Master's thesis

NTNU
Norwegian University of Science and Technology
Faculty of Engineering
Department of Ocean Operations and Civil Engineering

Ramees Kalathingal Thody

Dynamic Response Analysis of Catamaran Installation Vessel During the Mating Process of a Wind Turbine onto a Floating Spar Buoy

Master's thesis in Ship Design
Supervisor: Karl H.Halse
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MASTER THESIS 2019

FOR

RAMEES KALATHINGAL THODY

Dynamic Response Analysis of Catamaran Installation Vessel During the Mating Process of a Wind Turbine onto a Floating Spar Buoy

Background

An innovative installation method using a catamaran vessel was proposed by NTNU at SFI MOVE research centre and the purpose of this technique is to reduce the installation cost by cutting down the operation time taken for the installation. According to this, four wind turbines including blades, rotor, nacelle and tower are preassembled at shore and are carried on a catamaran vessel to the site and then installed to the floating structure (typically floating monopile/spar buoy) using a low lift mechanism.

Objectives

The objective of this work is to quantify the performance of the proposed installation technique and if possible, provide suggestions to improve the performance, on the grounds of relative motions at the mating point and the forces arising in the coupling elements while the mating process is underway. To help with the project scope, numerical modelling techniques are implemented to capture the dynamic behaviour of the spar-vessel system.

Research Questions

- How to develop a simulation environment of which can capture the complex response behaviour of the catamaran-offshore wind tower-spar buoy system in terms of relative motions and coupling forces between the bodies.
- How to reduce the relative motions between the bodies while the mating process of offshore wind turbine and spar buoy is underway.

Work tasks

- Develop a numerical simulation model of the proposed installation concept in SIMO and incorporate possible modifications to improve the performance of the concept.
- Analyse how the modelled system responds to different environmental variables, in terms of relative motions between the bodies and the forces acting on the coupling elements between them during installation.
- Estimate the limiting sea states for the installation process based on the critical parameters.

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Karl H. Halse

Supervisor

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Preface

This thesis was prepared towards the completion of my Master of Science degree in Ship Design in the Department of Ocean Operations and Civil Engineering (IHB) at the Norwegian University of Science and Technology (NTNU). The project was supervised by Associate Professor Karl Henning Halse and was submitted during the spring semester of 2019.

As part of the SFI MOVE project, NTNU has presented the concept of catamaran installation vessel to install the offshore wind turbines on to the floating foundations out at sea. This project intends to explore the dynamic responses of the proposed catamaran installation vessel and provide suggestions to improve the performance of the whole installation process, on the grounds of relative motions at the mating point and the forces arising in the coupling elements while the mating process is underway.

Ålesund, June 2019

Ramees Kalathingal Thody

Acknowledgement

These two years of my mater studies have been a wonderful personal journey for me and this thesis act as the closure of my master’s degree education. Therefore, here I would like to mention some of the personalities whose efforts needs to be acknowledged.

Firstly, I would like to thank my supervisor Karl Henning Halse for all of his support and guidance throughout the semester. He has been extremely patient with me and always tried to motivate me to think outside the box and instil new ideas.

I would also like to thank Thiago Gabriel Monteiro for spending his valuable time during the weekly discussions and also for his contributions to develop the heave compensation module in SIMO which played a crucial role in my thesis.

I would also like to show my sincere gratitude to all those who worked in this project before me and I am sure that without all their efforts, I would not be able to complete this project within this limited time.

Finally, I would like to thank my parents and my sister, for their unconditional love and support throughout my life.

Summary

Present day energy production and consumption techniques are deeply rooted in methods which are unsustainable and therefore cannot be relied upon. Hence, there is an urgent call for an alternative clean and renewable energy source and as if now, offshore wind energy has proved as an ideal candidate for this scenario. An innovative installation method using a catamaran vessel was proposed by NTNU at SFI MOVE research centre and the purpose of this technique is to reduce the installation cost by cutting down the operation time taken for the installation.

This project intends to explore the possibilities to quantify the performance of the proposed catamaran installation vessel and if possible, provide suggestions to improve the performance of the whole installation process, on the grounds of relative motions at the mating point and the forces arising in the coupling elements while the mating process is underway. To help with the project scope, numerical modelling techniques are implemented to capture the dynamic behaviour of the spar-vessel system.

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Chapter 1

Introduction

Ever since the industrial revolution, humans are relying almost entirely on fossil fuels to satisfy our endless energy demands. Recently there is a great focus on renewable energy sources mostly by acknowledging the fact that the conventional fossil fuel sources are shrinking which results to an unstable market. Studies clearly stated that it is not possible to continue depending on traditional fuel sources due to the exponential growth rate of energy demand (1). Furthermore, there is a constant strain on the energy sector to adopt more eco-friendly methods due to the increased environmental awareness of modern society. Consequently, humans are compelled to search further for alternative options which are renewable and sustainable.

Currently, we have many promising alternatives to look forward to and among them, it is believed that there is a huge potential in harvesting energy from wind. In recent years, the world has experienced a shift of focus towards wind energy and as a result, the global wind power capacity has increased by almost 10% in 2017 compared to the previous one (including both onshore and offshore wind farms) (2). It was no big surprise when more and more offshore wind farms started to develop as offshore wind is steadier and stronger than on land. Even though construction and maintenance activities are much more expensive compared to onshore projects, costs have been declining steadily and now is much less than what was it was expected to be (2). It is motivating to notice that since 2017, the prices have been in competitive terms with conventional energy sources in Europe despite the significant reduction in crude oil prices (4).

The early developments in the offshore wind industry were mainly concentrated on installing wind turbines on inshore regions where the shallow waters are available. It allowed continuing with fixed foundation turbines which are more familiar and requires technologically less demanding operations compared to installations in deep waters. Most of the wind turbines with fixed foundations are built in depths ranging from 30 to 60 meters and beyond this point it not advisable to employ these methods.

As a consequence of the water depth limitation imposed on the design of the wind turbine systems, most of the potential offshore wind fields remained unutilized until recently. It is at this point, the industry appeared to be noticing the significance of floating turbines as an alternative for the traditional onshore options. Floating wind turbines are wind turbines installed on a floating platform which are held in place using mooring lines and anchors to the seabed. They are installed in deeper seas where conventional fixed foundations are no longer feasible. Subsequently, with floating wind turbines, the full potential of the currently unexplored offshore sea can be exploited. However, installing a floating offshore wind turbine in a dynamic sea environment brings new challenges with it and is still a matter of research. In this project, efforts are made to measure the efficiency and performance of an innovative installation concept by virtually prototyping the installation operation. The modelling and multi body interactions taking place during the installation process is dealt by SIMO software.

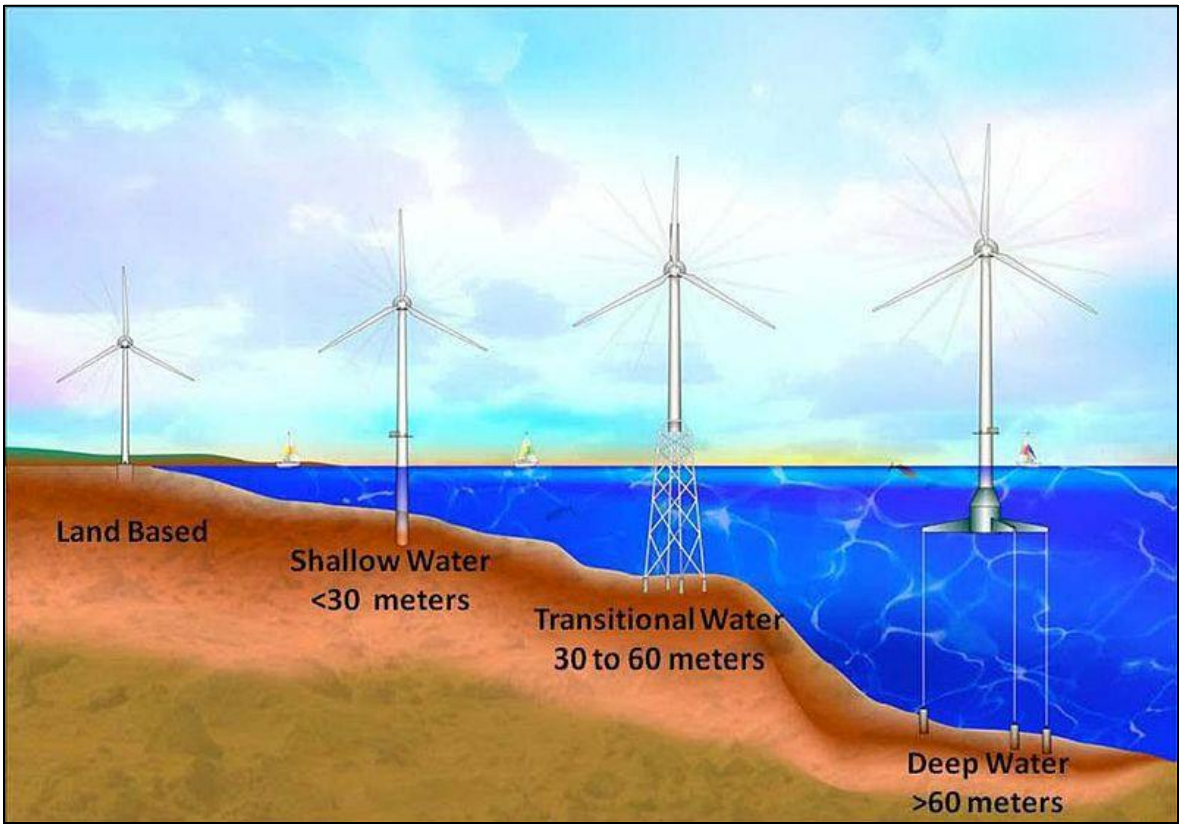


Figure 1:1 Transition of the wind turbine system from land-based systems to offshore (5)

1.1 Problem Definition

On having a closer look into the proportion of wind turbines installed at sea, it is quite evident that wind turbines with fixed foundations hold a major share of the aggregate. In fact, it was only in the year 2017, the industry has finally succeeded in installing a commercial floating offshore wind farm (Hywind Scotland). According to the estimates of European Wind Association, offshore wind turbines in deeper water has the potential to meet Europe's energy needs by four times (6) and therefore it is rational to expect exponential growth in a number of floating offshore wind farms in coming years. However, these advantages of floating wind turbines come with a cost of the highly complex installation process which involves multi-body interactions and that has to be performed in a dynamic sea environment. Research has been undergoing for a long time to overcome this difficulty and to implement a safe and cost-effective installation process for floating wind turbines. An innovative installation method using a catamaran vessel was proposed by NTNU at SFI MOVE research centre and the purpose of this technique is to reduce the installation cost by cutting down the operation time taken for the installation. To achieve this, whole wind turbine including blades, rotor, nacelle, and tower are preassembled and is carried on the catamaran vessel to the site and then installed on to the floating structure (typically floating monopile/spar buoy) using sliding grippers and lifting mechanism.

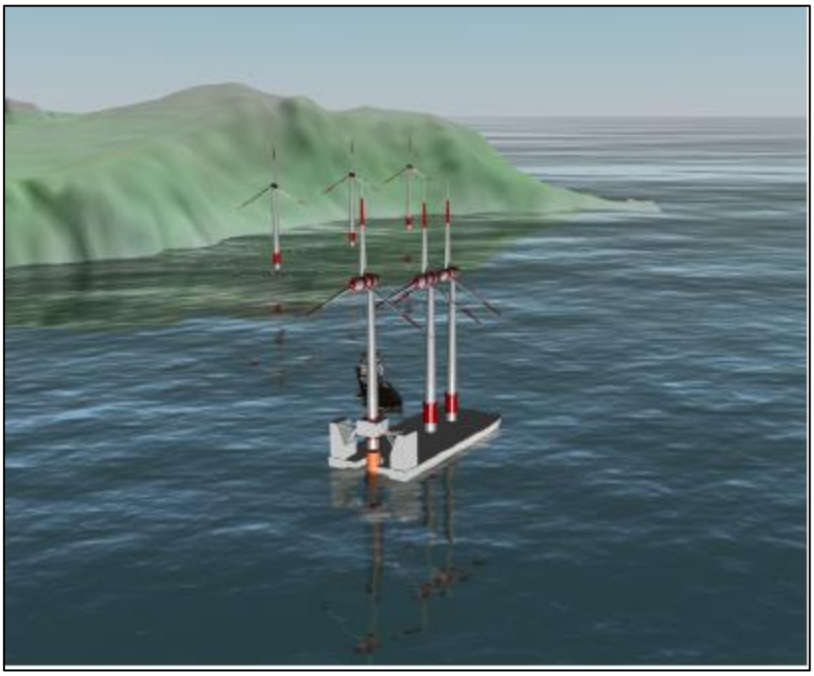


Figure 1:2 Wind turbine installation using a catamaran concept (3D visualization) (7)

This project intends to explore the possibilities to quantify the performance of the proposed catamaran installation vessel and if possible, provide suggestions to improve the performance of the whole installation process, on the grounds of relative motions at the mating point and the forces arising in the coupling elements while the mating process is underway. To help with the project scope, numerical modelling techniques are implemented to capture the dynamic behaviour of the spar-vessel system.

1.2 Motivation

The motivation for the commitment to investigate the chosen project has its roots mainly on two realms, first one is the acknowledgment of the unsustainable and environmentally hazardous choices of energy production and consumption in modern times and later one will be a strong drive to minimize the installation cost of offshore wind turbines by means of cutting down the weather downtime.

We are currently living in a world which is on the brink of mass extinction and will be the first one in history in which the culprit is conscious of his own actions and is totally aware of its consequences. We, humans, have demonstrated remarkable success in pushing most of the planet's diverse species into oblivion and is continuing without any regret. Our ever-growing dependence of fossil fuels to satisfy the energy demands since the industrial revolution has finally reached a point where we cannot repeat the things in the same way as before. It has reached a pivotal moment where the decisions taken has long-lasting non-return impacts. Therefore, it is a crucial time to rethink our energy policies and make a radical shift towards utilizing clean and sustainable renewable sources. Introducing novel techniques to solve the challenges faced by the renewable energy industry (such as offshore wind sector) can accelerate this shift of focus and this project has the potential to significantly contribute towards this cause.

The major obstruction along the road to accomplish a cost competitive installation method for the floating offshore wind turbines is the absence of a strategy to deal with the weather downtime during the installation procedure. Weather downtime is considered costly because once the environmental conditions exceed the operational limits, the operation ceases, and the vessel is in standby mode without any potential gain towards the project completion. In addition to that, the cost associated with the vessel, labour and with the time (in terms of reduction in operability time) can be detrimental from the economic perspective. Consequently, any approaches to reduce weather downtime are appreciated by the industry. This project, with its novel installation technique of offshore wind turbines, intends to reduce the possibility for weather downtime by eliminating the weather-sensitive heavy high lifts and thereby offers a promise of economically feasible installation operation of OWTs.

