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Analytical gradient-based optimization of offshore wind turbine substructures under fatigue and extreme loads

Kok-Hon Chew [a, b, *], Kang Tai [a], E.Y.K. Ng [a], Michael Muskulus [b]

[a] School of Mechanical and Aerospace Engineering, Nanyang Technological University, 639798, Singapore
[b] Department of Civil and Transport Engineering, Norwegian University of Science and Technology, 7491 Trondheim, Norway

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ABSTRACT

Design optimization of offshore wind turbine support structures is an expensive task due to the highly-constrained, non-convex and non-linear nature of the design problem. A good depth of detail in the problem formulation can give useful insights in the practical design process, but may also compromise the efficiency. This paper presents an analytical gradient-based method to solve the problem in an effective and efficient way. The design sensitivities of the objective and constraint functions are evaluated analytically, while the optimization procedure is performed in the time domain, subjected to sizing, eigenfrequency, extreme load and fatigue load constraints. A case study on the OC4 and UpWind jacket substructures show that the method was reliable and consistent in delivering superior efficiency and accuracy in the optimization study, as compared with the conventional finite difference approach. The global optimum was probably achieved in the design optimization process, where the large number of design constraints implemented can possibly be the blessing in disguise, as they seem to enable the optimizer to find the global optimum. Both the buckling and fatigue load constraints had significant influence over the design of tubular members and joints, while each component is oriented to maximize the utilization against the prescribed limit state functions.

1. Introduction

Offshore wind power has set foot in the renewable energy industry as early as 1991 when the Vindeby wind farm began operating in Danish waters. It was only over the last few years that the industry started to boom globally (mainly in Europe), when more focus is given to promote a clean and diverse energy mix, in view of the environmental impacts caused by fossil fuels [1]. Offshore wind is abundant and stable; and is a good power source to the populated cities mainly in coastal regions, without affecting the human habitat onshore. However, the current state of technology incurs a high levelized cost of energy (LCOE) which needs to be driven down [2]. For a 500-MW offshore wind farm to be built in the United States, recent studies have estimated that the capital costs are in the order of \$5000/kW to \$6000/kW, where the support structure system can contribute up to 22 percent of the total capital costs [3]. It has been identified as one of the key areas for cost reduction that can be attained through economies of scale and reduced material costs [4]. With the wind turbines growing larger and heavier, upscaling of current support structure designs to accommodate the increasing wind and wave dynamic loads when

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* Corresponding author. 50 Nanyang Avenue, School of Mechanical and Aerospace Engineering, Nanyang Technological University, 639798, Singapore.
E-mail address: khc860113@gmail.com (K.-H. Chew).

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venturing to deeper waters can be economically and technologically challenging. Development of novel concepts and evolution of existing designs are necessary to increase the structural strength-to-mass ratios for such applications, hence offering ample opportunity for structural optimization [5].

When optimizing the offshore wind turbine (OWT) support structures, accurate and extensive load simulations are required to develop reliable and cost-effective designs. On the one hand, coupled dynamic simulations are performed in the time domain, in order to capture the coupling effects and non-linearities within the aero-hydro-servo-elastic analysis [6]. On the other hand, the simulations have to be repeated for multiple design load cases (DLCs) representing different operational and environmental conditions, in accordance with the international standards [7]. Specialized software that supports the aero-hydro-servo-elastic modeling and analysis is normally employed to carry out the simulations. Nevertheless, static load analysis is still commonly employed within the industry, especially the optimization design studies. For instance, Uys et al. [8] minimized the material and manufacturing costs of a ring-stiffened monopile tower subjected to various buckling constraints, by using static wind loads. As for the dynamic response optimization, transient loads introduce time-dependent constraints, which can be treated in a discretized time domain by various approaches reviewed in [9]. Besides, design optimization of offshore tripod structures subjected to extreme loading conditions using the reliability-based and robust design optimization was investigated by Karadeniz et al. [10] and Yang and Zhu [11], respectively, while considering uncertainties in geometry, material properties and load parameters.

So far the aforementioned studies did not include fatigue failure analysis in the design process, which is rather critical for offshore structures. OWT support structures experience vibrations due to the excitation arising from environmental loads and rotor rotations. The fatigue load constraints are sensitive to dynamic response histories, and the evaluations of gradient information using the efficient analytical methods are very challenging [12]. Various simulation-based optimization approaches can be employed to combine both fatigue and extreme load constraints. Chew et al. [13] compared 3-legged and 4-legged jacket substructures subjected to both constraints in the time domain by varying the diameter-to-thickness ratios. Long et al. [14] performed optimization on a full lattice tower using a sequential approach in the frequency domain, where a static design was obtained from the extreme load analysis followed by redesign of member thicknesses against the fatigue loads. Furthermore, heuristic methods were implemented to search for the global optimal solution. Yoshida [15] optimized the dimensions and the positions of flanges and access ports for a wind turbine tower using the genetic algorithm. Schafhirt et al. [16] improved the method by incorporating reanalysis within the genetic algorithm to speed up the optimization process while reducing the number of iterations.

In general, the design optimization procedure requires a large number of iterative calculations since the problem is highly constrained and non-convex. Gradient-based optimization is well-known for fast convergence by utilizing sensitivity information to determine the best direction for improvement, but has the problem of getting stuck in local optima. Currently, most of the research conducted has adopted finite difference methods to obtain the gradients of objective and constraint functions, due to the complexity of problem formulations and the high dependency on specialized software to solve the dynamic problems [17,18]. Recent studies have shown that the finite difference approximation can be erroneous when used in the evaluation of gradients for extreme and fatigue load constraints during the design of OWT structures [19,20]. This may result in an inefficient and unreliable gradient-based optimization procedure.

In this paper, an integrated optimization framework that is based on the analytical gradient-based approach is proposed for the design of OWT support structures. The purpose of the study is:

1. To investigate the overall performance of the proposed methodology, by evaluating (i) the accuracy of the dynamic modeling and analysis; (ii) the efficiency of the analytical optimization approach and (iii) whether the method can find or get close to the global optimum, or will get stuck in a local optimum.
2. To study the influence of various design constraints (eigenfrequency, extreme load and fatigue load constraints) on the structural design and the optimization procedure.

Section 2 provides the problem formulation and discusses various design constraints implemented in the study. Section 3 illustrates the optimization framework. Section 4 presents a case study, followed by results and discussion in Section 5.

2. Optimal design problem formulation

The dynamic response optimization of OWT support structures is a constrained non-linear programming (NLP) problem, which can be illustrated using the following expression:

$$\text{Find } \mathbf{b} \tag{1}$$

$$\text{to minimize } f(\mathbf{b}) \tag{2}$$

$$\text{subject to } g_i\big(\mathbf{b}, \mathbf{z}(t_j), t_j\big) \le 0; \quad i = 1, \cdots, p, \quad j = 1, \cdots, q \tag{3}$$