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An integrated dynamic analysis method for simulating installation of single blades for wind turbines

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A B S T R A C T

Installation of blades for wind turbines is challenging due to large lifting height and high precision. Assessment of blade dynamic responses during installation needs advanced simulation tools which are limited at present. This paper aims at developing an integrated simulation tool SIMO-Aero for single blade installation for both onshore and offshore wind turbines. Based on the cross-flow principle, the aerodynamic model is established by accounting for the effect of wind turbulence and dynamic stall. Then it is coupled with SIMO to achieve the integrated simulation tool SIMO-Aero which can account for blade aerodynamics, vessel hydrodynamics and system mechanical couplings. The aerodynamic code is verified by code-to-code comparisons with HAWC2. Furthermore, SIMO-Aero is applied in case studies on the wind-induced dynamic responses of a DTU 10 MW blade during installation using a jack-up crane vessel which is assumed to be rigid, including the crane, and rigidly fixed to the seabed. The characteristics of system dynamic responses prior to mating the blade onto the hub are studied. It is shown that the blade motions are dominated by the pendulum motion. Critical parameters of the installation process are identified. The extreme responses of critical parameters are further studied under turbulent winds and wind gusts.

1. Introduction

In recent years, air pollution and global warming have become important issues to the world, leading to an urgent need of clean, renewable and reliable energy sources such as wind energy. The wind industry has grown significantly in the last decades. The global cumulative installed wind capacity reached 487GW by the end of 2016, which includes about 14.4GW installed offshore (Global Wind Energy Council, 2017). At the same time, the size of wind turbines also increases fast. In 2016, 8MW wind turbines were successfully installed at Burbo Bank offshore wind farm (DONG energy, 2016). The trend towards larger turbine size leads to larger blade size, higher installation height and increased sensitivity to wind condition (and also wave condition for offshore turbines), which adds difficulties to the installation of turbine components, especially the blades.

The three most commonly used methods for blade installation are respectively single blade installation, bunny ear and whole rotor lift (Uraz, 2011). Among those, single blade installation is most frequently used for offshore installation in recent years, due to small deck space requirement and flexible blade orientations during installation (Ahn et al., 2017). During the installation process, the blade is lifted and installed in a feathered position, which is kept during the whole installation operation (Kuijken, 2015; Siemens, 2014b; High Wind NV, 2015). As shown in Fig. 1, the single blade can be installed in various orientations such as horizontal, vertical or even inclined. For inclined-blade installation, longer crane boom is required as the blade needs to be lifted higher than the hub height. The vertical-orientated installation needs to rotate the blade prior to installation since it is horizontally stored on the vessel deck, which makes the process more complex. The horizontal orientation installation is most preferred since no rotation of blade is required. Besides, installations of blades for offshore wind turbines are commonly conducted by jack-up crane vessels rather than floating ones since they provide a very stable working platform.

Wind condition is the one of the main constraints for blade installa-

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(a) Horizontal mounting (Siemens, 2014b) (b) Vertical mounting (Liftra, 2012) (c) Inclined mounting (Liftra, 2012)

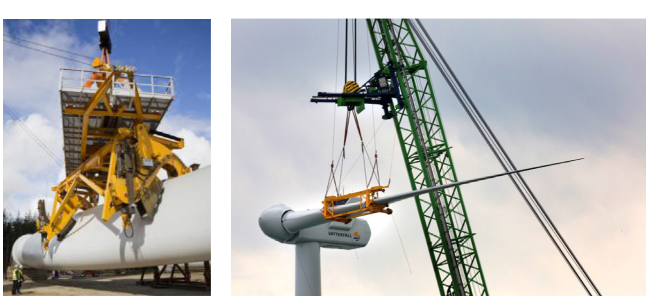
Fig. 1. Single blade installation of offshore wind turbine blades with various orientations.

tion wind turbines since it directly affects the waiting time for suitable weather window, which causes large economic cost. By now, most of the lifting equipment for single blade installation can operate under wind speed of 10 m/s. There are also advanced installation equipment such as Blade Dragon (Liftra, 2012), B75 lifting yoke (Siemens, 2014a) and Boom Lock (High Wind NV, 2015). The Blade Dragon, which is shown in Fig. 1(b)~1(c), has a remote control system and can install blades with all orientations. It claims that installation of blades can take place at a speed below $12m/s$. The B75 lifting yoke in Fig. 2(a) is claimed to be capable of installing blades in average wind speed up to $14m/s$. It has automatic sling connection and can actively yaw itself to adjust the blade position during installation. The Boom Lock in Fig. 2(b) is a system mounted on crane boom to control the blade movement, which is claimed to allow installation of blades in average wind speed up to $15m/s$.

