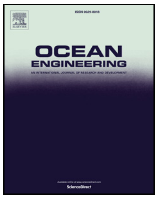
ARTICLE IN PRESS

Ocean Engineering xxx (xxxx) xxx–xxx

Contents lists available at ScienceDirect

Ocean Engineering

journal homepage: www.elsevier.com/locate/oceaneng



Development and application of a simulator for offshore wind turbine blades installation

Zhengru Ren[a,b,c], Zhiyu Jiang[a,c,*], Roger Skjetne[a,b,c], Zhen Gao[a,b,c]

[a] *Centre for Research-based Innovation of Marine Operations (SFI MOVE), Norwegian University of Science and Technology (NTNU), NO-7491 Trondheim, Norway*
[b] *Centre for Autonomous Marine Operations and Systems (AMOS), NTNU, NO-7491 Trondheim, Norway*
[c] *Department of Marine Technology, NTNU, NO-7491 Trondheim, Norway*

ARTICLE INFO

Keywords:
Offshore installation
Blade installation
Simulation model
MATLAB® and Simulink®

ABSTRACT

In an offshore environment, offshore wind energy resources are more available and stable, but the investment cost is much higher than that of onshore wind. The installation cost is a crucial factor of the investment. With the increasing number of planned and approved offshore wind farms, offshore wind turbine installation and relevant operations have received tremendous attention. Therefore, expediting the turbine-structure mating operations through a higher level of automation in offshore wind turbine installations may provide important economic benefits. To achieve a higher automation level and reduce the weather waiting time during the installation of offshore wind turbines, a flexible simulation-verification framework with high fidelity is needed. However, state-of-the-art wind turbine numerical analysis code is neither convenient nor open enough for applications concerning the design and verification of control algorithms. MATLAB/Simulink is among the most widely utilized numerical platforms by control engineers and researchers. This paper describes the development of a modularized blade installation simulation toolbox for the purpose of control design in MATLAB/Simulink. The toolbox can be used to simulate several blade installation configurations, both onshore and offshore. The paper presents the key features and equations of the different modules, exemplified by a single blade installation operation. Code-to-code verification results are presented and discussed with both quasi-steady wind and three-dimensional turbulent wind field.

1. Introduction

With the growing interest and need for clean energy, wind energy has become increasingly popular in recent years. Wind turbines are categorized into onshore wind turbines and offshore wind turbines (OWTs) based on their installation locations. Because of their high initial installation and lifespan maintenance costs, the price of offshore wind energy remains more than three times higher than onshore wind energy (Moné et al., 2017). Installation expenses significantly influence the cost of offshore wind energy. Hence, techniques that can make the OWT installation more efficient are of great value.

For wind turbine blade installation, several approaches have been developed. For example, assembled rotor installation, bunny-ear configuration, and single blade installation are often used (Kaiser and Snyder, 2010; Zhao et al., 2018; Kuijken, 2015). The selection among these approaches is a trade-off among the equipment capacity, number of offshore lifting operations, weather, etc. All these factors influence the offshore operational time, deck usage, and the overall installation cost. As the example of this paper, single blade installation is a wind turbine blade installation method that is especially suitable for large-scale OWTs, as individual lifts of the blades are much easier than maneuvering of a full rotor-tower-nacelle assembly offshore. This method also facilitates deck usage and requires low crane capacity of the installation vessel. Blades are lifted and mated separately. When the weather conditions allow the operation, one blade is held by a yoke and lifted by a crane from the deck, with the blade root approaching the hub. After moving the blade to the mating position at the hub, the mating operation proceeds if the blade root motion is limited within a specified range. The single blade installation approach provides a more efficient deck utilization and reduces the transportation time, for instance, by allowing more turbine components to be carried in one trip. The disadvantage is that this installation approach typically requires more operation time. Using state-of-the-art lift equipment, the single blade installation approach is only allowed to be conducted up to a mean wind speed of approximately $8-12$ m/s at the hub height (Gaunaa et al., 2014). Hence, increasing the weather window for the installation work and making the lifting operation more time efficient will greatly reduce the installation costs.

---

[*] Corresponding author. Centre for Research-based Innovation of Marine Operations (SFI MOVE), NTNU, NO-7491 Trondheim, Norway.

E-mail addresses: zhengru.ren@ntnu.no (Z. Ren), zhiyu.jiang@ntnu.no (Z. Jiang), roger.skjetne@ntnu.no (R. Skjetne), zhen.gao@ntnu.no (Z. Gao).

https://doi.org/10.1016/j.oceaneng.2018.05.011
Received 26 January 2018; Received in revised form 11 April 2018; Accepted 5 May 2018
0029-8018/

Please cite this article as: Ren, Z., Ocean Engineering (2018), https://doi.org/10.1016/j.oceaneng.2018.05.011

Research on intelligent marine operations are seeing increasing attention (Johansen et al., 2003; Fang et al., 2014; Skaare and Egeland, 2006; Ren et al., 2018; Wang et al., 2018; Tian et al., 2018). The typical objectives are to enhance the overall efficiency, ensure safety, broaden the operating window, and, ultimately, gain economic benefits. Because single blade installation approach demands large amount of offshore working time, the installation cost can be reduced if the mating operations are accelerated by enhancing the automation level for the blade installation system. To the best of the authors' knowledge, no studies have looked into such issues. Therefore, there is an urgent need for highly efficient and user-friendly simulation tools for use during the controller design process for marine installations.

