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CgWind: A high-order accurate simulation tool for wind turbines and wind farms

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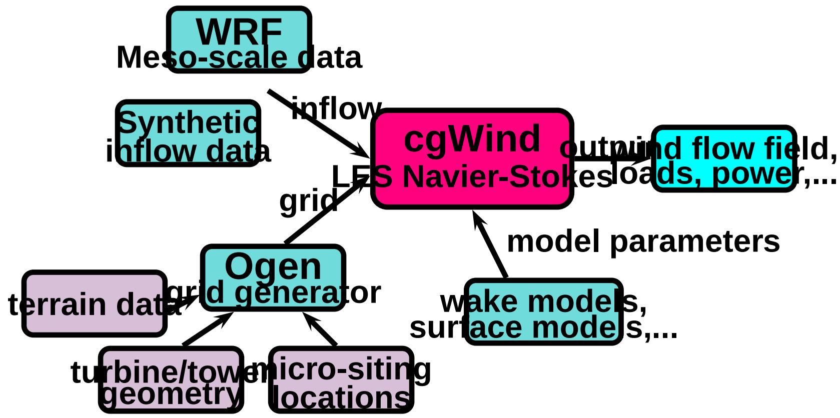
ABSTRACT: CgWind is a high-fidelity large eddy simulation (LES) tool designed to meet the modeling needs of wind turbine and wind park engineers. This tool combines several advanced computational technologies in order to model accurately the complex and dynamic nature of wind energy applications. The composite grid approach provides high-quality structured grids for the efficient implementation of high-order accurate discretizations of the incompressible Navier-Stokes equations. Composite grids also provide a natural mechanism for modeling bodies in relative motion and complex geometry. Advanced algorithms such as matrix-free multigrid, compact discretizations and approximate factorization will allow CgWind to perform highly resolved calculations efficiently on a wide class of computing resources. Also in development are nonlinear LES subgrid-scale models required to simulate the many interacting scales present in large wind turbine applications. This paper outlines our approach, the current status of CgWind and future development plans.

1 INTRODUCTION

CgWind is a new, high-fidelity simulation tool designed to meet the modeling requirements of advanced wind energy resources. These new resources, targeting 20% of the US electrical supply by 2030, require the development of larger and lighter wind turbines as well as more accurate estimates for the performance of turbines in realistic terrain and atmospheric conditions. To model such systems, CgWind couples large eddy simulation (LES) models, based on the incompressible Navier-Stokes equations, with moving grid techniques that resolve the flow near the turbine blades. Both LES and detached eddy simulation methods will be available in CgWind. In particular, CgWind is incorporating nonlinear LES models that capture anisotropy at the subgrid-scale and are well-suited for atmospheric boundary layer flows. Our modeling framework enables the use of advanced numerical methods to design and predict the performance of individual wind turbines and large-scale wind parks.

CgWind's technology exploits the composite grid approach, which leverages the computational benefits of overlapping, structured grids to represent complex geometry. These grids are ideal for the high-order accurate compact discretizations used by CgWind as well as the matrix-free geometric multigrid algorithm that enables large-scale, high-resolution computations with realistic geometry. The composite grid approach, also known as overlapping or Chimera grids, provides a natural and efficient mechanism for modeling bodies in relative motion. Each turbine blade and tower is meshed independently with high quality, structured grids and assembled automatically into a collection of overlapping grids. When the geometry moves (e.g., the blades rotate or deform), the



new configuration undergoes local regridding, which is orders of magnitude faster than the global remeshing methods used in many unstructured mesh approaches. Overlapping grids also provide a natural framework for structured adaptive mesh refinement that will allow CgWind to automatically enhance resolution in regions of the computational domain with important flow features (e.g., wake vortices). The memory footprint and CPU performance advantages of high-order accurate methods on structured grids allows CgWind to perform simulations at spatial resolutions currently unobtainable by other approaches.

CgWind will also interface to the Weather Research and Forecasting (WRF) meso-scale model to simulate wind-farm scale problems for siting studies and wind park performance analysis. In particular, WRF can provide time varying inflow conditions to CgWind, thereby incorporating the local weather conditions. Terrain data can be imported from GIS sources, meshed, and incorporated into the model. For large-scale park models, CgWind provides an interface for wake models thereby obviating the need to highly resolve all the turbines in a large scale wind park.