1.3 Scope of Work

Present day energy production and consumption techniques are deeply rooted in methods which are unsustainable and therefore cannot be relied upon. Hence, there is an urgent call for an alternative clean and renewable energy source and as if now, wind energy has proved as an ideal candidate for this scenario. However, the wind energy sector does not promise a hundred-percentage false proof technology and has its own loopholes that need to be tackled. The major obstacle associated with the offshore wind turbines is the longer installation periods (and thereby installation cost) which is in direct relationship with the increased weather downtime. With the innovative installation approach proposed by the NTNU at SFI MOVE research centre, it is expected to cut down the installation time and launch the offshore wind technology to a feasible cost-effective position.

The scope of this project spans around modelling and exploring the dynamic response of the proposed catamaran-spar-tower system while the mating process is undergoing under various sea conditions defined by significant wave height (H_s) and peak time periods(T_p) and identifying the critical parameters in the operation. However, it is to be noted that the scope of this project is limited to the study of events happening after initiating the mating process and before transferring the tower weight on to the top of spar buoy. To ensure safe and successful transfer of offshore wind tower to the top of Spar buoy from installation vessel, it is important to take account of the relative motions and forces in the coupling elements connecting installation vessel, spar, and tower. Modifications to the previously proposed concept model are expected to be derived from this project. Numerical modelling techniques will be adopted, and a time domain analysis using SIMO software will be performed to execute the listed tasks.

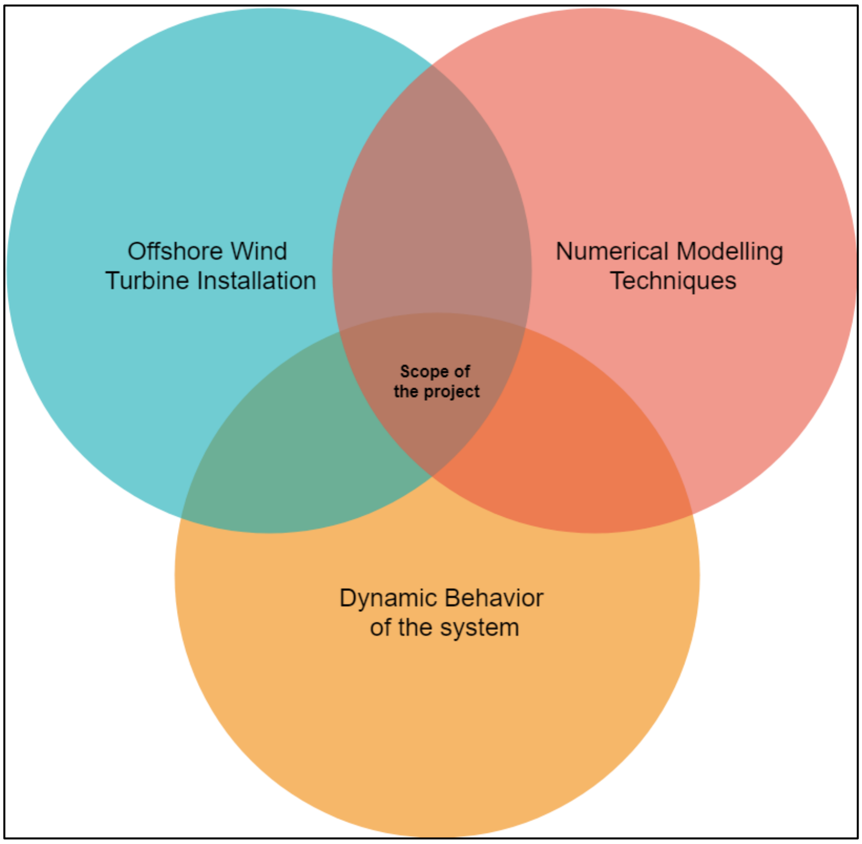


Figure 1:3 Scope of the project

1.4 Objectives

The objectives of the project are given as follows:

- Develop a numerical simulation model of the proposed installation concept in SIMO and incorporate possible modifications to improve the performance of the concept in terms of relative motions and forces in the coupling elements.
- Analyse how the modelled system responds to different environmental variables, in terms of relative motions between the bodies and the forces acting on the coupling elements during the mating process*.
- Estimate the limiting sea states for the mating process* based on the limiting parameters.

***** The process mentioned here refers to the events happening after initiating the mating process and before transferring the tower weight on to the top of spar buoy

1.5 Research Questions

The definition of objectives leads to the following research question:

- How to develop a simulation environment which can capture the complex response behaviour of the catamaran-offshore wind tower-spar buoy system in terms of relative motions and coupling forces between the bodies.
- How to reduce the relative motions between the bodies while the mating process of offshore wind turbine and spar buoy is underway.
- How the coupled system behaves under varying environmental conditions?

Chapter 2

State of Art

2.1 Current Installation Practises/Concepts of Floating Offshore Wind Turbines

As the industry became aware of the unexploited potential of the offshore wind energy in deeper waters, a wide variety of platform models were developed and tested by the designers in the energy sector. Right from the start itself, it was clear that the familiar wind turbine systems with fixed foundations cannot be feasible in these deeper waters and subsequently, floating wind turbine systems were preferred. However, this choice didn't come without its own challenges and many of them were different from that of the well-known oil and gas industry. For example, in the traditional oil and gas industry, very few structures are installed but the size of the installed structures can be large. Conversely, in the offshore wind sector, a large number of small structures must be installed at the site and this has a tremendous impact on the installation procedure and the selection of the vessel for it.

In the shallow waters, jack up barges were always preferred as they provide enough stability of the vessel since the vessel is literally supported by the legs extended to the ground and therefore not affected by the action of waves.

Figure 2:1 Jack up barge installing the wind turbines in a wind farm (8)

As the industry started showing much more interest in deeper waters due to more steady wind availability and the lack of shallower depths in countries such as Japan due to narrow continental shelf, the deepwater installation became a necessity in these regions. Unfortunately, jack up barges are limited by the depth restriction and as a consequence, their operability is narrowed to the shallower seas. Hence, they are suitable for the nearshore installation of wind turbines which are almost completely based on the fixed/jacket foundation and not quite used for the floating platform installations.

Since floating OWT are a recent phenomenon, many methods and models of OWT are tried and some of the notable projects are listed below.

2.1.1 Hywind Scotland

Hywind Scotland is the first successful commercial offshore floating wind farm installed and operating in the world. The project was undertaken by Equinor and was planned to install a 30 MW wind turbine farm 25 km offshore Peterhead in Scotland. The wind farm is located in the sea where the water depth is more than 100 meters and hence only feasible option was floating OWT. With the advantage of years of experience from the Oil and Gas industry, Equinor came up with an appropriately modified design for the floating wind turbine by using its vast knowledge in offshore activities. Equinor used a spar buoy as the floating platform for the OWT which was tested prior to the installation.

Figure 2:2 Spar buoy design proposed by Equinor (9)

The spar buoy showed satisfactory performance in the sea environment and was less prone to the pitching motions as the buoy was constructed in a way that weight distribution increased from the top to bottom and thereby moving the centre of gravity of the structure towards the bottom. This provided enough arm to resist the pitch motion waves and as a result, fewer motions are experienced.

For the installation, Equinor brought all the components into a single place where enough draft was available and decided to construct the whole assembly in a sheltered space where it is protected from the external effects of the waves and wind. The mating operation of OWT on the floating spar buoy was done by the world’s second largest crane vessel (Saipem 7000) (10). The mounting operation was highly sensitive in nature and eventually was performed in confined space. The full assembly was later transported to the site with the help of towing vessels and anchored to the site. With the described approach, Equinor has found a successful strategy to deal with the dynamic motions occurring while installing in the offshore field.

Figure 2:3 Operation phases of installation of floating turbines (done in confined waters) (9)

2.1.2 Atkins Reusable Transportation Frame

As a part of the Hywind challenge, Atkin introduced a simple and elegant design to transport the wind turbines from the port to offshore site. The method was to use a reusable transportation frame (**Figure 2:4**) where four fully assembled OWT are attached.

As similar to the Hywind project, Atkin also prefers to assemble the entire structure from the port and later tow into the wind farm site. One of the difficulties with this particular installation procedure is that it imposes a draft restriction to the assembled OWT. As a result, only a couple of ports which has deeper inshore locations are capable of conducting this installation method. It also indirectly forced the designer to reduce the weight/size of the OWT to meet the draft restrictions. To overcome this particular challenge, Atkin comes up with the transportation frame where the OWT can be towed at the reduced draft. It allowed to avoid complex weather sensitive offshore lifts and the OWT can be mounted on top of spar buoys near the quayside. It increased the transportation efficiency as it allowed the towing operation of multiple fully assembled OWT to the site at the same time. Atkin also claims superior motion characteristics and a reduction in weather restrictions compared to individual tow of wind turbine (12).

Figure 2:4 Atkins reusable transportation frame (12)

2.1.3 MODEC's D-Spar and Float-on/Float-off Installation Method (13)

In contrast to the Hywind and Atkin's installation methods, MODEC prefers to perform the mating of fully assembled OWT with spar buoy at the sea. The spar buoy is preinstalled in the sea and the assembled OWT is brought to the site and is mounted on the spar buoy with the help of twin forks in the transportation vessel. While installing, the spar buoy is pulled up and connected to the wind turbine.

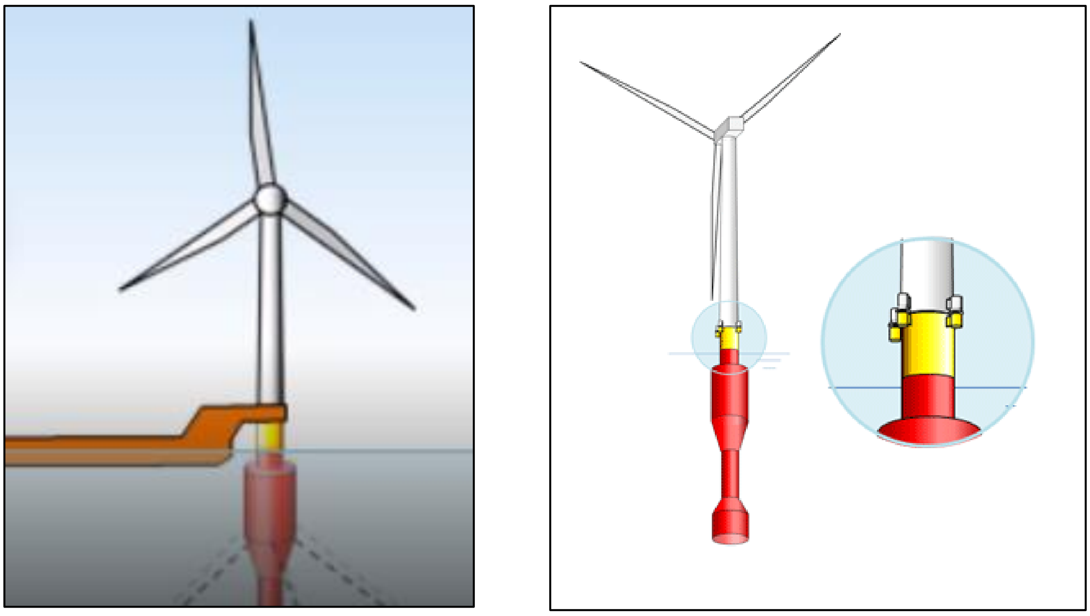


Figure 2:5 MODEC's Float-on/Float-off Installation Method (13)

2.1.4 Installation of Assembly Using Inversed Pendulum Principle

An ingenious wind turbine installation method based on the inverted pendulum principle was proposed by Guachamin-Acero et al on 2017. It consists of pre-assembled rotor-nacelle-tower structure transported to site in a barge equipped with an upending frame and a medium size heavy lift crane. Once the operation starts, the barge is connected to the pre-installed floating structure and is slowly upended using the crane vessel until the rotor-nacelle-tower rests on the top of the floating structure. In this method, there is no restriction set by the requirement for the sensitive high capacity crane vessels. However, special attention should be given to achieve coordination between the forward movement of the crane vessel and the lifting operation.

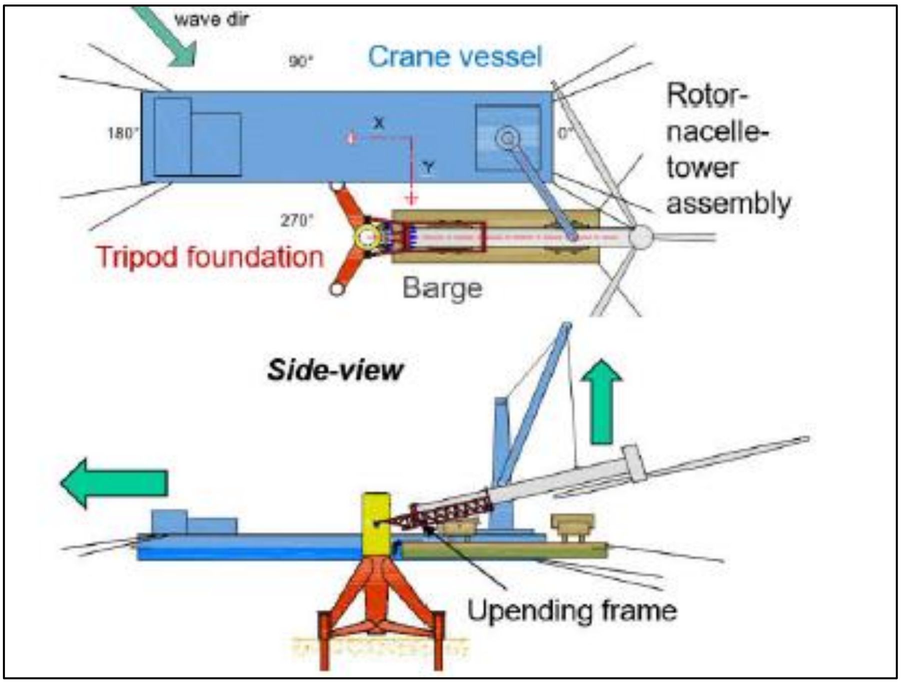


Figure 2:6 Proposed installation technique based on inverse pendulum principle (14)

2.2 Catamaran Installation Vessel Concept Proposed by NTNU

As it was mentioned earlier, Equinor has successfully executed the installation of floating offshore wind farms in Hywind Scotland and has proved that it is possible to harvest energy via floating offshore wind turbines installed at sea. However, it is important to note that unlike Norway, most of the yards in the world have a draft restriction for the operation and construction and thereby making it unsuitable for the mating operation that must be done inshore under confined waters. On further close examination of the Equinor's Hywind project, it is not easy to skip the fact that it took 4-5 days to tow the vessel from Stord (Norway) to Scotland and usually it involves more than one vessel for a single wind turbine. So, both the distance to the site and the availability of the yards with enough draft are limiting the possibility of adoption of Equinor's Hywind installation strategy around the world.

It calls for an alternative installation approach were the complex mating operation between spar buoy and pre-assembled rotors, nacelle, tower structure must be done at the offshore site in a safe and controlled method and at the same time trying to avoid the complexities of having a lifting operation where the tower is lifted by cranes and has a high lifting point .

