INSTALLATION OF PRE-ASSEMSBLED OFFSHORE WIND TURBINES USING A CATAMARAN VESSEL AND AN ACTIVE GRIPPER MOTION CONTROL METHOD

Jingzhe Jin[1], Zhiyu Jiang[2,3], Sigrid Ringdalen Vatne[1], Zhengru Ren[2,3,4], Yuna Zhao[2] and Zhen Gao[2,3,4]

[1]SINTEF OCEAN AS, PB4762 Torgarden, Trondheim, Norway

[2]Department of Marine Technology, NTNU, 7491 Trondheim, Norway

[3]Centre for Research-based Innovation of Marine Operations (SFI MOVE), NTNU, Norway

[4]Centre for Autonomous Marine Operations and Systems (SFF AMOS), NTNU, Norway

To increase the competitiveness of offshore wind industry, cost-effective and time-efficient installation methods are needed. This work examines a novel installation concept using a catamaran vessel, which is specially designed to carry up to four tower-nacelle-rotor assemblies and perform offshore installation. The main challenge is to reduce the tower bottom motions induced by the vessel motions when it is placed on top of the foundation. A bottom fixed wind turbine foundation is considered in this study. An onboard gripper system is used to move the tower assembly along the vessel and perform the installation of turbine assembly onto turbine foundation. 1) Vessel is first positioned with its stern connected to the foundation through another gripper system, allowing only relative heave motions. 2) The turbine assembly is then transported to the vessel stern and it is hold right above the foundation. 3) Before the actual lowering and installation, the gripper and assembly are under active motion control so that they are kept steady in the vertical direction relative to the foundation top. 4) Once 3) is realized, the actual lowering and installation can start with active motion control on, to avoid unnecessary contact between assembly and foundation. The 3rd phase of the installation is numerically simulated. In the numerical simulation, an active force in vertical direction is added to control the assembly's vertical motion. The numerical simulation is performed using SIMO and RIFLEX under the SIMA environment.

Keywords: offshore wind turbine (OWT), installation, gripper system, motion control, catamaran vessel

INTRODUCTION

The offshore wind industry has been growing fast in the last decades. The installed capacity has an annual increase of 30% in recent years and the trend is expected to continue in future. Total installed offshore wind capacity reached 14.384 GW worldwide by 2016 [1]. It is expected that the installed capacity of offshore wind turbines will reach 66GW by 2030 [2]. And this implies installations of about 650 6-MW offshore wind turbines every year.

There are a few general trends in the development of offshore wind industry.

1) There is significant cost reduction for some offshore wind farms in the last three years, observed in the bidding phase [3].
2) Larger wind farms are installed in deeper waters and further away from shore.
3) The rated power and the turbine size are continuously increasing. The first 8MW turbines entered into the market in 2016 and was installed in the Irish Sea in the UK.

These trends from the long-term perspective will reduce the cost of offshore wind farms, but also bring challenges to transportation and offshore installation of the wind turbines.

The assembly and installation cost for OWT is high and can be about 20% of the capital expenditures for a bottom fixed offshore wind farm [4]. It is therefore important to have cost-effective installation methods. Summaries of recent work on numerical simulation of OWTs installation are given in [5, 6].

Most of the offshore wind turbines today are installed via crane operations using jack-up vessels. One way to reduce the installation cost is to reduce the number of offshore lifts. A novel concept was proposed in the SFI MOVE project for installing bottom-fixed and floating OWTs [7]. This concept utilizes a catamaran vessel which carries maximum four tower-nacelle-rotor assemblies in one installation task. Hydrodynamic response of the catamaran installation vessel during installation operation is studied in [8]. Since the turbine tower, rotor and nacelle are assembled beforehand, it requires only one lift for each OWT installation. A gripper system is onboard the catamaran vessel. The gripper system can move the turbine assembly along the longitudinal direction of the vessel and lower the assembly down to the foundation, where active motion control is often needed to secure a safe mating without large contact force.

In this paper, an active motion controller is developed to reduce the motions of the assembly before it is positioned on top of the foundation. A PD controller is designed and the control force is added on the assembly in the numerical simulations in SIMO/SIMA through an external force DLL[9]. The performance of "active motion control" is numerically examined in this paper by comparing the assembly motion with and without active motion control.

