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Dynamic reliability based design optimization of the tripod sub-structure of offshore wind turbines

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ABSTRACT

This work presents an efficient methodology for the Reliability Based Design Optimization (RBDO) of the tripod sub-structure of offshore wind turbines considering dynamic response requirements. The cost of supporting structure of offshore wind turbines is so high that optimization in the design stage is a basic requirement. Traditional design optimization methodology for offshore structures uses deterministic modeling. However, the existence of uncertainties, such as manufacturing tolerances, material properties, and environmental loads, requires a probabilistic optimization technique. Uncertainties in the offshore wind turbines design process may have a strong effect on its dynamic responses but very little researches have been conducted to incorporate the uncertainty property into design optimization of the supporting structures. In this study, a framework of a dynamic reliability based design optimization for tripod sub-structures was proposed. Firstly, a Finite Element (FE) model of a tripod sub-structure of the NERL 5 MW wind turbine was constructed for dynamic response analysis in time domain and generating several accurate sampling points. Secondly, an efficient approximate model was built utilizing these sampling points to replace the original time consuming dynamic response analysis of FE model. At last, this approximate model was used during the optimum iterative procedure with a global optimization algorithm to gain the final best design point considering uncertainties. In this optimization methodology, some sizes of structural components, applied loads, and some material properties are considered as random variables. The structural stress and natural frequency are considered as constraints and the weight of the structure is considered as the objective function. The reliability of the structure is finally determined through Monte Carlo simulations. The results show that the proposed methodology can obtain a reliable design with better dynamic performance and less weight. Compared with the deterministic optimization, the presented dynamic Reliability Based Design Optimization of tripod sub-structure of offshore wind turbines is more rational and practical and this efficient methodology can be applied in the design of other similar offshore structures.

1. Introduction

Compared with onshore wind energy, offshore wind energy has several advantages such as abundant resource, stable wind speed and small influence to human beings. These merits greatly stimulate the development of offshore wind turbines [1]. The supporting structures of offshore wind turbines are constantly subjected to various dynamic forces like winds, waves and currents. For offshore wind turbines, more attentions have been paid to the cost reduction and the safety requirements. Offshore wind turbine has a higher cost due to the manufacturing, transportation and installation of support structures than onshore wind turbine. The height of large wind turbine tower may be up to 100 m with weight more than hundreds of tons which accounts for about half of the total weight. The supporting structures are subject to random winds and waves and some effects of random factors generated by electrical equipment, material properties and hydrodynamic performances. So if the supporting structure damaged, the economic benefits of the offshore wind turbine in the future would be used up once to pay for the maintenance costs and the transportation expenses [2].

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In recent years, many researchers have focused on the study of offshore wind turbine. Jonkman [3] built horizontal axis wind turbine blade model on the basis of aerodynamics and produced FAST software for real time simulation of wind turbine operational status. Zaaijer [4] etc. made a stiffness matrix of the mud under water to simply simulate the leg restraints of supporting structure of stationary offshore wind turbine; Park [5] etc. made dynamic response analysis of an offshore platform which was subjected to seismic movements. They established a three dimensional numerical model of the platform and analyzed the bearing capacity of the legs at the pipe–soil contact under seismic wave.

