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Feasibility study of offshore wind turbine substructures for southwest offshore wind farm project in Korea

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ABSTRACT

Korea has huge potential for offshore wind energy and the first Korean offshore wind farm has been initiated off the southwest coast. With increasing water depth, different substructures of the offshore wind turbine, such as the jacket and multipile, are the increasing focus of attention because they appear to be cost-effective. However, these substructures are still in the early stages of development in the offshore wind industry. The aim of the present study was to design a suitable substructure, such as a jacket or multipile, to support a 5 MW wind turbine in 33 m deep water for the Korean Southwest Offshore Wind Farm. This study also aimed to compare the dynamic responses of different substructures including the monopile, jacket and multipile and evaluate their feasibility. We therefore performed an eigenanalysis and a coupled aero-hydro-servo-elastic simulation under deterministic and stochastic conditions in the environmental conditions in Korea. The results showed that the designed jacket and multipile substructures, together with the modified monopile, were well located at soft–stiff intervals, where most modern utility-scale wind turbine support structures are designed. The dynamic responses of the different substructures showed that of the three substructures, the performance of the jacket was very good. In addition, considering the simple configuration of the multipile, which results in lower manufacturing cost, this substructure can provide another possible solution for Korean's first offshore wind farm. This study provides knowledge that can be applied for the deployment of large-scale offshore wind turbines in intermediate water depths in Korea.

1. Introduction

As global energy demand increases, wind energy is considered as the most cost-effective energy source among all the currently exploited renewable energy sources. In recent years, offshore wind energy has attracted particular attention because of better wind conditions, unlimited sites and negligible visual impact compared with onshore wind energy, and a number of studies have been conducted on offshore wind energy [1–5]. Although the offshore wind industry has experienced rapid development over the past 10 years, there is still a high global demand for offshore wind energy production [6, 7]. As the world's 13th largest economy, relying on imported sources for 97% of its energy consumption, Korea is investing US$9.27 billion to build a 2500 MW offshore wind farm by 2019 off the southwest coast [8]. Consequently, there is an urgent need for more research on offshore wind turbine (OWT) design and analysis based on local environmental conditions in Korea.

At present, the cost of offshore wind energy is higher than its onshore counterpart; one of the challenges is to build a reliable and cost-effective wind turbine [9]. The cost of the OWT substructure (i.e., the entire structure below the yaw system) is around 20–30% of the capital cost [10,11]. The design and analysis of the substructures are thus important issues. Various substructures are available for the OWT, such as the monopile, gravity-based structure, tripod, suction bucket, jacket and floating platform [9]. The type of substructure for the OWT

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mainly depends on the water depth, turbine size and soil conditions. To date, most wind turbines have been installed in shallow water with the monopile or gravity substructure, and these solutions may be stretched to deeper water and larger wind turbines. Gravity-based substructures were used for the 5 MW turbines of the Thornton Bank wind farm in Belgium in up to 27 m water depth [12], and the feasibility of a monopile substructure for 5 MW turbines in water depths up to 30 m was discussed by Seidel [13]. Two 5 MW turbine models were used in the German Alpha Ventus wind farm on tripod and jacket substructures in 30 m water depth [14]. Jackets are used in 45 m water depth in the Beatrice Demonstrator Project [15], and tripiles are currently installed in the BARD offshore 1 project in Germany in 40 m water depth [16].

As of 2012, more than 90% of the world's OWTs have been installed in Europe and a number of studies of offshore substructures have been conducted [17–20]. Subroto et al. [21] designed and analyzed three different substructures: monopole, tripod and jacket based on the Dutch reference site. Zaaijer [22] analyzed different substructures for a 6 MW wind turbine in 20 m water depth. However, the OWT is a site-specific design and studies focusing on Korean local environments have only been conducted to a limited extent [23,24]. Designing the optimal substructures based on the local conditions is essential for Korea's first offshore wind farm.

This study focused on the OWT substructures located in the Korean Southwest Offshore Wind Project in a water depth of 33 m. At this water depth, monopiles become technically and economically challenging to install, whereas jackets and multipiles offer promising solutions for offshore wind power. A jacket, as well as a multipile substructure, is designed based on the local environmental conditions for 5 MW large-scale OWTs. The mass, natural frequencies and dynamic responses of the OWT with these substructures were compared with the baseline monopile substructure to evaluate the feasibility of their performance.

