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The impact of a passive tuned mass damper on offshore single-blade installation

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ABSTRACT

Single-blade installation is a method suitable for the installation of blades on large wind turbines. For single-blade installations on offshore monopile-type wind turbines, a jack-up vessel is often involved, and each blade is mated with the hub at the tower top. Prior to the alignment phase, the blade root and the nacelle at the tower top experience relative motions. The blade-root motions are induced by the wind loads, and the nacelle motions are due to the resonant vibrations of the monopile support structure under wave loading. To alleviate the relative motions and to facilitate the alignment process, external passive tuned mass dampers can be installed on the monopile support structures. This work investigates the application potential of tuned mass dampers in single-blade installation. Multibody simulations were conducted under collinear wind and waves conditions, and the relative motions between the blade-root and the hub were analysed. It was found that when an optimally tuned passive damper is considered for the monopile structure, the reduction in the critical motion radius can reach up to 30%.

1. Introduction

Monopile support structures remain the most popular substructure type in the European offshore wind industry, representing 88% of all installed foundations in 2016 (Pineda and Tardieu, 2016). This type of support structure has a single column and is relatively cost effective for shallow water depths less than 40 meters (m). With the largest announced monopile diameter approaching 8 m (Garus, 2017), the major concern with monopile support structures relates to their sensitivity to wave loading (Veldkamp and Van Der Tempel, 2005). The dimensioning of these structures is often driven by fatigue loads. When designing the eigen frequencies of the tower, a common practice is to avoid coincidence with the fundamental frequencies (1P) and the blade passing frequencies of a 3-bladed rotor (3P) (Shirzadeh et al., 2013). Still, along with the growing sizes of wind turbines, the first eigen frequencies of the fore-aft and side-side modes may approach the upper limit of wave frequencies (0.25 Hz) and cause greater resonant responses of the support structures.

Installations of monopile-type wind turbines often involve a heavy lift vessel. Upon arrival on site, the pile is upended and driven into the seabed by a hydraulic hammer, and the transition piece is grouted onto the pile. Then, the wind turbine components, including the tower, nacelle, hub, and blades, are to be installed. A number of options exist for turbine installation with varying numbers of pre-assembled components (Kaiser and Snyder, 2010; Wang and Bai, 2010). Among the options, there is a method that involves one lift for the tower, one lift for the nacelle and hub, and separate lifts for each blade. This method allows for a more efficient use of deck space but may be susceptible to delays because of high winds. Single-blade installation refers to the method of blade installation and was reported to be convenient up to wind speed from 8 to 12 m/s (Gaunaa et al., 2014). Fig. 1 illustrates typical scenarios of single-blade installation for offshore monopile-type wind turbines. To improve this performance, efforts have been made to better understand the blade aerodynamics during installation (Gaunaa et al., 2014, 2016; Wang et al., 2012, 2014; Kuijken, 2015), and to develop numerical simulation tools (Zhao et al., 2017). Specialised installation equipment (ApS, 2017; NV, 2017) has also been created to cater to the market need. For example, the Boom Lock technology (NV, 2017) enables to mitigate the blade motions by locking the crane hook during the lifting process. These mitigation measures focused on the blade responses. On the other hand, according to industrial experiences (Stettner, 2017), monopile vibrations are another source that contribute to delays during single-blade installations. In a recent work (Jiang et al., 2017), it was shown that in the final blade installation stage, the hub motions at the

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(a)

(b)

Fig. 1. Image of a horizontal single blade mounting on offshore wind turbines (a) side view (Image source: Siemens Wind Power GmbH) (b) top view (Image source: A2SEA A/S).

tower top can be more important than the blade responses given the presence of significant resonant responses of the monopile.