For the tower design, on the one hand, we want to maintain the structural safety; on the other hand, we want to reduce the cost of offshore wind turbines. Both safety and economic aspects should be considered in the design process. Thus an optimal design needs to be offered to solve this contradiction. In recent years, researchers have carried out some offshore structure optimization designs [6,7]. However, they did not consider uncertainties in the loading, geometry of the structure and material property. Most of their work considered static optimization design only. Uys [8] etc. made a deterministic optimization for a steel tower of wind turbine. This optimization considered the constraints of the tower shell buckling and the local buckling of ring stiffener. The tower diameter, thickness and number of internal ring stiffeners were optimized to reduce costs. Karadeniz [9] et al. added reliability analysis in the optimization of turbine tower with segments. In his study, a reliability analysis model was built; ultimate strength and buckling were taken as probabilistic constraints; and tower cross section and thickness were optimized with different probabilistic constraints. Deterministic optimization usually obtains the optimum solutions near the constraint boundaries, leaving little or no room for uncertainties. Without considering uncertainties and the probabilistic quantification, deterministic optimization design with a safety factor may be either unsafe or too conservative [10,11]. Therefore, focusing on the cost and reliability is needed in the design of supporting structure of offshore wind turbines. However, there are two obstacles to the dynamic reliability based design optimization of the structure. Firstly, the dynamic characteristic of support structure is very complex that an optimization design considering uncertainties is extremely computationally expensive. Secondly, failure cases are usually prone to happen during the optimization loops. So the dynamic reliability based optimization of the supporting structure of offshore wind turbine must be every efficient in order to handle these problems. Unfortunately, existing optimization strategies do not provide sufficient information to meet this demand. The dynamic characteristics are important for the safety of offshore wind turbines. Many researches have performed precise predictions of such dynamic properties analytically and experimentally [12]. However, all aforementioned studies are based on deterministic optimization, and the uncertainties and variations are not incorporated into the design optimization. Therefore, developing a new strategy of dynamic reliability based design optimization becomes the main purpose of this work.

In this work, the reliability based design optimization of tripod sub-structure of offshore wind turbines under dynamic constraints is studied. A metamodel is constructed to replace the original numerical simulation of Finite Element model. By using metamodel technique, additional uncertainties, including material property, geometric property and loads, are incorporated into the structure design. Global optimization algorithms are executed on the metamodel to find the minimum mass subjected to probabilistic constraints. The reliability of the optimal design is checked using Monte Carlo simulations. Comparison of deterministic optimization and stochastic optimization is also given.

2. Theories

2.1. Optimization using metamodel

Metamodels are used to construct the approximations of the analysis code and describe the functional relationship between design variables and corresponding responses [13,14]. And Kriging model is one of these approximations. For one optimization problem, we know the design space of input parameters, and then we can calculate the output response. The metamodel technique can describe the black boxed system according to the already known input and output information. Fig. 1 shows the basic principal of metamodel construction process. In the picture, the coarse network on the left side is the original system which includes input and output information. According to the sampling points extracted from the coarse network, we can construct the Kriging model which approximately describes the relationship between input and output. The dynamic optimization can be based on this smooth network of Kriging model without losing too much accuracy.

The metamodel can take place of the original time consuming and complicated simulation codes (such as the Finite Element model) to predict the response of the system. During the reliability based design optimization, the metamodel can replace the simulation codes for calculating, as shown in Fig. 2.

2.2. Theory of metamodel

Design of Experiment (DOE) tries to sufficiently and economically arrange design experimental factors, the factor levels and the number of experiments on the premise of a clear experimental objective.

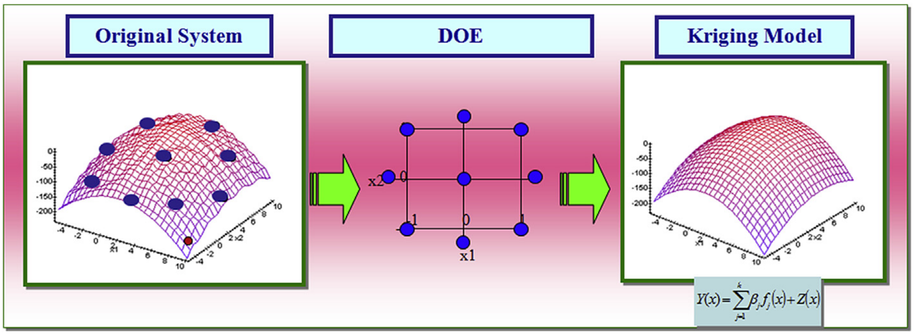

Fig. 1. Basic principal of metamodel construction.