Since the installation of blades for wind turbines is challenging, it is of importance to establish and use advanced numerical simulation tools to study the dynamic response of blade during installation. The dynamic response could be further used to predict the available weather windows if the installation criteria are known.

However, so far a limited number of studies on blade installations for wind turbines have been published. Some studies focus on the aerodynamic modeling of blades during installation or under standstill conditions. The characteristics of aerodynamic loads acting on a blade under installation conditions are quite different from a blade of an operating wind turbine. Wang et al. (2014) studied the hoisting forces on a wind turbine blade during installation using computational fluid dynamics (CFD) under constant wind conditions. Gaunaa et al. (2016) assessed the performance of cross-flow principle on the DTU 10MW reference blade in standstill situations using extensive three-dimensional CFD calculations. The authors concluded that the cross-flow principle gives a good estimation of aerodynamic loading when the blade pitch angle is within $[-50^\circ \quad 50^\circ]$. These CFD analyses specialize in accurate estimation of aerodynamic loads based on solving Navier-Stokes equations. However, they require significant computational efforts and cost. Thus, it is not suitable for simulation of marine operations.

Others focus on the installation process of blades for wind turbines. Wang et al. (2012) studied the hoisting force of a 1.5MW wind turbine



(a) (b)

Fig. 2. Advanced equipment for installation of blades for offshore wind turbines: (a) B75 lifting yoke (Siemens, 2014a); (b) Boom Lock (High Wind NV, 2015).

rotor using Bladed (GL Garrad Hassan, 2010). Gaunaa et al. (2014) proposed a general scaling method regarding the mean and standard deviations of aerodynamic loads on a single blade in yawed and pitched wind conditions. Kuijken (2015) examined possible ways to improve single blade installation in higher wind speed using HAWC2 (Larsen and Hansen, 2015). However, Bladed and HAWC2 are designed to calculate time-domain responses for wind turbine systems which are already in operation. Moreover, they cannot provide accurate models for mechanical couplings such as lift wires, slings and tugger lines, which are of great importance in the modeling of blade installation for wind turbines. Therefore, more sophisticated simulation tools for analysis of blade installation for wind turbines should be developed.

In this paper, a novel coupled simulation tool SIMO-Aero is developed for wind turbine blade installation in which an aerodynamic code is fully coupled with SIMO, a software specialized in numerical simulation of marine operations. The aerodynamic modeling is firstly described considering the effect of turbulent wind inflow and dynamic stall. Then the aerodynamic code is coupled with SIMO to establish the integrated simulation tool SIMO-Aero. SIMO-Aero is similar to SIMO-Riflex-Aerodyn (Kvittem et al., 2012) and SIMO-Riflex-AC (Cheng et al., 2016) which are fully coupled simulation tools integrating an external aerodynamic model with SIMO and Riflex for time-domain simulations of offshore wind turbine systems during installation. The SIMO-Aero proposed in this paper can be used to study the dynamic responses of single-blade-installation system for both onshore and offshore installations. Moreover, it has great potential to develop more efficient methods for installation or removal of blades for offshore wind turbines using a floating crane vessel.

The aerodynamic code in the integrated simulation tool is verified against HAWC2 results using the DTU 10MW reference wind turbine blade (Bak et al., 2013). The developed simulation tool is applied in a series of load cases to study the characteristics of wind-induced dynamic responses of the blade installation system in turbulent winds and extreme operating gust winds.

2. Aerodynamic modeling

In this section, the aerodynamic modeling of a single blade is presented based on the cross-flow principle. Before going into details of the aerodynamic model, the coordinate systems used in the modeling are clearly defined.

2.1. Reference frame

As shown in Fig. 3, three coordinate systems were used, i.e., the global coordinate system $OXYZ$, body-fixed coordinate system for the blade $oxyz$ and local airfoil (blade cross-section) coordinate system $o_c x_c y_c z_c$, which are all right-handed coordinate systems. The origin o of the blade body-fixed coordinate is located at the blade center of gravity (COG). The y-axis is in the spanwise direction and x-axis is positive towards the trialling edge while z-axis follows the right-hand rule. The instantaneous rotational motions of the blade around X, Y and Z axis are respectively roll(ϕ), pitch(θ) and yaw(ψ). When ϕ, θ and ψ are all zero,