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Multidisciplinary design optimization of offshore wind turbines for minimum levelized cost of energy

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A B S T R A C T

This paper presents a method for multidisciplinary design optimization of offshore wind turbines at system level. The formulation and implementation that enable the integrated aerodynamic and structural design of the rotor and tower simultaneously are detailed. The objective function to be minimized is the levelized cost of energy. The model includes various design constraints: stresses, deflections, modal frequencies and fatigue limits along different stations of the blade and tower. The rotor design variables are: chord and twist distribution, blade length, rated rotational speed and structural thicknesses along the span. The tower design variables are: tower thickness and diameter distribution, as well as the tower height. For the other wind turbine components, a representative mass model is used to include their dynamic interactions in the system. To calculate the system costs, representative cost models of a wind turbine located in an offshore wind farm are used. To show the potential of the method and to verify its usefulness, the 5 MW NREL wind turbine is used as a case study. The result of the design optimization process shows 2.3% decrease in the levelized cost of energy for a representative Dutch site, while satisfying all the design constraints.

1. Introduction

Due to concerns over the environmental impact of fossil fuel emissions and fossil fuel exhaustion, the amount of wind energy generated has been increasing at a faster pace in the last few years. Although wind energy has evolved considerably during the last decades, there are many advances required to design economic and reliable wind turbines.

One of the promising concepts that can contribute to these goals is the use of multidisciplinary design optimization (MDO). MDO uses numerical optimization techniques to design engineering systems involving multiple disciplines or components Martins and Lambe [1].

In the context of wind power design optimization two subjects are of interest: the design optimization of wind turbines and wind farm layout optimization.[1] The scope of this paper is wind turbine design optimization considering aerodynamics and structure as the two main disciplines, with the simultaneous design of the rotor and tower as the two main components.

Over the past decade, several authors have developed techniques for optimizing either the rotor or tower, with most of the studies being focused on rotor optimization. A brief overview of these studies is presented below.

1.1. Rotor design studies

A method for optimizing wind turbine gross parameters, such as rotor diameter and hub height for a specific site was presented by Diveux et al. [9]. Similarly, Fuglsang and Thomsen [10] conducted rotor design optimization with several site-specific environmental inputs to minimize the cost of energy (COE). Benini and Toffolo [11] used a multi-objective evolutionary algorithm to optimize the aerodynamic shape of a stall-regulated wind turbine blade.

Maalawi and Negm [12] presented an optimization study to make an exact placement of natural frequencies of the blade to avoid resonance. Maalawi and Badr [13] optimized the rotor chord and twist to produce the largest possible power output. Jureczko et al. [14] studied the blade structural lay-up optimization to minimize its mass.

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[1] For wind farm layout optimization the interested reader can consult various references Beyer et al. [2], Grady et al. [3], Castro Mora et al. [4], Marmidis et al. [5], Kusiak and Song [6], Emami and Noghreh [7], Meyers and Meneveau [8].

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The blade structural optimization of laminated composite shells was studied by Lund and Stegmann [15]. The shape and thickness of the structure were fixed and the problem dealt entirely with the design of the lay-up of the composite laminate. Méndez and Greiner [16] used a genetic algorithm to obtain optimal chord and twist distributions in wind turbine blades to maximize the mean expected power depending on the Weibull wind distribution at a specific site. Lee et al. [17] studied blade shape optimization to obtain the maximum average annual power for a given offshore wind farm. A two-step optimization procedure was established: the operating condition optimization as step one, and the geometric blade shape design and blade performance analysis optimization as step two.

Kenway and Martins [18] studied the blade aerostructural design optimization to maximize the energy output while considering site-specific winds. Xudong et al. [19] used an aeroelastic model of the rotor to do aerodynamic and structural design with the rotor torque and thrust as the design constraints.

Blade aerodynamic shape optimization using different tip-loss corrections in blade element momentum (BEM) theory was studied by Clifton-Smith [20]. The blade aerodynamic shape optimization with a probabilistic approach was studied by Lee et al. [21].

To enhance the aerodynamic performance of blades, the sectional aerodynamic design optimization was studied by Kwon et al. [22]. Design optimization of a wind turbine blade was presented by Jeong et al. [23] to minimize the fluctuation of the bending moment of the blade in turbulent wind.

