Proceedings of 15th International Marine Design Conference (IMDC-2024)
June 2-6, 2024
Amsterdam, the Netherlands

Design of Floating Installation Vessel for Offshore Installation of Floating Offshore Wind Turbines

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ABSTRACT

The installation of the present wind farms Hywind Scotland and Hywind Tampen are both carried out by towing the fully assembled wind turbine from the assembly site in the Norwegian fjords to the final offshore site. In the present study an alternative installation method is proposed where the fully assembled tower is transported to the site on the installation vessel and mounted onto the preinstalled floating substructure (a spar buoy). The paper presents a brief outline of the design process for the proposed concept and gives an overview of the work done to evaluate variations of the installation vessel and the proposed lifting mechanism. The paper is a summary of the results obtained by a project team in SFI MOVE addressing marine operations related to installation of floating offshore wind turbines.

KEY WORDS

Offshore installation; Wind turbines; Novel marine design concept; Wave-induced motion; Co-simulation.

INTRODUCTION

Offshore Wind Turbines (OWTs) can be categorized into bottom-fixed and floating OWTs based on the type of foundation for the wind tower. Traditionally, the installation of bottom-fixed offshore wind turbines has been carried out using jack-up vessels with large cranes. As the offshore wind industry move to deeper waters, the bottom-fixed turbines gradually become less attractive and floating OWTs become the only possible alternative. The installation of floating OWTs can no longer be carried out by bottom-fixed jack-up vessels. The preferred installation method for floating OWTs has been to complete the assembly of the wind turbine in sheltered waters and tow it to the installation site. However, for offshore wind farms far from a coastline where the OWT assembly can take place, alternative installation methods are desired. As a part of the research project SFI MOVE (NTNU, 2024), a team of researchers has proposed an alternative installation process by designing an installation vessel which is capable of mounting the fully assembled wind turbine onto a floating substructure at the offshore installation site. This paper is a summary of the work carried out by the project team from SFI MOVE.

Floating OWTs needs to have sufficient buoyancy to carry the weight of the turbines and some kind of mooring system to facilitate station-keeping of the floating system. Figure 1 illustrates three typical floating OWT concepts which all have been built. The spar-shaped substructure is the one with most industrial application so far, and the work in SFI MOVE has used this concept to assess the feasibility of performing an offshore installation of a floating offshore wind turbine.

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Submitted: 23 February 2024, Revised: 30 April 2024, Accepted: 1 May 2024, Published: 20 May 2024

Conference paper, DOI: https://doi.org/10.59490/imdc.2024.845 e-ISSN: 3050-4864

The fundamental principle in the concept is to follow a procedure like this:

1. Tow-out of substructure – Horizontal towing of the spar-shaped substructures.
2. Upending and Mooring – Upending and mooring of the spar-shaped structures.
3. Assembly of OWT – Inshore assembly of the Offshore wind turbine (OWT) (tower, nacelle and blades).
4. Transport of OWT to site – Installation vessel to carry 3-4 fully assembled OWTs to the site.
5. Mounting of OWT – Installation vessel mounting the OWTs onto the moored substructure using a low-height lifting mechanism.

The work presented in this paper focusses on the last part of this procedure.

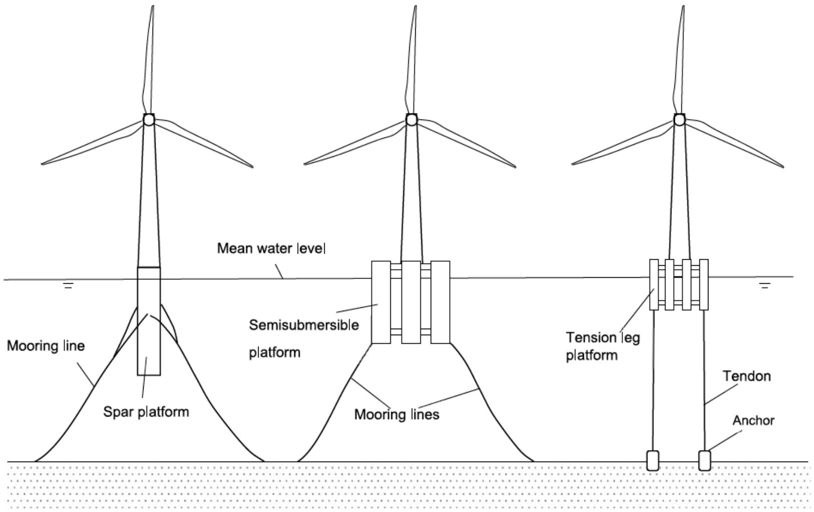


Figure 1. Schematic of various floating offshore wind turbine concepts (From Jiang, (2021)).

The paper is organized as follows: First an outline of how the design process evolved from the original idea to the development of the concept and the presentation of the final concept. The most important modelling issues and the critical response parameters are also described. Then the system modelling, and the various computer models are described. This includes how the relative motion between the two floating bodies are evaluated, how the dynamics of the lifted object influences the relative motion, and several other aspects which have been studied by the project team. The SFI MOVE project was an 8-year research project, and the various parts of the work have already been published. However, since the project lasted such a long period, and has resulted in several publications, the purpose of the present paper is to give an overall summary of the work done in the project. The new contribution from this paper is that it conveys the design strategy and concept idea in a condensed and more readable way, compared to the original and individual publications.

DESIGN OUTLINE

Original Idea

The underlying idea for the development of an installation vessel for floating wind turbines was to keep investment costs down. Hence, a relatively small vessel was proposed. To save time during installation, the idea of carrying more than one fully assembled wind turbine from the onshore assembly site and to the offshore was followed. Therefore, a vessel with sufficient weight-carrying capacity and sufficient stability characteristics was needed. To be able to perform the installation at the offshore site it is important to keep the relative motion between the lifted OWT and the floating substructure within some limitations. Consequently, we want to minimise the relative motions between the two floating structures, and we want to control the motion of the lifted OWT. Both improved stability characteristics and reduced vessel motions will presumably be achieved by increasing the vessel size. However, this alternative will come at an increased cost. The optimal ratio of vessel cost vs. vessel size is not investigated in this study.

The design of the proposed installation vessel was partly motivated by other recent studies by Huisman (Bereznitski, 2011) and Ulstein (Skipsrevyen, 2011), see Figure 2. In Huisman's concept a relatively small installation vessel is proposed and to ensure sufficient stability the vessel needs a large width which is achieved by using a catamaran hull. Ulstein has proposed a novel idea of carrying several wind turbines which can be installed from the same vessel. The concept proposed by SFI

MOVE builds on both these ideas and includes a catamaran hull to obtain sufficient stability with a relatively large deck area to cover 3-4 wind turbines.

(a) (b)

Figure 2. Huisman (a) and Ulstein (b) have both proposed concepts for installing fully assembled wind turbines onto floating substructures.

(a) (b)

Figure 3. Huisman (a) and Offshoretronic (b) introduce different crane systems to handle the installation of wind turbines onto floating substructures.

To lift the fully assembled tower from the installation vessel and onto the floating platform, some kind of lifting arrangement is needed. Again, the project found inspiration in existing solutions. Figure 3 shows two proposed alternatives from Huisman (2009) and Offshoretronic (2020). In the traditional lifting crane (like the one proposed by Huisman), the crane tip must be above the top of the tower. With the turbines gradually increasing in size, this leads to higher and higher cranes, which becomes more and more challenging from a stability perspective. In Offshoretronic's solution, the weight of the tower is carried by wires which are attached to a collar in the lower end of the tower. In this way, the lifting structure can be designed to avoid the extreme heights, thereby reducing the negative effect on the stability of the vessel. To avoid the extreme height of the lifting arrangement the proposed concept has a similar idea as the one proposed by Offshoretronic.

Concept Development

An initial design of a floating installation vessel together with an initial design of a low-height lifting mechanism was proposed by Hatledal et al. (2017), see Figure 4. The concept included a catamaran hull as the installation vessel; with a dynamic position system for station-keeping. The low-height lifting mechanism included a gripper mechanism to reduce the relative motion between the floating installation vessel and the moored floating substructure (a spar buoy) and a hydraulically controlled lifting mechanism (see Figure 5).

Compared with traditional methods using jack-up vessels, this concept avoids the use of high and heavy offshore cranes and can transport and install the pre-assembled OWT's in an efficient manner. Consequently, the operational time has the potential of being reduced from "a few days" to "a few hours". A more comprehensive work on the same concept was carried out by Jiang et al. (2018). In this work the technical feasibility of the concept in terms of acceptable relative motions between the lifted OWT and the spar buoy was confirmed, but again rather high contact forces were found in the sliding gripper which connects the installation vessel to the spar-shaped substructure. The contact forces were too high in both the gripper mechanism and the lifting mechanism.

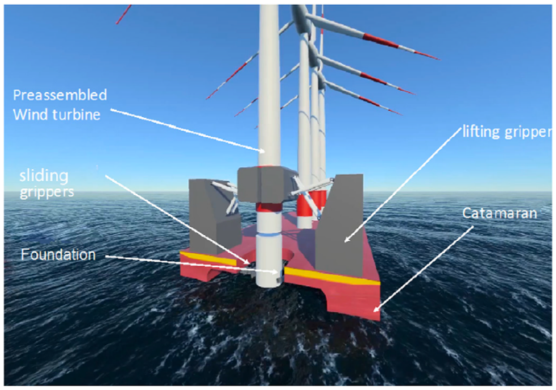


Figure 4. Initial design of the offshore installation vessel (from Hatledal et al (2017)).

