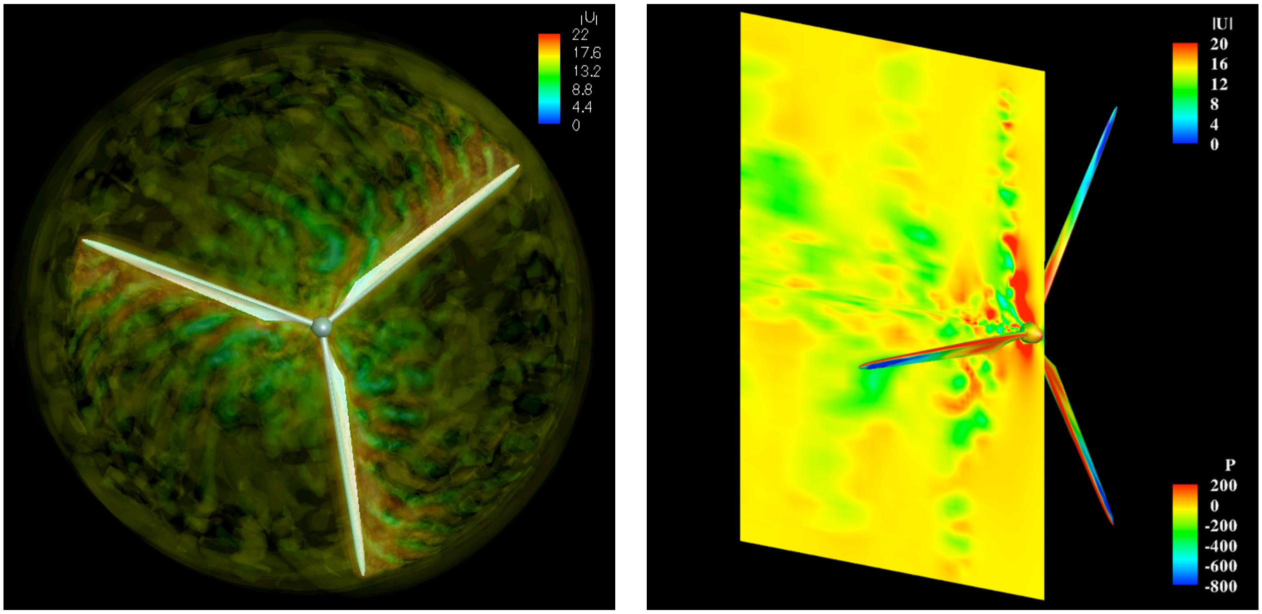

(a) (b)

Figure 1: To illustrate our current modeling capabilities, we carried out a preliminary 3D simulation of a full-scale wind turbine rotor. The blade diameter is 120 m, the wind speed is 15 m/s, and the rotation rate is 10 RPM. This computation makes use of over $2,000,000$ second-order NURBS isogeomeric elements and 90 processors on a Dell PowerEdge Linux Cluster. (a) Isosurfaces of air speed behind the rotor show the complexity of the turbulent flow. (b) Pressure on the rotor blades and velocity isocontours at a vertical plane. These simulations enable the prediction of the wind loads on the turbine blades, which are critical for efficient blade design. The blade efficiency directly translates to lower cost in wind energy conversion.

Project Description

Leading the Wind Energy Research through Advanced Computer Modeling

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1 Innovation and Objectives

The rising costs and highly fluctuating prices of oil and natural gas, as well as their constantly diminishing supplies worldwide, create the need for cheaper, sustainable alternative energy sources. Wind turbines, which harvest wind energy and convert it to electrical power, create such an energy source that is playing an increasingly important role and receiving much attention from government and industry sectors around the world. To lead in wind energy as a Nation, we must lead in wind energy research.

There are currently over 25,000 wind turbines in the US that produce 17 GW of electricity, enough to power 4.5 million homes. The total generation capacity rose by 45% in 2007 and is forecast to triple by 2012. Currently 1% of all electricity comes from wind power. The US government and industry sectors would like to see this figure reach 20% by 2030. Leading-edge wind energy research will be essential in meeting this goal.

Wind turbines are designed for optimized operation for a given set of environmental conditions. Good aerodynamic design of turbine blades increases the power extracted from the wind stream and thus maximizes the efficiency, while minimizing the cost of wind energy conversion. Therefore optimizing the shape of the blades presents an important engineering challenge that we must address very effectively. At the same time, wind turbines must be able to withstand the expected wind loads, as well as the loads caused by earthquakes or ocean currents (e.g., in the case of offshore wind turbines). Hence, another important issue is accurate prediction of the loads on the wind turbine due to a variable set of environmental conditions. Furthermore, given the loads, appropriate materials that are light and durable, such as composites, need to be employed in manufacturing. Arrays of wind turbines also present an engineering challenge, as very little is known how wind turbines upstream affect those downstream and how far apart and at what orientation the turbines should be placed to optimize the power output.

