Commun. Comput. Phys.
doi: 10.4208/cicp.OA-2017-0196

Vol. **24**, No. 5, pp. 1503-1522
November 2018

Scalable Domain Decomposition Algorithms for Simulation of Flows Passing Full Size Wind Turbine

Rongliang Chen[1], Zhengzheng Yan[1], Yubo Zhao[1] and Xiao-Chuan Cai[2,*]

[1] *Shenzhen Institutes of Advanced Technology, Chinese Academy of Sciences, Shenzhen 518055, P.R. China.*
[2] *Department of Computer Science, University of Colorado Boulder, Boulder, CO 80309, USA.*

Received 14 September 2017; Accepted (in revised version) 30 November 2017

Abstract. Accurate numerical simulation of fluid flows around wind turbine plays an important role in understanding the performance and also the design of the wind turbine. The computation is challenging because of the large size of the blades, the large computational mesh, the moving geometry, and the high Reynolds number. In this paper, we develop a highly parallel numerical algorithm for the simulation of fluid flows passing three-dimensional full size wind turbine including the rotor, nacelle, and tower with realistic geometry and Reynolds number. The flow in the moving domain is modeled by unsteady incompressible Navier-Stokes equations in the arbitrary Lagrangian-Eulerian form and a non-overlapping sliding-interface method is used to handle the relative motion of the rotor and the tower. A stabilized moving mesh finite element method is introduced to discretize the problem in space, and a fully implicit scheme is used to discretize the temporal variable. A parallel Newton-Krylov method with a new domain decomposition type preconditioner, which combines a non-overlapping method across the rotating interface and an overlapping Schwarz method in the remaining subdomains, is applied to solve the fully coupled nonlinear algebraic system at each time step. To understand the efficiency of the algorithm, we test the algorithm on a supercomputer for the simulation of a realistic 5MW wind turbine. The numerical results show that the newly developed algorithm is scalable with over 8000 processor cores for problems with tens of millions of unknowns.

AMS subject classifications: 65F10, 65F08, 68W10, 76D05, 76U05

Key words: Wind turbine aerodynamics, 3D unsteady incompressible flows, domain decomposition method, fully implicit methods, parallel computing, unstructured finite element method.

*Corresponding author. *Email addresses:* rl.chen@siat.ac.cn (R. Chen), zz.yan@siat.ac.cn (Z. Yan), yb.zhao@siat.ac.cn (Y. Zhao), cai@cs.colorado.edu (X.-C. Cai)

1 Introduction

Wind power is becoming more popular as a renewable energy. The global wind energy council's data shows that the worldwide installed wind power capacity has grown exponentially during the last decade and will continue to grow at a high rate [16]. Wind turbines are the main facility designed to exploit the wind energy. As the demand increases, the industry is moving in the direction of large-scale designs, such as the Vestas V164-8.0MW offshore turbine [40], whose blade length is 80 meters. In the design process, high resolution aerodynamic simulation plays an important role and the computing is challenging because of the large computational domain, the high Reynolds number, and the relative motion of the computational subdomains. Computation at such scales requires large-scale parallel computers and scalable parallel algorithms.

In the last decades, most of the wind turbine aerodynamic simulation research focused on low fidelity methods, such as the blade element momentum method [19,20,33], based on the blade element theory and the momentum theory, which is simple to implement and computationally inexpensive, but is unable to adequately resolve the details of the complex flow structures. Recently, with the rapid development of supercomputers, some high fidelity simulation methods based on the 3D unsteady Navier-Stokes equations are proposed. In 2002, Sorensen et al. [38] introduced a framework based on the Reynolds-Averaged Navier-Stokes model, discretized with an implicit finite volume method for the 3D wind turbine rotor aerodynamic study, where the tower is ignored in the calculation. Bazilevs et al. [4,5,21] combined the large eddy simulation, finite element method, and fully implicit time integration to study the fluid-structure interaction issues of the wind turbine rotor. In simulating wind turbine aerodynamics, only a handful of researchers considered a full wind turbine system, in which the rotor, nacelle, and tower are all included. This is due to the additional computational challenges associated with the simulation of objects in relative motion. For the full wind turbine system, Bazilevs et al. proposed an ALE-VMS technique coupled with a non-overlapping sliding-interface method and a non-uniform rational B-splines based method in [22,23]; Li et al. [32] investigated the detached eddy method with semi-implicit temporal discretization and finite difference spatial discretization based on the dynamic overset grids for the grid deformation and relative motions. Some more studies for full wind turbine systems can be found in [17,45]. Most of the works just mentioned focused on the model accuracy of the methods, not on the parallel scalability which is very important in order to obtain high resolution simulations.

In high fidelity simulations, in order to obtain sufficiently accurate solutions, fine computational meshes are needed, thus requiring large scale parallel computers for their memory capacity and processing speed. It is clear by now that the increase of computing power is no longer from faster processor cores, but from the increase of the number of processor cores. In this study, we focus on developing a scalable parallel method for the simulation of 3D unsteady incompressible flows around a full wind turbine system involving rotor and tower. To deal with objects with relative motion, generally speak-