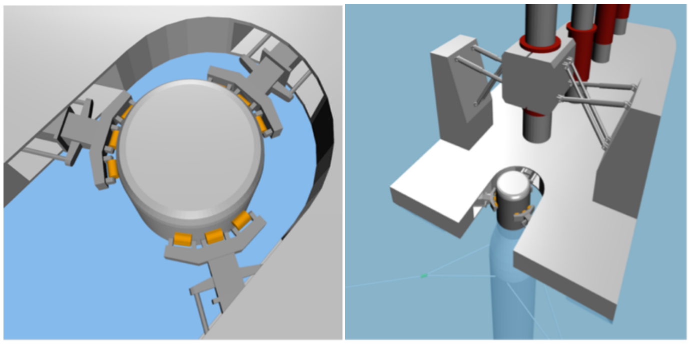


Figure 5. Illustrations of the gripper design and the lifting mechanism (From Hatledal et al (2017)).

An improved concept was proposed to reduce the relative motion between the OWT and the Spar substructure. The lifting mechanism was updated and mounted on a motion-compensated platform which was designed to follow the wave-induced motions of the Spar buoy, see Figure 6. Following this approach, the concept evolved to an alternative where the low-height lifting gripper mechanism was replaced by a set of lifting wires in a low-height truss-frame structure and balanced by a set of stabilizing wires, as shown in Figure 7 (left).

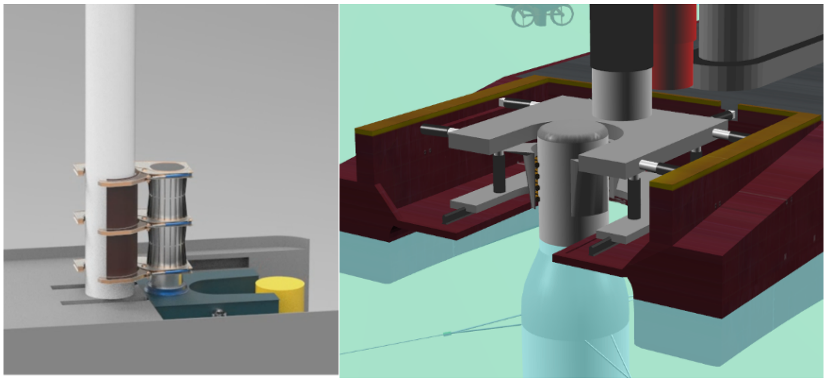


Figure 6. Illustrations of the modified gripper design and the motion-compensated platform.

The relative motion is controlled by active winch control. Vågnes et al. (2020) studied the effect of including a preliminary active heave compensation (AHC) system based on a PID controller to control the relative vertical displacement between the mating points. The main conclusion to be drawn from that study was that by introducing the AHC system, the relative displacement was reduced by approximately 50% at the resonant periods. Xu et al. (2020) proposed a simple but more general 6DOF active compensation control algorithm for the system. This study confirmed the findings from the study by Vågnes et al. (2020) which was limited to control of the vertical motions only. Ren et al. (2021a) developed a control algorithm using singular perturbation theory to minimize the relative heave motions between the mating points of the OWT and the floating spar foundation.

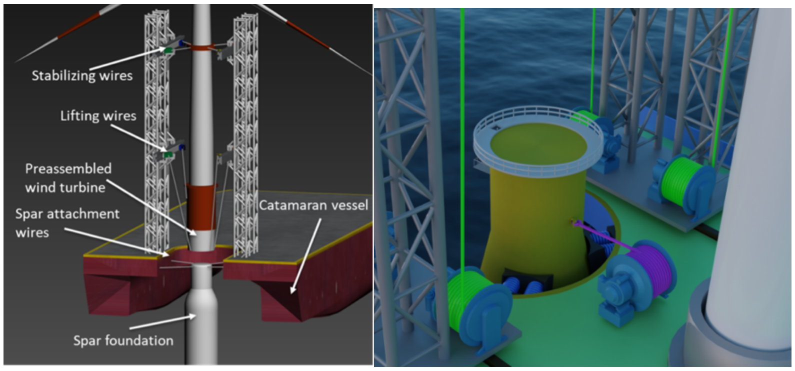
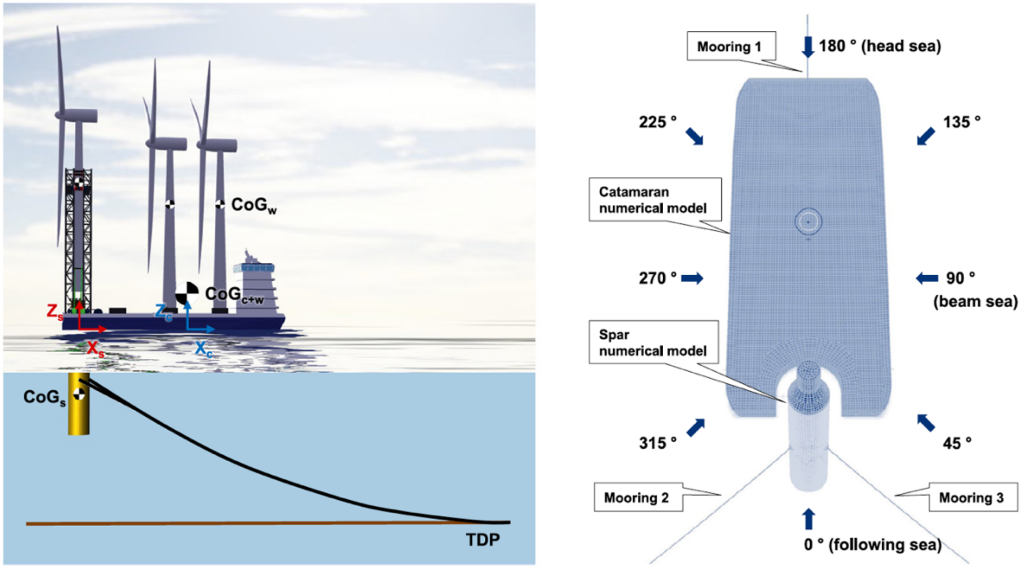


Figure 7. Improved concept with separate lifting and stabilising wires (left; from Vågnes et al (2020)) and the mechanical damping device between the catamaran and the SPAR (right; from Hong et al. (2022)).

The idea of the SFI MOVE concept is that the installation vessel can carry fully assembled wind turbines to the site and that an offshore installation operation is carried out on site. A detailed procedure of the steps involved in this offshore marine operation is described in Hong et al. (2022). A short summary of the involved steps is given below.

1. **Mobilization.** Assembled offshore wind turbines (OWTs) are loaded onto the installation vessel.
2. **Transportation.** The installation vessel transports the OWTs to the operation site.
3. **DP activation.** The dynamic position (DP) system is activated for station-keeping of the installation vessel.
4. **Mechanical coupling on.** The mechanical coupling system connects the installation vessel to the spar buoy.
5. **Lifting and hovering.** One of the OWTs is lifted and hovers on top of the spar buoy. Active motion compensation is activated.
6. **Lowering and mating.** The lifted OWT is lowered and mated onto the spar.
7. **Mechanical coupling off.** The assembled OWT is now connected to the spar and the floating OWT is disconnected from the installation vessel.
8. **Next location.** The installation vessel moves to the next installation location.



(a) Side view

(b) Numerical models and orientation of wave headings

Figure 8. Side view (a) and Top view (b) of the catamaran installation vessel and the wave directions (from Hong et al. (2023b).

An illustration of the concept is shown in Figure 8. The concept allows the floating substructure (the spar buoy) to be preinstalled and moored at the installation site. The work presented in this study is limited to step no. 5 “Lifting and Hovering”.

The main dimensions of the installation vessel, the spar buoy and the wind turbine are given in Table 1.

Table 1. Design parameters of the wind turbine, catamaran and spar (data from Hong et al, 2022).

Parameter		**Wind turbine**	**Catamaran**	**Spar**
Rated power	[MW]	10	-	-
Hub height	[m]	119	-	
Rotor diameter	[m]	178.3	-	
Length over all	[m]	-	153	90
Width over all	[m]	-	60	14
Draft	[m]	-	8	70
Fairlead position	[m]	-	-	35
Body origin in global coordinate system	[m]	-	(63, 0, 0)	(0,0,0)
Center of Gravity (CoG)	[m]	(-0.3, 0, 84.2)	(-0.1, 0, 21.2)	(0, 0, -51.1)
Displacement	[ton]	1 302	18 309	12 642
Radius of gyration about CoG (Roll)	[m]	41.85	48.12	20.10
Radius of gyration about CoG (Pitch)	[m]	41.85	58.75	20.10
Radius of gyration about CoG (Yaw)	[m]	4.79	42.52	5.69
Roll-pitch inertia about CoG	[t m^2]	0	-76.4	0
Roll-yaw inertia about CoG	[t m^2]	-1.55 E4	-6.46 E6	0
Pitch-yaw inertia about CoG	[t m^2]	0	6.75	0

Modelling Issues

The evaluation of the various concepts was based on modelling the complex dynamic system and a subsequent simulation of the dynamic behaviour of the system. Hence, the main part of this work has been to establish proper computer models of the various parts of the system. In the following the modelling of the main parts of the concept are discussed. Figure 9 illustrates how the main parts of the system can be isolated and modelled separately.

