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Design of monopile supported offshore wind turbine in clay considering dynamic soil–structure-interaction

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A B S T R A C T

This paper addresses the feasibility of soft–soft and soft–stiff design approaches considering a 2 MW and 5 MW monopile supported three bladed offshore wind turbine (OWT) founded in clay. The serviceability limit state and fatigue life of the structure are checked in order to assess the safety. Resonance condition is also avoided keeping the fundamental frequency of the system away from the rotor frequencies. The OWT system is modeled using linear beam and soil–structure interaction is accounted for incorporating American Petroleum Institute based cyclic *p–y* springs attached to the monopile. Aerodynamic and hydrodynamic loads are applied on the structure and dynamic analysis is carried out using a finite element method in time domain. Overall mass of the structure is examined considering two design approaches in order to obtain an economical design solution. The study shows that soft–soft design is possible for 2 MW OWT subjected to rated wind speed for long tower. Rotor nacelle assembly mass and tower height is found to have governing role in soft–stiff design and on the material consumption. Embedded depth of monopile beyond critical depth has marginal impact on design. Fatigue life is observed to be governing design criteria for OWT at stiff clay.

1. Introduction

Offshore wind turbine (OWT) has the potential to produce reliable quantities of sustainable energy [1]. In order to generate more electricity, modern wind turbines are built with large rotor diameter and installed at greater water depth, which significantly increases the cost of an offshore project [2,3]. Hence, an appropriate design of OWT including support structures provides a more economically profitable solution since foundation includes about 30–40% of the total project cost [4–7]. Monopile is often used as foundation for OWT since it is proved to be economical at shallow water depth [8,9]. Monopile foundation supports slender tower with rotor and nacelle assembly (RNA) on the top and it sustains complex aerodynamic and hydrodynamic loads from wind and ocean waves [10,46]. Major challenges in design of monopile supported OWT is to satisfy the serviceability limit state (SLS) under long term cyclic loads [11–13,47,50]. In addition, resonance condition is avoided for an OWT structure keeping the fundamental frequency of the system $\pm 10\%$ away from the rotor frequency (1 P) and blade passing frequency (3 P) [14,47,50]. Apart from SLS and resonance avoidance criteria, fatigue limit state in terms of fatigue life needs to be satisfied to its expected service life [15,50].

Three possible design approaches for the design of an OWT are soft–soft approach (i.e. the fundamental frequency of an OWT < 1 P frequency), soft–stiff approach (i.e. the fundamental frequency of OWT lies in between 1 P and 3 P frequencies) and stiff–stiff approach (i.e. the fundamental frequency of an OWT > 3 P frequency) [8,16]. Soft–soft approach is often preferred because it requires less mass, hence economical [17,18]. Reduction of mass may possibly reduce the cost of the structure, however it results in flexible structure which is more sensitive under dynamic loads [19]. On the other hand softer structure reduces the hydrodynamic load, however increases the risk of fatigue damage [20]. A stiff structure may satisfy the safety requirements, however results in very expensive structure [8]. It was observed that at or near resonance, fatigue life of an OWT reduces marginally if the system is designed in soft–stiff approach [21]. Hence, soft–stiff region is considered to be most common design approach for OWT [15]. In recent years rotor diameter and rated power capacity of OWT increased substantially, however overall mass of the structure is minimized using modern control mechanisms [22]. Increase in rotor diameter requires higher hub height – this reduces the natural frequency of the system. Rotor frequency of modern variable speed OWT typically varies from 0.17 to 0.4 Hz for 2 MW turbine [19], and from 0.115 to 0.25 Hz for 5 MW turbine [23]. This means that structure may be susceptible to

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resonance even at low frequencies for large capacity OWT [24]. Hence, a comprehensive design appraisal of an OWT incorporating all possible failure mechanisms is indeed required in order to ensure dynamic stability and economic viability of the system [19].

Research studies on design issues of an OWT in order to reduce the risk of failure incorporating dynamic soil–monopile–tower interaction are limited in number. LeBlanc [20] outlined various design considerations for OWT support structure in sand considering long term response of monopile under cyclic loads. However, tower interaction was not accounted for analysis and no explicit design guideline was suggested. An optimum design of wind turbine tower and foundation system was carried out by Nicholson [25] without taking into account of dynamic soil–structure interaction. It was observed that foundation stiffness greatly affects the optimal design of an OWT. Morgan and Ntambakwa [26] pointed out the strength, stiffness and stability of foundation are the essential design criteria for wind turbine foundation design. They indicated that cost of the foundation can be minimized if appropriate soil–structure interaction including fatigue and ultimate limit state is accounted for wind turbine analysis. An assessment of general design of OWT is outlined by Tempel [16] following existing design documents. It was observed that lowering the natural frequency of OWT leads to wave induced fatigue damage. A review on cost effective design of OWT on the basis of theoretical basics of dynamics were addressed by Tempel and Molenaar [19]. They pointed out that soft–soft design could be an alternative approach for large capacity OWT. Camp et al. [27] outlined various design aspects of OWT considering different foundation modeling techniques and hydrodynamic loading and suggested that combination of soil–monopile and tower in dynamic model is essential in order to achieve an optimized design. Furguson et al. [17] carried out a site specific study on design of an OWT structure. They suggested that soft–soft approach could be a cheaper solution, however careful dynamic analysis is required. Based on a site specific study, Kuhn [18] indicated that a relatively stiff foundation with soft tower could lead to a cost effective structure because of less wave loading. Schaumann and Boker [28] carried out a quantitative assessment of governing parameters on the cost effective solution for monopile supported OWT structure. They pointed out turbine size, water depth and soil condition are the important parameters for a site specific design assessment. Wijngaarden [29] outlined a feasibility study of various supporting structures for OWT considering different design considerations and found that monopile foundation is an efficient solution up to 20 m water depth. In order to get further insight, a compressive time domain analysis of the overall dynamics was suggested.