Besides the fundamental engineering issues, wind turbines face challenges associated with their everyday operation and maintenance. Transmission of electric power from windmill farms to power homes, factories and other places, presents a challenge, especially for wind turbines placed in remote areas. Maintenance for sustained operation is a significant issue. Wind turbines collect dust and attract debris, and need to be cleaned and lubricated in order not to loose operational efficiency. Wind turbines also interfere with natural habitat of birds and bats, creating an environmental concern, and generate a noise that is unpleasant to humans.

Given the above considerations, wind turbines present several major engineering challenges and would greatly benefit from the use of advanced predictive modeling tools. Computer modeling plays a key role in the design and analysis of complex engineering systems. Automobile crash analysis, as well as the design and evaluation of commercial and military aircraft routinely use advanced computational tools. As such, wind turbines should also benefit from such advanced tools. However, advanced, high-fidelity computational methods for wind turbine analysis that would be capable of addressing the engineering and operational issues mentioned above are notably lacking. In this projectl we plan to directly and expeditiously address this need.
The over-arching aim of this work is to jump-start, take the lead in, and set the standards for advanced computer modeling of wind turbines, where the fluid-structure interaction (FSI) modeling of the wind-blade interaction is crucial for realistic and reliable engineering analysis and prediction.

To achieve this goal, we propose the following specific research targets:
Target 1: Development of reliable and efficient computational technologies for FSI of wind turbines.
Target 2: Application of the technology developed to engineering simulation of specific wind turbine configurations.

2 Technical Approach and Research Plan

This section outlines how we plan to address the research targets set in the previous section.
Target 1: Development of reliable and efficient computational technologies for FSI of wind turbines.
Geometry modeling and mesh generation. There is essentially no published work on geometry modeling and mesh generation for wind turbines, which presents a significant challenge for the computational community to even begin simulating wind turbines. We propose to develop a template-based wind turbine geometry modeling based on volumetric NURBS (Non-Uniform Ra-

tional B-Splines). This geometry representation has the following benefits: 1. NURBS can be directly used in engineering analysis. As an analysis tool, they were first proposed in the context of *isogeometric analysis* [21]. Isogeometric analysis was successfully used in computation of fluids, solids and structures, and FSI in [2, 7, 8, 15, 1, 13, 5, 4, 3, 12]. Wind turbines are dominated by the rotational motion of the blades, for which NURBS are well-suited and present an added benefit due their ability to represent circular and cylindrical shapes exactly [6]; 2. NURBS are a CAD standard. As a result, existing CAD representations of wind turbines can, with some adaptation, be reused to create volumetric NURBS models. Using NURBS for both geometry modeling and simulation of wind turbines gives a seamless integration of design and analysis, which presents a major unsolved difficulty in other engineering simulation areas; 3. Complex geometrical shapes can be represented using NURBS with a relatively small number of parameters, which is favorable for optimization; 4. NURBS representation can also be easily converted into unstructured hexahedral and tetrahedral meshes for standard finite element analysis procedures.

We intend to use both the standard finite elements and NURBS-based isogeometric analysis for simulation in a complementary fashion. The former is widely used in academia and industry, which will maximize the broader impact of this work; the latter is an emerging computational technology at the forefront of the computational research and is naturally suited for our application.

The template-based geometry modeling approach entails the construction of one or more (small number of) template geometries of wind turbine designs. The templates will include and closely approximate the geometry of the rotor blades and hub (nacelle), the tower and the flow domain around. The template geometry is then deformed to the actual geometry of the wind turbine by appropriately minimizing the error between them. Once the geometry model is generated, an analysis-ready geometry is produced with user control over mesh refinement and domain partitioning for efficient parallel processing. The advantage of this approach is that it can be specialized and optimized for a particular class of geometries. For example, the template-based approach was developed and successfully employed for NURBS modeling and FSI simulation of vascular blood flow with patient-specific configurations in [32].