While currently under development at Lawrence Livermore National Laboratory, CgWind is intended to be community tool for use by turbine manufacturers, wind park designers and wind energy researchers. The software is modular and contains well-defined interfaces for custom or proprietary wake and turbulence models. Built upon the openly available Overture software framework (www.llnl.gov/casc/Overture), CgWind will be freely downloadable. The first version of CgWind will be released for testing within the year, and we aim for our first public release within two years.

2 OVERVIEW OF CGWIND

The major components of CgWind are outlined in figure 1. Geometry inputs, including the tower/turbine/nacelle designs, terrain data and micro-siting locations of the turbines, are fed through the overlapping grid generator, Ogen, to construct the computational grid. The time-varying inflow conditions to the simulation are obtained from either synthetically determined turbulent profiles using numerical and statistical methods (Tamura, 2009), or from data obtained from the large eddy simulation output from meso-scale atmosphere models such as WRF. CgWind will take these geometry and inflow conditions and compute the three-dimensional wind flow field for the wind farm. From the computed flow, derived quantities such as the loads on the turbine blades and the predicted power output can be determined.

3 OVERLAPPING GRIDS AND AMR FOR MOVING GEOMETRY

The overlapping grid method, as discussed in Chesshire and Henshaw (Chesshire and Henshaw, 1990), allows complex domains to be represented with smooth, structured grids which can be aligned with the boundaries. The overlapping grid approach is particularly attractive for a number of reasons, with one being that smooth grids are important for obtaining accurate numerical solutions, especially when using high-order accurate methods. Boundary fitted grids are important for the accurate implementation of boundary conditions and for capturing boundary layer phenomena. The use of structured grids is important for performance and low memory use. Moreover, since the majority of an overlapping grid often consists of Cartesian grid cells, the speed and low memory advantages inherent with Cartesian grids can be substantially retained.

An overlapping grid $\mathcal{G}$ for a physical domain Ω consists of a set of $\mathcal{N}_g$ component grids G_g, i.e.,

$$\mathcal{G} = \{G_g\}, \qquad g = 1, 2, \ldots, \mathcal{N}_g \; .$$

The component grids overlap and cover Ω. Each component grid is a logically rectangular, curvilinear grid defined by a smooth mapping, $\mathbf{C}_g$, from parameter space to physical space, $\mathbf{x} = \mathbf{C}_g(\mathbf{r}), \;\; \mathbf{r} \in [0,1]^3, \;\; \mathbf{x} \in \mathbb{R}^3$. The mapping is used to define grid points at any desired resolution as required when a grid is refined.

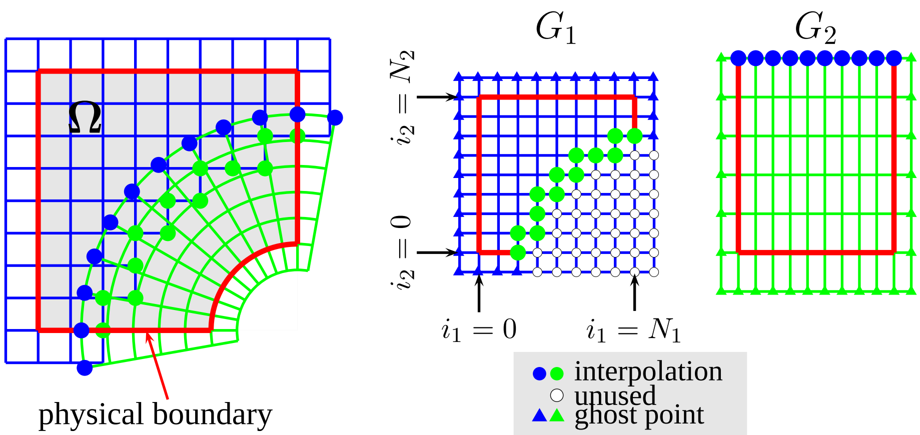


Figure 1: Left: an overlapping grid consisting of two structured curvilinear component grids. Middle and right: component grids in the unit square parameter space. Grid points are classified as discretization points, interpolation points or unused points. Ghost points may be used to implement boundary conditions.

