IMMERSED BOUNDARY APPROACH FOR WIND FORECASTING OVER COMPLEX TERRAIN USING GPU CLUSTERS

Inanc Senocak and Rey DeLeon
Department of Mechanical and Biomedical Engineering, Boise State University, Boise, Idaho, USA 83725-2075

Summary We present a multi-GPU parallel incompressible flow solver to forecast winds over complex terrain. We adopt a dual-level parallel strategy that interleaves MPI with CUDA. We represent arbitrarily complex terrain in the computations using the immersed boundary approach and extend it to atmospheric rough-wall boundary layers. We perform large-eddy simulation over complex terrain using the localized Lagrangian dynamic Smagorinsky model.

INTRODUCTION

Increasing the percentage of wind energy in overall energy production is much more complex than simply installing wind farms in windy areas. Utility companies have to maintain balancing reserves to address the intermittency of the wind. High electricity production due to sudden wind ramps also jeopardizes the integrity of the grid. Utility companies have also been investigating innovative solutions to safely increase the capacity of existing powerlines to avoid the lengthy and expensive process of building new powerlines. *Thermal rating* is the maximum current that can be carried through a power line without causing the line to sag to unsafe heights or lose its structural integrity. *Dynamic rating* is the concept of adjusting the thermal rating of power lines based on prevailing real-time weather conditions such as wind speed, and direction, incident solar radiation and ambient temperature. In *static rating* conservative assumptions (full sun, high ambient temperatures and low wind speeds) on weather conditions are used for safety reasons. However, static ratings were found to cause unnecessary curtailments for wind power generation. When there are strong winds to generate power, power line cooling is expected to be strong, thanks to high winds. Dynamic rating concept promises to increase capacity on existing power lines with minimum investment

Clearly, there is a need for a wind forecasting capability that can reliably predict wind speed and direction over complex terrain where significant number of wind farm installations has occurred in recent years. However, there is substantial amount of uncertainty when predicting wind speed and direction over complex terrain and any wind solver should operate in the forecasting mode to be a useful tool in real applications.

We present a micro-scale wind solver where turnaround time of complex terrain wind flow simulations are accelerated on emerging clusters of graphics processing units (GPU). In micro-scale atmospheric flows computational domain size can range from several hundred meters to several kilometers, and grid resolution is on the orders of tens of meters to be able to resolve the wind profile at the turbine hub height (~80m). At these spatial scales, large-eddy simulation (LES) technique is applicable, but it needs to be augmented with near-surface models to address surface roughness, insufficient spatial resolution, and fluxes of heat and moisture. Any wind forecasting capability should also address the computational expense of LES. To this end, GPU clusters emerge as a promising hardware solution to help realize micro-scale wind forecasting. Mesh generation for complex terrain is also a bottleneck in wind forecasting, where a poor mesh quality can induce substantial numerical errors and improving the mesh quality can be very time consuming. Therefore, we adopt Cartesian immersed boundary (IB) methods [1] to automate and accelerate the mesh generation process in wind flow simulations over complex terrain. Equally important, Cartesian mesh topology maps well on to the computer architecture of modern GPUs, which helps greatly in harnessing the full potential of GPUs for fast computations

NUMERICAL METHODS

We solve the filtered form of the three dimensional Navier-Stokes equations for incompressible flow using the projection algorithm. We adopt second order central differencing for spatial terms and the second order Adams-Bashforth scheme for time marching. We solve the pressure Poisson equation with a geometric multigrid method.

Turbulence modeling over complex terrain is challenging because massive flow separation can take place. Dynamic subgrid scale models are particularly attractive for complex terrain flows, but a localized model is needed because there are no homogeneous directions. Therefore we use the Lagrangian dynamic Smagorinsky model [2] which calculates the Smagorinsky coefficient by averaging along flow pathlines and thus suitable for arbitrarily complex terrain.