As part of the SFI MOVE project, NTNU presented the catamaran installation vessel concept as a solution to this particular dilemma in which the mating operation can be done in the open sea. Preliminary feasibility studies have been performed and the possibility of using this approach as a viable installation procedure was discussed (7) (15) (18). However, it does present some of its own challenges and one of the major drawbacks was how to deal with the relative motions of spar buoy and vessel while the mating operation is underway. Also, an efficient strategy to reduce the sudden increase in the draft of the spar buoy upon transfer of the tower weight to its top has not yet developed and must be investigated.

The proposed installation procedure (15) is shown in the **Figure 2:7**. The installation process starts when the vessel is connected to the spar buoy using grippers and if the weather conditions are favourable, the sliding grippers grip the spar buoy. In stage 4, the OWT assembly is lifted up in the air and carried to the aft of the vessel along with the guides. In step 6, the relative motions of spar buoy and lifted OWT is examined with high accuracy and if the relative motions are within allowable limits, the mating operation is carried out and the bolts are fitted in step 7 and 8. Once mating is done, the catamaran is disconnected from the assembly in stage 9.

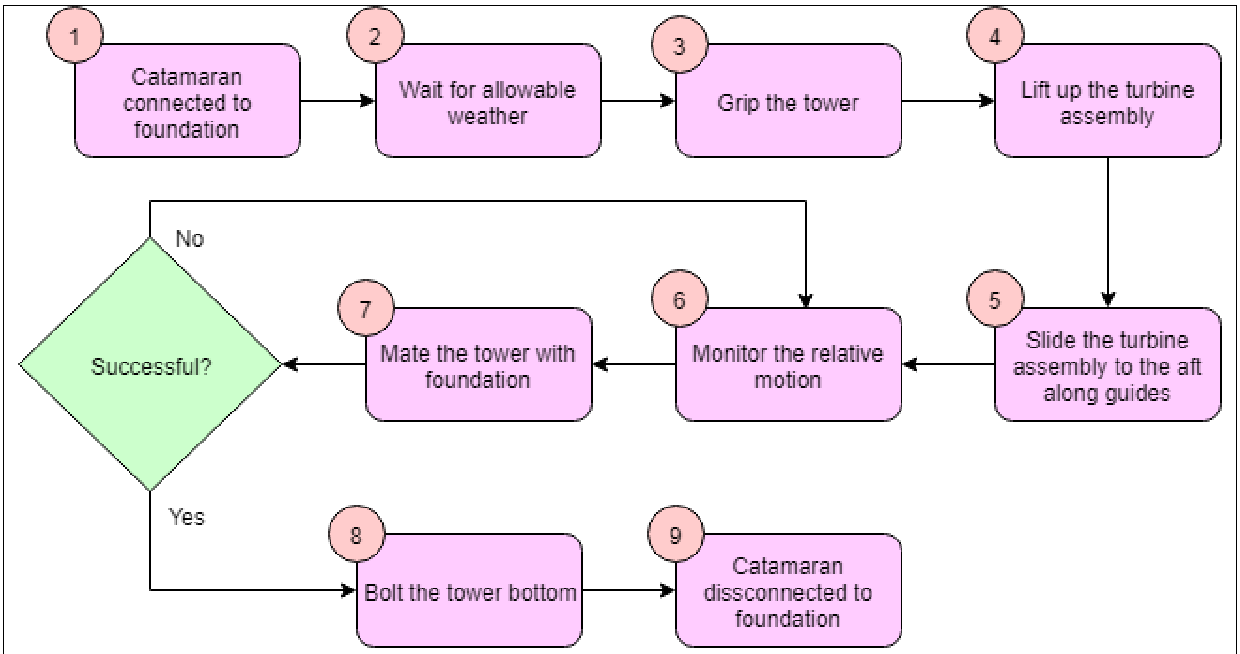


Figure 2:7 Proposed installation procedure using Catamaran installation vessel

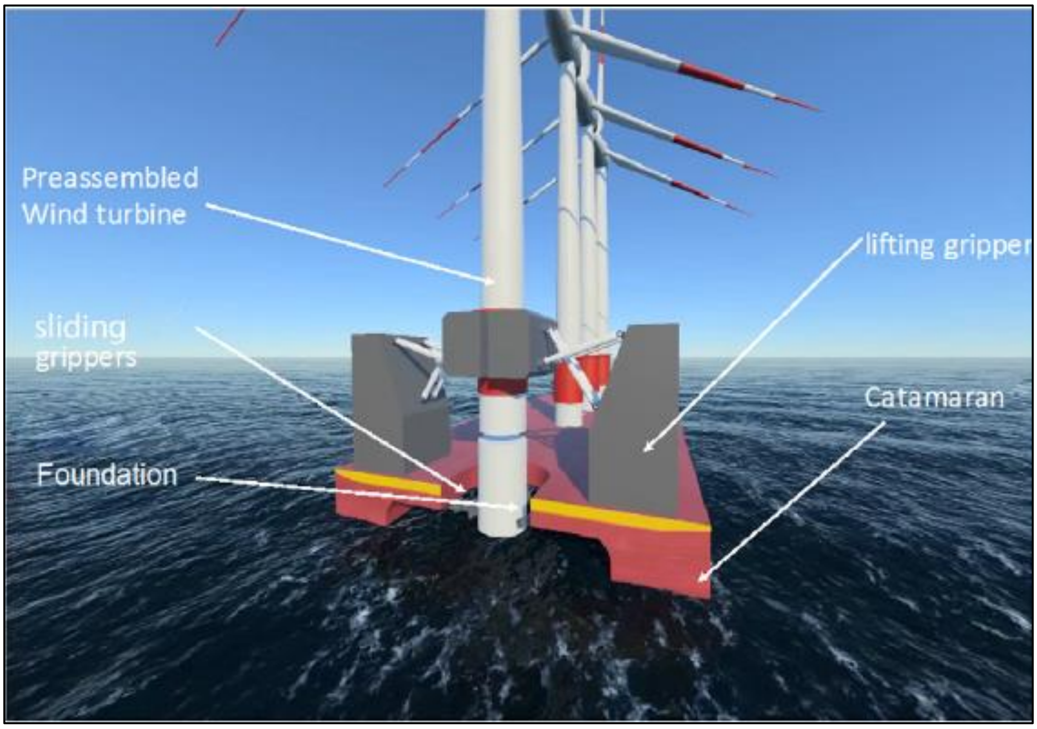


Figure 2:8 Wind turbine installation using a catamaran concept (Simulation environment) (7)

Various initial feasibility studies have been done on the proposed OWT installation vessel by NTNU with each of them focussing on different aspects of the installation method. However, the scope of this study is limited to the mating operation of OWT with floating spar buoy, efforts are invested within this domain.

This project will be focussing on some of the critical issues mentioned earlier and try to model the installation scenario in SIMO and estimate the limiting weather conditions considering the relative motions and forces between different bodies and coupling elements connecting them. It is also important to notice that in the previous studies (15), the installation vessel and OWT were connected with rigid connections and this influences the results of the simulation. Nevertheless, in this project, an attempt was done to model the connections between bodies with more flexible couplings which more or less to match with the actual installation scenario. More details on coupling elements are discussed in chapter SIMO Modelling.

2.3 SIMO as a Tool for Multi-body analysis

SIMO (Simulation of complex Marine Operations) is a software developed by the MARINTEK and it deals with the complex multi-body calculations such as flexible modelling of station-keeping forces and coupling mechanisms. It can perform a non-linear time domain simulation and include active and passive forces.

To analyse the response of a multibody system, we need to express the system as a mathematical expression and then solve for the variables. The equation of motion for the coupled catamaran – spar buoy – tower system can be written as:

$$\left(M + A(\infty)\right)\ddot{x} + D_1\dot{x} + D_2 f(\dot{x}) + Kx + \int_0^t h(t-\tau)\,\dot{x}(\tau)d\tau \;=\; q(t,x,\dot{x}) \qquad (jiang\_et\_al)$$

Table 2:1 Parameter Definitions

Item	Details
M	Mass matrix
x	Rigid body motion vector
A	Frequency-dependent added mass matrix
D_1	Linear damping matrix
D_2	Quadratic damping matrix
K	Coupled stiffness matrix
h	Coupled retardation function of Spar and Catamaran
q	Exciting/External forces

Once the equation of motions is defined, SIMO tries to solve this equation in each time step. **Figure 2:9** explains briefly how a time domain analysis of marine operation takes place in SIMO.

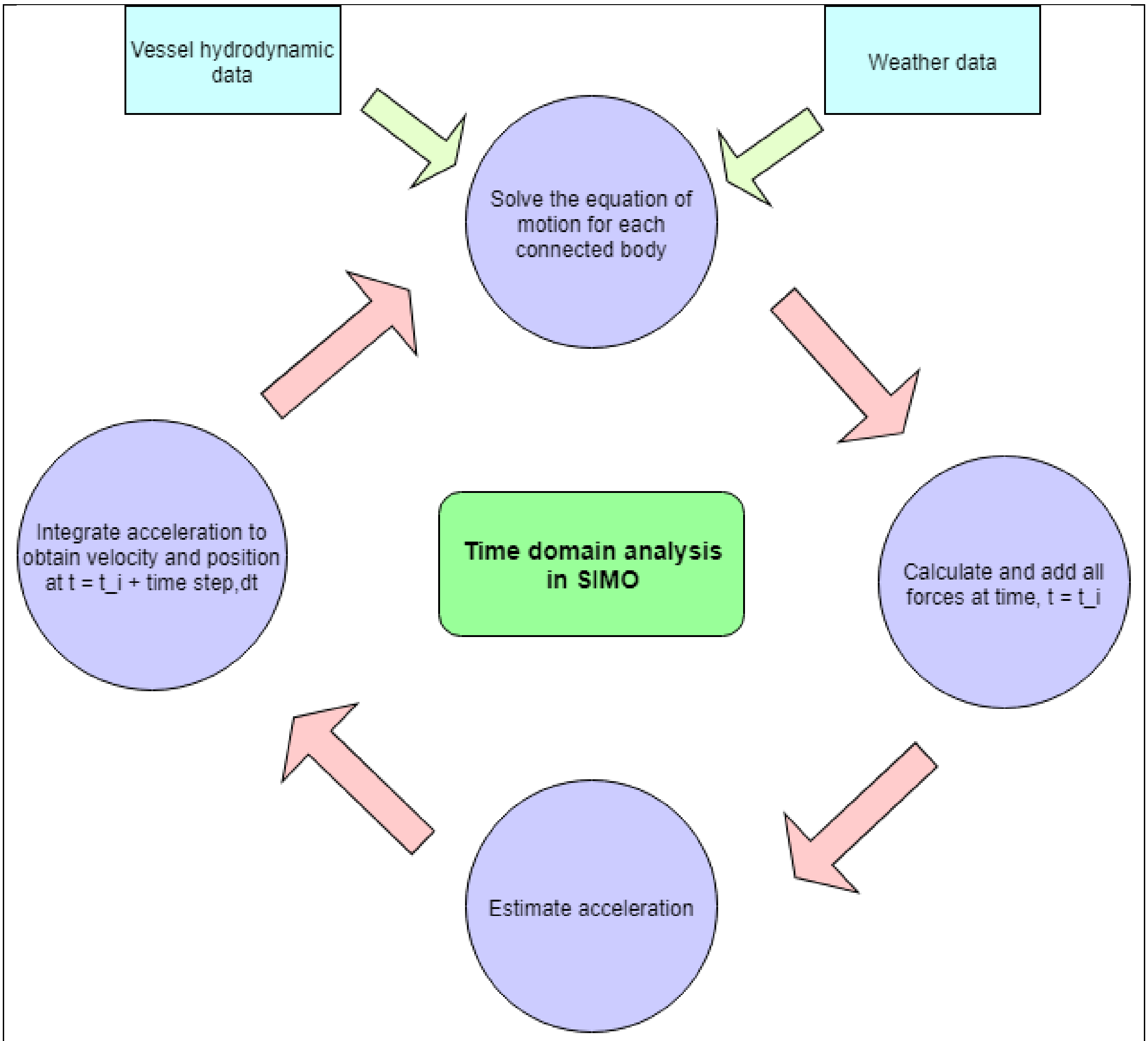


Figure 2:9 Time domain analysis of complex bodies in SIMO

2.4 Critical review

In section 2.1, various installation methods to install floating offshore wind turbines were introduced and each one has its own advantages and disadvantages. In **Table 2:2**, both strengths and weakness of some the discussed installation procedure are listed.

Table 2:2 Pros and cons of OWT installation methods

Method	**Advantages**	**Disadvantages**
OWT installation with Jack up barges	Familiar process, Well documented and tested approach, No serious issues regarding the vessel motions in waves	Restricted to shallower regions and thereby not applicable for most of the floating OWT installation sites
Mating operation of OWT and spar buoy is done at the harbour and towed out into the offshore field	The only successfully tested procedure, Complex mating operation is done in the sheltered region and hence small dynamic relative motions between spar buoy, vessel and OWT	Operation is limited to very few yards where deeper waters are available, Towing operation can be expensive and time-consuming
Mating operation of OWT and pre-installed spar buoy is done at the offshore site using the inverted pendulum method	No restriction on the yard water depth and does not need sheltered regions, No requirement for heavy crane vessels	Coordination between forward movement of the crane vessel and the lifting operation is challenging, Each barge can carry only one OWT and it increases the installation time.
Mating operation of OWT and pre-installed spar buoy is done at offshore site with catamaran installation vessel	No restriction on the yard water depth and does not need sheltered regions, No requirement for heavy crane vessels, Multiple OWT can be carried in a single vessel, Lesser weather downtime	Relative motions between spar buoy, vessel and lifted OWT can complex

2.5 Summary

Different OWT installation methods and challenges with each of them are discussed in the previous sections. With the proposed installation technique by NTNU, the mating operation can be undertaken at the offshore site so that many restrictions (e.g. draft limitation of shipyards) and time-consuming towing operations can be eliminated. However, the design must be improved to reduce the dynamic responses of the connected bodies in the water. Since the operation involves complex multi-body calculations, SIMO, a software well known for modelling of connected bodies, can be utilized for the study.

Chapter 3

Methodology

This section outlines the strategy planned for this project. This project is mainly divided into three segments. They are:

- Develop a concept model for the motion compensation system to reduce relative motions and forces in the coupling elements between the bodies and generate a numerical simulation model of the proposed installation concept by incorporating the suggested modifications.
- Analyse the dynamic responses of the modelled multi-body system under varying environmental parameters and estimate the improvement in the performance of the system in terms of relative motions and coupling forces.
- Determine the limiting sea states for the proposed concept to conduct the mating operation based on the critical parameters.

Through the systematic division of scope of the project, the whole project is expressed in a sequence of milestones that needs to be achieved and is expressed in the flowchart **Figure 3:1**.

A brief explanation of how to attain the milestones defined in **Figure 3:1** is given below.

1. **Import SIMO models of catamaran & spar buoy from previous studies**

   The hydrodynamic properties of the catamaran installation vessel and spar buoy were calculated using HydroD (17) in previous works and this data is imported into the SIMO software for further analysis.

