ABSTRACT

Current methods for installation of offshore wind turbines are all sensitive to the weather conditions and the present cost level of offshore wind power is more than twice the cost of land-based units, increasing with water depth. This paper presents numerical simulations of a novel experimental gripper design to reduce the environmental effects applied to a catamaran type of vessel during wind turbine installation. In SFI MOVE project in NTNU Aalesund, our team proposed a novel wind turbine installation process. A new catamaran vessel will carry pre-assembled wind turbines to the installation location. Two new designed grippers on the deck will make a lifting operation to install the wind turbine onto the turbine foundation. Three prismatic grippers with several rolling contact points at the end are attached in an arc at the catamaran’s aft, designed to grasp the turbine foundation in order to make a connection between the two in the horizontal plane. This paper will only emphasize the contact responses between the turbine foundation and the three grippers during the wind turbine installation process. Numerical simulations are carried out using the virtual prototyping framework Vicosim which is developed by NTNU Aalesund. The simulation results show validation of a key part of the proposed new wind turbine installation idea.

INTRODUCTION

The last few decades have witnessed a strong, increasing interest in offshore wind power technologies. Europe is the world leader in offshore wind power, with the first offshore wind farm (Vindeby) being installed in Denmark in 1991 [1]. After that, several countries including for example Germany, Netherlands and the UK began to give great efforts to develop offshore wind farms and related technology.

In 2013, offshore wind power contributed to 1,567 MW of the total 11,159 MW of wind power capacity constructed that year [2]. Recently, there is a firm commitment in the EU and other nations to reduce the dependency of fossil fuels. Development of offshore wind technologies is a central element in the worldwide energy strategy, with a target by 2020 to obtain a total installed capacity of 40 GW and a forecasted investment of EUR 65.9 billions [3]. For 2030, the forecast is a total installed capacity 150 GW and total investments of EUR 145.2 billions. Significant development are also seen in China, Japan, Korea and USA.

It is noted that higher wind speeds are available offshore compared to on land, so the offshore wind power contribution in terms of electricity supplied is higher [1]. Norway has a long coastal line with naturally strong winds. In 2013, Norway produced around 2 MW wind energy as the number nine country in the EU [4]. With the development of technology, offshore wind turbine installation is getting more demanding. The near-term large commercial market is mainly for bottom-fixed wind farms at shallow to intermediate water depths (50m). However, new technology will be required urgently to face the current difficulties. First, the offshore wind farms will move to deeper water up to 100 m. Second, the wind turbines will become more powerful in order to improve the energy efficiency. Thus, the whole system will be bigger and heavier, making the installation process
more challenging. Third, the maintenance and all year operation safety will be of more focus. In the end, technically, there is a significant interest in developing floating concepts with expected large volumes after 2020.

Offshore wind turbine installation is always challenging. The normal installation procedure includes the following main steps: foundation installation, wind tower installation, and turbine installation. Cables laying, port logistics, and maintenance services are also some key issues for offshore wind farm industry.

Currently, the foundations are getting larger and different. Mainly, two types of wind turbines foundations are designed and implemented by industry, including the fixed foundation and floating spar. The first one is more common and classic, which are furthermore divided into monopole, jacket, tri-pile, and gravity base [5]. Floating spar as a new flexible foundation for wind turbines is recently proposed and more challenging.

Here, installing the foundation is not the focus of this paper. Instead, how to install the windmill tower on the floating spar is the key research topic for SFI MOVE project. Currently, wind turbines will be transported to the site in pieces. Then different units will be installed on the foundation piece by piece. Technology and experience gained from installation of oil and gas facilities have been used for installation in open waters [6, 7]. This implies use of large and highly specialized vessels with high day-rate. Contrary to the one of its kind installation tasks for development of petroleum fields, installation of a large number of turbine units in a wind farm is far more cost sensitive. A considerable number of different installation vessel types with dedicated handling equipment have been suggested. Current methods for installation of offshore wind turbines are all sensitive to the weather conditions and the present cost level of offshore wind power is more than twice the cost of land-based units, increasing with water depth. Methods with more industrial installation in series may give a more acceptable cost level. This implies a need for less weather-sensitive installation operations. The further development is driven by cost of energy, where the cost of installation and maintenance (i.e. marine operations) and related logistics can turn out to be a show-stopper. Development of better methods/procedures, vessels and equipment to increase the weather window for installation and also access for inspections is crucial [8]. This gives us another motivation to propose a fast installation procedure.