2. Methodology

2.1. Coupled aero–hydro–servo–elastic analysis

OWTs are subjected to highly variable loads, including aerodynamic loads from wind, hydrodynamic loads from waves and currents, and gravity and operational loads. In this section, we describe a number of theories used to model the OWT system, including the aerodynamic and hydrodynamic loads.

The aerodynamic loads are calculated using the blade element momentum (BEM) theory with common engineering corrections that account for the dynamic inflow, tower shadow, skew inflow and shear effects on induction. The thrust force and torque on the rotor can be calculated as follows [25]:

$$F_{\mathrm{thrust}} = B\int_0^R \frac{1}{2}\rho U_{\mathrm{rel}}^2 (C_l \cos\varphi + C_d \sin\varphi) c\, \mathrm{d}r \tag{1}$$

$$Q = B\int_0^R \frac{1}{2}\rho U_{\mathrm{rel}}^2 (C_l \sin\varphi - C_d \cos\varphi) cr\, \mathrm{d}r \tag{2}$$

where B is the number of blades, U_{rel} is the relative wind velocity and C_l and C_d are the lift and drag coefficients, respectively.

The hydrodynamic loads for the OWT basically come from waves and currents. To determine the hydrodynamic loads, a time series of the wave kinematics is first generated. A JONSWAP or a Pierson–Moskowitz wave spectrum is created from the user-defined value of the significant wave height, H_s, and the peak wave period, T_p [26]. Subsequently, the random-phase-amplitude model is used to generate a wave time series from the created wave spectrum. For the substructures (monopile, jacket and multipile) mainly consisting of slender members with the diffraction parameter D/λ less than 1/5, the relative-motion Morison's equation can be applied to calculate the wave loads (Eq. (3)) [27]. The hydrodynamic loads on a slender member per unit length are:

$$F_{\mathrm{Morision}} = C_m \cdot \frac{1}{4}\pi\rho D^2 \dot{u}_w - (C_m - 1)\frac{1}{4}\pi\rho D^2 \dot{u}_s + C_d \cdot \frac{1}{2}\rho D(u_w - u_s)|u_w - u_s| \tag{3}$$

The first term of the equation is the inertia force, which depends on the water density ρ, the inertia coefficient C_m, the cylinder diameter D and the water acceleration $\dot{u}_w$. In addition, the second term, the water added mass force, also contributes to the inertia force. The water added mass force depends on the cylinder geometry, water density, inertia coefficient and structural acceleration $\dot{u}_s$. The last term in Eq. (3) is the drag force, which depends on the cylinder diameter, the drag coefficient C_d and the relative velocities.

The coupled aero–hydro–servo–elastic analysis was carried out in the time domain using Bladed V4.3 from Germanischer Lloyd Garrad Hassan [28]. The fourth order Runge–Kutta integration with a time step of 0.05 s was used to solve the system equation of motions. A detailed comparison of the dynamic responses of the OWT with different substructures was performed.

2.2. Wind turbine models

The National Renewable Energy Laboratory (NREL) 5 MW offshore baseline model was used in this study; this is a conventional three-bladed, upwind, variable-speed, variable blade-pitch-to-feather-controlled, horizontal-axis wind turbine. Its main dimensions and characteristics are shown in Table 1 [29]. Three fixed-type substructures were considered in this work at the same reference site: monopile, jacket and multipile. Same tower and rotor-nacelle-assembly (RNA) were used in this work. During the design process, different heights of connection point between platform and tower for each substructure resulted in different hub heights.

2.2.1. Monopile

The properties of the monopile were based on Jonkman's model [29]. To facilitate comparison with other foundation types, the pile

Table 1
Specifications of NREL offshore 5 MW wind turbine.

Rated power	5 MW
Rotor orientation	Upwind
Control	Variable speed, collective pitch
Drivetrain	High speed, multiple stage gearbox
Rotor/hub diameter	126 m/3 m
Hub height	90 m above MSL
Cut-in, rated, cut-out wind speed	3 m/s, 11.4 m/s, 25 m/s
Cut-in, rated rotor/generator speed	6.9 rpm, 12.1 rpm, 670 rpm, 1173.7 rpm
Rated tip speed	80 m/s
Overhang, shaft tilt, precone	5 m, 5°, 2.5°
Rotor mass	110,000 kg
Nacelle mass	240,000 kg
Tower mass	347,460 kg