2. **Include necessary modifications in the imported model**

   Mass and moment of inertia of the imported model are checked and modified if necessary. Despite placing all the wind towers at the deck, this project focus on the mating operation of the tower with spar buoy and hence one of the towers is lifted and moved to aft.

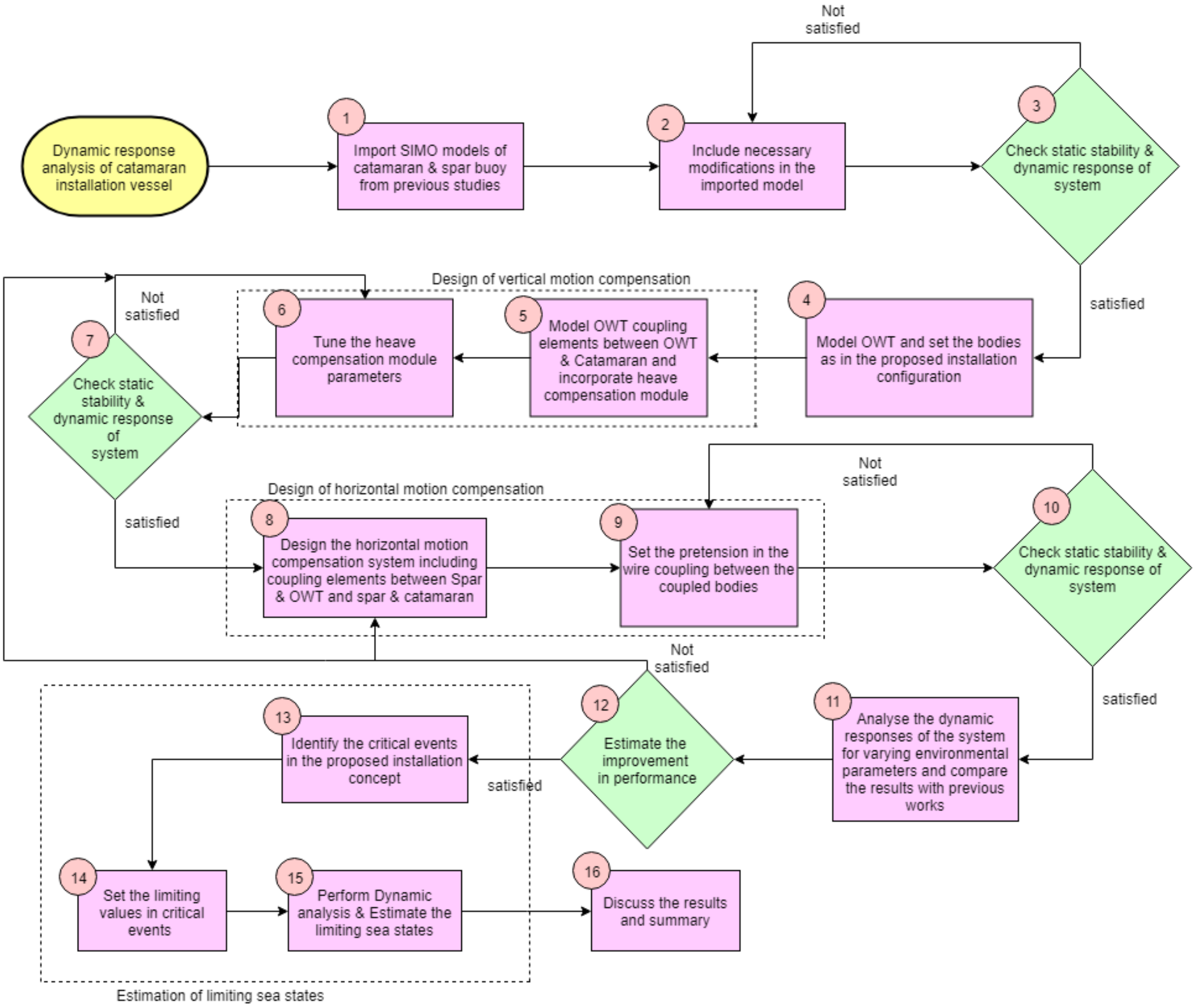


Figure 3:1 Planned strategy for the completion of the project

3. **Check static stability & dynamic response of the system**

   Static analysis is performed to check the equilibrium condition. A time domain analysis is also performed to evaluate the system responses.

4. **Model OWT and set the bodies as in the proposed installation configuration**

   The scope of this report is to look into the dynamic responses during the mating stage of floating OWT and therefore the configuration of the vessel and spar buoy during this time should be specified to the software. A graphical representation of the configuration can be seen in **Figure 2:8**.

5. **Model OWT coupling elements between OWT & Catamaran and incorporate heave compensation module**

Since this project deals with multi-body dynamics, appropriate coupling elements between different bodies must be modelled from the range of options available in SIMO, to keep the bodies intact. According to previous studies (15), (18), the dynamic responses of the coupled spar buoy, vessel, lifted OWT is too large and therefore a heave compensation system for reducing this motion was suggested. A heave compensation module developed as part of the SFI MOVE project will be incorporated into the SIMO model.

6. **Tune the heave compensation module parameters**

   The incorporated heave compensation module is based on the PID controller and the controlling parameters should be fine-tuned to get the desired output.

7. **Check static stability &dynamic response of the system**

   Static analysis is performed to check the equilibrium condition. A time domain analysis is also performed to evaluate the performance of the heave compensation module incorporated in the model.

8. **Design the horizontal motion compensation system including coupling elements between Spar & OWT and spar & catamaran**

   Once a reasonable degree of reduction in relative motion in the vertical direction between spar buoy and the lifted tower is achieved, efforts to design a horizontal compensation system has to be initiated. Even though the catamaran and spar are kept in place with the help of thrusters and mooring wires, relative motions at the mating point in the horizontal plane exist and it should be reduced. The suggested motion compensation system includes winches and wires connecting spar buoy, catamaran and lifted tower.

9. **Set the pretension in the wire coupling between the coupled bodies**

   The objective of the horizontal motion compensation system is to reduce the relative motions in the horizontal plane at the mating point. This can be achieved by modelling a very rigid connection between involved bodies. However, this leads to large forces in the coupling elements which is not preferred. So, the flexibility of the coupling is varied over a range of values to obtain satisfactory results. This is performed by changing the pretension in the wires connecting bodies.

10. **Check static stability & dynamic response of the system**

    Static analysis is performed to check the equilibrium condition. A time domain analysis is also performed to evaluate the performance of horizontal motion compensation module.

11. **Analyse the dynamic responses of the system for varying environmental parameters and compare the results with previous works**

    Since one of the objectives of this project was to suggest modifications to improve the performance of the proposed installation concept, the dynamic responses of the system are compared with that of previous works.

12. **Estimate the improvements in performance**

    The improvements in the concept are estimated and modifications to the suggested designs are done till satisfactory results are obtained.

13. **Identify the critical events in the proposed installation concept**

    To estimate the limiting sea states for the operation, critical events along the process has to be identified. Dynamic responses of the system such as relative motions (both vertical and horizontal) at the mating point, forces in the coupling elements are some of the potential candidates.

14. **Set the limiting values in critical events**

    This stage intends to define the range of allowable values for the system responses defined in stage 13. The limiting values for the selected system responses are decided by referring the previous works and considering the availability of machinery and other accessories required for the installation in the market.

15. **Perform dynamic analysis**

    Weather conditions at the installation site are selected according to section 7.2.3. The dynamic analysis of the modelled system is performed and the weather characteristics which gives system responses that are lower than the limiting values are selected.

16. **Discussion and Conclusion**

    A summary of the results of the project is prepared. Possible limitations of the project are discussed and potential topics for further research are identified.

Chapter 4

Details of the Operation

4.1 Installation Concept

A Catamaran installation vessel was proposed by NTNU at research centre SFI MOVE and according to the initial proposed design (*jiang_et_al*), four pre-assembled rotors, nacelle, tower structure can be transported to the site on the installation vessel. Once the vessel is in installation configuration, a pair of lifting grippers are used to transfer the assembly to the top of the spar buoy while the sliding grippers are holding the spar buoy in position so that the assembly is gradually transferred. The transfer is done by taking account of the relative motions between the vessel and spar buoy.

This chapter describes the suggested modifications that can be incorporated into the proposed installation concept mentioned above. Several design solutions were tried during the time span of this project and the dynamic response of the system obtained from simulation was compared with each other to decide the suitable configuration. Section 6.3 explains and verifies the rationale behind the choice of the recommended improvements by comparing the simulation results with that of the previous studies. In the previous studies, the OWT lifting mechanism were not included in the numerical model and hence did not considered the response of the multibody system with the mechanical coupling elements used for lifting of the OWT while installing. Consequently, in this project, a more detailed description of the preassembled OWT lifting and handling mechanism using hydraulic winches and roller supports are provided. More details regarding this are included in the following sections.

Also, it is vital to acknowledge the relative motions of the OWT and spar buoy during the installation phase as huge impacts forces are expected if they are left unnoticed. For this reason, a heave compensation system was incorporated into the model so that the lifting mechanism is controlled in such a way that there are no relative motions between the OWT bottom and top of spar buoy. In this way, it is possible to control the lowering process of OWT and thereby the large impact forces can be avoided.

Similarly, vertical alignment of both Spar and lifted OWT is important to successfully complete the mating process and in the previous models, it was achieved by restricting the Spar movement with the help of sliding grippers. Since this connection was too rigid, both vessel and Spar behaved as a single body and large motions and forces were observed.

Consequently, a more flexible concept model for motion compensation of the system is included where winches located in catamaran are used to lift the spar buoy through a small distance and in that way, forces the spar buoy to follow the motions of catamaran vessel during the installation process. In addition to that, both OWT and Spar buoy is connected by wire ropes where the tension in the ropes are controlled by tugger winches in the vessel. A docking cone is also proposed between the top of Spar buoy and OWT bottom to guide the lifted tower on to the top of the spar buoy and also to cushion the impact forces arising from the excessive motions in the horizontal plane while mating.

More details regarding the proposed motion compensation system are provided in section 4.2.

4.2 Installation/mating Operation Configuration

Since this project focuses on the mating operation of OWT with the floating platform (spar buoy), the simulation model is arranged in such a way that the spar buoy is placed aft of the catamaran as shown in Figure 2:8. The DP controlled Catamaran vessel is kept in the position with the help of 4 thrusters and catenary mooring lines connected to Spar buoy are used to restrict its motion in the horizontal plane. This layout is directly derived from previous studies.

As for the lifting system, four hydraulic winches are provided and the OWT is connected to the winches through wire ropes. The winches are arranged as shown in Figure 4:1. To account for the relative motions between spar buoy and lifted OWT, the hydraulic winches are heave compensated in such a way that lifted OWT follows the motion of the top of spar buoy and hence the relative motions are reduced. Once the installation/mating process begins, it is possible to slowly release the ropes from the winch drum in a controlled manner and gradually lower the OWT towards spar buoy.

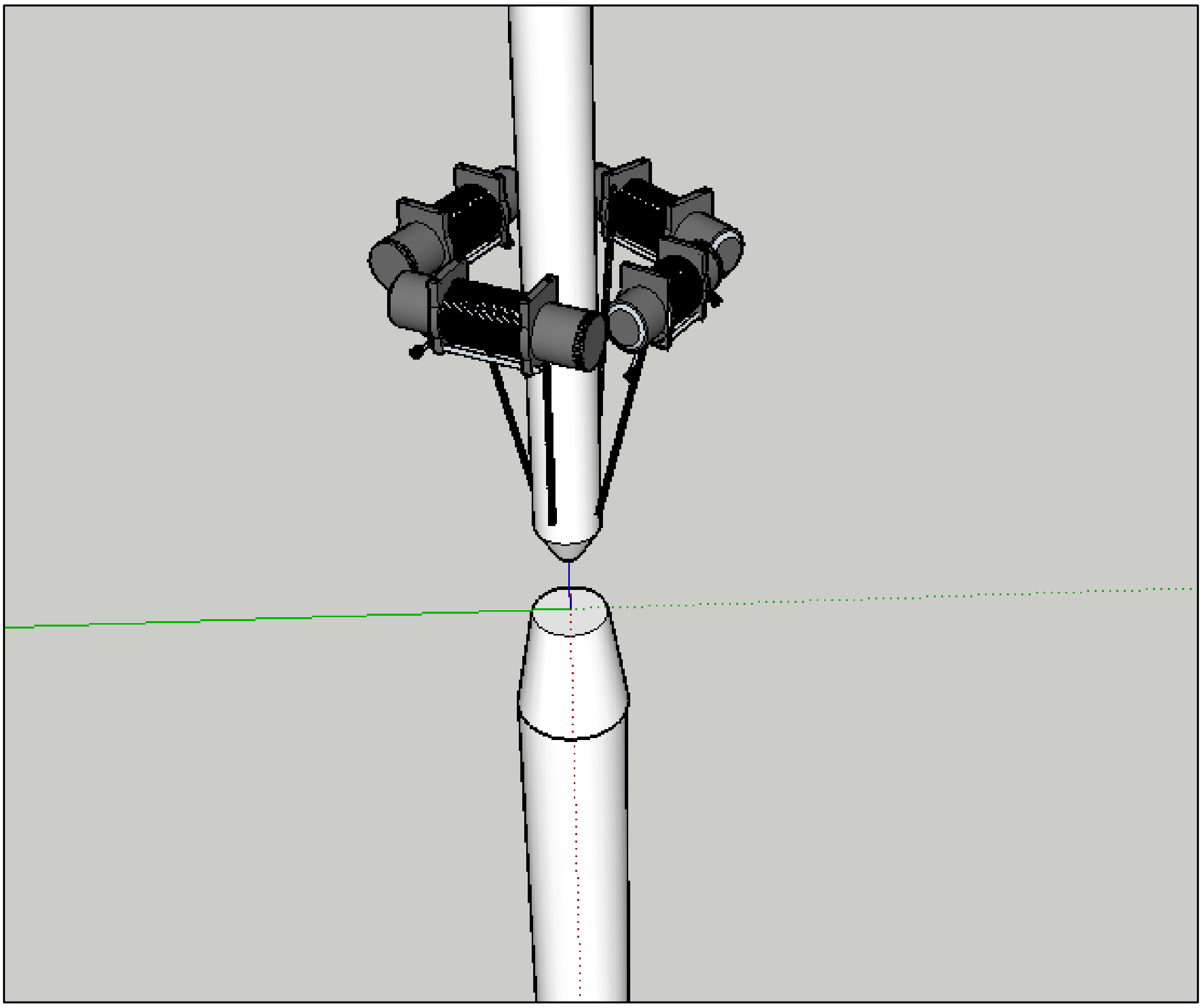


Figure 4:1 Proposed arrangement of lifting winches

When a module/object is lifted using a crane or other lifting mechanism, typically its center of gravity will be below the suspension/holding point and it provides the system some stability in the vertical plane. However, in this case, the OWT weighs around 1115 MT and 100 m long (details of OWT are followed in section 4.3) and suspending such a huge mass from a height more than the length of the OWT will results to further complications such as loss of vessel stability and excessive pendulum motions in the vertical plane and also requires more complex systems to perform the task. As a result, a low lift mechanism was preferred and OWT is lifted by four winches at the bottom. Regardless of the advantages of having a low lifting point, this configuration brings an inherent instability to the lifted object in the vertical plane and the lifted object will tend to topple over. Therefore, to hold the assembly in the desired vertical position, roller supports are provided in the proposed installation concept model. Figure 4:2 shows the graphical representation of the proposed design for the roller supports.