PROBLEM FORMULATION

As illustrated in Figure 1, a catamaran vessel is positioned with its stern close to a bottom-fixed OWT foundation. A few turbine assemblies are stored onboard. The stern part of the catamaran vessel is connected to the foundation via another gripper system (which allows the relative heave motions between the vessel and the foundation). The assembly is then gripped and placed on to the foundation. The installation consists of the following four steps.

1) Vessel is first positioned close to the foundation, with its stern around the foundation. 2)The assembly is then transported to the vessel stern and it is held right above the foundation, by onboard gripper system. 3) Before the actual lowering and installation, the gripper and assembly are under active motion control so that they are kept steady at a given vertical position relative to the foundation top. 4) Once 3) is realized, the actual lowering and installation starts. Active motion control stays on to avoid unnecessary contact between assembly and foundation.

Due to weather-induced vessel motions, there is relative motions between the turbine assembly and foundation. The horizontal motion of the vessel is controlled by onboard dynamic positioning (DP) system. The turbine assembly moves together with the vessel in the horizontal plane. In the vertical direction, uncontrolled lowering of the turbine assembly onto the foundation could result in large impact loads. To avoid this, the vertical motion of the lifting grippers together with the assembly motions has to be compensated in order to ensure a safe landing onto the foundation.

In step 3) and 4) of the installation process, active motion control is turned on. The assembly is first positioned steadily above the foundation top in the vertical direction. It is then slowly lowered down to the foundation. This paper studies step 3) and applies an external force onto the assembly to control its vertical motion. The target of the motion control is to hold the assembly steady at its mean position in vertical direction. Heaving motion of the assembly bottom is taken as reference in the motion control design.

The turbine assembly moves together with the grippers. Motion control of lifting grippers (and turbine assembly) is realized through a hydraulic pumping system. For the turbine assembly itself, the lifting grippers provide an external force in addition to gravity and wind force and with this external force applied, the vertical motion of the assembly is as required. This paper studies the magnitude of the needed external force. How to design a pumping system to realize the needed external force and gripper motion simultaneously is not considered in this study.

NUMERICAL MODELLING

Numerical modelling is performed using SINTEF OCEAN's simulation program SIMO in the SIMA environment [9]. SIMO is also available as part of SESAM's DeepC package. It is a time domain simulation program for the study of motions and station keeping performance of single or multiple body system. Hydrodynamic coefficients need to be provided as inputs to SIMO. It includes flexible modelling of station keeping forces (turret/spread mooring and dynamic positioning) and connect mechanisms among the multiple bodies (ropes, fenders, bumpers, and docking cones). SIMO is also used to simulate complex marine operations: offshore crane operation, subsea installation, jack/deck installation and removal, installation of TLPs and GBS, OWTs, and so on.

In order to simulate the motion behavior of the complete system and apply the required control force, it is modeled as a three-body system, including the assembly, the catamaran vessel and the foundation (which is a fixed body in this paper). In the current model, the wave loads on the catamaran vessel are considered since the wave-induced motions of the catamaran is the main reason for large motions of the turbine assembly, while the wave loads on the foundation and the wind loads on the turbine assembly are not considered.

The origin of the global coordinate system is on the calm water surface and at the center of foundation top (at calm water surface). The global X-axis is parallel to the longitudinal direction of the catamaran vessel and points toward vessel bow; the global Y-axis points toward port side of the vessel and the global Z-axis points upward.

Catamaran vessel

A catamaran vessel designed in the SFI Move project is applied here. Main particulars of the vessel are given in Table 1 [10].

Table 1. Main particulars of catamaran vessel

Particular	Value
Length overall (m)	144
Breadth moulded (m)	60
Draft (m)	8
Displacement mass (tonnes)	18502.9
Vertical centre of gravity above baseline	28.6
Number of turbine assemblies on board	4

Hydrodynamic coefficients of the catamaran vessel are taken from [8]. And the coefficients were calculated by using WAMIT [11], including wave excitation force, added mass and radiation damping forces. Mean wave drift forces are calculated by WAMIT as well and Newman's approximation is applied in SIMO to formulate the 2nd order wave force. About 10% of critical damping is applied for the roll motion, to include the viscous damping effect. Four thrusters and a Kalman filter based controller are used as the DP system. The thrusters compensate the slowly varying wave force but not the wave frequency force onto the vessel in the horizontal plane.