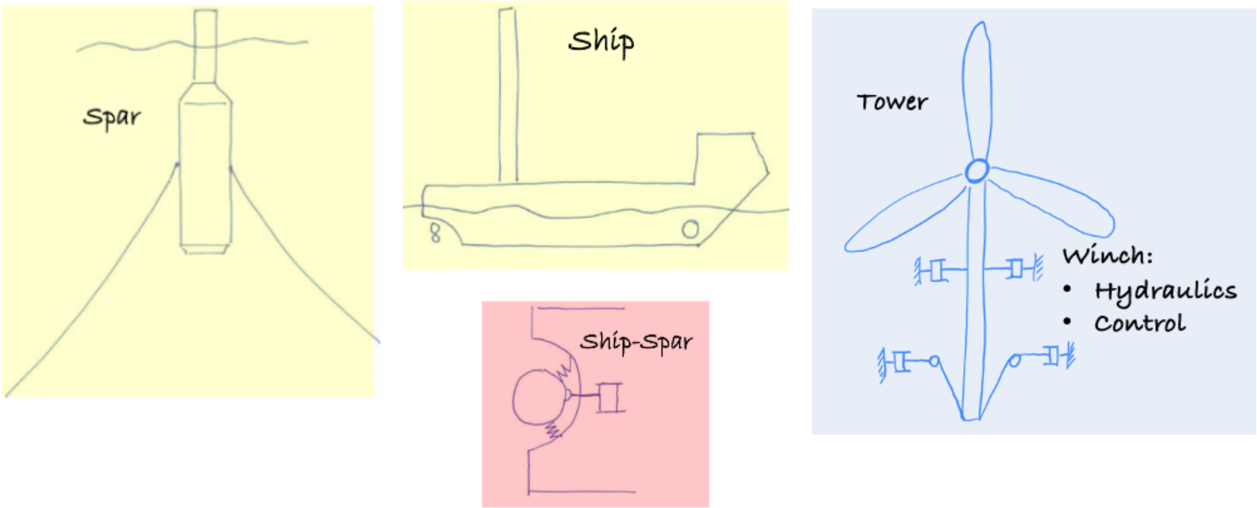


Figure 9. The system is comprised of two floating rigid bodies (ship and spar), a complex payload (wind tower) which is lifted and balanced by a set of wires all hydraulically controlled from several winches, and a mechanical connection system between the ship and the spar to reduce the relative motion between these.

In establishing reliable computer models of the total system, there are at least three main areas which needs to be addressed:

1. **Hydrodynamic modelling.** The hydrodynamic properties of two floating bodies (the ship and the spar buoy) needs to be established. To calculate the proper hydrodynamic loading for two rigid bodies floating close to each other, the hydrodynamic interaction between them needs to be accounted for. Furthermore, the sloshing mode between the two hulls of the catamaran must be included in the analyses and for the small water plane area of the spar buoy, the second order hydrodynamic loading may be important. In addition, the viscous effects of both the catamaran and the spar buoy should be accounted for in the modelling.
2. **Structural modelling.** The system may be modelled as two rigid floating bodies and one rigid lifted complex payload (the wind tower). The mechanical connections between the catamaran and the spar as well as the lifting arrangement connecting the catamaran and the wind tower need to be carefully modelled. In addition, the influence of the flexibility of the lifting mechanism should be considered. It is important to establish the eigenmodes of the complex system and thus to understand the dynamic characteristics of the system.
3. **Modelling of the control system.** There are several control systems which needs to be properly modelled. For the station-keeping of the installation vessel a dynamic positioning (DP) system needs to be modelled. During the mating phase, a proper winch control system needs to be modelled to reduce the relative motion between the spar motion and the lifted tower. Furthermore, it may be necessary to include an active control scheme to the mechanical connection between the catamaran and the spar buoy to reduce the relative motion between the two floating objects (thus reducing the relative motion of the mating points at the lifted tower and the spar).

For the modelling and analysis of complex multi-domain systems like this, several general-purpose simulation platforms exist like MATLAB/Simulink, Dymola, Algoryx, 20-Sim etc. On the other hand, there are also tailor-made time-domain simulation software to handle marine operations in the design phase. These software tools can handle hydrodynamic effects, structural dynamics, as well as hydraulic and control systems to some extent. However, none of these monolithic integrated solutions can handle high-fidelity and efficiency in a flexible way (Yuan et al. 2022).

Co-simulation with FMI/FMU

It would be better if the whole system could be distributed to separate domain solvers, and then recollecting the various connecting parameters in a common general simulation. A practical problem with this idea is that there can be compatibility issues between the different simulator environments. To solve all of this, a co-simulation approach has been developed along with an interface standard called Functional Mock-up Interface (FMI). In an FMI-based co-simulation, the individual local domain models are compiled as Functional Mock-up Units (FMU). This approach also allows to protect the intellectual properties of individual models as the different FMUs only needs to share and exchange a limited set of parameters.

In Yuan et al. (2022) a framework to analyse the proposed installation concept using co-simulation following the FMI/FMU approach was presented, see Figure 10.

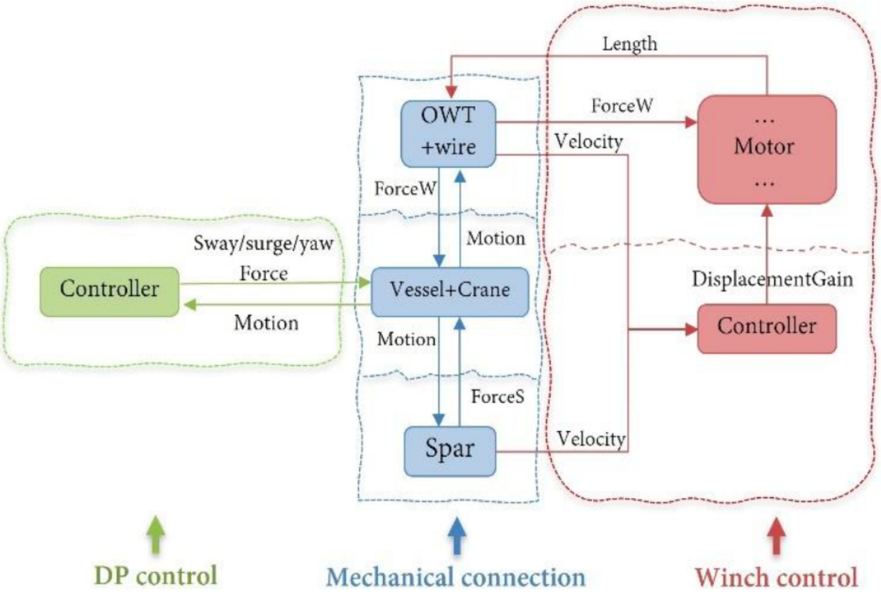


Figure 10. A framework for an FMI-based co-simulation of the installation concept (Yuan et al. 2022).

SYSTEM MODELLING AND COMPUTER MODELS

Several studies have been conducted to evaluate the proposed concept, the methods used have some unique variations and are described in more detail in each of the studies, but the overall method is the same and is briefly described in the following. The critical response for performing a successful mating operation of the OWT onto the floating spar buoy is the relative motion between the bottom of the OWT and the top of the spar. The underlying processes for this relative motion are formed by the motion of the two floating bodies: the catamaran and the spar buoy. Hence, to get a thorough understanding of the dynamic responses of the concept, the fist attempts were to study the relative motion between the stern of the catamaran (as if the lifted OWT was a rigid part of the catamaran) and the top of the spar buoy, see e.g. Hong et al. (2023b). In the next type of analysis, the OWT was a separate dynamic object hanging in a set of lifting wires, this adds complexity to the dynamic processes and the need to include a control strategy to the concept was recognised, see Ren et al. (2021b). It was also realised that with the high and slender crane structure lifting the OWT one could expect some dynamics from the crane structure. A study which compared the importance of including flexibility of the lifting crane structure was carried out by Ataei et al. (2023). And finally, as the dynamics of the lifting structure is one of the underlying dynamic processes dictating the relative motion between the OWT and the spar buoy, a study to compare the influence of using a different installation vessel was conducted. In Liu et al. (2023b) the relative motion between the OWT and the spar buoy when using a SWATH installation vessel was compared with the original catamaran installation vessel. The different scenarios are illustrated in Figure 11.

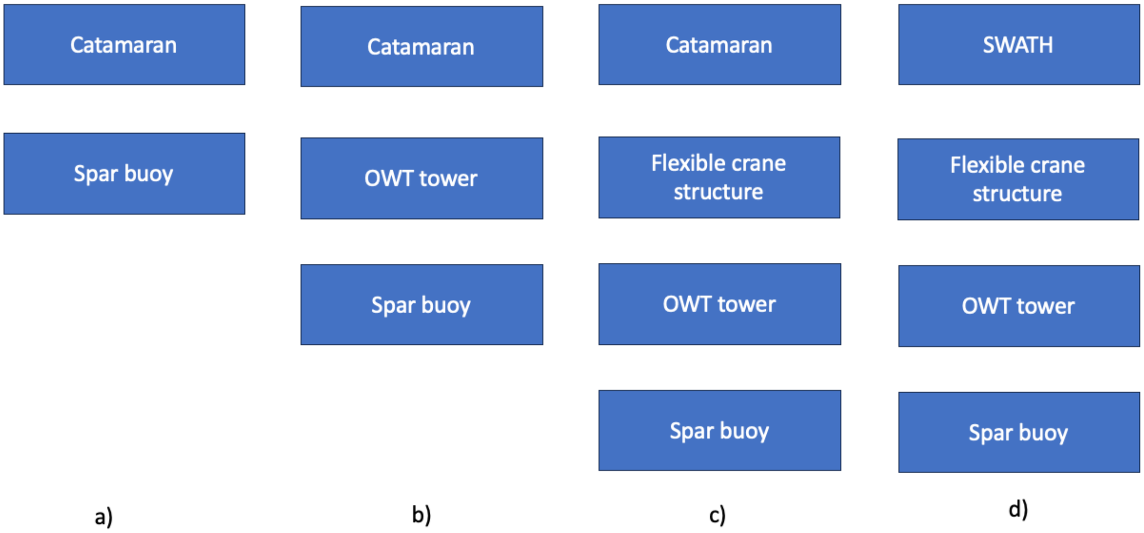


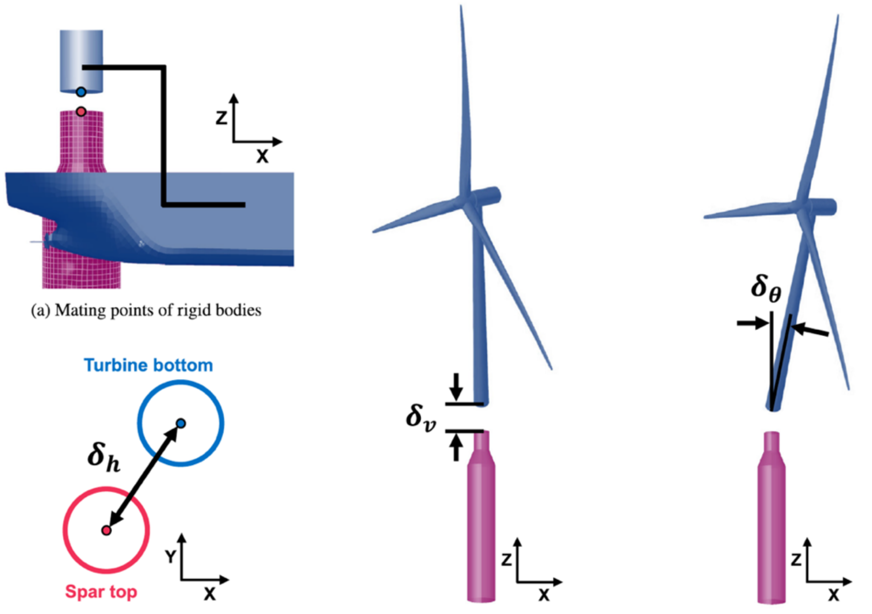
Figure 11. The study includes analyses with various level of sophistication of the computer models.

