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Reliability-based design optimization of monopile transition piece for offshore wind turbine system

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ABSTRACT

This paper presents a reliability-based design optimization (RBDO) method for a monopile transition piece in an offshore wind turbine system. Two design approaches are investigated for the cost-effective and reliable design of the monopile transition piece: deterministic optimization (DO) and RBDO. First, dynamic response analysis of a reference offshore wind turbine is conducted to estimate design loads considering site conditions off the southwest coast of Korea. Second, DO for minimizing the mass of a conical monopile connection is carried out, including an assessment of the reliability of the DO design. Next, RBDO is performed to achieve a design with the desired reliability while concurrently minimizing the mass of the monopile transition piece. The present study shows that the structural design of the monopile connection is mostly dictated by the fatigue limit state and that DO does not guarantee structural reliability even though the design satisfies all limit state function conditions. The proposed RBDO process is shown to speed up the design cycle and enhance the reliability of the grouted connection for offshore wind turbine support structures.

1. Introduction

The monopile support structure of offshore wind turbines needs to have high reliability for the turbine systems to withstand the complex extreme nonlinear loads of the harsh environmental conditions in the ocean, which cause fatigue, structural failure, and, occasionally, even critical accidents. Furthermore, its manufacturing, installation, maintenance, and operation costs need to be feasible. Because a turbine system's capital cost is determined by its target reliability, it is important to achieve a tradeoff among the failure consequences, material consumption, and failure probability at the design stage.

Many studies have investigated the feasibility of different fixed support structures such as monopile, tripod, jacket, triple, and gravity-based foundation [1–4]. However, support structure design in consideration of system reliability has been limited to very simple ways of implementing safety or load factors [5]. There are two types of uncertainties in designing a support structure: uncertainties in loads and uncertainties in strength and stiffness of the structure. Uncertainties in loads originate owing to (1) the natural randomness of environmental factors such as wind, waves, and currents; (2) statistical uncertainty in estimating and modeling the environmental parameters; (3) physical model uncertainties due to the aero-hydro-servo flexible structural simulation model of the integrated turbine; and (4) the analytical and numerical structural analysis model. Uncertainties in strength and stiffness originate owing to the natural randomness of the material strength and stiffness and model uncertainties due to the resistance model.

Studies have extensively focused on the effect of extreme waves such as nonlinear and breaking waves on the estimation of support structure loads by the physical modeling of complex phenomena [6–9] and their uncertainty propagation to extreme wave loads. For accurate and effective load estimation, stochastic procedures based on the first-order reliability method (FORM) and Monte Carlo simulation (MCS) have been proposed [10–12]. The dynamic responses of an integrated offshore wind turbine and design loads are obtained by time-domain simulations of a coupled aero-serve-hydro-elastic model. A dynamic simulation model contains high levels of uncertainty. NREL's (National Renewable Energy Laboratory) OC4 project, Europe Community's Upwind project, and others

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have undertaken long-term code validations [13–15]. These codes have been validated both in terms of the accuracy of the dynamic simulation and the predictability of a wide range of design spaces for different support structures [1,5,16]. Currently, although the simulation accuracy has been validated for the design of an offshore wind turbine, site-specific conditions need to be considered carefully [17]. Another uncertainty is caused by the simplified analytical models and characteristic parameters in design standards for the support structure of an offshore wind turbine [19–21]. It is originally based on those of offshore oil and gas production platforms that are mainly subjected to axial loads instead of bending moments [22]. In contrast, the large-scale wind blades of offshore wind turbines cause bending moments on the support structure owing to the complicated aerodynamic loads and the nonlinear dynamic response and fatigue of the structure [23,24].

Despite such diverse uncertainties, support structures are generally designed based on a deterministic limit state design for the estimated design loads and partial safety factors [25–27]. The structural systems' performance is optimized in consideration of their sizes, shapes, and material characteristics. Because a deterministic design, especially an optimum one, is likely to meet the boundary of the feasible region that consists of design constraints, it is usually associated with a high failure probability [28–31]. A reliability-based design optimization (RBDO) methodology that simultaneously achieves the target reliability and minimum cost is developed for the limit state design of the monopile connection of a 5 MW offshore wind turbine. Finally, we verified that RBDO of large-scale offshore wind turbines is clearly necessary for achieving a reliable and cost-effective design. This study proposes an optimum design methodology to ensure the reliability of offshore wind turbines during the design stage.