To start a control design for such a complex process as an OWT installation, a numerical model is surely needed. Open-source MATLAB/Simulink toolboxes, such as the MSS GNC and MSS Hydro toolboxes (Perez et al., 2006; MSS. Marine Systems Simulator, 2010) and MSS MarPowSim (Bø et al., 2015), are widely applied for marine control systems, e.g., the dynamic positioning of surface vessels and power management systems. However, these toolboxes lack modules to model wind turbine installations. Commercial software for marine operations, such as SIMA (MARINTEK, 2016; Jiang et al., 2015), are widely used during analysis and design. However, their closed-source policy and tedious customization of external dynamic-link libraries (DLLs) for the design of control systems weaken their applicability to control design and analysis. State-of-the-art aeroelastic codes for designing of wind turbines under normal operations, including HAWC2 (Larsen and Hansen, 2007), FAST (Jonkman and Buhl, 2005), and Bladed (Bossanyi, 2009), are based on blade element momentum (BEM) theory. Complex aerodynamic performances, such as blade tip flow, wake dynamic inflow, and dynamic stall, are modeled. Code-to-code comprehensive simulations (Jonkman et al., 2008), prove that these codes agree well with each other. Single blade installation has been studied using HAWC2 (Gaunaa et al., 2014; Jiang et al., 2018). Taking HAWC2 as an example, although they can interface with MATLAB/Simulink through TCP/IP or use some DLLs to implement simple control laws, there are disadvantages. First, setting up the interface and debugging the model are often time consuming. Furthermore, limitations of the supported modules restrict its flexibility and complexity, except for the blade, during modeling. Other limitations include fixed time steps and cumbersome user interfaces. In addition, numerous codes and toolboxes, for example, wind turbine gearbox (Haastrup et al., 2011), a wind turbine sub-model in an in-house computational fluid dynamics (CFD) code (Hallanger and Sand, 2013), and a computational aeroelastic tool with the Boundary Element Method (Calabretta et al., 2016), have been developed that are relevant to wind turbine simulations. None of these, however, is able to simulate blade installation.

This paper presents the development of an open-source object-oriented simulation-verification blade installation modeling toolbox targeting the design and analysis of automation and control functions. The code is developed primarily for wind turbine blade installation, but it can also be used in related fields with simple modifications. The resulting functions and modules are integrated in the **MarIn** (**Mar**ine **In**stallation) toolbox, which is under development within the SFI MOVE center at NTNU. The modularized code in MATLAB/Simulink can be used in place of commercial software with verified numerical correctness.

The main contributions of this paper are the development of an object-oriented MATLAB/Simulink-based simulation verification toolbox for the blade installation of OWTs and a verification of the model against the mainstream commercial software HAWC2.

The paper is structured as follows. In Section 2, the problem formulation and development guidelines are proposed. In Section 3, relevant coordinate systems and coordinate transformations are introduced. The models of the wire ropes, winches, and hook are presented in Section 4. The blade dynamics, wind velocity with turbulence model, and wind-induced loads are presented in Section 5. Code-to-code verification with steady wind is conducted in Section 6 to confirm that the code calculates the correct aerodynamic loads acting on the blade. In Section 7, a single blade installation process is modeled as an example, and time-domain simulations are conducted to verify the model. Finally, the conclusion summarizes the paper.

Notations: In this paper, scalars, vectors, and matrices are denoted with normal lowercase letters, bold lowercase letters, and bold capital letters, respectively. $|\boldsymbol{x}|$ stands for the Euclidean norm, i.e., $|\boldsymbol{x}|^2 = \boldsymbol{x}^\top\boldsymbol{x}$. The overline $\bar{a}$ denotes the upper bound of a variable a, and $\boldsymbol{I}_n$ and 0_n are the identity matrix and the zero matrix of size, respectively. A nomenclature is given Appendix A.

Color codes in figures: To avoid confusion, the colors in the following diagrams have the following meanings:

- Blue: Coordinate frame
- Red: Load (force/moment)
- Green: Wind velocity

Superscripts and subscripts: Normally, the superscripts denote the coordinate systems. To simplify the expression, the global reference frame is adopted without any superscripts. The subscripts below have the following corresponding meanings:

- b Blade
- h Hook
- l Lift wire
- m Winch motor
- p Pulley (crane tip)
- r Wire rope
- s Slings
- t Tugger line
- TI Turbulence intensity
- w Wind
- y Yoke

2. Blade installation framework

2.1. Description of single blade installation

In this section, a commonly used single blade installation configuration is introduced to help the reader understand the necessary components in the toolbox and the basic ideas utilized during the modeling of such a process. The configuration of a single blade lifting operation is depicted in Fig. 1. In this example, a monopile foundation

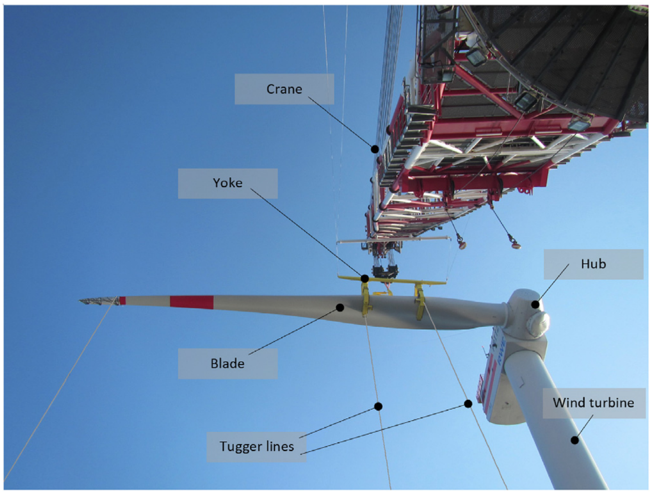


Fig. 1. The mating phase during a single blade installation (Image source: RWE GmbH (RWE Innogy GmbH, 2014)).