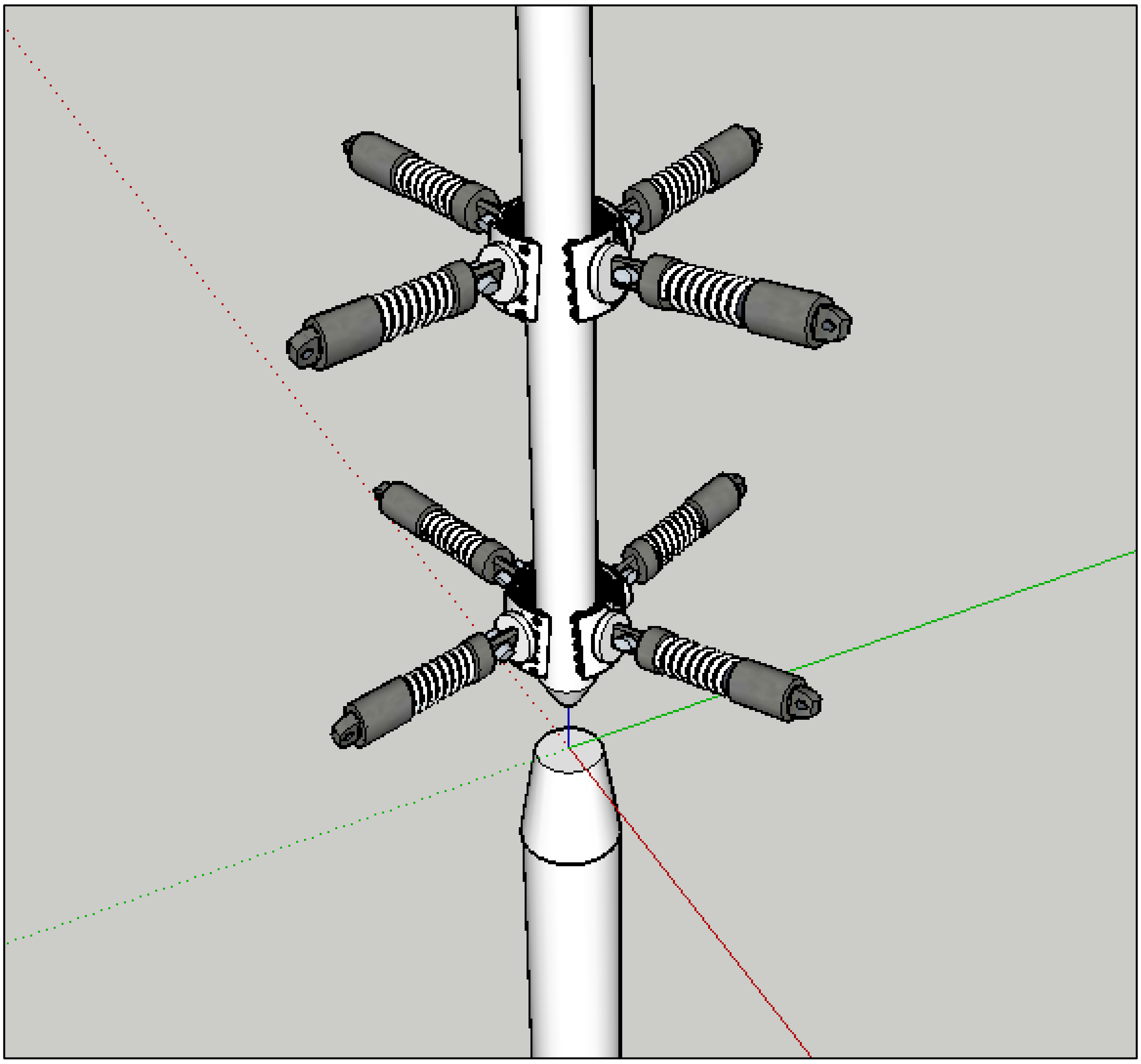


Figure 4:2 Proposed arrangement of roller supports

One of the ways to reduce the relative motions between Spar and OWT is to reduce the relative motions between floating spar buoy and catamaran at the mating point as motions of the lifted tower are directly linked to the catamaran motions. Therefore, it makes easier for the heave compensated winches to control the releasing rate of the OWT lifting wires and follow the motion of the moving Spar if there are fewer relative motions exists between the catamaran and floating spar buoy. So, for this matter, spar buoy is coupled with catamaran through wire ropes linked to winches placed in the vessel and these are used to lift the spar through a small distance. A schematic diagram of the proposed system is shown in **Figure 4:3**.

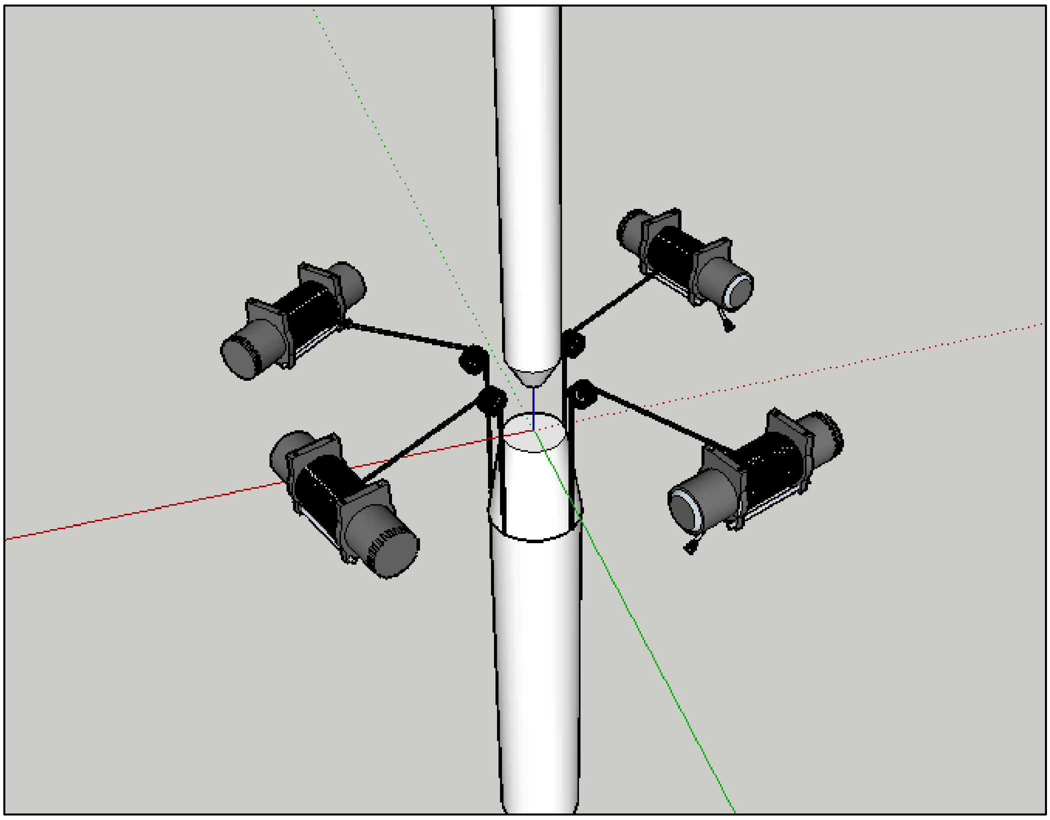


Figure 4:3 Proposed arrangement of winches connecting wires between spar buoy and catamaran

When the spar buoy is lifted up, wire ropes will be tensioned, and it behaves as a spring between two bodies and tries to reduce the relative motions. The tension in the wire ropes also reduce the relative horizontal motions as shown in **Figure 4:4**.

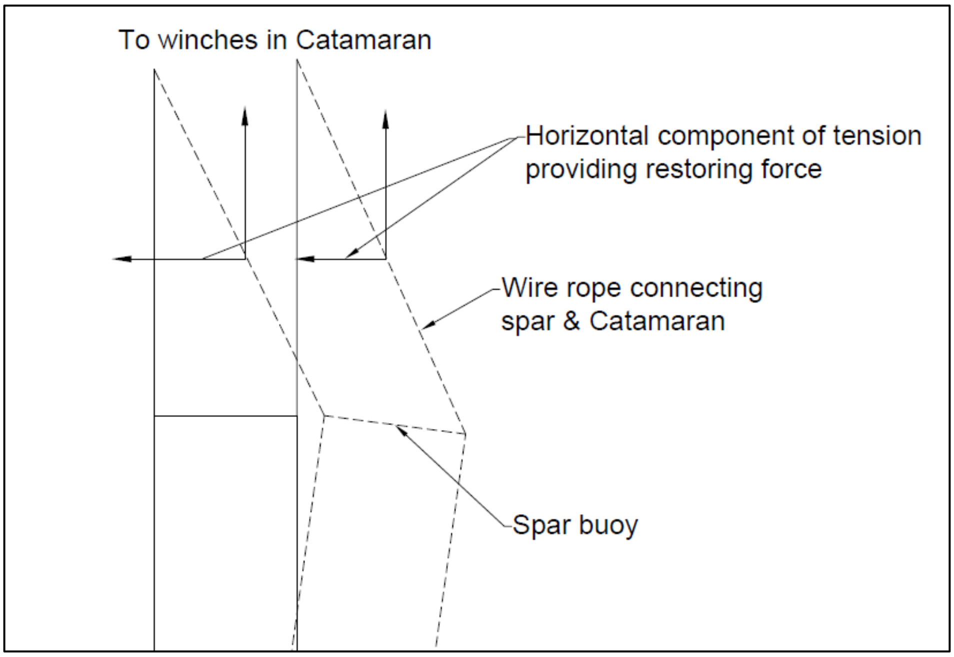


Figure 4:4 Mechanism of horizontal motion reduction by wires connecting spar and catamaran

Besides that, to reduce further horizontal relative motions between spar and OWT, both are connected using wire ropes which goes to tugger winches placed in the vessel as shown in **Figure 4:5**.

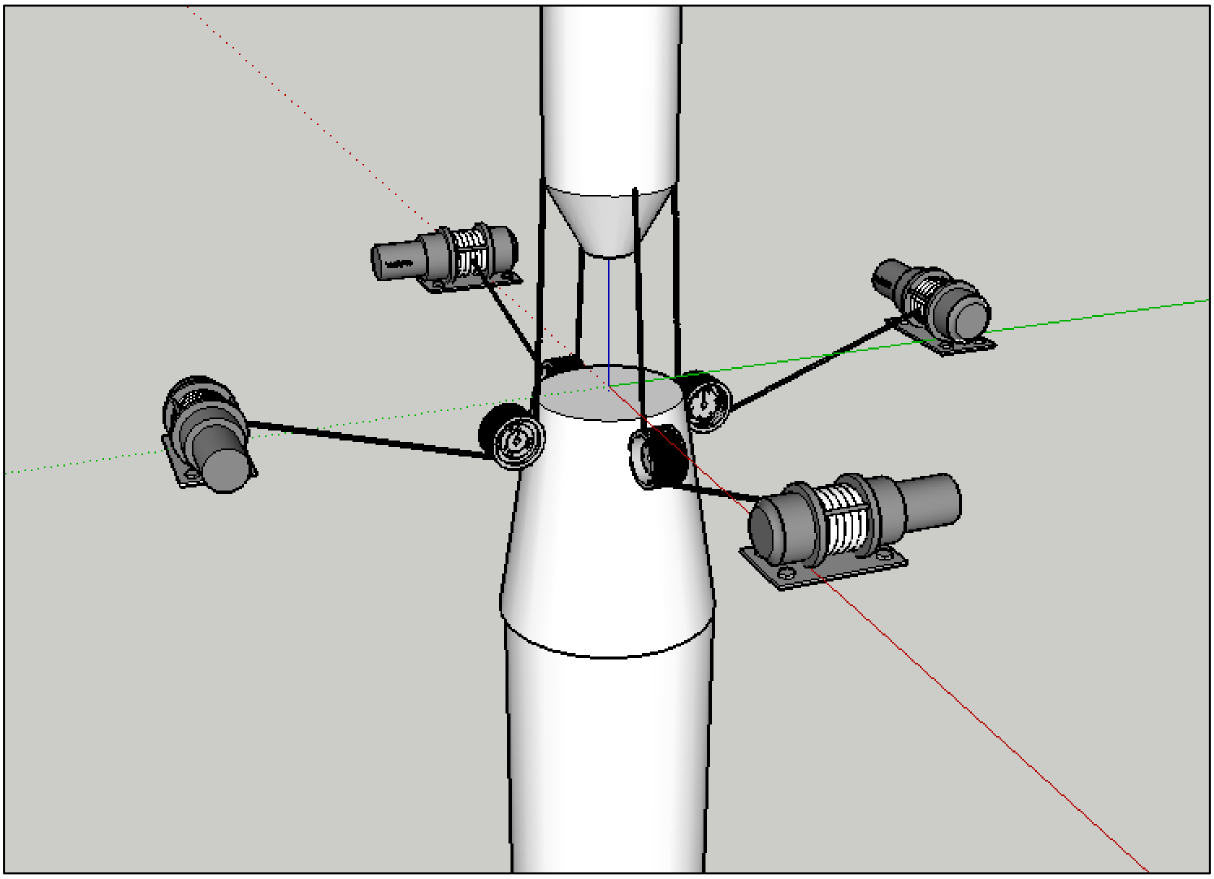


Figure 4:5 Proposed arrangement of winches connecting wires between spar buoy and Tower

As a consequence of the chosen arrangement, floating spar buoy/OWT will always experience a restoring force when moved from the desired position set as per the installation conditions. It is to be noted that results from numerical simulation indicate that the spar motion in the horizontal direction is minimized considerably (refer section **6.3.3**) which in turn helps to align the lifted OWT on top of Spar buoy most of the time.

In addition to the suggested modifications to reduce the relative motion of the bodies, a docking cone was recommended to make the mating operation easier as the docking cone will guide the tower into the spar buoy during mating operation. It also cushions the impact forces due to sudden relative motions of the bodies and restrict the bodies from outcrossing the boundary of the bodies.

Refer section **4.4** for the details of coupling elements.

4.3 Vessel, Spar and OWT Characteristics

Considering the fact that this project concentrates on the installation process (specifically the mating phase) of offshore wind turbines from the floating catamaran rather than improving the current design of either installation vessel nor the Spar buoy, characteristics of the vessel, floating Spar buoy and OWT were adopted from the previous studies (*jiang_et_al*).