Wind turbine assembly

Once transported to the vessel stern part, the assembly is held above the foundation and ready to be installed. The origin of the local assembly body coordinate system is at the lower end of the assembly, which is about 20m above calm water surface. Orientation of the local body axes are the same as that of the global coordinate system. Main particulars of the turbine assembly are summarised in Table 2.

Table 2. Main particulars of turbine assembly

Particular	Value
Height overall (m)	119
Mass (tonnes)	1180
Vertical COG in body coordinate system (m)	85.5

Gripper modelling

The actual gripper system is shown in Figure 1. The gripper system consists of the gripper, hydraulic pumping cylinders, and solid fastening walls at vessel sides. The gripper has two parts. One part is connected to the port side of the vessel and the other part to the starboard side through hydraulic pumping cylinders. The complete gripper system together with the turbine assembly can move along the longitudinal direction of the catamaran vessel. In the installation phase, the gripper system is parked at vessel stern. And the motion of the gripper system along vessel longitudinal direction is locked. The hydraulic pumping cylinders can move the gripper and the turbine assembly relative to the vessel in translation but not in rotation. To model the gripper system in reality, three different types of couplings are applied in SIMO.

1) A docking cone is applied to connect the tower assembly and the vessel in the horizontal direction. The docking cone is position at the lower end of the turbine assembly. 2) Moment coupling is applied to control the rotation of turbine assembly relative to the vessel. Rotation stiffness is introduced for three rotation directions. 3) A fender plane is defined on the vessel and its position is right under the turbine assembly bottom. Four point fenders are applied between turbine assembly bottom and the fender plane. At equilibrium, the point fenders take the turbine assembly weight.

Fixed foundation

The cylindrical foundation is bottom fixed. Water depth is 65m. It has a diameter of 9m and the foundation top is at mean water surface level. In this study, the hydrodynamic coupling between the catamaran vessel and the foundation is not considered. In SIMO modeling, the foundation is defined as a body of "prescribed" type and the prescribed position is fixed.

Application of external force onto turbine assembly

Once turbine assembly is positioned above the turbine foundation and ready to be installed, active motion control is turned on. The vertical position of the turbine assembly is controlled so that relative motion between assembly and foundation in vertical direction is as small as possible.

To model the active motion control mechanism in SIMO simulation, an external force is added onto the turbine assembly in the global vertical direction to realize motion control. The external force is introduced into SIMO time domain simulation through a DLL. At each time step, information of the body motion at current time step becomes available to the DLL, the needed force to change the current body motion to the desired body motion at the next time step is calculated by the DLL and exported back to SIMO main program. SIMO then calculates body motion at the "next" time step and calls DLL, till the end of the simulation. It is necessary to specify at which point the external force shall be applied on the body. The DLL is called at every time step during the dynamic motion calculation.

PD control

The control force applied in SIMO simulation is determined through a PD controller (**P**roportional and **D**erivative). An error state e is defined as the difference between current assembly vertical position and its mean position in the global coordinate system, given by

$$e = Z(t) - Z_d \quad (1)$$

where $Z(t)$ is the vertical position of turbine assembly base center in the global coordinate system and Z_d is its desired vertical position. The control objective is to reduce the vertical motion at the assembly base, i.e., $e \to 0$ as time $t \to \infty$. The applied external force F_{ext} is given by

$$F_{ext} = -K_p e - K_d \dot{e} \quad (2)$$

where K_p and $K_d > 0$ are the proportional and derivative control gains. Pole placement technique is used to determine the values of K_p and K_d. The controller is more powerful with enlarged gains, resulting better stabilization performance. Meanwhile, higher gains, however, mean rapid growing expenses to devices. Therefore, a tradeoff is necessary to select reasonable control gains for the PD controller.

NUMERICAL SIMULATIONS

Numerical simulations are performed for the responses of the complete system in irregular waves, with and without motion control. The main response of interested in the vertical motion of the assembly and the control force.

Simulation without active motion control

When the assembly is held by the gripper without active motion control, the assembly is rigidly connected to the vessel. In this case, the assembly vertical motion is derived from the vessel motion. Irregular wave is considered and JONSWAP wave spectrum is applied. No current or wind is considered. Duration of each simulation is 1 hour.

Standard deviation of the vertical assembly motion under different wave conditions is summarized in Table 3.