NEW OFFSHORE WIND TURBINE INSTALLATION PROCESS

One aim of SFI MOVE project is to explore new methods for erection, installation and maintenance of offshore wind turbines, aimed at reducing the installation and maintenance costs. Our team recently proposed a novel wind turbine installation process on floating spars, which includes the following features:

1. A new catamaran vessel with full DP function, carrying complete pre-assembled wind turbines.
2. A set of novel designed deck grippers make a heavy lifting operation to install the wind turbine, which has active heave compensation function (ACH).
3. A set of grippers designed on the catamaran vessel to grasp the spar in order to connect the vessel with the spar in the horizontal XY-plane. Passive rollers on the grippers allows for vertical motion along the Z-axis.

The main components of included in the concept is shown in Fig. 1. The whole wind turbine installing procedure on floating spar have the following steps, as shown in Fig. 2. The steps are as follows:

(a) The catamaran vessel carries pre-assembled wind turbines to the installation location. Before the installation, three grippers on the catamaran vessel grasps the spar to decrease the relative movement and contact force.
(b) The heavy lifting grippers on the deck locks onto and lifts a pre-assembled wind turbine, then the whole mechanism will slide to move the wind turbine above the spar. With a guiding mechanism between the wind turbine and the spar, the gripper installs the wind turbine on spar as one step. During the operation, the vessel runs DP, and the lifting grippers runs ACH.
(c) The heavy lifting grippers disengages the lock and moves back.
(d) The heavy lifting mechanism slides back.
(e) The three spar grippers disengages the lock and moves back.
(f) The vessel moves forward and leaves the operational position.

In this paper the emphasis for discussion is only for the spar grasping grippers, designed to reduce the environmental effects applied to a catamaran type of vessel during wind turbine installation. This paper will try to present our preliminary results of the project.
Numerical simulations are carried out using Vicosim which is a virtual prototyping framework (VP) developed by the Mechatronics lab at NTNU Aalesund [9, 10]. Vicosim is a flexible Java based simulation framework built around the Entity-Component model. Vicosim is rendering agnostic, thus leaves the decision on how to visualize the simulation to the end-user. Vicosim provides a network interface, allowing the simulation to be accessed by other applications, such as a web browser or a desktop application, allowing for virtual collaboration. In this work, the high fidelity physics engine AgX Dynamics by Algo-ryx Simulations AB is used to handle rigid body dynamics and environmental effects. Simulations are carried out in the time domain with a time-step of 100 Hz, and runs in real-time.

Virtual Prototyping for Concept Design and Verification

The installation process is a kind of marine operation, but very challenging and demanding. We proposed a new wind turbine installation idea as mentioned before. The overall system design, allowing for the configuration of vessel and grippers, including mechanical sub-system, control sub-system, hydraulic sub-system and verification of operational performance as a part of the design process. Developing such a system could integrate engineering design, control theory and hydraulic performance in such a way as to allow the virtual prototyping environment to provide pre-testing, fault finding, error investigating, and operation verification functions. The results from the project will generate new opportunities for collaboration and allow for more efficient work processes, thus improving the technological level.
and productivity of the maritime industry.

The last years have seen an increasing interest in developing computer-based design and analysis tools for different applications. Some general-purpose simulation environments are well-known in research and education, including MATLAB/Simulink, Modelica, SimulationX, 20-sim, etc. In parallel, a great number of specialise analysis software for structures, hydrodynamics, computational fluid dynamics, power systems and control systems are currently used in the design process to assess special sub-system performance, for example, PSCAD for the power systems, Adams for dynamics, Flexcom3D for structures, dSPACE for control systems, and GT-Suite for engine systems. Integrating the above two approaches in offshore wind turbine installation process simulation is non-trivial due to differences in the emphasis on system modularity and model accuracy in the software and the required specialised training for the user [11].

Vicosim will integrate the current technology and know-how, and it is expected to bring significant new scientific advances into the maritime industry. New solutions, design concepts and equipment combinations can be simulated and tested in a laboratory environment before being built. Such virtual prototypes will encourage rapid innovation, and they will help to bring design, training and operations closer together. We will try to emphasize the following issues:

1. Develop and apply experimental methods for validating numerical analysis methods.
2. Investigate and qualify alternative erection methods for offshore wind turbines.
3. Investigate and qualify methods for series-installation of offshore wind turbines, comparing costs for alternative fixed and floating concepts.
4. Systematically suggest constructive re-design of details that may enable new and cost-saving methods for turbine installation and change-out of blades and light nacelle components.