Figure 2 shows a simple overlapping grid consisting of two component grids, an annular boundary-fitted grid and a background Cartesian grid. The left sub-figure shows the overlapping grid while the middle and right sub-figures show each grid in parameter space. In this example, the annular grid cuts a hole in the Cartesian grid so that the latter grid has a number of unused points that are marked as open circles. The other points on the component grids are classified as either discretization points (where the PDE or boundary conditions are discretized) or interpolation points. The information that characterizes each point is supplied by the overlapping grid generator, Ogen (Henshaw, 1998), and is held in an integer mask array. In addition, each boundary face of each component grid is classified as either a physical boundary (where boundary conditions are implemented), a periodic boundary or an interpolation boundary. Typically, one or more layers of ghost points are created for each component grid to aid in the application of boundary conditions.

Figure 3 shows an overlapping grid for a mockup of a wind-farm with terrain that illustrates the use of overlapping grids. In this example, simple representations for the tower and blades are used. More accurate descriptions of the tower, nacelle and blades along with terrain data for specific sites will be used in actual simulations. Figure 4 shows sample computations of flow past prototypical turbines that illustrate the effects on the flow field when high-spatial resolution is used to capture fine scale turbulent features. High-resolution and high-order accurate methods reduce the numerical dissipation that smooths fine-scale vortical structures and improves the prediction of how these flow structures interact with down stream turbines.

The adaptive mesh refinement approach adds new refinement grids where the error in the numerical solution is estimated to be large. Our approach to AMR on moving, overlapping grids follows that described in (Henshaw and Schwendeman, 2006, 2008, 2003) for compressible flows, although a number of extensions will be needed for solving incompressible flows. In the basic approach, refinement grids are added to each component grid and are aligned with the parameter space coordinates. The refinement grids are arranged in a hierarchy with grids on refinement level l being a factor 2 or 4 (typically) finer than the grids on level $l-1$. An AMR regridding procedure is performed every few time steps. This procedure begins with the computation of an error estimate based on the current solution. Once the error estimate is obtained, grid points are flagged if the error is larger than a user specified tolerance. A new set of refinement grids is generated to cover all flagged points, and the solution is transferred from the old grid hierarchy to the new one. Further details are given in Henshaw and Schwendeman (Henshaw and Schwendeman, 2003)).

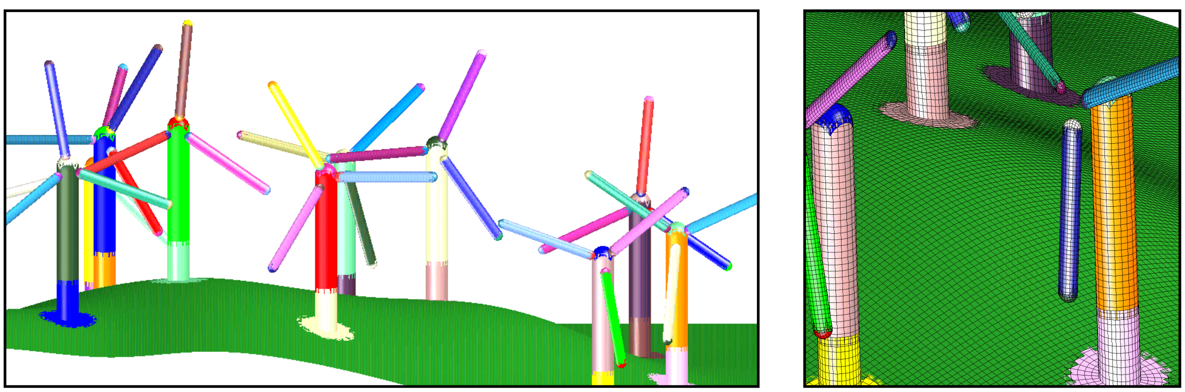


Figure 2: Overlapping grids for a mockup of a collection of turbines on model terrain. Boundary fitted structured grids provide an accurate representation of the geometry (each grid is represented by a different color). Cartesian background grids (not shown) allow efficient approximations to be used throughout most of the domain.

4 NUMERICAL APPROACH FOR THE NAVIER-STOKES EQUATIONS

We solve the incompressible Navier-Stokes (INS) equations with a pressure-velocity formulation and a split-step method where the pressure is computed in a separate step. For a given domain Ω, with boundary $\partial\Omega$, the governing equations are

$$\begin{aligned} \mathbf{u}_t + (\mathbf{u}\cdot\nabla)\mathbf{u} + \nabla p - \nu\Delta\mathbf{u} - \mathbf{f} = 0, &\qquad t>0, \quad \mathbf{x}\in\Omega \\ \Delta p + \nabla\mathbf{u} : \nabla\mathbf{u} - \alpha\nabla\cdot\mathbf{u} - \nabla\cdot\mathbf{f} = 0, &\qquad t>0, \quad \mathbf{x}\in\Omega \end{aligned}$$