Damping is critical insofar as structural resonant responses are concerned. For an offshore monopile structure without external dampers, the total damping consists of structural damping, soil damping, hydrodynamic damping, and aerodynamic damping. The overall damping ratio of the first fore-aft mode is approximately 1% (Damgaard et al., 2013; Shirzadeh et al., 2015). During wind turbine installation, there is even less damping on the monopile structure because of the lack of aerodynamic damping from the rotating blades. Thus, supplemental dampers can offer potential solutions for the structural control of monopiles during single-blade installations. There are passive, active, and semi-active damping strategies (Spencer and Nagarajaiah, 2003). Passive systems are simple in form and require no external energy input. Mass-spring-damper systems with constant parameters are such examples. It is necessary to tune the system parameters to absorb energy at one of the natural frequencies of the structure. In contrast, active systems are complex and require control systems with force actuators. These systems have greater load reduction potential at the expense of larger power consumption (Lackner and Rotea, 2011a). Semiactive systems offer the reliability of passive devices while maintain the versatility and adaptability of fully active systems (Spencer and Nagarajaiah, 2003). In some cases, feedback control is used by semiactive systems to tune the system parameters in response to the structural motions, and the system can operate on battery power. There is a wide range of damping devices, such as tuned mass dampers (TMDs), tuned liquid column dampers (Colwell and Basu, 2009; Mensah and Dueñas-Osorio, 2014), viscous fluid dampers (Shirzadeh and Kühn, 2016), and magnetorheological dampers (Caterino, 2015). Early applications are found in civil engineering structures, including buildings and bridges (Spencer and Nagarajaiah, 2003; Connor, 2003). Among the various forms of dampers, TMDs have been recently considered for offshore bottom-fixed and floating wind turbines (Lackner and Rotea, 2011a, 2011b; Namik et al., 2013; Stewart and Lackner, 2014; Si et al., 2014; Brodersen et al., 2017). Lackner and Rotea (2011a) demonstrated that TMDs can improve the structural responses of barge- and monopile-type offshore wind turbines, targeting the dominant fore-aft mode for monopile-type wind turbines and the platform-pitch mode for barge-type wind turbines, respectively. In another work, Lackner and Rotea (2011b) considered the active control approach and showed a beneficial effect on fatigue load reduction of a barge-type floating wind turbine. Si et al. (2014) applied a passive TMD for a spar-type floating wind turbine and found that the TMD is most effective when the spar platform is working at above-rated wind speeds in resonant motion. Stewart and Lackner (2014) studied a monopile-type wind turbine and reported the effects of TMDs on reducing the tower base moment, especially in the side-to-side direction. These studies addressed the effect of TMDs on wind turbine performance under operational and parked conditions.

To the author's knowledge, no publication is found regarding application of TMDs in scenarios of offshore single-blade installations. Motivated by the application potential of TMDs and the challenges faced during single-blade installation, this work will investigate the influence of a passive TMD on the final blade installation stage. The outcome of this paper may be used to facilitate the application of TMDs during offshore wind turbine installations, and to reduce the cost of energy of offshore wind turbines. The remainder of this paper will be organised as follows. Section 2 defines the research problem and presents the analysis procedure. Section 3 introduces the developed numerical tools and the modelling approach. Section 4 introduces the fundamentals of the response surface methodology. Section 5 describes the representative monopile system and the single-blade system. Section 6 specifies the load cases for the numerical simulations. Section 7 presents a comparison of the simulation results with and without TMD. Finally, Section 8 concludes the paper.

2. Problem statement

Single-blade installations are often performed under the assistance of a jack-up installation vessel. Before the blade installation starts, the jack-up vessel is elevated well above the wave zone, providing a stable base for the lifting operation. During the installation, each blade is lifted by the crane to the hub height and attached to the hub individually. Fig. 2(a) illustrates a scenario of the blade final installation stage. The origin of the global coordinate system is placed on the monopile structure at the mudline level. Unless otherwise specified, the global coordinate system is referred to in the following. As the blade root approaches the hub, the wind-induced blade-root oscillations are primarily in the *yz*-plane, and the tugger lines constrain the blade motions. The blade root and the hub make an alignment pair. Located at the tower top, the hub also experiences fore-aft motions in the *yz*-plane, especially when the waves are collinear with the wind. At this stage, the relative motions between the blade root and the hub can be reliably measured by the onboard monitoring system such as the Differential Global Positioning System (DGPS) and the Real-Time Kinematic (RTK) satellite navigation technology (Hofmann-Wellenhof et al., 2012).

Often, the blade root and the hub are not perfectly aligned (Fig. 2(b)). η_r is defined as the relative motion radius. This value is the distance between the centres of the blade and hub and varies with time. In practice, there is a circular safe boundary with a radius of R_{sb}. If $\eta_r < R_{sb}$, the centre axes can be manually aligned. Otherwise, a time delay may be expected for the alignment operation. Fig. 2 sketches the outcrossing process of η_r over the safe boundary. The starting point of η_r is within the safe boundary, and it outcrosses the boundary twice along the black track. For any specified time interval, the outcrossing number can be counted, and the outcrossing rate refers to the frequency of outcrossings. The lower the outcrossing rate, the higher success rate of alignment. The outcrossing rate, ν, is a function of η_r. Herein, the critical outcrossing rate, ν_{cr}, is defined as the allowable outcrossing rate for a specified R_{sb}. ν_{cr} is