The proposed concept has primarily been studied by modelling and analysing the system using the features available in SIMO (MARINTEK, 2016). In Hong et al. (2023a) the modelling and analysis capabilities of SIMO were compared with the Orcaflex software (Orcina, 2024). The modelling capabilities in Orcaflex are slightly different than in SIMO but follows the same overall structure and the resulting response analyses gave no different conclusions than obtained from the SIMO analyses. SIMO is a time-domain simulation program for simulating motions and station-keeping of multibody systems. The installation vessel and the floating substructure (the spar buoy) were modelled as two rigid bodies connected by mechanical couplings. Thrusters and mooring system were added to the installation vessel and the floating substructure, respectively. The hydrodynamic properties including interaction effects were calculated using the Sesam module HydroD (DNV, 2024b). Wind coefficients have been estimated using the HAWC2 software (Larsen & Hansen, 2007). The panel models used in HydroD were established using the Sesam module Genie (DNV, 2024a).

Relative Motion Between Installation Vessel and Floating Substructure

The first attempts to study the dynamic behaviour of the concept simplified the analysis model by assuming the lifted OWT to be a rigid part of the installation vessel. The idea was to study the relative motion between the two floating bodies.

Base Case – Stern Installation. The present work is focusing on step 5 **Lifting and hovering** defined above, and analyses were carried out (e.g. by Hong et al. 2022) to understand the dynamic behaviour of the concept and to evaluate the installation criteria to be used. The main critical response which has been studied in detail is the relative motion between the lifted OWT and the floating spar buoy. Figure 12 illustrates how the relative motion is defined and how it can be split into a horizontal displacement, a vertical displacement and an angular component. Comprehensive analyses have been carried out to study the relative motion between the bottom of the lifted OWT and the top of the floating spar buoy. As the underlying mechanisms for the relative motion are the wave-induced motion of the two floating structures (the installation vessel and the spar buoy), the initial efforts were to study the relative motion between the two mating points indicated in Figure 12 (a) between the OWT rigidly connected to the installation vessel and the spar buoy.



(a) Mating points of rigid bodies

(b) Relative horizontal displacement, δ_h

(c) Relative vertical displacement, δ_v

(d) Relative alignment, δ_θ

Figure 12. The definition of the main critical response parameter; the relative motion between OWT and spar buoy (From Hong et al (2022)).

In Figure 13 we see the footprints of a 1-hour simulation of the system. In the upper part of the figure, we see the heave and surge motion and in the lower part of the figure we see the roll and pitch motion. The wave direction is head sea. The pitch motion of both the catamaran and the spar buoy clearly dominates the response pattern. Since the mating point is located at the stern of the catamaran, the response at the mating point also has a significant pitch-induced heave component. For the relative motion at the mating point this results in quite severe motions both in the horizontal (surge) and the vertical (heave) directions.

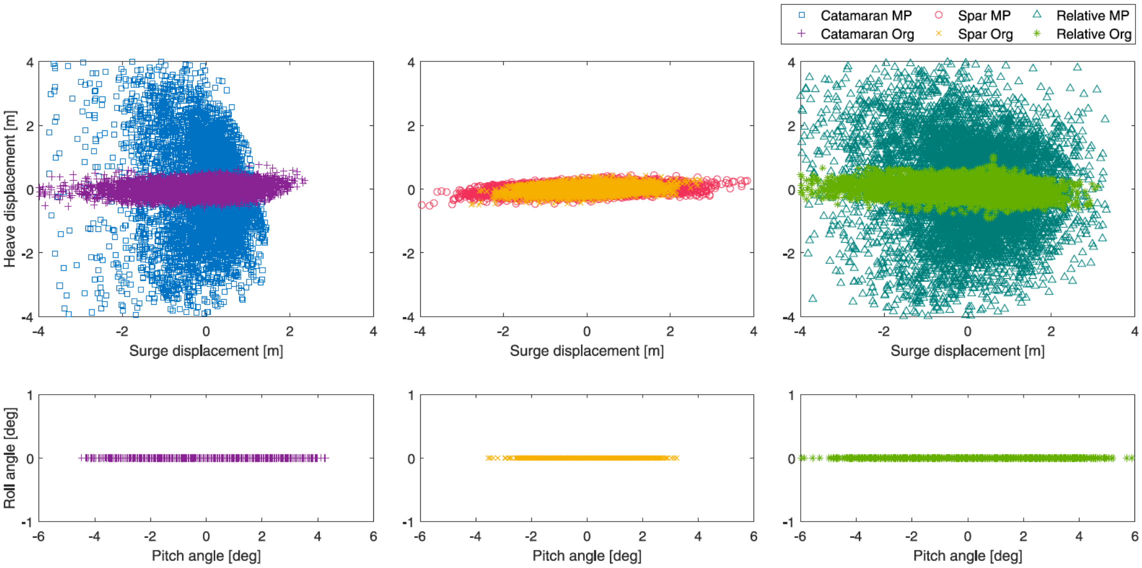
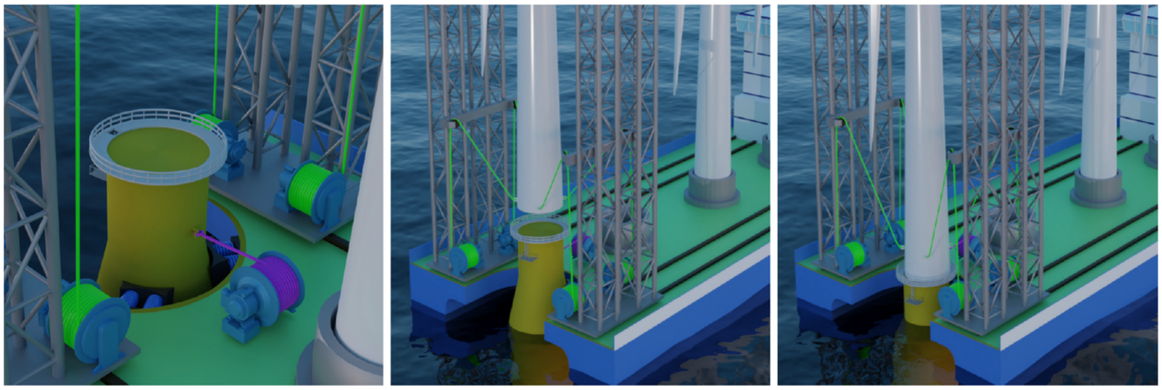


Figure 13. Footprints of 1-h simulations for body responses at the mating points and the body origin of the catamaran and the spar as well as the relative motion between the two mating points. The results are shown without any mechanical coupling between catamaran and spar ($\theta = 180°, H_s = 2\ m, T_p = 11\ s$). (From Hong et al. 2022).

The main challenge for the proposed concept was to reduce the relative motion between the lifted OWT tower and the floating substructure (the SPAR buoy). Figure 14 illustrates how the mating part of the operation can be carried out. In Figure 14 (a) we see how the mechanical coupling is defined, Figure 14 (b) shows the phase which is analysed in detail in this work and Figure 14 (c) shows how the OWT is mated on top of the floating spar buoy.



(a) Step 4: mechanical coupling connection (b) Step 5: lifting and hovering (c) Step 6: lowering and mating

Figure 14. Illustration of the main steps during the installation phase, (from Hong et al. (2022)).

Effect of Mechanical Coupling. To reduce the relative motion at the mating point, Hong et al. (2021, 2022) introduced a mechanical coupling connection between the catamaran and the spar buoy, see Figure 14(a). The mechanical coupling system consists of fenders and pre-tensioned wires designed to create a condition where the two floating bodies remain in close contact, reducing the relative motions between the moored floating spar buoy and the DP-controlled floating installation vessel. Figure 15 provides a visual representation of the 1-hour simulation for different pretension levels in the wire system, with the blue squares and red circles representing the footprint of the catamaran and spar mating points, respectively, and the green triangles representing the footprints of the corresponding relative motion between them. Figure 16 further compares the standard deviation of the relative surge, heave and pitch motions for different pretension levels and wave conditions, highlighting the system's effectiveness in reducing relative motions.