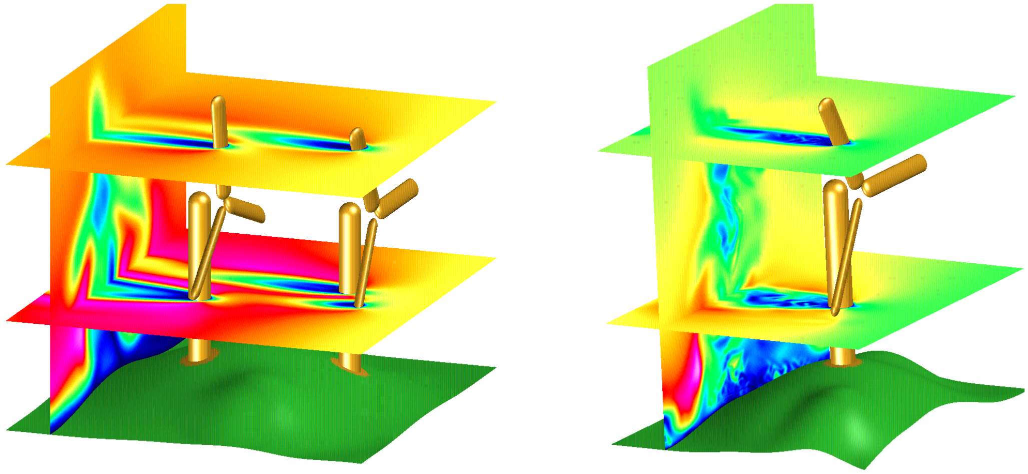


Figure 3: Left: low-resolution simulation of two model turbines showing the flow speed plotted on various cutting planes (the blades are not rotating). Right: higher-resolution simulation of a single turbine that shows the finer scale features that can be captured (from a computation with 35M grid points).

with appropriate initial conditions, $\mathbf{u}(\mathbf{x}, 0) = \mathbf{u}_I(\mathbf{x})$, and boundary conditions, $\mathcal{B}^F(\mathbf{u}, p) = 0$. Here $\mathbf{u} = \mathbf{u}(\mathbf{x}, t)$ is the velocity, p the pressure and ν the kinematic viscosity. The term $\alpha\nabla \cdot \mathbf{u}$ in the pressure equation acts as a damping term on the divergence of the velocity. When buoyancy effects are important, an additional temperature equation is added following the Boussinesq approximation as described in (Henshaw and Chand, 2009). The use of LES turbulence models add an additional term to the equations as discussed in section 5. Second- and fourth-order accurate schemes have been developed to solve these equations on overlapping grids, see (Henshaw, 1994; Henshaw and Petersson, 2003) for details. High-resolution compact schemes, which provide up to eighth-order accuracy, are currently under development.

4.1 Approximate factorization methods and compact schemes

Compact finite difference approximations have long been known to efficiently provide high order accuracy with greater spectral resolution than standard finite difference approximations (Hirsh, 1975; Lele, 1992). These schemes implicitly define a difference approximation along a grid line and generally require the solution of tri- or penta-diagonal linear systems. The efficiency and accuracy of these schemes have led to their popularity in LES applications, e.g., (Ekaterinaris, 1999; Laizet and Lamballais, 2009; Nagarajan et al., 2003). Most compact schemes for fluid dynamics applications use explicit discretizations in time leading to methods that require extremely small time steps when grids are highly stretched and refined near physical boundaries (i.e., near boundary layers). Furthermore, it is common to use specialized one sided differences near the boundary to close the linear system at each end of a line solve. These one sided differences are of lower accuracy in order to preserve the bandwidth of the linear system. It is tempting to combine compact schemes and approximate factorization methods in order to discretize the time derivative implicitly thereby allowing larger time steps while retaining the efficiency of tri-diagonal or penta-diagonal solvers. Beam and Warming were the first to mention such an approach, although the details were omitted (Beam and Warming, 1976). More recently, Visbal and Giatonde (Visbal and Giatonde, 2002) and Sherer and Scott (Sherer and Scott, 2005) describe compact difference methods on overlapping grids with approximate factorization for the time discretization. However, their method does not fully integrate the compact scheme into the approximate factorization, relying instead on traditional, and lower order accurate, discretizations for some terms.

