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Review of computer-aided numerical simulation in wind energy

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ABSTRACT

Many advances have been made during the last decade in the development and application of computational fluid dynamics (CFD), finite element analysis (FEA), numerical weather modeling, and other numerical methods as applied to the wind energy industry. The current information about this area of study may help researchers gage research efforts. Specifically, micro-siting, wind modeling and prediction, blade optimization and modeling, high resolution turbine flow modeling, support structure analysis, and noise prediction have been the main focuses of recent research. The advances in this area of research are enabling better designs and greater efficiencies than were possible previously. The trends toward system coupling, parallel computing, and replacing experiments are discussed. The shortcomings of recent research and areas of possible future research are also presented.

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1. Introduction

Numerical simulation has become a valuable asset to research in wind energy and helped the industry become more efficient and productive. It has enabled new designs and levels of efficiency not

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possible before [1,2]. Much research is being done to improve the accuracy and applicability of numerical tools. Researchers need to understand the current status and trends within this area of study to gage research projects. The recent articles in this paper came from relevant journals, and are presented to explore advances and trends in numerical simulation as applied to wind energy to satisfy this need. Micro-siting, wind modeling and prediction, blade optimization and modeling, high resolution turbine flow modeling, support structure analysis, and noise prediction are the main focuses of the studies presented here.

Determining the exact placement of wind turbines in a wind farm, or micro-siting, used to consist of guess work and simple models, but numerical methods are enabling optimization of placement and better understanding of wake interactions of turbines. Without these recently possible techniques, wind energy could not be harnessed to its full potential. The atmospheric boundary layer (ABL) also was the subject of some speculation, but measurements coupled with new numerical techniques have made accurate determination of a site's wind energy potential possible. Much advancement has been made in these areas, but there is plenty of room for improvement. Improvements could be made not only through new techniques and methods, but also through combinations and optimizations of recently devised models.

Advancements have been made in large-scale applications, such as the aforementioned, but smaller-scale and more detailed models also have been the subject of recent research. CFD can be employed alone or coupled or in conjunction with existing structural analysis tools to analyze, optimize, or create blade designs for wind turbines. Force and fatigue analysis, power output optimization, and damage prediction for complex, modern blades are now possible because of the recently developed numerical techniques. Consideration of detailed models of blades, generators, and support structures simultaneously is now possible. Prediction of noise generation and minimizing noise are even possible.

All of the methods outlined in this paper have been made possible by increases in computing power and improvements in computing techniques. A technical improvement is coupling CFD, FEA, and other numerical tools together to utilize the strength of each. Increasing computing power is not limited to a single, local system. Multiple, parallel, dedicated server arrays have been created and utilized for demanding, large CFD solutions, enabling faster, larger, and more detailed results than ever before.

2. Turbine micro-siting and wind farm layout optimization

Wind farm micro-siting is the process of determining the most efficient and economical configuration for wind turbines within a wind farm. Researchers recently have applied numerical simulation techniques to this process. These new techniques have helped optimize and analyze situations not possible before, such as flow in complex terrain [3] and cost optimization models [2].

2.1. Wind flow analysis

Computational fluid dynamics (CFD) and numerical methods can be used to analyze flow over complex terrain in order to better micro-site a wind farm. Coastal areas are attractive farm locations because of the relatively high wind speeds, but these and other attractive regions often have complex terrain and unsteady wind flow. CFD and numerical modeling aid, and sometimes make possible, micro-siting in these areas. As an example, Palma et al. [4] analyzed flow in such a region with CFD, and results were accurate when compared to observations and experiments. Their method predicted regions where flow was unsteady, separated, or had too much vorticity for turbines. Their CFD setup and meshing are shown in Fig. 1. A similar study used custom code based on large eddy simulation (LES) to analyze flow over complex terrain [3]. The custom method was accurate in predicting wake regions behind hills and other features.

Micro-siting in an urban environment with buildings is another focus of recent research. Ledo et al. [5] employed the Reynolds-Averaged Navier–Stokes (RANS) method to perform such an analysis. They found flat-roofed buildings best for turbines. The model used a semi-log wind profile to simulate realistic wind. While analysis of complex terrain is useful in micro-siting, considering the effects of the turbines on the atmospheric boundary layer (ABL) and each other is important.

Turbines and the ABL interact in the real world, and the effects of this interaction can significantly impact farm performance. Traditional wall roughness models are used to estimate the effect of turbines on the ABL, but Johnstone and Coleman [6] used a large array of turbines to simulate this effect more accurately. They used the actuator disc method to approximate turbine geometry. The study found that turbines of mixed height may be more efficient.

These recent studies have provided useful methods for finding suitable locations for wind turbines in complex environments, but most of those considered here do not include turbine geometry in their models. Including turbine geometry and using more advanced methods, such as LES, could be the focus of further research. Table 1 compares the presented research in wind flow analysis by listing the employed methods and programs, major contribution of the study to the field, the blade model, and results. Having feasible and accurate methods to simulate the wind and blade geometry improve farm efficiency, but a good engineering design model considers many more variables.

2.2. Algorithmic and cost-analyzing methods

CFD can be coupled with algorithms which use cost, spacing, geography, and turbine interconnections as variables in order to find the optimum farm layout. Models considering a more complete list of variables can optimize and predict, not simply analyze, wind farm layouts. One such model approaches micro-siting as a constrained optimization problem where power must be maximized and distance between turbines minimized [7]. The model employs a Gaussian particle swarm optimization algorithm. Only one type of turbine at one height can be analyzed, and cost and other restrictions are not considered. Torres et al. [8] used a similar model in the CFD program EllipSys3D, employing LES and the SIMPLE algorithm, to optimize the layout of a wind farm. They used the actuator disc model and analyzed wake–wake interactions. Another optimization study [9] treated wakes as particles generated by turbines. The particles flow in a pre-calculated flow field, and the decrease in velocity due to wake interaction is analyzed. Since the flow field is pre-calculated, no new CFD calculations need to be done for each new layout. Fig. 2 shows an example of an optimized wind farm layout on a topographical map produced by this method. These models can optimize power output, but may not necessarily produce the most economical layout. This goal requires a cost model.

Numerical models which use cost as a variable increase a farm's return and help make wind energy more competitive. One optimization study defined cost in terms of rotor diameter [10]. The model simultaneously selects the optimal rotor diameter and turbine locations for maximum power generation. The model can improve power output significantly, but does not consider hub height. A more advanced model [2] uses CFD wake analysis in conjunction with an evolutionary algorithm for micro-siting based on geography, wind data, installation cost, and turbine