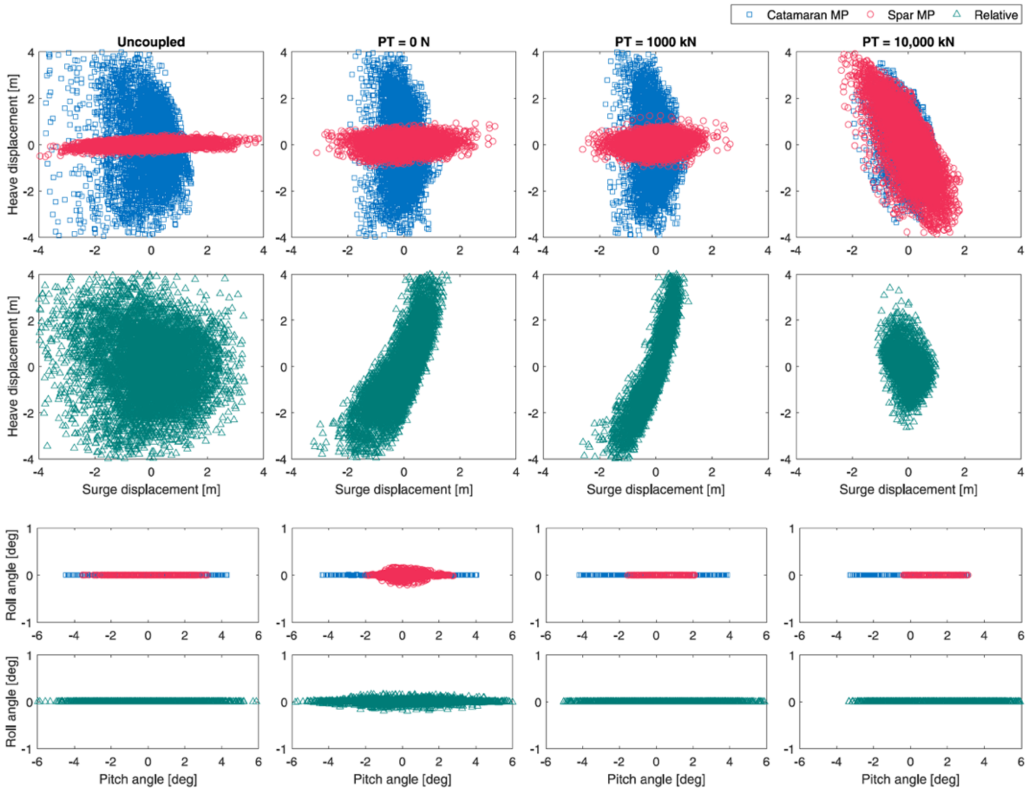


Figure 15. Footprints of 1-h simulations of the mating points with different mechanical coupling conditions ($\theta = 180°, H_s = 2\ m, T_p = 11\ s$). (From Hong et al. 2022).

The simulation results provide clear insights into what effect the mechanical coupling has on reducing the relative motions. The introduction of the system significantly reduces relative horizontal motion, even in the absence of pretension, with a 60-83% reduction in the standard deviation of the relative surge motion depending on the wave condition and pretension. However, the pretension needs to be increased beyond a certain level to reduce the relative vertical motion. When the pretension is increased to 10,000 kN, the relative vertical motion is affected and reduced, and the standard deviation is reduced by 55-72%, depending on the wave condition. This reduction is due to the frictional force of the fender system, emphasizing the need for evaluation and development for durability and reliability. The relative pitch motion was less affected by introducing the mechanical coupling as can be seen from the bottom row of Figure 16.

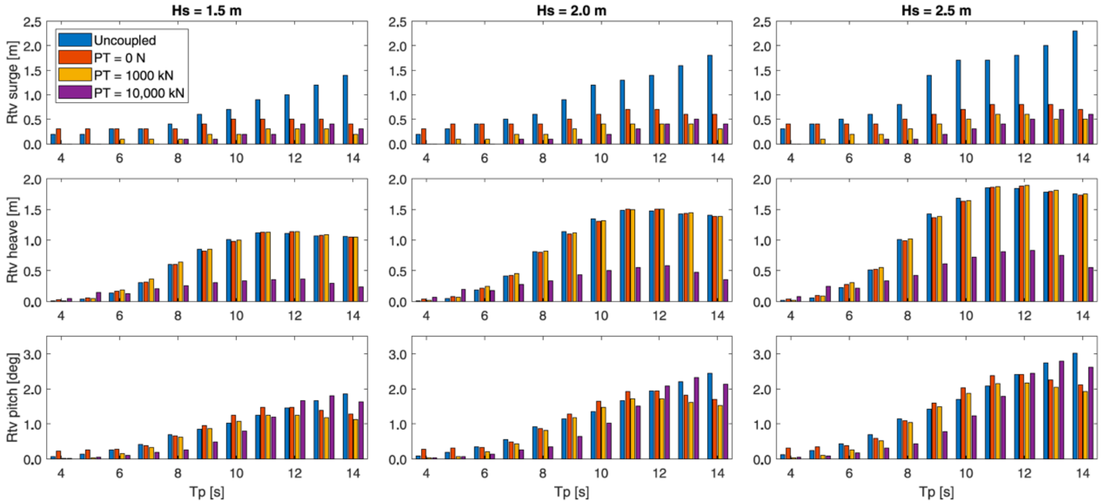


Figure 16. Comparison of standard deviation of the relative motions under varying pretension levels and wave conditions ($\theta = 180°, H_s = 1.5 - 2.5\ m, T_p = 4 - 14\ s$). Top row – surge; middle row – heave; bottom row – pitch, (From Hong et al. 2022).

Effect of Moving the Mating Location from Stern to Side. The pitch motion of both the installation vessel and the spar buoy has proven to dominate the resulting relative motion between the OWT and the spar. To reduce the relative motion between the OWT and the spar buoy, this motivated a study of moving the mating location to the mid ship of the installation vessel. In Figure 17 (Hong et al., 2024) three different installation systems are shown: a) The initial stern installation, b) The side installation, c) The side installation with a mechanical damping system.

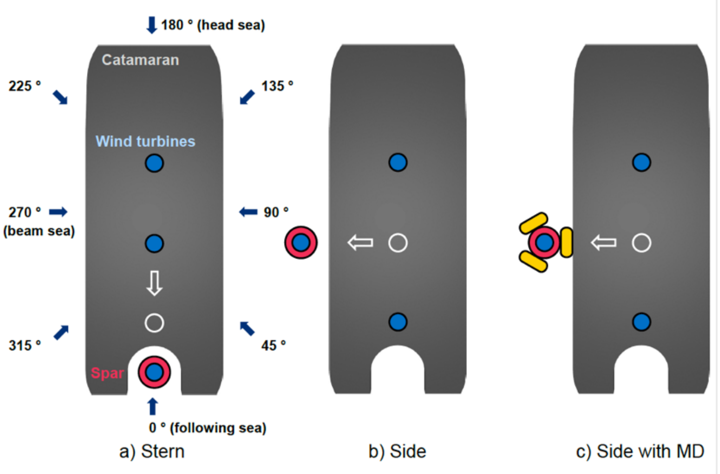


Figure 17. An overview of the three alternative installation systems which are compared (from Hong et al. (2024)).

In Figure 18 the relative responses (mean + st.dev.) for the three different installation systems are compared. From these results, we see that the relative vertical responses are clearly reduced when the mating location is moved from the stern to the side. However, the in-plane relative responses are not reduced simply by moving the mating location to the midship of the installation vessel. By including a mechanical damping system, the in-plane relative response is reduced significantly. Hong et al. (2024) have shown that the side installation alternative with a mechanical damping system has reduced the relative motion by 70-90% compared to the base case stern installation.

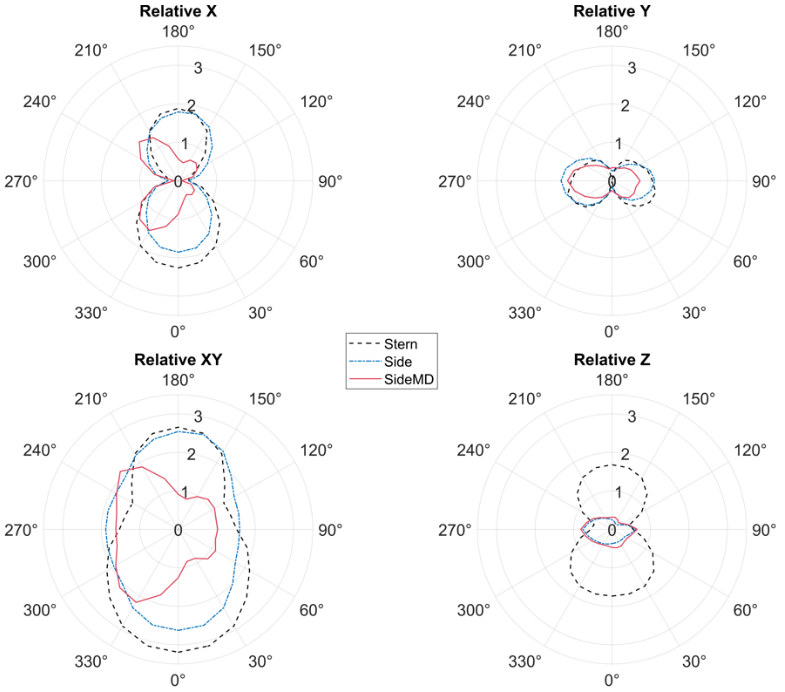


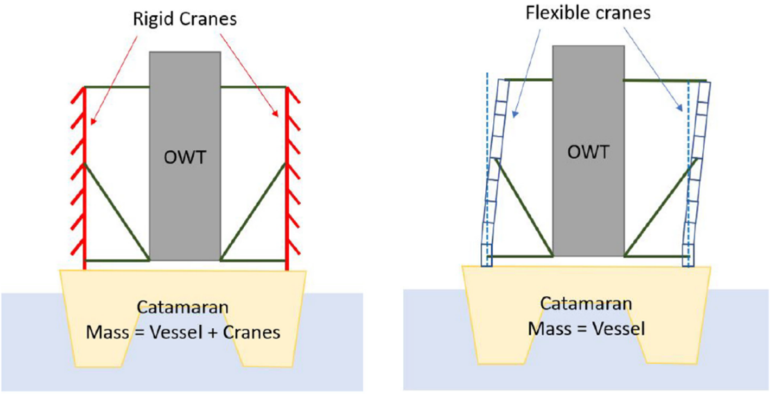
Figure 18. Comparison of the relative response (mean + st.dev.) for the three different installation systems ($H_s = 2.5\ m, T_p = 10\ s, \theta = 0 - 360°$ in steps of 15 degrees)

Relative Motion Between Lifted Object and Floating Substructure

The lifted OWT forms a third moving body with its own dynamic characteristics. In Vågnes et al (2020) a study of the complete system including the dynamics of the lifted OWT was carried out. This was an initial analysis and not all design parameters were fixed. It was observed that the natural periods of the lifted OWT was clearly below the range of wave excitation, but it complicated the dynamic response pattern. An active heave compensation model was introduced in the analyses which reduced the relative motion significantly but to the price of increased tension in the lifting wires. The results were still promising, and it was decided to proceed with more detailed studies on the motion of the floating bodies as well as with the modelling of the lifting structure.