In CgWind we have developed a new approach for incorporating compact schemes with approximate factorization methods. Our method does not require lower order accurate approximations in the factorization and preserves the order of accuracy at boundary points. The former feature is accomplished by altering the individual line solves in each step of the ADI-like factorization method. The preservation of accuracy at boundaries is accomplished through special centered boundary conditions, newly derived one side-biased compact schemes and banded solvers that can handle an extended matrix format for the first and last equations. Our approach results in a robust numerical method that retains the spatial accuracy of compact difference schemes.

4.2 Matrix free multigrid

A key to performing efficient parallel simulations with CgWind is the development of a new, parallel, high-order accurate *matrix-free* multigrid (MG) algorithm. In a moving geometry problem (e.g., moving turbine blades), the computational grid changes at each time step. The implicit system for the Poisson equation for the pressure will thus change at each time step. Most state-of-the-art linear solvers (e.g., Krylov, Algebraic MG) have relatively expensive setup phases (e.g., to form a preconditioner) and are less efficient when solving equations from high-order approximations that are not diagonally dominant. We have previously developed a second-order accurate multigrid solver for overlapping grids that achieves near text book convergence rates and is orders of magnitude faster than Krylov solvers (Henshaw, 2005).

For CgWind, we are developing a high-order, matrix-free multigrid algorithm for overlapping grids that incorporates compact difference approximations and is be tailored to wind-turbine applications by using implicit line and plane smoothers on the highly stretched boundary layer grids. There are a number of challenges that must be addressed in developing this method. For example, appropriate smoothers, fine-to-coarse transfer operators and boundary conditions must be developed for the compact difference approximations. The matrix-free multigrid algorithm will be memory efficient and fast (with optimizations for Cartesian grids) and should maintain the mesh independent convergent rates that are obtained by classical multigrid algorithms on single Cartesian grids.

5 NONLINEAR TURBULENCE MODELS

Two computational techniques used for turbulent flow simulations in both turbine scale applications and atmospheric boundary layers are Reynolds Averaged Navier-Stokes (RANS) and LES. Unsteady RANS simulations are aimed at capturing larger coherent structures in a flow while most of the turbulent effects are parameterized. LES attempts to resolve turbulent eddies in the inertial range. Unsteady RANS simulations, which are currently the main tool for turbine scale simulations, are appropriate for capturing time-averaged flow characteristics, but are unable to capture true variability of the atmospheric flow, especially as it interacts with moving structures. Therefore unsteady RANS simulations cannot accurately predict the extremes of dynamic loads on turbine blades. Due to the characteristics of these rapidly evolving flows and fluid-structure interactions, the LES approach, which resolves both the most energetic eddies and turbulent eddies in the inertial range, is needed for highly accurate simulations.

We will implement improved turbulence (sub-grid) models for LES, applicable to a full range of atmospheric stability conditions. In particular, wind turbines may operate within atmospheric boundary layers whose shear and associated turbulence production can affect turbine performance, fatigue and lifespan. Night-time low-level jets are one important example of such stably stratified boundary layer flows (Thorpe and Guymer, 1997). In these flows both backscatter of energy and shear induced anisotropy must be accounted for in the sub-grid scale (Mason and Thomson, 1992; Sullivan et al., 1994). To capture both inertial transfer effects, including backscatter of energy, as well as its redistribution among the normal sub-grid-scale stress components, Kosović (Kosović, 1997; Kosović and Curry, 1999) developed a phenomenological nonlinear sub-grid scale (SGS) model that, in addition to the classical, linear, Smagorinsky term, includes two additional nonlinear terms that represent contraction of a strain rate tensor with itself and with a rotation rate tensor. We will implement this nonlinear SGS model in CgWind.

6 STATUS AND FUTURE PLANS

CgWind is currently within its first year of active research and development. Our current efforts include development of the compact difference/approximate factorization approach combined with a complimentary multigrid method for the pressure equation. Our existing fourth order accurate incompressible Navier-Stokes solver and grid generation infrastructure form the heart of this work and are currently used for scoping and scaling studies. In the forthcoming year we plan to integrate Kosović's nonlinear SGS model to compliment the existing Smagorinsky-style model in the existing code. Other future plans include coupling boundary conditions to data generated by the Weather Research and Forecasting meso-scale model for more realistic diurnal variations of "free-stream" conditions. We plan to have our first release to collaborators in 2011 with an open release of the software the following year.

7 ACKNOWLEDGEMENTS

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