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Active Single-Blade Installation Using Tugger Line Tension Control and Optimal Control Allocation

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The single-blade installation is a common method for the installation of wind turbine blades. In an offshore installation, a jackup vessel is often involved, and a crane is used to lift, move, and bolt each blade onto the rotor hub at the tower top. To reduce the blade pendular motions, tugger lines are connected to the suspended blade. Active control of the tension force on the tugger lines has been recently investigated to reduce the blade motion. In this situation, a pre-tension is needed during the mating process, as only positive tension can be provided by the tugger lines. To further improve the effectiveness of active force control, we propose an active control strategy with a three-tugger-line configuration in this work. The placement of the third tugger line is examined. The proportional–integral–derivative (PID) control strategy is adopted, and allocation is achieved by convex programming. Aeroelastic simulations are carried out to verify the active control scheme under turbulent wind conditions. The results show that the proposed active control scheme is an effective means of reducing the translational motion of the blade root relative to the hub in the mean wind direction.

INTRODUCTION

Offshore wind turbines (OWTs) have attracted increasing global attention due to their advantages, such as saving land resources and providing superior energy quality. However, during an OWT installation, much time is wasted waiting for the allowable weather window. Hence, OWT assembly and installation are expensive, accounting for 19% of the overall OWT capital expenditures (Moné et al., 2017).

As the blade span exceeds 100 m, the task of lifting an entire rotor assembly offshore may face challenges beyond transportation issues. Single-blade installation, one of many OWT blade installation approaches, involves the lifting of one blade by the main crane and the attaching of the blade to the hub on the top of the turbine tower. The suspended blade and the crane boom are connected by tugger lines, typically without any active control. State-of-the-art single-blade installation is limited to a mean wind speed of 8–12 m/s (Gaunaa et al., 2014). The benefits of the single-blade installation are a wider range of installation vessels, lower crane capacity, and higher deck usage. More efficient lifting and mating operations are required because of the increased number of offshore lifts.

Several publications on various aspects of single-blade installation can be found. The aerodynamic and aeroelastic behaviors of the installation scheme are studied by Gaunaa et al. (2016). The motion characteristics and critical parameters have been investigated (Jiang et al., 2018; Verma et al., 2019a, 2019b). A simulation verification model of single-blade installation for the purpose of control design is proposed in Ren et al. (2018b). To enhance the level of automation and overcome the influence of human operators (Zhen et al., 2019), the control algorithms for optimal lifting operation and stabilizing are proposed and verified with the simulation verification model (Ren et al., 2018a; Ren, Skjetne, and Gao, 2019). Specialized commercial products, such as the LT575 Blade Dragon developed by Liftra and the Boom Lock technology from High Wind have been developed to advance the single-blade installation.

In addition to the blade motion, the motion of the foundation influences the success rate and impact force of the blade's final mating operation (Jiang et al., 2018). In this paper, a monopile foundation is considered the support structure (Jiang et al., 2017). Currently, monopiles are the most cost-effective type of support structure. An offshore structure is exposed to the environmental load effects of current, wind, and waves; hence, the turbine hub motion becomes quite complex (Cheng et al., 2019a, 2019b; Zhou et al., 2019). The dynamics of monopile foundation are presented in Jonkman et al. (2008). High-fidelity hub motion tracking algorithms are presented in Ren, Skjetne, Jiang, et al. (2019). In this paper, a closed-loop feedback control scheme single-blade installation is proposed that uses a proportional–integral–derivative (PID) controller for the tugger line forces.

The paper is structured as follows. The system description and problem formulation are presented in "Problem Formulation," followed by a brief introduction to "System Modeling." The next section discusses the capability of four different configurations of tugger lines. Additionally, a PID controller and an online control allocation based on convex programming are proposed. In "Simulations," simulations are conducted using HAWC2 coupled to a

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KEY WORDS: Single-blade installation, PID controller, wind turbine installation, control allocation, offshore wind turbine, marine operation, crane, coupled simulation.