The remainder of this paper is organized as follows. Section 2 introduces the characteristics of the 5 MW monopile reference turbine model adopted in this study. In Section 3, the design loads of the monopile connection of the reference turbine are analyzed for the support structure considering site-specific conditions off the southwest coast of the Republic of Korea. Section 4 describes the analytical and numerical structural analysis of the monopile connection for the reference turbine based on the design loads predicted in Section 3. Section 5 presents the deterministic design problem with a partial safety factor based on the ultimate and fatigue limit state designs for a monopile connection by describing the limit state functions; furthermore, sensitivity analysis and DO design of the monopile connection are conducted. In Section 6, the reliability of the DO design is evaluated by reliability analysis. In Section 7, RBDO is undertaken for the monopile connection design to achieve the target reliability with minimum mass. The cost-effectiveness and reliability of the initial, optimum, and RBDO designs are compared. GH bladed [32], a commercial code, is used to calculate the ultimate design loads. PIAnO [33], developed by the author, is used for stochastic design and analysis.

2. Characteristics of reference turbine model

2.1. NREL 5 MW baseline offshore wind turbine

NREL's offshore 5 MW baseline wind turbine is used as a reference in this study. This turbine is developed based on Senvion 5 MW prototype wind turbines and is considered representative of typical utility-scale land- and sea-based multi-megawatt turbines. Table 1 lists the parameters of this turbine.

2.2. Monopile support structure with grouted transition piece

The monopile support structure of an offshore wind turbine consists of two parts: the monopile penetrating the seabed and the transition piece connecting the monopile and the tower. The advantages of a monopile support structure, when compared with the other bottom fixed support structures, include minimal seabed preparation requirements, most competitive manufacturing costs owing to the simple structure, and the most experienced support structure with offshore wind turbines. The disadvantages include structure flexibility at large water depths, time-consuming installation owing to the grout setting time, and manufacturing constraints for large diameters and thickness that makes it very difficult to go beyond 30 m water depth.

Table 1
NREL 5 MW baseline wind turbine [2].

Rating	5 MW
Rotor orientation	Upwind
Control	Variable speed, collective pitch
Drivetrain	High speed, multiple stage, gearbox
Rotor diameter	126 m
Hub height	90 m
Cut-in, rated, cut-out wind speed	3 m/s, 11.4 m/s, 25 m/s
Cut-in, rated rotor speed	6.9 rpm, 12.1 rpm
Rated tip speed	80 m/s
Overhang, shaft tilt, precone	5 m, 5°, 2.5°

The state-of-the-art in monopile connection is to implement a conical pile with or without shear keys and transition piece connected by high-strength grout that can withstand the large dynamic bending moments [20]. The grouted connection serves to install the transition piece on the pile and to fix the offshore wind turbine at the right position safely. Fig. 1 shows the initial reference design implemented in this study. Table 2 lists the grouted connections' geometric design parameters and material properties. This design achieves the structural safety requirements based on Det Norske Veritas (DNV) design guidelines [20].

3. Design load analysis

The structural design of offshore wind turbines is based on the verification of the structural integrity of each component under external conditions such as wind, waves, and currents as well as other environmental and turbine conditions. The loads induced by external conditions are divided into three categories: initial and gravitational loads, aerodynamic loads, and hydrodynamic loads. Design loads are obtained by the time domain simulation of coupled aero-servo-hydrodynamic-elastic models. The ultimate

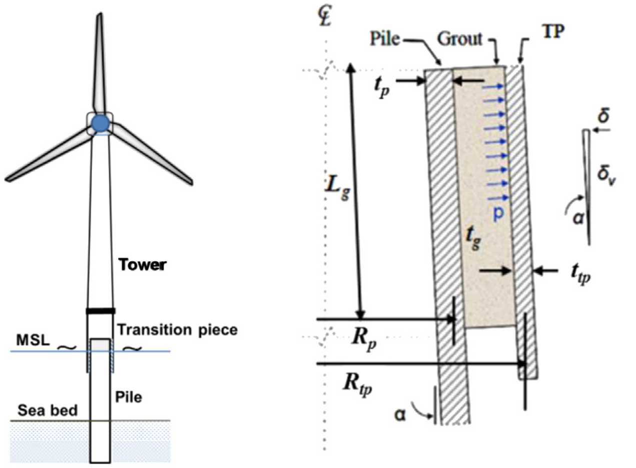

Fig. 1. Configuration of monopile connection of reference design.