The properties of the proposed installation vessel, floating Spar buoy, and Offshore wind tower are as follows:

Table 4:1 Details of the catamaran, spar buoy and tower

Catamaran (with four wind turbines)	
Length Overall (m)	144
Breadth (m)	60
Draft (m)	8
Space between hulls at water line (m)	38
Dispalcement (MT)	18502.9
Spar Buoy	
Draft (m)	70
Diameter at top (m)	9.5
Diameter at water line (m)	14
Dispalcement (MT)	11045
Offshore Wind Turbine	
Height (m)	100
Rotor Mass (MT)	160
Nacelle mass (MT)	355
Tower mass (MT)	600
Total mass (MT)	1115

4.4 Mechanical Couplings Between Bodies

It is clear that the proposed installation process at sea includes multibody interactions and thereby mechanical couplings are necessary to transfer the resulting forces and motions between bodies so that any of the individual components is not left behind to behave independently.

4.4.1 OWT Lifting System/ Heave compensated Winches

When the mating phase of the installation process starts, OWT will be connected to the wires from four winches and then lifted up in the air. The winches are arranged 90 degrees to each other and along the sides of the OWT as shown in Figure 4:1.

The wires from winches are arranged in the vertical direction so that the weight of OWT is carried by the winches. However, the wires make a small angle between the vertical line because of the practical reasons (as there will always be some gap between the point of attachment to winch and OWT). Since the winches are heave compensated, the wires are released in a controlled rate to reduce the relative motion between the spar buoy and lifted OWT. The controller releases or withdraws the winch wires based on the deviation of the Z position difference of both spar buoy top and OWT bottom from the desired set value and hence the winch is always trying to keep the distance constant.

4.4.2 Roller Supports along the OWT length

Roller supports are fixed to the lifting module to prevent the lifted OWT from toppling over due to the low lifting point. They cushion the impact forces arising from the rotating unstable OWT on the lifting module structure and also dissipates the energy through the dampeners. They decelerate the load throughout the stoke and finally, the OWT will stop before hitting the lifting module structure. In mechanical terms, roller supports can be thought of as spring + damper system which provides a reaction force and decapitates the energy through its stroke length. Another feature of the roller supports is it ensures that the motion of OWT is undisturbed in the vertical direction as rollers are provided on the part which is in contact with the OWT.

In the proposed concept, two sets of roller support are suggested and will be placed at the top and bottom of the lifting module and each set will contain four supports as shown in Figure 4:2. The distance between both sets are kept as 30 m and there is a possibility to increase this distance if the loads in supports are high. Through this manner, a restoring moment is acted upon the OWT and can reduce the tendency of tower to fall over.

4.4.3 Motion compensation System between lifted OWT, Spar Buoy & Catamaran

It is important to keep the lifted OWT bottom and floating Spar top to be aligned most of the time during the installation and failure to do so will adversely affect the installation process. The heave compensated system along with the roller supports will try to make sure that the relative motions in vertical directions are minimized by controlling the lifted OWT position based on the vertical motion of Spar buoy. But since Spar buoy is floating and is subjected to the waves, it also moves in the horizontal plane and hence, not always aligned with the lifted OWT. This calls for a mechanism to restrict the spar buoy motion and in the previous studies, this was done by providing a sliding gripper which was rigidly attached to the Catamaran. However, this results in very high motions and forces at the connection point and hence to be modified.

As a consequence, a motion compensation system with winches connecting OWT and Spar buoy & Spar buoy and Catamaran is proposed in this project. Four wire ropes are connected to spar and a winch situated in the installation vessel is used to lift it from water through a small distance. This arrangement can be thought as a spring coupling between the two bodies and when there are no waves forces, the spar is at the equilibrium position. But when the forces from waves start to act on the system, relative motions between the bodies will displace the system from its equilibrium position and restoring forces are induced in the wire ropes which forces the system to move as a single body, both in the vertical and horizontal plane. Similarly, both spar and OWT are connected by wire ropes from tugger winches from catamaran and tension in the ropes are controlled so that they are always aligned to each other. The bodies are connected by a set of wires from winches located on the Catamaran. Figure 4:4 explains graphically how the motion compensation system works during installation. A 3D model of the proposed concept is shown in Figure 4:3 and Figure 4:5.

4.4.4 Docking Cone

When the mating operation is initiated and as the OWT is lowered towards Spar buoy, impact forces in the vertical and horizontal directions are expected at the mating point as the distance between them is nearing to zero. To protect the structures from high impact loads due to their relative motions and also to guide the lifted OWT to the top of Spar buoy, a docking cone is provided at the bottom of the OWT and accordingly, a receiver is also given at the top of the Spar buoy.

Once the docking cone enters to the receiver (or else called LMU) and moves towards the receiver walls made of elastomer, restoring force starts acting on the cone based on the distance between the LMU walls and cone current position and it will reduce the impact forces on the structures and also reduces the excessive motions.

Chapter 5

SIMO Modelling

Numerical modelling of an installation scenario is complex in nature and most of the times, modifications are required to represent the actual situation. This chapter describes how the proposed installation scenario is modelled in SIMO.

In this project, the operation was modelled as three rigid bodies namely, Spar buoy, Catamaran installation vessel and offshore wind turbine which are connected by coupling elements. It is assumed that remaining three wind towers are rigidly connected to the deck and hence considered as part of the Catamaran.

5.1 Modelling Details of Vessel, Spar, and OWT

Considering the fact that this project is an extension to previous studies, the Catamaran and Spar models used in former studies (*jiang_et_al*) were imported to the SIMO environment along with their hydrodynamic properties. Spar and Catamaran were kept in place with the help of mooring lines and DP controlled thrusters respectively and is similar to prior models.

The global coordinate system of SIMO is earth fixed and initially placed at mean water level and body origin of the spar buoy. Every individual component has its own local coordinate system and is positioned with respect to the global reference point as shown in **Figure 5:1**.

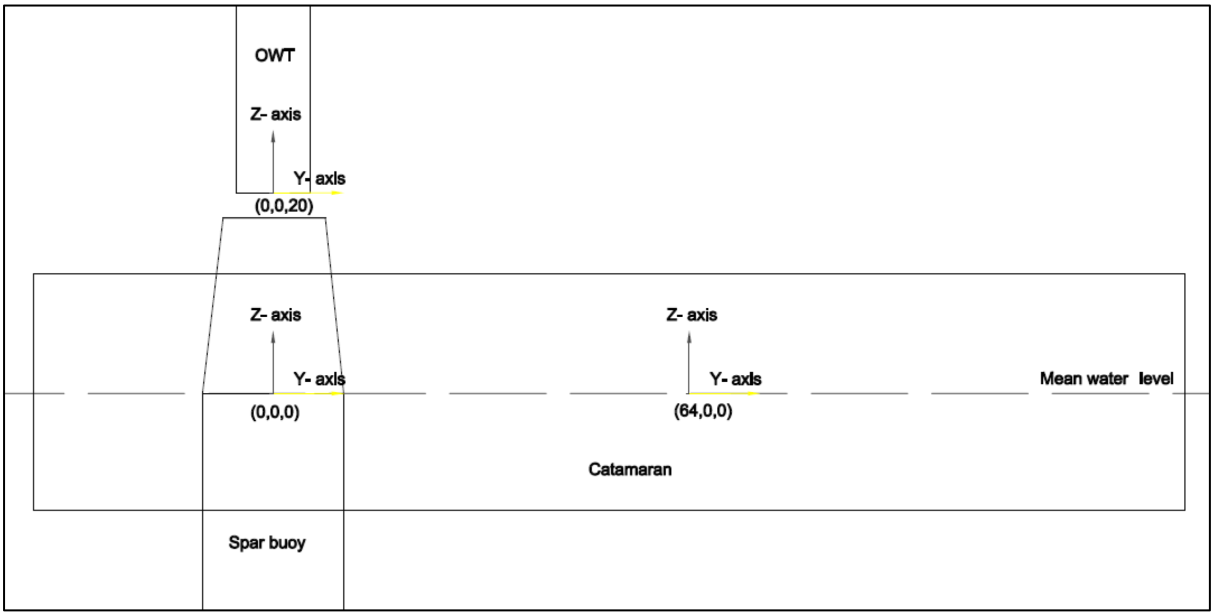
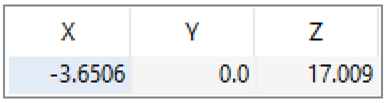


Figure 5:1 Definition of coordinate system in SIMO for modelled bodies

The modelling details of individual bodies are as shown below.

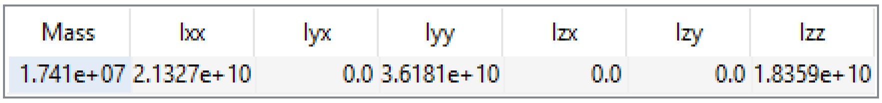
- Catamaran

Centre of Gravity:



X	Y	Z
-3.6506	0.0	17.009

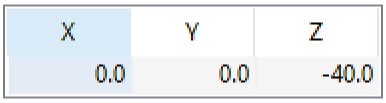
Mass coefficients:



Mass	Ixx	Iyx	Iyy	Izx	Izy	Izz
1.741e+07	2.1327e+10	0.0	3.6181e+10	0.0	0.0	1.8359e+10

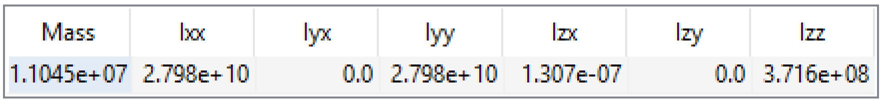
- Spar Buoy

Centre of Gravity:



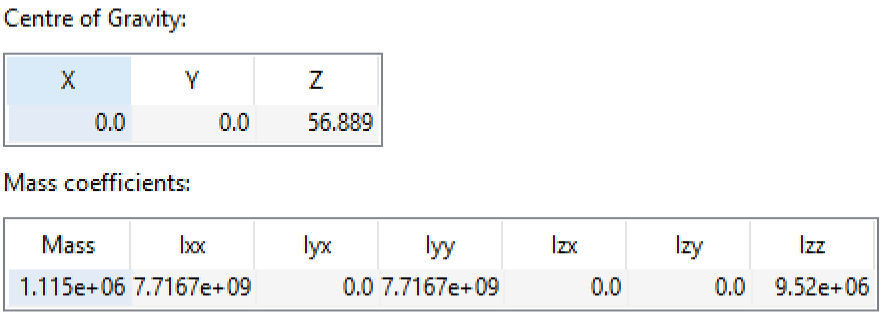
X	Y	Z
0.0	0.0	-40.0

Mass coefficients:



Mass	Ixx	Iyx	Iyy	Izx	Izy	Izz
1.1045e+07	2.798e+10	0.0	2.798e+10	1.307e-07	0.0	3.716e+08

- Offshore Wind Turbine



Centre of Gravity:

X	Y	Z
0.0	0.0	56.889

Mass coefficients:

Mass	Ixx	Iyx	Iyy	Izx	Izy	Izz
1.115e+06	7.7167e+09	0.0	7.7167e+09	0.0	0.0	9.52e+06

Mass and center of gravity location for the individual bodies are defined according to the local coordinate system of the bodies in SIMO and all the values are defined in SI unit system. The output from the SIMO simulation is expressed in terms of local coordinate systems and hence to find the motion of a point which is rigidly connected to one of the bodies, S, can be calculated using the equation

$$\vec{S} = (s_1 + z_l s_5 - y_l s_6)\hat{\imath} + (s_2 - z_l s_4 + x_l s_6)\hat{\jmath} + (s_3 + y_l s_4 - x_l s_5)\hat{k} \qquad \textit{Eqn (1)}$$

Table 5:1 Definition of the parameters

Item	Details
$s_1 to\ s_6$	Motion of bodies at their local coordinate axis
x_l, y_l & z_l	Distance between the point of interest and the local coordinates of the bodies to which the point is rigidly connected in X, Y & Z directions.

5.2 Modelling Details of Coupling Elements

SIMO offers a range of options to model the coupling between the connected bodies. Since the installation operation involves interactions between three bodies, it is important to properly define the connections between them. The details of coupling systems are as follows:

5.2.1 OWT Lifting System

Wind turbines are lifted by the winches using wires ropes and in SIMO, they are modelled as simple wire couplings. Simple wire couplings can be represented as linear springs with elongation, Δl

$$\Delta l = \frac{T}{k}$$

Table 5:2 Definition of parameters

Item	Details
T	Wire tension
k	Effective axial stiffness

The tension in the wires can be calculated by measuring the elongation in the element which is related to the endpoint locations. End points of the modelled simple wire elements are connected to lifted tower and catamaran. The details of the modelled wire rope are given in **Table 5:3**.

Table 5:3 Details of the simple wire coupling

Damping (N.s)	EA (N)
$9.0*10^6$	$9.0*10^9$

In actual installation scenario, winches are used to pay in and out the lifting wires to control the position of the lifted wind tower. In SIMO, a fictitious winch located at one endpoint of the wire rope is used to replicates this operation based on the input characteristics. An external controller developed as part of the SFI MOVE project was incorporated into the SIMO model to regulate the winch speed and thereby reduce the relative heave motions between tower and spar buoy. The external controller decides the winch velocity based on the difference in vertical locations of the tower bottom and top of spar buoy in the global coordinate system and compares with the set distance between them. The external heave compensation module is based on PID controller and hence the PID controller parameters have to be tuned for this particular model. The tuning of PID controller was performed by iterating different values for its proportional, integration and differentiation gains (kp, ki and kd respectively). **Appendix A – Tuning of Heave Compensator** describes the strategy adopted for tuning the external controller. The modelling details of the external controller is shown in **Figure 5:3**. **Figure 5:2** shows how the tower is lifted up in the SIMO model using simple wire couplings.