Table 3. Std. of vertical motion at different wave condition

No.	***Hs (m)***	***Tp (s)***	***Dir(deg)***	***Std (m)***
1	2	6	0	0.24
2	2	8	0	0.60
3	2	10	0	0.78
4	2	12	0	0.81
5	2	8	30	0.51
6	2	8	60	0.46
7	2	8	90	0.32

Simulation with active motion

Results from the previous section illustrate the motion amplitude of the turbine assembly when it is hold rigidly by the gripper system. In this section, active motion control is applied through an external force onto the assembly body in SIMO. Time domain simulations are performed for the coupled turbine assembly and vessel system with couplings between them and an external force applied onto the assembly. Wave condition 4 is applied in the simulation. The applied PD control gains are summarized in Table 4.

Table 4. Applied PD coefficients for external force control

Case No.	K_p	K_d
1	1.18e+06	2.36e+06
2	4.72e+06	4.72e+06
3	7.38e+06	5.9e+06

Vertical motion time histories of the assembly under wave condition 4 are presented in Figure 2. Black line is without motion control, blue line, red line and green line are with PD controller No 1, 2 and 3, respectively.

In the SIMO model, the turbine assembly sits on the vessel through four point fenders. In reality, the gripper holds the turbine assembly and there are no fenders/ springs involved. If one wants to understand the total force between gripper and turbine assembly in reality, one needs to look at the sum of the applied external force and forces at the four point fenders, as shown in Figure 3. The force is presented in non-dimensional format as the ratio between actual force and turbine assembly weight. The applied external force is shown in Figure 4. Statistics of motion and force are summarized in Table 5.

Table 5. Applied PD coefficients for external force control

	PD1	PD2	PD3
vertical motion std. (m)	0.538	0.297	0.224
std. of total force/gravity force	0.019	0.011	0.008
std. of ext. force/gravity force	0.082	0.139	0.156

RESULTS AND DISCUSSION

A novel concept was proposed in the SFI MOVE project for installing bottom-fixed and floating OWTs. The installation vessel is a catamaran vessel carrying up to four tower-nacelle-rotor assemblies onboard. The assembly is held by a gripper system during an installation. In order to reduce unnecessary contact between assembly and foundation, active motion control is applied during the installation.

This paper studies the phase after assembly placed above the foundation and before the start of lowering operation. During this phase, active motion control is on to control relative motion between assembly and foundation. The active motion control is realized by adding an external force onto the assembly body in SIMO. The force is controlled through a PD controller.

The numerical simulation results show that the applied external force is effective in controlling the vertical motion of the assembly. The total and applied external force in vertical direction on the assembly body is also presented. It is shown through a proper controller design, the assembly motion can be controlled with reasonably large external force.

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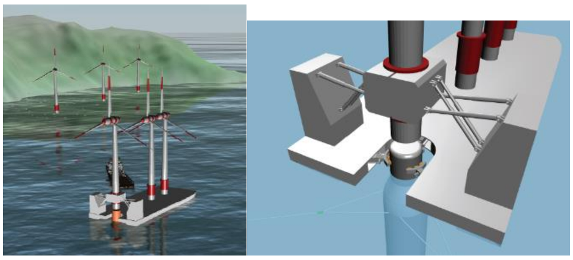

Figure 1: Applied catamaran vessel and gripper system

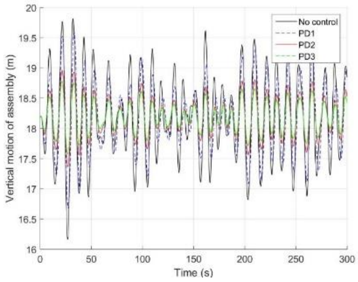

Figure 2: Vertical assembly motion

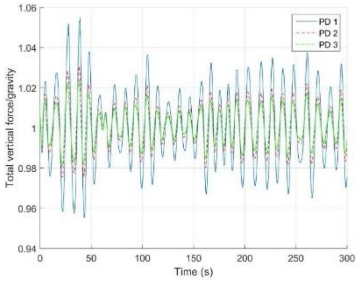

Figure 3: Total vertical force

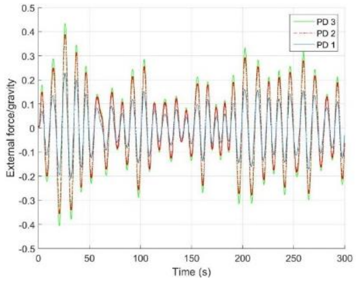

Figure 4: External vertical force