We adopt the immersed boundary method with the direct forcing approach and extend it to atmospheric turbulent flows. The linear interpolation reconstruction scheme that was adopted in the original direct forcing approach may work well for turbulent flows if the grid resolution is fine enough to capture the viscous sublayer, but this is never the case for atmospheric flows with a rough underlying surface. A linear interpolation scheme underestimates the surface stresses because a logarithmic or power wind profile is typically observed in atmospheric flows. Therefore, we reconstruct the velocity field along the surface normal direction and interpolate the velocities following a logarithmic profile. We also maintain consistency between the subgrid scale model and reconstruction scheme for satisfactory results. We represent the complex terrain as an STL CAD geometry which stores the normal direction of each triangular element on the surface. We use this information to calculate the reconstruction scheme along the surface normal direction.

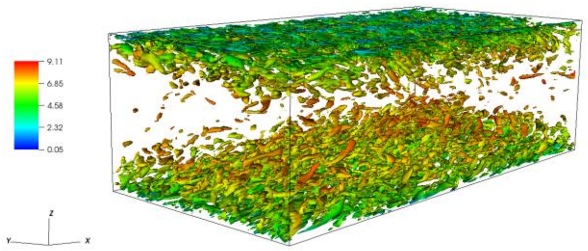
PARALLEL IMPLEMENTATION

The IB method and LES capability was integrated into a dual-level parallel CFD code [3,4], which is specifically designed for GPU clusters using MPI and CUDA and it overlaps GPU to CPU data copies and cluster communication with computations on the GPU using asynchronous memory copy operations with CUDA streams. Our flow solver has been tested for parallel performance on the NCSA Lincoln Tesla GPU cluster in earlier studies. For the lid driven cavity benchmark problem we have shown that dual-GPU performance of our solver is 26 times faster than an 8-core CPU performance.

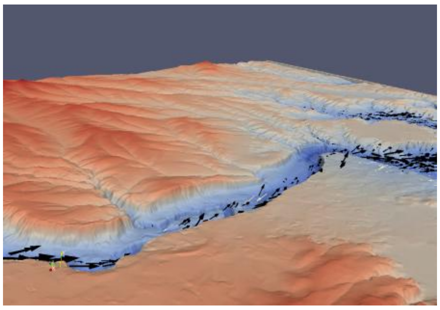
We solve the pressure Poisson equation resulting from the projection algorithm with a full-depth, parallel 3D geometric multigrid (MG) solver that employs an amalgamation strategy on GPU clusters to avoid truncation of the multigrid cycle Truncating the MG cycle greatly reduces the convergence rate which is an issue that arises when implementing multigrid in parallel. Therefore, our implementation employs an amalgamation strategy that brings the coarsened subdomains to a single process.

RESULTS

In order to validate our wind solver on GPU clusters, we first perform a turbulent channel flow simulation at a friction Reynolds number of 395 and compared our results with existing DNS data in literature. Figure 1a shows the



(a)



(b)

Figure 1. (a) LES of turbulent channel flow at Re_τ=395 using the Lagrangian dynamic Smagorinsky model. Vortical structures are visualized using the Q-criterion and colored by the velocity magnitude. (b) Visualization of preliminary wind simulations over the test area in Idaho for dynamic line rating project.

instantaneous vorticity field in the channel. Turbulence statistics obtained from LES agree well with DNS data. The overall simulation was completed on 8 Tesla C2070 GPUs in less than 45 hours, including the spinoff time.

Figure 2b presents a preliminary simulation of wind flow over a complex terrain region in Idaho. This area is equipped with 14 weather stations. Wind speed and direction are collected 10m above the ground. A direct comparison of simulations with these measurements will be available in future.

CONCLUSIONS

Cartesian grid immersed boundary methods are well-suited for the computer architecture of modern GPUs and provide new opportunities to forecast winds over complex terrain for renewable energy applications. However, special care is needed when representing arbitrarily complex terrain in an immersed fashion and extending the IB method to turbulent flows with a rough boundary layer.

References

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