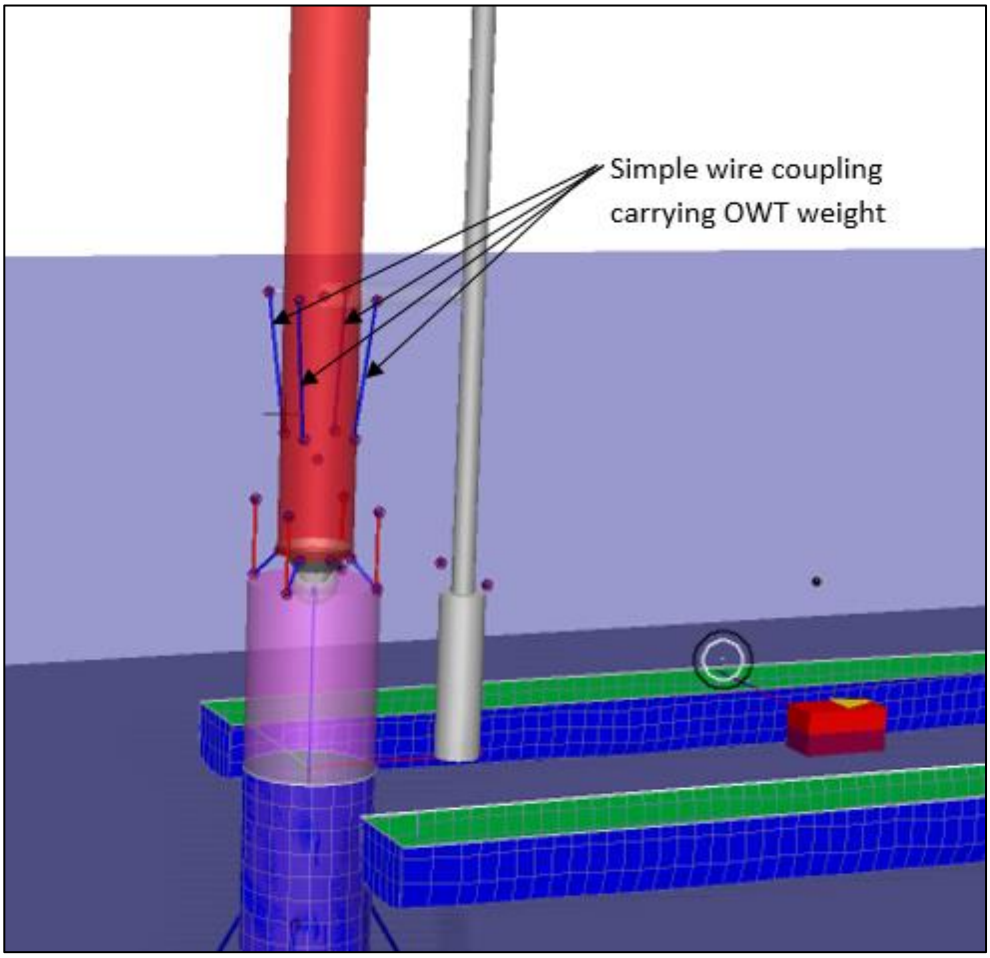
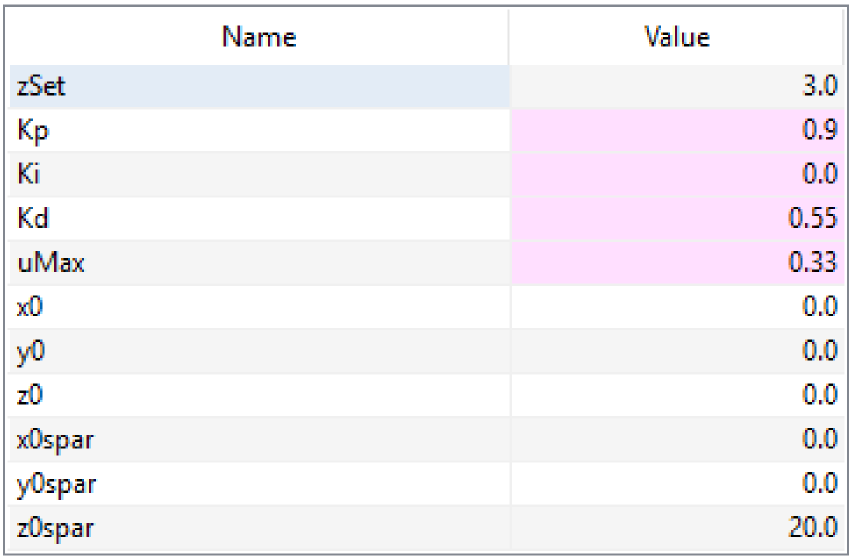


Figure 5:2 SIMO model showing simple wire coupling



Name	Value
zSet	3.0
Kp	0.9
Ki	0.0
Kd	0.55
uMax	0.33
x0	0.0
y0	0.0
z0	0.0
x0spar	0.0
y0spar	0.0
z0spar	20.0

Figure 5:3 Details of the external controller

Table 5:4 Definition of parameters of the external controller

Item	Details
$zSet$	Distance between OWT and Spar
Kp	Proportional gain
Ki	Integral gain
Kd	Derivative gain
$uMax$	Max winch velocity
x_0, y_0, z_0	Location on the OWT to track position (in relation to the local reference frame)
$x_{0spar}, y_{0spar}, z_{0spar}$	Location on the Spar to track position (in relation to the local reference frame)

5.2.2 Roller Supports

Roller supports are used to keep the lifted OWT upright without toppling over and to soften the impact forces on the lifting module using spring + dampener system. To model roller supports in SIMO, bumper elements are used as coupling elements between lifted OWT and installation vessel. A coupling defined by bumper elements consists of two bumper bars (or a pair of lines as shown in Figure 5:4) where one of them is attached to the lifted OWT and other to the lifting module (lifting module is assumed to be rigidly connected to the vessel).

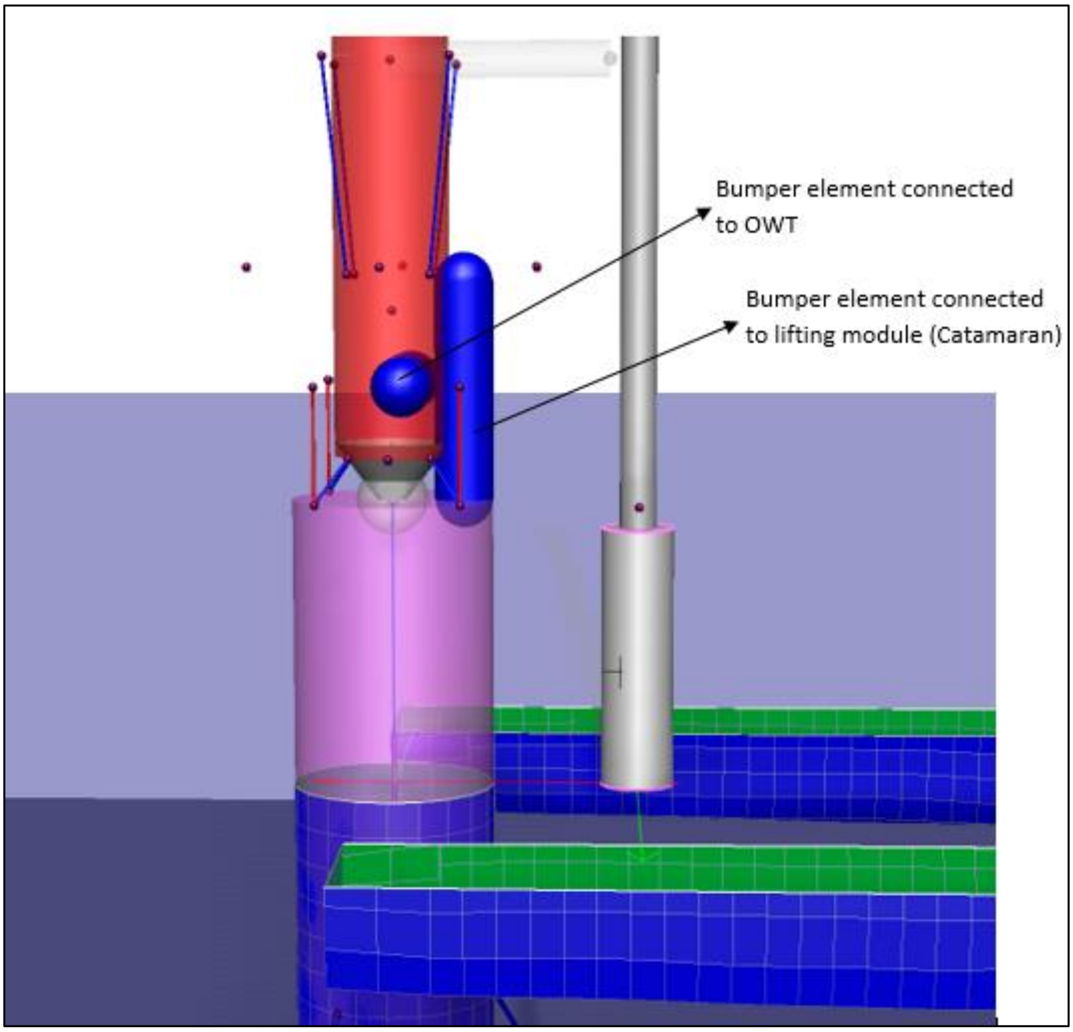
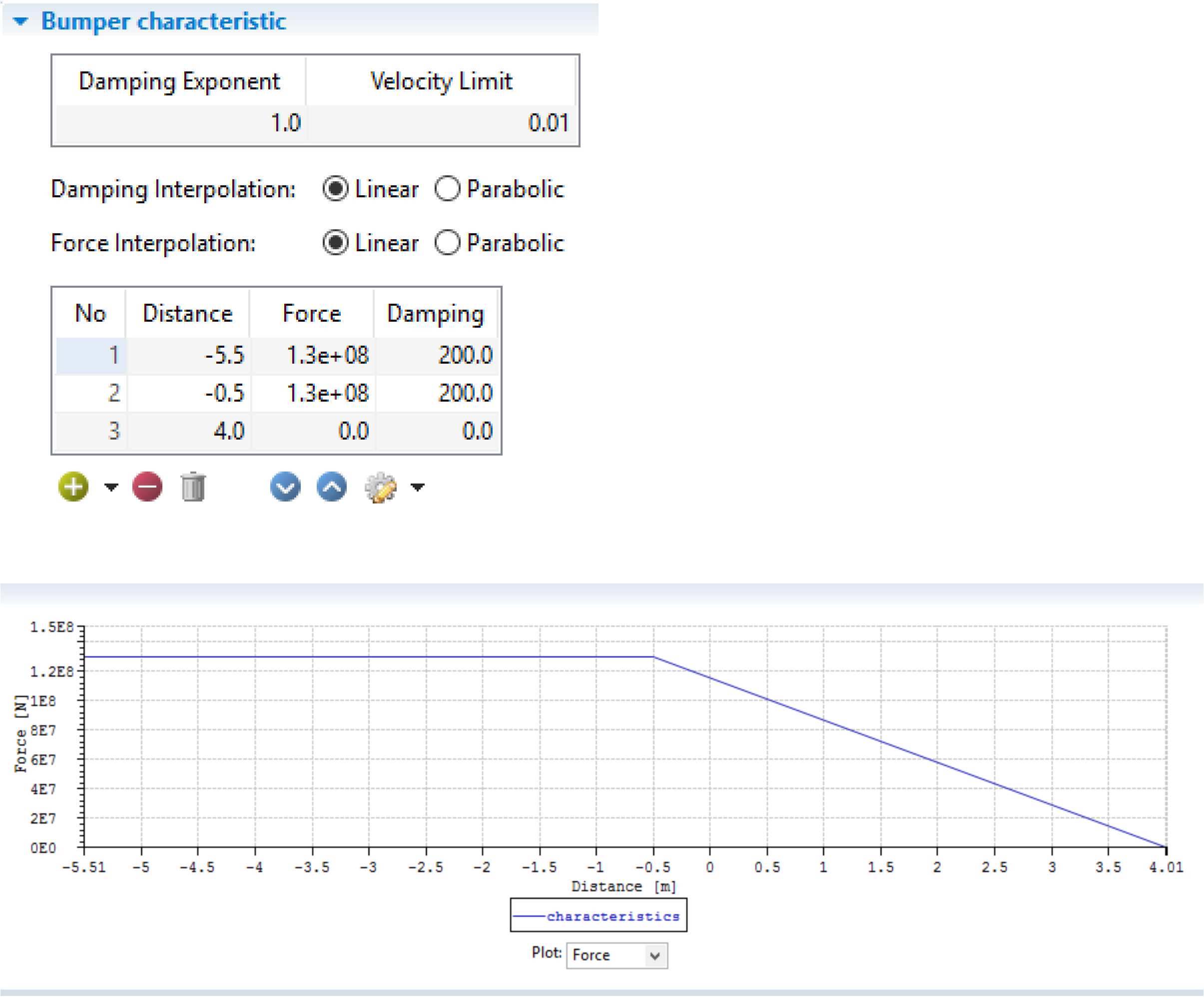


Figure 5:4 Bumper coupling element modelled in SIMO

When these two bars come in contact with each other, a contact force is applied to the interacting bodies and it is possible in SIMO to define the nature and amount of this contact force based on the distance between the bumper bars. During the installation, the roller supports are always kept in contact with the OWT and try to apply the restoring force when the tower has made an angle with the vertical plane and started to topple from its initial position. When OWT starts to make an angle with the vertical plane, the roller supports starts to apply restoring forces based on the compression in their springs. Hence, it is correct to assume that the restoring force by roller supports can be modelled as a function of the distance between the OWT and lifting module walls and this is the principle behind using the bumper elements as coupling elements. The contact force produced by the bumper elements can be modelled as a function of distance and **Figure 5:5** shows the force/distance relation modelled for the bumper element in this report.


Bumper characteristic

Damping Exponent	Velocity Limit
1.0	0.01

Damping Interpolation: ● Linear ○ Parabolic

Force Interpolation: ● Linear ○ Parabolic

No	Distance	Force	Damping
1	-5.5	1.3e+08	200.0
2	-0.5	1.3e+08	200.0
3	4.0	0.0	0.0

Plot: Force

Figure 5:5 Stiffness and damping characteristics of the bumper

When the OWT is in its upright position, the distance between OWT and module walls is 4 m and hence there will be no forces applied by the roller supports. As OWT starts to roll over to one side, the roller supports starts to apply restoring force based on the force-distance curve shown in **Figure 5:5**. It is also possible to include the damping in the same fashion and is included in this model.

It is important to note that in a coupling defined by bumper elements, the sliding friction between the bumper bars are neglected. It comes as an advantage from the modelling perspective as the roller supports are designed to have the least interruption with the vertical movement of the OWT, and without sliding friction between bumper bars, they can be used to replicate the actual scenario.

To restrict the OWT from falling over, a restoring moment has to applied on OWT and for this matter, two bumper sets distanced at 30 m are modelled as shown in **Figure 5:6**.

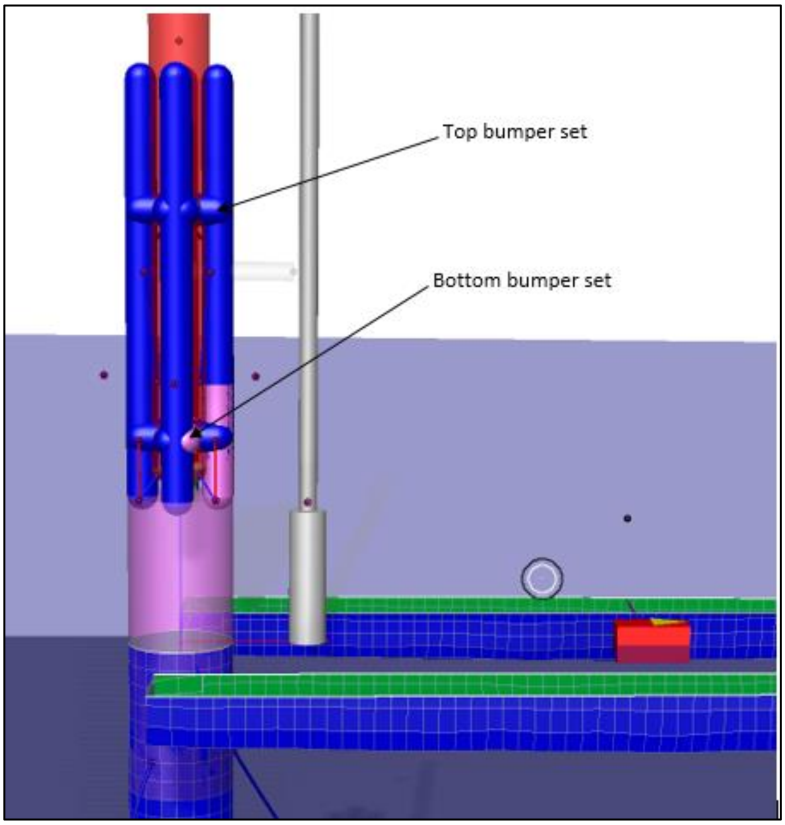


Figure 5:6 Two sets of bumpers modelled in SIMO

5.2.3 Horizontal Motion compensation System between lifted OWT - Spar Buoy & Catamaran

Heave compensated winches coupled with roller supports keep the vertical relative motions of bodies to a minimum but to keep the lifted OWT aligned to the top of the spar buoy, special arrangements to connect the OWT and Spar with Catamaran using wire ropes and winches have to be included. Figure 5:7 shows how OWT, Spar, and Catamaran are modelled as connected bodies using the wire ropes from winches in Catamaran.