Advanced computational FSI technologies. Advanced computational methods for wind turbine analysis are likewise lacking. Standalone fluid mechanics simulations with simplified wind turbine configuration were reported in [30, 31], some at significantly-reduced scale and some with significant limitations in terms of the representation of the exact geometry and prediction of the FSI involved. Structural analyses of the individual turbine blades under assumed load conditions or loads coming from separate computational fluid dynamics simulations were also reported (see, e.g., [18, 19]). To the best of our knowledge, no coupled fluid–structure simulations of the full-scale wind turbine assembly or arrays of wind turbines were attempted. There is no doubt that coupled fluid–structure simulations at full scale are essential for accurate modeling of wind turbines. The motion and deformation of the wind turbine blades depend on the wind speed and airflow, and the airflow patterns depend on the motion and deformation of the blades. The equations governing the airflow and the blade motions and deformations need to be solved simultaneously, with proper kinematic and dynamic conditions coupling the two physical systems. Without that the modeling cannot be realistic. This problem presents a significant computational challenge because of the high wind speeds, complex and sharp geometric features, and sizes of the wind turbines under consideration. This in part explains the current, modest nature of the state-of-the-art in wind turbine simulation.

We propose to, as the first step, develop computational analysis procedures that couple airflow with rigid rotation of the wind turbine and simulate the turbine operation under different wind conditions. Millions of grid points and hundreds, perhaps thousands, of processors will be required for accurate simulations. The Reynolds number of the flow is in the range of several hundred million, indicating a strongly advection-dominated and fully turbulent flow. Simulating these phenomena requires accurate, stable and robust numerical formulations and increased grid resolution. The residual-based variational multiscale method will be employed for turbulence modeling [2] in conjunction with the robust discontinuity-capturing techniques The former was successfully employed in simulations of boundary layer flows at high Reynolds numbers [8], while the latter was shown to perform well in a number of engineering applications [29, 24, 11]. NURBS-based isogeometric analysis, as well as standard finite elements will be employed as a simulation modality.

The Arbitrary Lagrangian-Eulerian (ALE) formulation [20, 14, 22, 17, 16, 3] will be the basis of most production-level computations. The Deforming-Spatial-Domain/Stabilized Space–Time (DSD/SST) formulation [25, 26] and the Stabilized Space–Time FSI (SSTFSI) technique [28, 27], due to their high-order time accuracy, albeit somewhat at higher computational expense, will be employed for computing results that will be used for verification and validation of the ALE computations.

The simulations will produce detailed, unsteady loads on the turbine blades and the tower, which are suitable for more detailed structural analyses of the individual components of the wind turbines. This will also enable us examine the structural response of a wide array of composite materials employed in the manufacturing of turbine blades and towers (see, e.g., [18]). The structural problem will entail the well known challenges associated with long thin structures and complicated material models, requiring advanced numerical modeling. A new user-element capability for a commercial FEM software LS-DYNA [10] was recently developed and used in [9] for simulating shell structures modeled with NURBS surfaces. This new capability, which allows a user to "bring his own discretization" and take advantage of the wide range of material models, nonlinear algorithms and other solver technology developed over several decades, will be employed for the structural computations. Fluid–structure interaction procedures will be devised that take advantage of the existing LS-DYNA structural analysis capabilities.

We will further extend our numerical formulations to couple airflow with beam and shell structures used for wind turbine structural models. Motions beyond rigid rotation are significant, especially in the offshore environments, and will be incorporated in the analysis for accuracy.

Specific Aim 2: Application of the developed technology for engineering simulation of specific wind turbine configurations. The techniques developed in Specific Research Aim 1 will be employed in the simulation of existing wind turbine configurations at full scale. We propose to simulate on land and offshore designs with the associated wind speeds, focusing on wind loads on the turbine blades and tower. These are of great importance in design and manufacturing and are very hard or impossible to obtain using experimental techniques.

Wind turbine rotation is not merely driven by the wind stream impacting the blades. Sophisticated controls are implemented to initiate rotor motion, adjust the blade angle and the rotation speed, and other parameters, depending on the wind conditions. These control mechanisms will be researched, implemented and simulated as a part of the coupled FSI framework. The methods developed will allow us to examine in detail, for example, what are the instantaneous wind loads as the blades are changing their pitch angle during the rotation. To the best of our knowledge, no such analyses or simulations have been reported.

As a pilot study, using a template-based approach, we created a full-scale isogeometric model of the wind turbine rotor. The rotor diameter is set to 120 m. The wind speed and the rotor angular frequency are assumed to be 15 m/s and 10 RPM, respectively. This situation corresponds to an offshore wind turbine case, where the blade diameter is significantly larger than the on land designs, and the wind speeds are higher. The airflow domain is discretized with over 2,000,000 rational quadratic NURBS elements. The computation was carried out with 90 processors. The results are shown in Figure 1 and indicate the complexity of the underlying physical phenomena and corresponding simulation challenges involved.

3 Qualifications and Resources

The PIs are uniquely positioned to perform the proposed research. PI Bazilevs is one of the original developers of isogeometric analysis and is a world authority in the field. He is also one of the leading researchers in FSI modeling.