A Novel Gripper Mechanism Between Catamaran and Turbine Foundation for Offshore Wind Installation

The simulated catamaran vessel, visible in Fig. 1, is about 144 m long, 60 m wide and with a mass of approx. 14000 tons. Key characteristics are given in Tab. 1. The vessel is designed to carry four pieces of pre-assembled wind turbines in total. Each with a mass of approx. 1200 t and height of roughly 100 m. Two large grippers on the deck will provide heave lifting capacity to install the wind turbine onto the spar in one step. In this work, the catamaran dynamic positioning (DP) system has been implemented using constraints. The DP system is configured to reduce the yaw, sway and surge motion of the catamaran rigidbody. A compliance of $1E - 14$ is used to constrain yaw, while a value of $2.5E - 8$ is used for the sway and surge. The remaining three DOF are free to move.

### TABLE 1: CATAMARAN DATA

<table>
<thead>
<tr>
<th>Length</th>
<th>Width</th>
<th>Draught</th>
<th>Mass</th>
<th>Longitudinal metacentric height</th>
<th>Transverse metacentric height</th>
</tr>
</thead>
<tbody>
<tr>
<td>144 m</td>
<td>59 m</td>
<td>6.1 m</td>
<td>1401.24 t</td>
<td>214.1</td>
<td>107.9</td>
</tr>
</tbody>
</table>

During operation, three sliding grippers are mounted in a major arc on the inside of the catamarans aft, designed to grasp the spar as seen in Fig. 6. The angle from the left and right gripper to the middle one is 120 degrees. After the grasing, the vessel and spar will be connected in the horizontal XY-plane, in order to make the lifting and installation possible. This connection is stiff, but allows for some movement back and forth. In the Z direction, there will be vertical sliding motion provided by the three passive rollers on the end tip of each gripper. The coordinate system used in this paper is a right handed one with Z up, and X forward. The gripper consists of a hydraulically actuated sliding mechanism, with a range of 3 m. The position of the grippers are controlled by a set of PIDs during operation. Note that, in this work, the hydraulics are not modelled, and are implemented using stiff prismatic constraints. The compliance along the axis of translation is set to $1E - 8$, which allows the prismatic to “give in” when the force is large. Three cylindrical rolling joints are placed along an arc at the end, each with a radius of 0.35 m and length of 1 m. The rolling joints are passive, designed to reduce friction as the vessel moves vertically up and down due to heave motion. The cylinders are angled such that each of them has a normal vector perpendicular to the cylindrical spar surface. A closer look at the design is shown in Fig. 3. Data for the contact material used by AgX to handle roller-spar contacts is given in Tab. 3.

The design used for simulations described in this paper is targeting a spar with a diameter of 9 m in the splash zone. Other key characteristics of the spar is given in Tab. 2. It floats in the water, and is attached to the seabed by three mooring lines as seen in Fig. 5. Key parameters used to model the wires are given in Tab. 4. The seabed is located 150 m below the water surface.

As the simulation starts, the gripper ends are located approx. 0.7m away from the spar surface in the translational axis. PID controllers are responsible for moving the gripper ends towards the spar surface such that they make contact. The maximum allowed translation speed for the prismatic joint has been set to 1 m/s. The initial positioning of the key simulation objects can be seen in Fig. 4.

Environmental Modeling

The motion profile of the waves present in the simulation is given by a single regular wave with amplitude (A) of 1 m, i.e.
wave height of 2 m. The frequency (f) of the waves are set to 0.15 Hz, i.e., a period of $6.667 \text{ sec}$. Three directions for the waves are used, as seen in Fig. 7. The dimensions of the water is 1200x1200x150 m, with a grid resolution of 128x128. Objects in the simulation are affected by wave effects, however there are some limitations to the current hydrodynamic implementation in AgX. More specifically, objects will not affect the water in any way. Meaning that an object will not be affected by another objects’ movement nearby and object movements in water will not produce waves. Further details about the hydrodynamic implementation used by AgX can be found in [12].

In this preliminary work, wind and underwater current has not been considered.