An active heave compensation control alternative was also studied by Ren et al. (2021a) and they confirmed the importance of reducing the relative motion between the OWT and the spar buoy by some kind of active control. In Ren et al. (2021b) an anti-swing control model of a fully assembled wind turbine lifted by several lifting wires from a floating installation vessel, was proposed. In this approach, the control scheme also manages to control the in-plane motion. The control scheme is based on the knowledge of inverse dynamics and range-based localization. It has a simple form without considering state-space equations but can effectively reduce the pendular payload motion without detailed system configuration.

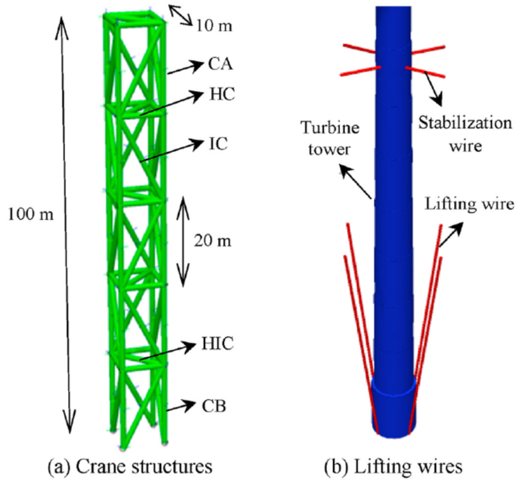
Effect of Including Flexibility in the Crane Structure. In Ataei et al. (2023), the effect of including the flexibility of the lifting crane was studied. Compared to the case where the crane was assumed as a part of the rigid body vessel motion, the flexibility introduced increased responses and shifted the resonance frequencies considerably. In this work the truss-framed crane structure was simplified with a simple beam structure with equivalent constant cross-section properties. The principle is illustrated in Figure 19. The conclusion from this investigation was that the flexibility increased the relative response between the lifted OWT and the spar buoy. In particular, the relative alignment between the OWT tower and the floating spar buoy is increased when the flexibility of the lifting arrangement is considered. Furthermore, it is observed that the standard deviation of the forces in the lifting wires increases when the flexibility is accounted for.



(a) Model 1: Rigid cranes (b) Model 2: Flexible cranes

Figure 19. Modelling the flexibility of the high truss-shaped structures used to lift the OWT (Ataei et al., 2023).

The behaviour of the truss-shaped crane structure was further studied by Gao et al. (2023). In their work the individual truss members were defined as illustrated in Figure 20. An additional observation from this work was that a particular concern should be raised about possible buckling failure of the lower truss members.

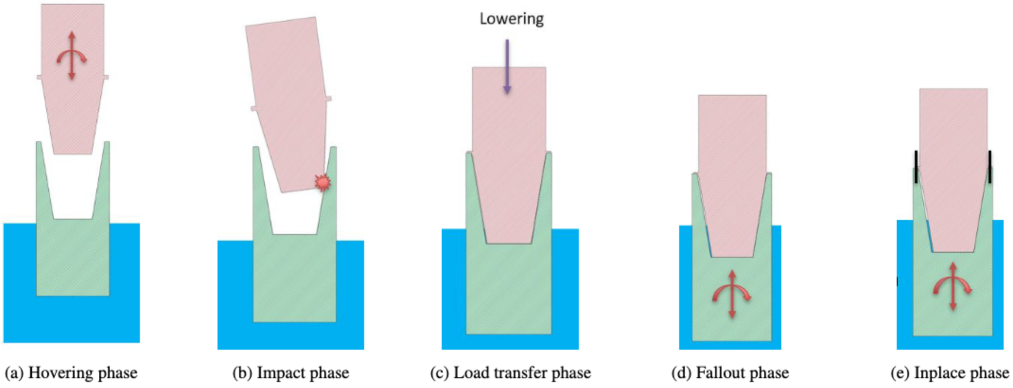


(a) Crane structures (b) Lifting wires

Figure 20. Crane structure and wire systems

Design of Quick Connection Device – Impact Issues

To succeed with an offshore installation of fully assembled OWTs onto floating substructures, the connection between the two objects needs to be optimized. The current solution with grouted or bolted connections has inherent difficulties which needs to be improved if an offshore installation should be possible. Grouted connections are unsuitable as the grout needs substantial time to harden. Bolted connections require very low tolerances during the mating process, which can be challenging during offshore operations. Ateai et al. (2024) presents a concept where two conic cross-sections are forced into each other, and the load is carried by friction forces. Figure 21 illustrates the various phases during the mating operation.



(a) Hovering phase (b) Impact phase (c) Load transfer phase (d) Fallout phase (e) Inplace phase

Figure 21. Overview of the mating operation stages.

In Ataei et al. (2024) both global analyses to establish the relative motion between the two objects and local analyses to study the possible impacts and structural damage to the objects are performed.

Effect of Introducing an Alternative Installation Vessel

The critical response parameter for using the proposed installation concept is to minimize the relative motion between the lifted OWT and the floating spar buoy. Since the wave-induced motion of both the installation vessel (the catamaran) and the spar buoy determines the relative motion between the OWT and the spar buoy, the idea of using an installation vessel less susceptible to wave effects than a catamaran, was attractive. The Small Waterplane Area Twin Hull (SWATH) concept was designed to bring the vessels natural periods out of the typical wave frequencies. Huisman Equipment B.V. proposed in 2011 to use a SWATH as an installation vessel for fully assembled OWTs (Bereznitski, 2011). Later this concept was reinvestigated and modified by Lee at al. (2020). However, none of these studies included the floating substructure of the OWT or the mating process in the analysis work.

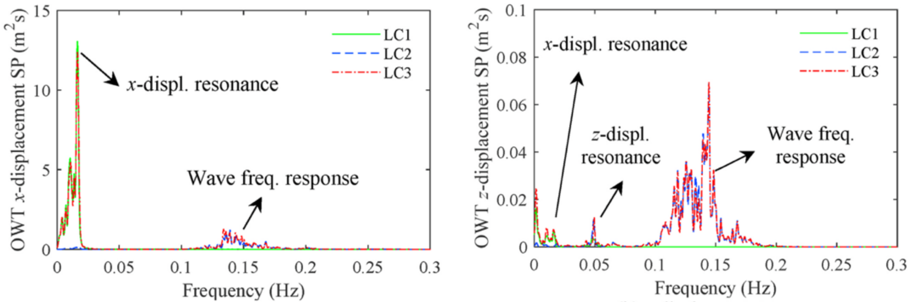
In the SFI MOVE program we have performed several studies to address the mating process. Liu et al. (2023a) studied the hydrodynamic performance of the SWATH and the response analysis of the coupled SWATH-spar system. A numerical model of a SWATH including second order difference frequency force effect and damping forces was established and compared with experimental data for a SWATH of comparable dimensions. The numerical model was modified to satisfy the criteria of weight-carrying capacity and hydrostatic stability for the proposed concept. Furthermore, a multibody numerical model for the SWATH-spar system was developed, where also the hydrodynamic interaction between the two floating bodies was included.

In Gao et al. (2023) the numerical model was developed further to include a structural model of the low-height lifting mechanism and a model of the lifted OWT. The environmental conditions were varied over a range of sea states also including wind loads in some cases, (see Table 2). The study was limited to wind and waves coming from the same direction (head seas).

Table 2: Loading conditions (LC) applied in the study by Gao et al. (2023).

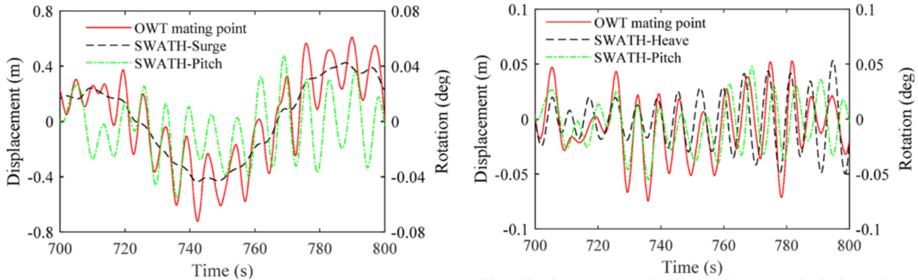
LC	U_w (m/s)	T_I (%)	H_s (m)	T_p (s)
LC1	7.0	24.8	-	-
LC2	-	-	1.0	7.3
LC3	7.0	24.8	1.0	7.3
LC4	5.6	28.0	0.5	6.8
LC5	8.3	22.9	1.5	7.7
LC6	7.0	24.8	1.0	[5,6,7,8,9,10]

Global dynamic response of both the OWT mating point motion, the lifting wire tension, and the strength of the lifting structure were studied. Both the wave and the wind spectra provide low frequency excitation forces to the system, and this study revealed that the wind-induced low-frequency motions of the lifted tower caused the SWATH to respond with low-frequent surge motions. In Figure 22, the displacement spectrum of the motion at the OWT tower mating point is presented, and for LC2, (without wind), the low-frequency response in x-direction is almost negligible.