Co-PI Tezduyar is the world leader in FSI research as is evidenced by his academic record. He pioneered the use of space–time finite elements for FSI and fluid–particle interactions and solved numerous challenging real-world problems, including the dynamics of hundreds of particles interacting in a flow field and the aerodynamics and FSI of very complex parachute designs.

Co-PI Benson is a world authority on computational solid mechanics and shell structures. He is one of the original developers of and currently a top contributor to LS-DYNA, a commercial FEM package widely used in industry.

Co-PI Hegemier is a world authority in solid mechanics, plasticity, and is most well known for his contributions to composite materials and structures. His several decades of experience with composite materials will enhance the structural aspects of the FSI developments proposed in this project.

The following computational resources will be used for code development and simulation:

- Ranger – a Sun Constellation Linux Cluster with $62,976$ processing cores, total memory of 123TB and peak performance of 579.4TFlops. Ranger is housed and serviced at the Texas Advanced Computing Center (TACC) and is the largest computing system in the world for open science research and is an NSF Track2 HPC acquisition.
- Lonestar – a Dell Linux Cluster with $5,800$ processing cores, total memory of 11.6TB and peak performance of 62TFlops. This machine is also a part of TACC high-performance computing resources.
- Cray XD1 Research Cluster and T*AFSM Laboratory – The Cray XD1 Research Cluster (http://rcsg.rice.edu/ada/ext/) at Rice University provides a powerful parallel computer resource. It is a 632 AMD64 CPU core machine with dual core 2.2 GHz AMD Opteron 275 CPUs and with 1 MB L2 cache. The Team for Advanced Flow Simulation and Modeling (T*AFSM) (http://www.mems.rice.edu/TAFSM/) laboratory provides a good, modern collection of servers, desktop computers and visualization hardware and software.

Additional high-perfomance computing resources will be employed at the San Diego Supercomputing Center (SDSC). The SDSC high-performance machines are available to researchers nationally through TeraGrid allocations and to University of California researchers through the Academic Associates Program (AAP). PI Bazilevs is a member of the TeraGrid network and a TeraGrid user.

4 Broader Impact

The outcomes of this work will provide the engineering community with unique computational approaches and tools to address the challenges involved in computer modeling and FSI simulation of wind turbines. Due to the flow flow conditions and the complexity of structural modeling, this problem presents a major computational challenge that has not been addressed yet. Advanced, high-fidelity computational methods for wind turbine analysis are notably lacking. The proposed research and its developments will open the door and simultaneously set the standard for computational practices in wind turbine engineering in the US and world-wide. It will provide a major technology transfer opportunity for wind energy industry in the US.

The results of this research will be distributed in the academic and industrial circles by means of published papers in refereed journals and conference proceedings. Because the topics of FSI and isogeometric analysis are at the forefront of the computational mechanics research, articles on these subjects typically receive enthusiastic support from all major international journals on computational mechanics and engineering. The PIs will continue successful organization of computational FSI and isogeomeric analysis symposia at international conferences. These conferences are heavily attended by the representatives from industry.

Co-PI Tezduyar and PI Bazilevs currently serve on the American Society of Mechanical Engineers Applied Mechanics Division (ASME-AMD) [23] Committee on Fluid–Structure Interaction as Chair and Co-Chair, respectively, allowing them to promote the topic of computational FSI with application to wind turbine simulation. As a part of this project, both investigators plan to develop and co-teach short courses on the subject largely aimed at the industrial community.

As previously mentioned, LS-DYNA is a commercial finite element software that enjoys widespread usage in industry. Every automobile manufacturer has LS-DYNA licenses and makes use of the software for car crash simulation. The recent release of LS-DYNA will have the first implementation of the user-defined element, a capability recently developed for LS-DYNA by Co-PI Benson and used by Co-PI Benson and PI Bazilevs in simulation of shell structures using NURBS-based isogeometric analysis [9]. This is the first instance of non-finite element calculations performed by commercial finite element software. The software developed may become a part of the LS-DYNA package and may be distributed to every major wind turbine manufacturer. LS-DYNA, for a nominal fee of $500 per calendar year, provides an unlimited number of software licenses to the Structural Engineering Department at UCSD. As part of this work we plan to make extensive use of LS-DYNA to develop FSI capabilities for wind turbine simulation.

It is envisioned that advanced computer modeling in the wind energy industry will play the same role as it currently does in the automobile and aerospace industries. Within a decade, every wind turbine manufacturer in the US will be performing computational analyses of the same level of complexity as car crash and aircraft aerodynamics. The proposed project will help our Nation to reach that point faster and with a world-wide research lead.

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