In this paper, an assessment of soft–soft and soft–stiff design approaches is carried out considering 2 MW and 5 MW OWTs. The design of OWT is assessed considering serviceability limit state and fatigue limit state criteria as given in the literature [11,25,30]. Resonance condition is avoided keeping the fundamental frequency of the system away from the 1 P and 3 P frequencies in order to achieve soft–soft and soft–stiff design approaches. Objective of this study is to examine the effect on design of an OWT due to feasible variation of tower height, RNA mass, diameter and thickness of tower and monopile and soil consistency conforming to the safety criteria. Overall mass of the structure for 2 MW and 5 MW turbines for the two design approaches are also examined in order to establish a cost effective approach. Monopile supported OWT structure founded in clay is modeled as a beam on nonlinear Winkler foundation approach. Widely accepted *p–y* method is used to model lateral soil resistance following the API [31] based cyclic *p–y*, *t–z* and *Q–z* curves. A dynamic analysis in time domain is carried out using finite element method. Finally a design strategy is suggested for sustainable design of OWT tower–monopile–soil system.

2. Computational model

2.1. Finite element model of OWT system

The monopile supported OWT is assumed to be embedded in a uniform deposit of clay. The system response is obtained using the beam on the nonlinear Winkler foundation model in which the monopile and tower is modeled as an Euler–Bernoulli beam. The monopile and tower is discretized into beam elements. The flexural rigidity of each elastic beam element is E_pI_p and has three degrees of freedom (two displacements and one rotation) at each node. A uniform cross-section for the monopile (i.e. from the mean sea level to monopile tip) and a tapered section of the tower (i.e. above sea level) is assumed in this study. The outer diameter of the tower at hub height is considered as half of the outer diameter of the tower at the base [1,21,23]. A uniform thickness of tower and monopile is considered for simplicity. The RNA mass is assumed as a point mass attached on the top of the tower (M_{RNA}) with a rotary inertia (J_{RNA}). A schematic diagram of the OWT structure model is shown in Fig. 1. Each beam element of monopile is attached to soil springs that generate the lateral resistance against pile movement within each element. Soil–structure interaction between soil and monopile is modeled by a series of soil springs following API [31] based non-linear *p–y* curves for cyclic loading. The lateral movement (y) of each element in monopile is resisted by the spring force p per unit monopile length acting on the element. Mobilized soil-monopile shear transfer at shaft and end bearing resistance at monopile tip are represented by *t–z* curves and *Q–* curves for clay respectively, as recommended in API [31]. The gap formation between soil and monopile is not incorporated due to simplicity.

2.1.1. Cyclic p–y, t–z and Q–z curves

In this study, cyclic *p–y* curves for clay, as proposed by Matlock [33], recommended in API [31] and DNV [11], are adopted for dynamic

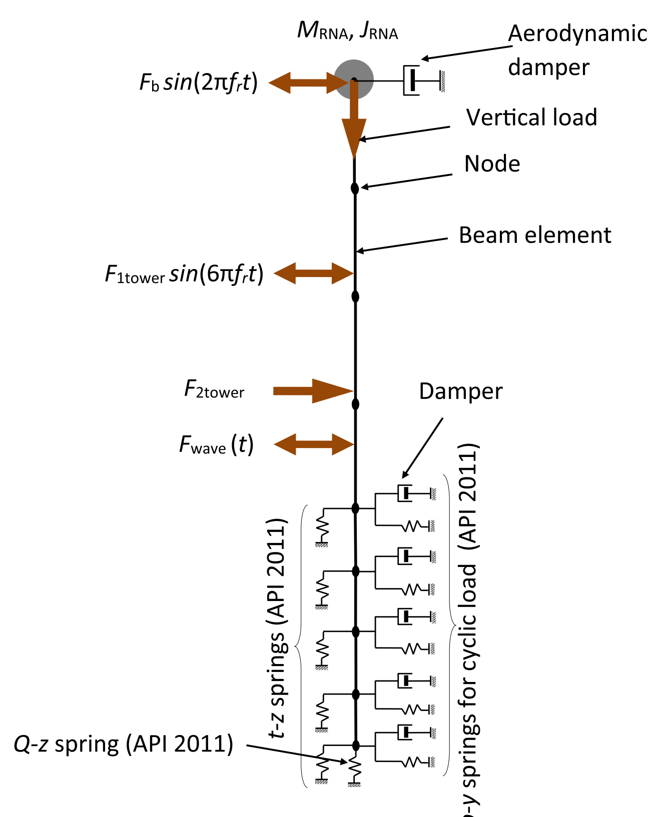

Fig. 1. Schematic diagram of finite element model of OWT system in clay.