## SIMULATION RESULTS

In this section, the simulation results will be given. The simulations are implemented in order to say something about the feasibility of a key part of the new wind installation idea, namely the catamaran-spar connection using three hydraulically actuated sliding grippers. This paper will just present the current preliminary results. More specifically, we aim to look at the contact responses and how the novel connection mechanism between a catamaran type vessel and the turbine foundation will improve the stability during wind turbine installation.

Figure 10, 11 and 12 shows the combined contact force of the rolling cylinders for the left, middle and right (when viewed from behind the catamaran) gripper mechanisms respectively. The forces are given according to the world coordinate system. Some sudden spikes are visible in the beginning. These can be explained by the fact that the spar and catamaran is moved by the waves, resulting in the spar hitting the grippers while they are still moving towards it. Figure 14 shows the directional contact forces acting on the spar, while the magnitude of the forces are given in Fig. 8. From these plots we find that the forces are generally larger when the wave direction is perpendicular to the catamaran.

Figure 9 shows the stabilisation effect of the gripping mech-
FIGURE 6: LOCATION OF THE SLIDING GRIPPERS

FIGURE 7: WAVE DIRECTIONS ACCORDING TO THE VESSEL.

FIGURE 8: SPAR CONTACT FORCES

FIGURE 9: REFERENCE ERROR

The lines show the euclidean distance in the horizontal plane between two reference frames. One frame moves with the spar, whilst the other is moving with the catamaran. Initially they are placed at the same location, on the spar, as seen by the green sphere in Fig. 4. Using the same reference frames, the displacement of the catamaran and spar is shown in Fig. 15. From these plots, it is clear that the surge and sway motions between the spar and catamaran are somewhat connected. Heave on the other hand is not, as the gripper mechanism allows the spar to move freely vertically due to the passive rollers. For further reference, orientation of the catamaran and spar is given in Fig. 16. As stated earlier, the catamaran utilises a physics-based DP system, which substantially reduces surge and sway motions as well as effectively eliminating yaw motions.

In Fig. 13, the movement of the prismatic actuator in the grip- per mechanisms is given. Here, we can notice that the actuators will move back and forth when the forces are large. This is due to the PDs actively trying to restore the position once an actuator has been pushed back due to excessive forces. Due to higher experienced forces in the case when the wave direction is perpendicular to the vessel, it is noted that the gripper is seen to move more in this case.
FIGURE 10: LEFT GRIPPER CONTACT FORCE

FIGURE 11: MIDDLE GRIPPER CONTACT FORCE

FIGURE 12: RIGHT GRIPPER CONTACT FORCE

FIGURE 13: GRIPPER TRANSLATION
CONCLUSION AND FUTURE WORK

In this paper, a novel and effective method has been presented for connecting a catamaran type installation vessel with a spar type wind turbine foundation during offshore wind installation. The method is planned to be used in conjunction with the top-side lifting mechanism seen in Fig. 1 and Fig. 2, in order to provide a more stable working condition during installation of the wind turbine onto the turbine foundation. The method is thought to be used with floating wind turbine foundations, but may be applicable for use against bottom-fixed foundations as well.

It is clear from the figures showing contact responses, that the forces involved in the operation are quite substantial. The effect these forces will have on real operational equipment must be further analysed. However, it is clear that the installation procedure should be performed with the catamaran aligned with the direction of the ocean waves in order to keep the contact forces as well as motion of the spar and catamaran as low as possible.

In the future the gripper mechanism may be improved by attaching two additional actuators at the end, so that the angle of the left and right cylinder attachments may be changed according to the diameter of the targeted foundation.

Also, it would be of interest to compare this approach coupled with a DP system against only using the DP. A coupled approach is likely to prove beneficial, at least when considering floating structures as the grasping would help aligning the foundation with the wind turbine, increasing the weather window somewhat.

Additionally, the complete installation procedure should be simulated, from grabbing a windmill from the deck to the placement on-top of the submerged foundation, in order to more fully validate the proposed installation idea. Also, irregular sea states should be included in future simulations, to better approximate real operational conditions. Also wind and underwater current could be included.

ACKNOWLEDGMENT

The research is supported by a grant from SFI MOVE (project no. 237929).

REFERENCES

**FIGURE 14**: SPAR CONTACT FORCE
FIGURE 15: CATAMARAN & SPAR DISPLACEMENT

FIGURE 16: CATAMARAN & SPAR ORIENTATION