Blade structural and aerodynamic optimization was presented by Bottasso et al. [24]. Design optimization is performed by a two-stage process. First, an aerodynamic shape optimization step is performed to maximize annual energy production (AEP), followed by a structural blade optimization to minimize weight. Second, both designs are combined to yield the final optimum solution.

The system-level design of a wind turbine blade using a multi-level optimization approach was studied by Maki et al. [25]. The shape optimization of the blade to maximize AEP, and the structural design of the blade to minimize the bending moment at the root were considered as single-disciplinary optimization strategy. Cost of energy was considered as the overall system-level objective, while performance improvements at the two single-disciplines were pursued at the same time.

1.2. Tower design studies

Negm and Maalawi [26] examined several optimization models such as mass reduction, stiffness maximization and vibration minimization for the design of a tubular wind turbine tower structures. Wind turbine tower optimization was studied by Yoshida [27] using a genetic algorithm to minimize the mass of the tower. Uys et al. [28] developed a procedure to minimize the cost of a mildly conical steel wind turbine tower to meet the structural requirements of slender structures.

A formulation for the optimal design of reinforced concrete towers was presented by Silva et al. [29]. Different tower heights were analyzed to obtain the best formulation in terms of cost. An integrated reliability-based design optimization of offshore towers was presented by Karadeniz et al. [30]. As a demonstration, they optimized a tripod tower subject to reliability constraints based on limit states of the critical stress, buckling and the natural frequency.

Similarly, Petrini et al. [31] proposed a system approach as a conceptual method for the design of offshore wind turbine structures. Numerical analysis has been performed to compare the design of three different support structure types (monopile, tripod and jacket) with respect to extreme loads, buckling, natural frequencies and life-time loads.

Torcinaro et al. [32] considered the optimization process of an offshore support structure intended for a 5–6 MW turbine. Support structure geometry and thickness were the design variables subjected to constraints on stresses, buckling and deformation. Mass is optimized using gradient based optimization algorithm.

Thiry et al. [33] used a genetic algorithm to minimize the structural weight of a wind turbine support structure for an offshore application. Haghi et al. [34] used a similar approach, but instead of using a genetic algorithm he used gradient-based optimization. Zwick et al. [35] presented an iterative optimization approach for a first stage of a complete analysis of a full-height lattice tower concept. The aim was to find a light-weight design to fulfill the ultimate and fatigue limit states of the members.

Molde [36] used Spall's simultaneous perturbation stochastic approximation method Spall [37] to automatically optimize thickness and diameter of the members in offshore lattice tower support structures. The objective was to minimize tower weight. Karpat [38] minimized the cost of wind turbine steel towers with ring stiffeners using a particle swarm optimization algorithm. The height and thickness of a flat ring stiffener, and the wall thickness and the diameter at some stations along the tower were selected as the design variables, subject to buckling and frequency constraints.

The work presented herein addresses some of the shortcomings of the previous work mentioned above by developing an integrated MDO method to simultaneously design the rotor and the tower of a wind turbine at the system level. The design found in this way is superior to the design found by optimizing each discipline or component separately, since MDO of the rotor and tower incorporates the dynamic interaction between the disciplines and components. This interaction is particularly important, due to the following factors:

1.2.1. Structural flexibility

Rotor and tower are the most flexible components of a wind turbine, and together they dominate the global dynamics of the system.

1.2.2. Energy yield

Rotor and tower (also the controller) have the highest impact on the annual energy yield of the wind turbine, therefore important to optimize simultaneously.

1.2.3. Cost

Rotor and tower (also the gearbox) have the highest cost share of a wind turbine. Typically, rotor and tower make up to 30% of the capital cost of a wind turbine Tegen et al. [39].

The remainder of the paper is structured as follows. First, the integrated architecture used to model the multidisciplinary aspects of the wind turbine is presented. This is an important aspect, since existing computational tools are not well suited to be used with numerical optimization that is fully automated.[2]

We then describe how this integrated multidisciplinary model is linked to the optimization algorithm. This enables running the design optimization process for as many iterations as the optimizer needs to find the optimum. Then, to verify the capability and effectiveness of the method, the 5 MW NREL research wind turbine Jonkman et al. [41] is used as a baseline design to optimize. Both the rotor and tower are designed simultaneously with all their relevant design constraints present. Finally, the results of the optimized 5 MW turbine are compared with the 5 MW NREL wind turbine, followed by a discussion and conclusions.

[2] See Ashuri and Zaaijer [40] for a list of the main computational tools currently used for wind turbine design.