(a) *x*-displacement (b) *z*-displacement

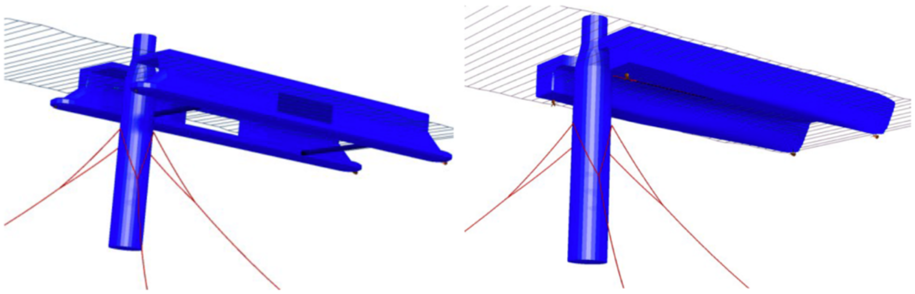
Figure 22. OWT tower mating point displacement spectrum. LC1 – wind only; LC2 – wave only; LC3 – both wind and waves included (from Gao et al., 2023).



(a) *x*-displacement vs SWATH surge and pitch motion (b) *z*-displacement vs SWATH heave and pitch motion

Figure 23. Mating point displacement vs SWATH motion (LC3)

Figure 23 show time series of both the mating point displacement and the SWATH motion. Here, we clearly see that the SWATH motion follows the low-frequent response of the lifted OWT tower. Although there also was a clear low-frequent response of the SWATH in surge due to waves only, this response was much smaller and did not cause a significant response of the OWT tower (see Figure 22).

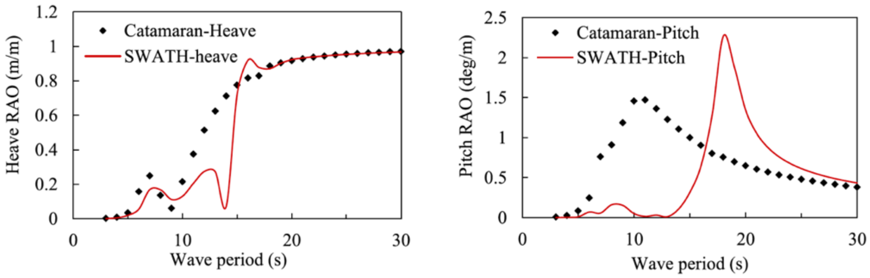

(a) SWATH and spar

(b) Catamaran and spar

Figure 24. Numerical model of the installation vessels and the spar buoy, (Liu et al. 2023b).

Liu et al. (2023b) have compared the relative response of the two mating points by using the SWATH installation vessel with the relative response by using the catamaran. The numerical model of the two cases is shown in Figure 24. Figure 25 clearly illustrates the different behaviour of the two installation vessels. We see that he natural period for the SWATH in pitch is around 18 s and consequently outside the most typical wave periods.

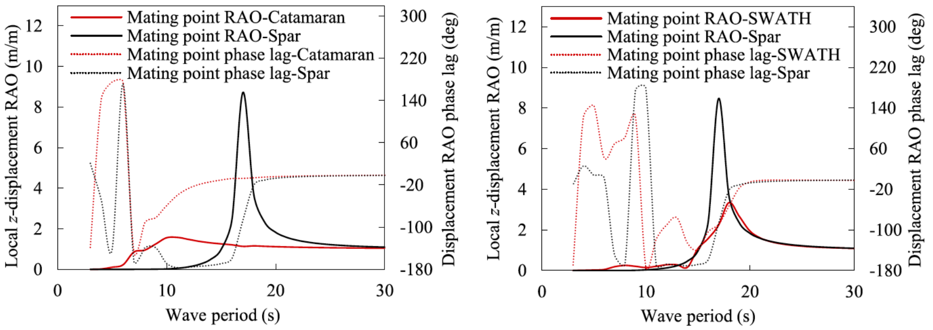
The critical response parameter for the success of the proposed concept is the relative motion between the mating point at the spar top and the mating point at the bottom of the OWT. The motion RAOs for the vertical displacement of the mating points are shown in Figure 26.



(a) Heave RAO comparison

(b) Pitch RAO comparison

Figure 25. Motion RAO comparison of the SWATH and the catamaran installation vessels, (Liu et al. 2023b).

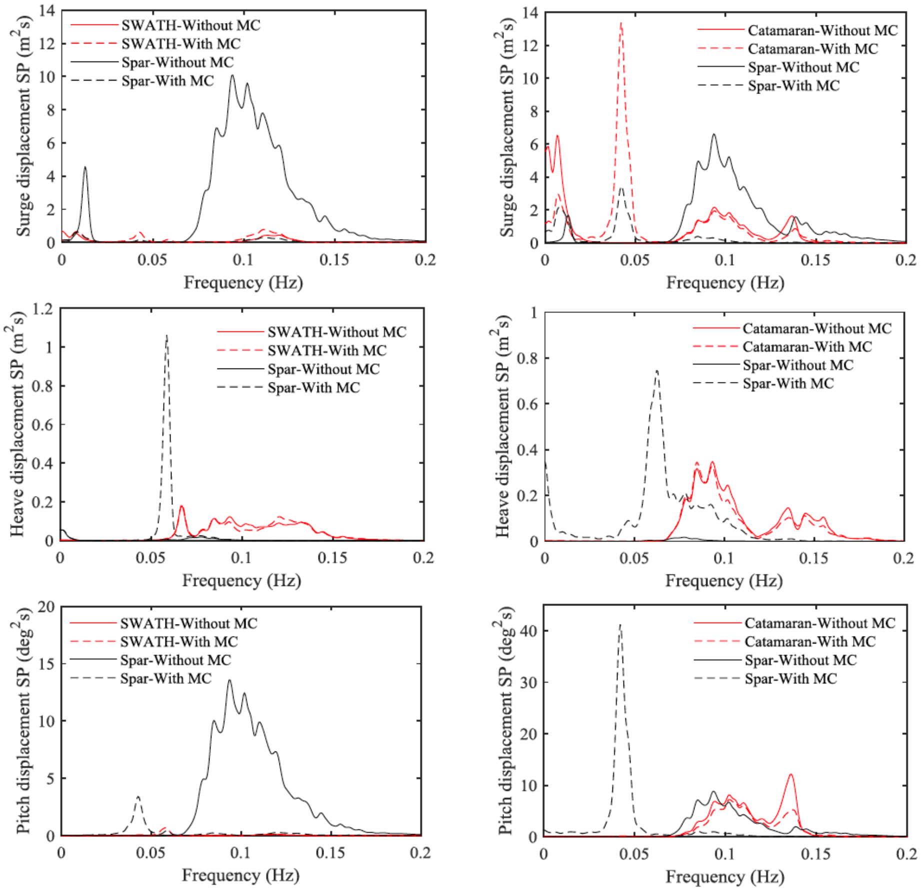


(a) Catamaran installation vessel concept

(b) SWATH installation vessel concept

Figure 26. Transfer functions for the vertical displacements of the mating points in the installation (Liu et al. 2023b)

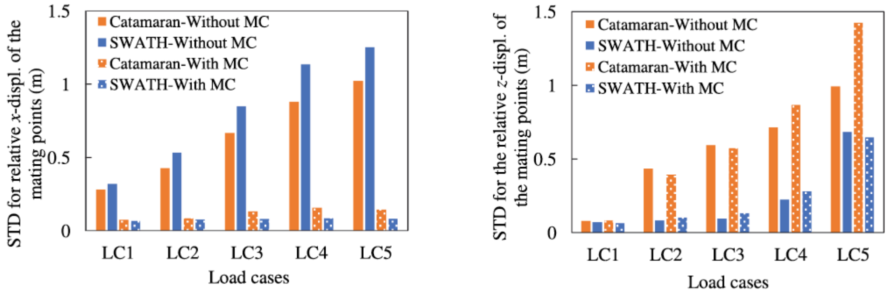
Considering a typical sea state with H_s = 2 m and T_p = 9 s, Liu et al. (2023b) studied the relative motion for the head sea condition. Figure 27 shows the resulting motion in terms of motion spectra for surge, heave and pitch responses both with and without a mechanical coupling between the installation vessel and the spar buoy.



(a) SWATH vessel concept (b) Catamaran vessel concept

Figure 27. Motion spectra for the vessel and the spar with and without mechanical coupling (MC), head sea condition, H_s = 2m, T_p = 9s, (from Liu et al. 2023b).

To improve the understanding of the differences of using the two different installation vessels as well as the importance of including a mechanical coupling between the installation vessel and the floating spar buoy, a series of loading conditions (LCs) were analysed in Liu et al. (2023b). The significant wave height was assumed to be constant in all cases (H_s = 2m) and the peak period was varied over five periods (T_p = 5s, 7s, 9s, 11s and 13s). The different loading conditions are numbered LC1-LC5. The standard deviations of the relative x- and z-displacement for the mating points are given in Figure 28 for both installation vessels and with/without the mechanical coupling.



(a) STD for the relative *x*-displacement (b) STD for the relative *z*-displacement

Figure 28. Standard deviation for relative response of the two mating points for both vessels (Liu et al 2023b).

CONCLUSIONS

A short summary of the most important findings from this study is given below.

- The proposed concept has shown to provide acceptable relative motions between the lifted OWT and the floating spar buoy, at least for wave headings mainly from bow and stern directions.
- The response pattern is dominated by the pitch motion of the installation vessel and the spar buoy.
- Because of the dominating pitch motion for the installation vessel, the position of the mating point will influence the relative vertical motion. Moving the mating point to the midship, reduces the relative vertical motion significantly.
- By introducing a mechanical coupling between the installation vessel and the spar buoy, the relative motion can be further reduced.
- By moving the mating point to the mid ship and introducing the mechanical coupling, the relative motion was reduced by 70-90% compared to the stern installation case.
- The flexibility of the lifting structure must be accounted for to provide precise dynamic response.
- The dynamics of the complex pay load can be controlled by a properly designed control algorithm.
- An alternative installation vessel less vulnerable to the wave excitation will improve the operability of the vessel.

