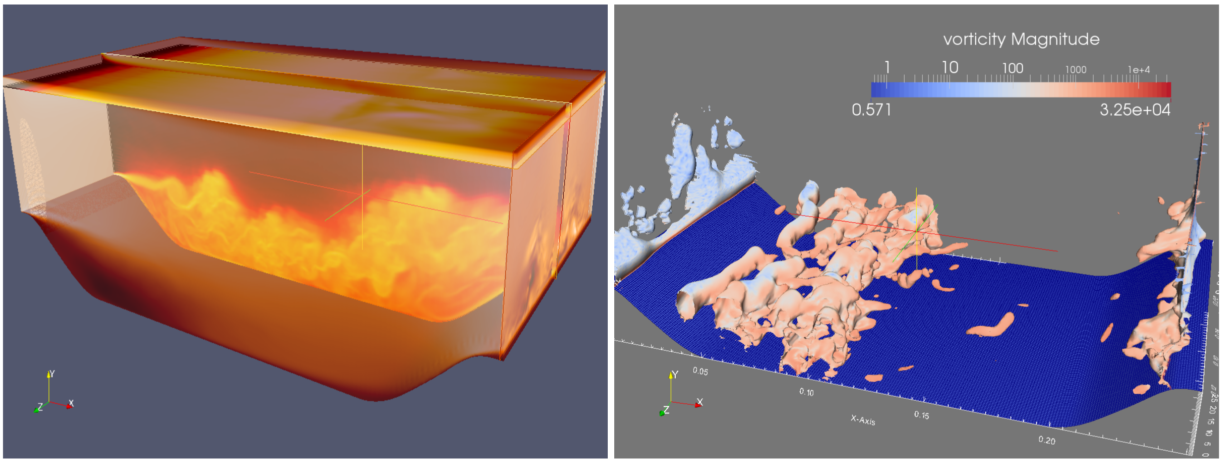

Figure 1. Periodic hill LES on a $512 \times 256 \times 256$ mesh [2]. On the foreground (left) is the mean velocity; the central plane shows ν_{sgs}; the top plane shows the TKE, and the outflow shows u'. On the right is shown the iso-surface of p' colored by the vorticity.

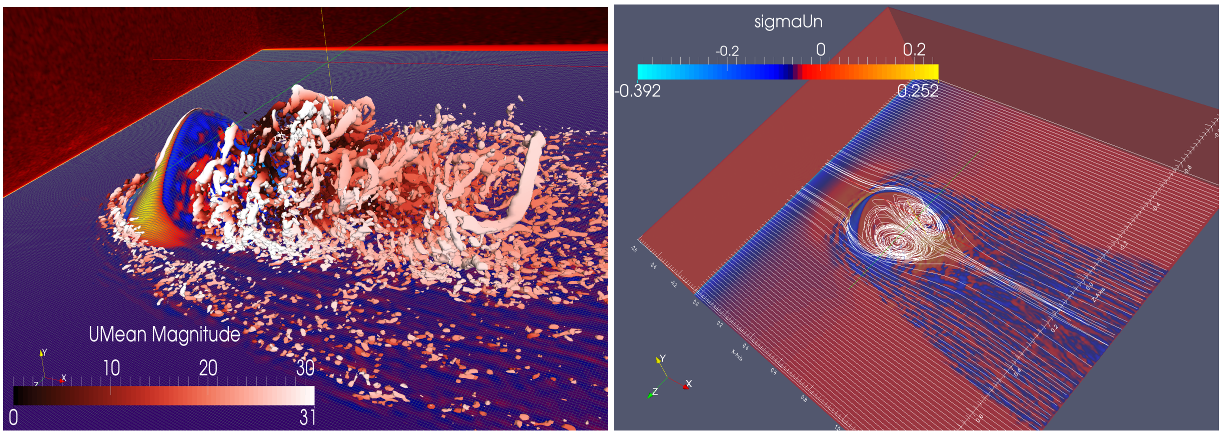

Figure 2. Axisymmetric hill [3] DES on a $512 \times 160 \times 448$ mesh. On the left is the iso-surface of the Q criterion colored by the mean velocity, showing the vortical structures on the leeward side of the axisymmetric hill. On the right, the figure shows the surface streamlines. Shown on the surface of the hill is the plot of the normal stress showing the separation line.

References

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