The present base case for installation of floating wind turbines is to tow the fully assembled wind turbines from the assembly site in the Norwegian fjords to the final offshore site. The proposed concept has shown to be a promising alternative to the present base case.

DATA ACCESS STATEMENT

Data will be made available on request.

CONTRIBUTION STATEMENT

Karl H Halse: Project administration; supervision; conceptualization; writing – original draft.
Sunghun Hong: Conceptualization; formal analysis; writing – review and editing.
Befahr Ataei: Conceptualization; formal analysis; writing – review and editing.
Ting Liu: Conceptualization; formal analysis; writing – review and editing.
Shuai Yuan: Conceptualization; formal analysis; writing – review and editing.
Hans P Hildre: Supervision; conceptualization; writing- review and editing

ACKNOWLEDGEMENTS

This work was supported by the Research Council of Norway (RCN) through the Centre for Research-based Innovation on Marine Operations (SFI MOVE, RCN-project 237929). The paper summarizes the work of a project group of MSc students, PhDs, PostDocs, project associates and Professors in the SFI MOVE project (2015-2023). Key contributors to the publications used to prepare this summary included also: Zhiyu Jiang, Zhengru Ren, Jiafeng Xu, Lars Ivar Hatledal, David Vågnes, and Houxiang Zhang.

REFERENCES

Ataei, B., Yuan, S., Ren, Z., & Halse, K.H., (2023). Effects of structural flexibility on the dynamic responses of low-height lifting mechanism for offshore wind turbine installation, *Marine Structures, 89, 103399.* https://doi.org/10.1016/j.marstruc.2023.103399.

Ataei, B., Ren, Z., & Halse, K.H., (2024). Design of quick-connection device for installing pre-assembled Offshore Wind Turbines. In preparation.

Bereznitski, A., (2011). Wind turbine installation vessel of a new generation. In *Proceedings of the ASME 2011 30th International Conference on Ocean, Offshore and Arctic Engineering Volume 5: Ocean Space Utilization; Ocean Renewable Energy.* June 19-24, 2011. OMAE2011-49138. https://doi.org/10.1115/OMAE2011-49138.

DNV (2024a). Conceptual modelling of offshore and maritime structures – GeniE. https://www.dnv.com/services/conceptual-modelling-of-offshore-and-maritime-structures-genie-89128. (Accessed: 2024-02-08).

DNV (2024b). Hydrodynamic analysis and stability analysis software – HydroD. https://www.dnv.com/services/hydrodynamic-analysis-and-stability-analysissoftware-hydrod-14492. (Accessed:2024-02-08).

Gao, L., Liu, T., Halse, K.H., & Jiang, Z., (2023). Numerical analysis of the offshore wind turbine pre-mating process using a low-height lifting system for a nonconventional installation vessel. *Ocean Engineering, 286, 115555.* https://doi.org/10.1016/j.oceaneng.2023.115555.

Hatledal, L.I., Zhang, H., Halse, K.H. and Hildre, H.P., (2017). Numerical simulation of novel gripper mechanism between catamaran and turbine foundation for offshore win d turbine installation. In *Proceedings of the ASME 2017 36th International Conference on Ocean, Offshore and Arctic Engineering Volume 9: Offshore Geotechnics; Torgeir Moan Honoring Symposium.* June 25-30, 2017. OMAE2017-62342, V009T12A030, ASME. https://doi.org/10.1115/OMAE2017-62342.

Hong, S., Vågnes, D., Halse, K.H., & Nord, T.S., (2021). Mechanical coupling effect on the horizontal response of floating offshore wind turbine installation using a catamaran with a low height lifting system. In *Proceedings of the 31st International Ocean and Polar Engineering Conference*, June 20-25, 2021, ISOPE-I-21-1229.

Hong, S., Yuan, S., Zhang, H., & Halse, K.H., (2023a). Comparative study for numerical modelling and analysis of floating offshore wind onsite installation, In *Proceedings of the ASME 2023 42nd International Conference on Ocean, Offshore and Arctic Engineering. Volume 8: Ocean Renewable Energy*. June 11–16, 2023. OMAE2023-101206, V008T09A026, ASME. https://doi.org/10.1115/OMAE2023-101206.

Hong, S., Zhang, H., Nord, T.S., & Halse, K.H., (2022). Effect of fender system on the dynamic response of onsite installation of floating offshore wind turbines, *Ocean Engineering, 259, 111830.* https://doi.org/10.1016/j.oceaneng.2022.111830.

Hong, S., Zhang, H., & Halse, K.H., (2023b). Hydrodynamic and environmental modelling influence on numerical analysis of an innovative installation for floating wind, *Ocean Engineering, 280, 114681.* https://doi.org/10.1016/j.oceaneng.2023.114681.

Hong, S., Zhang, H., & Halse, K.H., (2024). Optimizing onsite installation methods for floating offshore wind: Effect of lifting arrangement strategies and mechanical damping on relative motion reduction, Submitted to *The 34th International Ocean and Polar Engineering Conference*. June 16–21, 2024. Rhodes, Greece.

Huisman, (2009). Press Release, https://www.huismanequipment.com/en/media_centre/press_releases/163-14_Huisman-launches-customised-range-of-Wind-Turbine-Installation-Cranes. (Accessed 2024-02-18).

Jiang, Z., Li, L., Gao, Z., Halse, K.H. and Sandvik, P.C., (2018). Dynamic response analysis of a catamaran installation vessel during the positioning of a wind turbine assembly onto a spar foundation. *Marine Structures, 61, pp.1-24*. https://doi.org/10.1016/j.marstruc.2018.04.010.

Krishnakanth, R., (2014). *Concept design of an installation vessel to install fully assembled next generation offshore wind energy turbines*. [Master's Thesis, Delft University of Technology]. http://resolver.tudelft.nl/uuid:2024b8f8-56a3-4bd5-a62f-8e1227d7eff4.

Larsen, T. J., & Hansen, A. M. (2007). *How 2 HAWC2, the user's manual*. Risø National Laboratory. Denmark. Forskningscenter Risoe. Risoe-R No. 1597

Lee, S.-K., Chen, Z., Pan, Q., Lu, H., & Xu, L. (2020). Hydrodynamic design of SWATH for offshore wind turbine transportation and installation. In *Proceedings of the 30th International Ocean and Polar Engineering Conference*, October 11-16, 2020, ISOPE-I-20-1191.

Liu, T., Halse, K.H., Leira, B.J., Jiang, Z., Chai, W., Brathaug, H.P. and Hildre, H.P., (2023a). Dynamic response of a SWATH vessel for installing pre-assembled floating wind turbines. *Marine Structures, 88, 103341.* https://doi.org/10.1016/j.marstruc.2022.103341.

Liu, T., Halse, K.H., Leira, B.J. and Jiang, Z., (2023b). Comparative study of the mating process for a spar-type floating wind turbine using two alternative installation vessels. *Applied Ocean Research, 132, 103452.* https://doi.org/10.1016/j.apor.2022.103452.

MARINTEK. (2016). SIMO - theory manual version 4.8.4.

NTNU, SFI MOVE – Marine Operations (2024). https://www.ntnu.edu/move (Accessed: 2024-02-13).

Offshoretronic, (2020). New Concept https://offshoretronic.tech/new-concept. (Accessed: 2024-01-21).

Orcina (2024). *OrcaFlex – World-leading software that goes beyond expectation*. https://www.orcina.com/orcaflex/. (Accessed: 20204-02-08).

Ren, Z., Skjetne, R., Verma, A.S., Jiang, Z., Gao, Z., & Halse, K.H., (2021a). Active heave compensation of floating wind turbine installation using a catamaran construction vessel. *Marine Structures, 75, 102868.* https://doi.org/10.1016/j.marstruc.2020.102868

Ren, Z., Verma, A.S., Ataei, B., Halse, K.H., & Hildre, H.P., (2021b). Model-free anti-swing control of complex-shaped payload with offshore floating cranes and a large number of lift wires. *Ocean engineering, 228, 108868.* https://doi.org/10.1016/j.oceaneng.2021.108868.

Skipsrevyen, (2011). Ulstein vokser i Nederland (in Norwegian), https://www.skipsrevyen.no/artikkelarkiv-idea-heavy-equipment-ulstein-idea-equipment-solutions-bv/ulstein-vokser-i-nederland/696009 (Accessed: 2024-01-21)

SINTEF Ocean, (2021). SIMO 4.20.3 Theory manual.

Ulstein, (2015). Winner of Statoil Challenge. https://ulstein.com/news/winner-of-statoil-challenge (Accessed: 2024-01-21)

Vågnes, D., Monteiro, T. G., Halse, K. H., & Hildre, H. P. (2020). Low-Height Lifting System for Offshore Wind Turbine Installation: Modelling and Hydrodynamic Response Analysis Using the Commercial Simulation Tool SIMA. In *Proceedings of the ASME 2020 39th International Conference on Ocean, Offshore and Arctic Engineering. Volume 9: Ocean Renewable Energy*. August 3–7, 2020. OMAE2020-19183, V001T01A030, ASME. https://doi.org/10.1115/OMAE2020-19183.

Xu, J., Ataei, B., Halse, K.H., Hildre, H.P. and Mikalsen, E.T., (2020). Virtual prototyping of a low-height lifting system for offshore wind turbine installation. In *Proceedings of the ASME 2020 39th International Conference on Ocean, Offshore and Arctic Engineering. Volume 9: Ocean Renewable Energy*. August 3–7, 2020. OMAE2020-19166, V009T09A074, ASME. https://doi.org/10.1115/OMAE2020-19166.

Yuan, S., Ataei, B., Halse, K.H., Zhang, H., & Hildre, H.P., (2022). FMI-based co-simulation of low-height lifting system for offshore wind turbine installation, In *Proceedings of the ASME 2022 41st International Conference on Ocean, Offshore and Arctic Engineering. Volume 8: Ocean Renewable Energy*. June 5–10, 2022. OMAE2022-79844, V008T09A045, ASME. https://doi.org/10.1115/OMAE2022-79844.