The wire rope between the bodies is modelled as simple wire coupling with the properties as in Table 5:3. To tension the wires connecting the spar and catamaran, the length of the wires is defined as a smaller value than the required value calculated based on the initial distance between the connection points on spar buoy and catamaran. This allows the wires to be pre-tensioned and thereby lifts the spar buoy to a certain distance above the water. This replicates the action of a winch providing the tension to the wire ropes.

Appendix B – Pretensioning of Wire Connecting Spar Buoy and Catamaran explores the variation of dynamic responses of the coupled system for different pretensions set in the wire between catamaran and spar buoy and also explains the rationale behind the chosen pretension value.

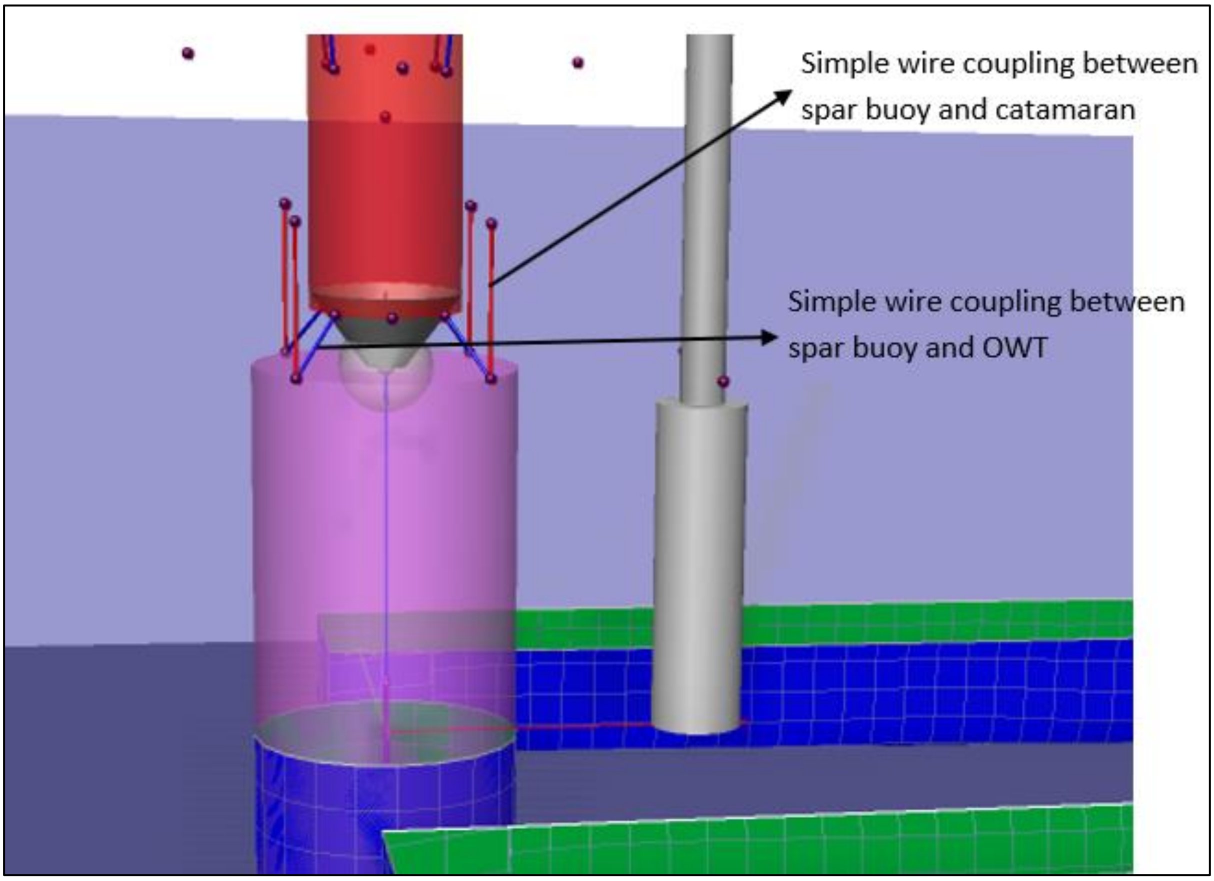


Figure 5:7 Horizontal motion compensation system between lifted OWT - spar buoy & catamaran modeled in SIMO

5.2.4 Docking Cone

In SIMO, docking cone can be used as a positioning element or as a coupling element. In this model, a docking cone coupling element is given between the OWT bottom and top of Spar buoy as shown in **Figure 5:8**. Once the docking pin enters the receiver on Spar top and moves towards the receiver walls, the model starts to give contact forces based on the predefined force/distance relationship. It is possible to model the internal walls as conical in shape where the distance to the wall is decreasing as the depth increases and hence varying stiffness properties along the length of the receiver cone. The characteristics of the docking cone is shown in **Table 5:5** and **Figure 5:9**.

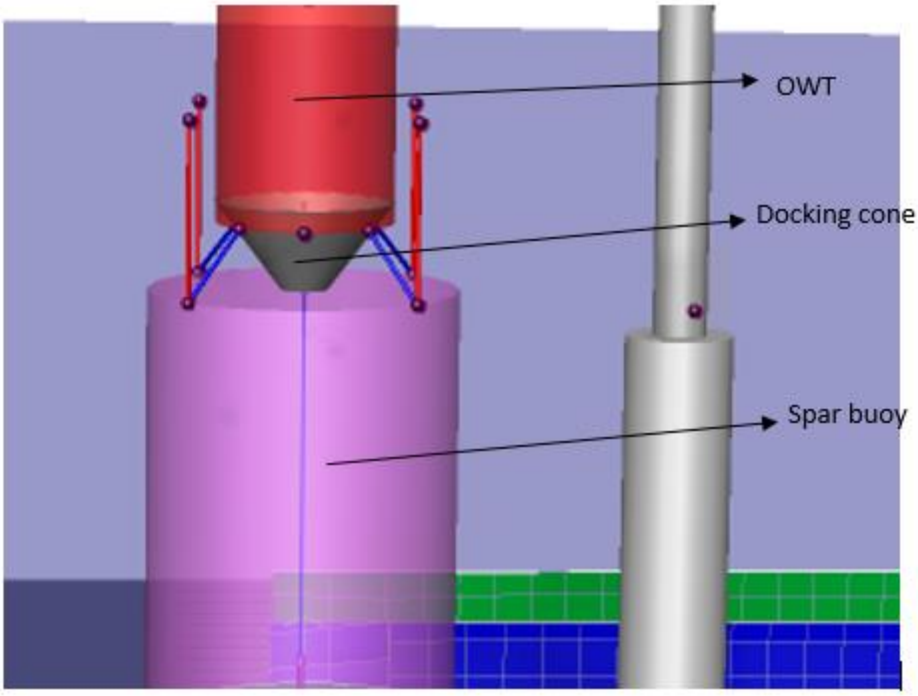


Figure 5:8 Docking cone modelled in SIMO

Table 5:5 Details of docking cone coupling

Axial distance (IAXPT - (m))	**Transverse offset (DIST - (m)) ***	**Force (N)**
0.0	0.5	0.0
	2.0	$1.0*10^6$
1.0	0.25	0.0
	1.75	$1.0*10^6$
2.0	0.25	0.0
	1.25	$1.0*10^6$
3.0	0.01	0.0
	1.0	$1.0*10^6$

* In-between the two distance values, the restoring force follows the linear curve

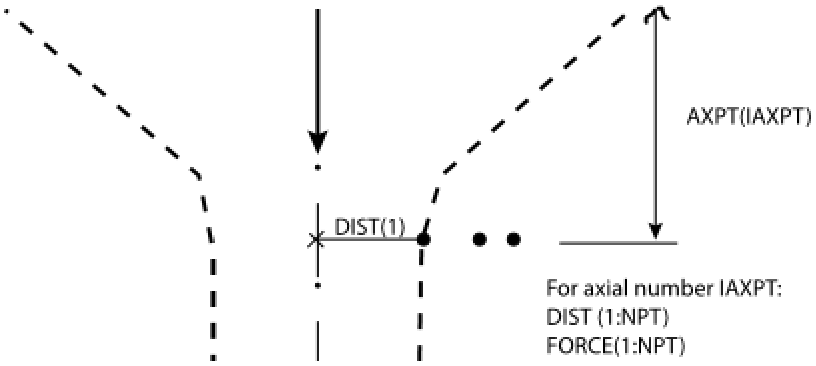


Figure 5:9 Definition of docking cone design variables [(19)]

Chapter 6

Analysis of the Coupled System

This chapter describes how the coupled multibody system modelled in SIMO behaves under the influence of different environmental conditions. Eigen values of the coupled system and the response of the system to different environmental variables are checked. Dynamic analysis of the system is performed to evaluate the performance of the suggested modifications.

6.1 Eigen Value Analysis of the System

Eigen values of a system play an important role in determining the behaviour of the model. Hence, calculating the eigen values for the model in discussion will be the first step to analyse the dynamic response of the system.

To calculate the natural periods of the system, the equation of motion for the coupled system must be solved in the frequency domain by neglecting the damping. The resulting equation will be:

$$(\omega^2(M + A) + C)X = 0$$

Table 6:1 Definition of the parameters

Item	Details
ω	Natural frequency
M	Mass matrix (Catamaran, Spar & OWT)
A	Added mass matrix
C	Total restoring stiffness matrix
X	Eigen vector

Before calculating the eigen values of the system, the equilibrium position of the coupled system has to be computed. A static calculation of the initial stage of the installation process, where the wind tower is lifted up and kept at a constant distance of 3 m away from the top of floating Spar buoy, is executed in SIMO and the equilibrium positions of the bodies in the global coordinate system of SIMO are shown in Table 6:2.

Table 6:2 Equilibrium position of the bodies after static calculation

Component	**Degree of freedom**					
	X (m)	**Y (m)**	**Z (m)**	**Roll (deg)**	**Pitch (deg)**	**Yaw (m)**
Catamaran	64.16	0	-0.50	0	-0.48	0
Spar Buoy	0	0	2.83	0	-0.16	0
Wind Tower	0	0	21.67	0	-0.49	0

Using the SIMO model, eigen vectors of each of the components in the model for their six degrees of motion are calculated and listed in Appendix C. The dominant modes for the natural periods are collected and listed in Table 6:3.

On analysing the natural periods and corresponding degrees of freedom listed in Table 6:3, it can be seen that most of the natural periods in different degrees of freedom are less than 20 seconds and are in the range of wave periods that are expected at the installation site (Refer section 7.2.3 for environment conditions considered on the installation site). As a result, the response of the system in these periods are critical and must be examined in detail. Lower natural periods for the tower is observed for surge, sway, heave motions and this can be interpreted as a consequence of lifting wires and horizontal motion compensation system. One of the interesting points to notice from the eigen value analysis is that for both spar buoy and catamaran, natural periods of surge and sway motions are almost the same. The possible explanations for this can be that since these two bodies are tightly coupled using wire ropes, they are behaving as a single body while moving in X and Y directions. Also, spar buoy exhibits dominant modes for pitch and heave motions for a period of 15.91 sec and the same can be found for the pitch motion of catamaran but with lesser value (0.67). This clearly indicates that both heave and pitch motions of spar buoy influence the catamaran behaviour and it forces catamaran to pitch at this period.

Table 6:3 Natural periods for the coupled body

Component	**Degree of freedom**	**Natural Period**			
Catamaran	Surge	229.65	260.10		
	Sway	229.65	260.10		
	Heave	6.46			
	Roll	9.56			
	Pitch	2.44	15.91		
	Yaw	35.8			
Spar Buoy	Surge	8.04	15.91	260.10	
	Sway	6.46	6.59	229.65	
	Heave	2.44	15.91		
	Roll	6.46	6.59	31.49	
	Pitch	6.46	8.04	15.91	35.78
	Yaw	6.46	6.59	7.77	35.80
Wind Tower	Surge	0.73			
	Sway	0.73			
	Heave	1.21			
	Roll				
	Pitch	4.17			
	Yaw	3.99	4.63		

6.2 Coupled System Response to Environmental Variables

Before estimating the limiting weather conditions for the proposed installation operation, it is crucial to check how the modelled system responds to the various environmental parameters. For this matter, a time domain analysis of the numerical model is conducted, and the results are discussed in this section.

In SIMO, a time domain analysis of the initial stage of the mating process is done where the wind tower is lifted up and kept at a constant distance of 3 m away from the top of floating Spar buoy. Since the feasibility of the proposed installation concept is measured in terms of relative motions at the mating point (in X, Y & Z directions) and the forces in coupling elements, variation of these listed properties were considered as the system response during the analysis. All simulations are done for 1800 sec with JONSWAP spectrum and in each analysis, with different environmental parameters are selected, and the system responses are recorded.

6.2.1 Variation of peak time period, Tp

From the eigen value analysis, it is obvious that the system responses will be varying drastically based on the peak time period of the wave spectrum. Wave with natural frequencies of the system will have more response compared to others and hence it is necessary to study this variation over the range of expected wave frequencies at installation site. Figure 6:1 to Figure 6:8 shows the system response for different wave spectra defined by Hs = 2m, wave direction = 0 (waves coming from stern of vessel) and a range of Tp = 4, 6, 8, 10, 12, 14, 16, 17, 18.

Figure 6:1 to Figure 6:3 shows the Standard deviation of relative motions in heave, surge and sway directions at the mating point between lifted tower and spar buoy. As described in section 5.1, the results from SIMO are given with respect to the local body axis and Eqn (1) is used to calculate the motions at the mating point from the local coordinate axis of bodies. It is clear from the graph that there is a peak at 12 seconds for a standard deviation of relative motions in both heave and surge directions.

Regarding the relative heave motion responses, the eigen periods calculated in section 6 indicated that higher response can be expected in heave natural periods of spar (15.91 sec) or catamaran (6.46 sec), but rather the system shows an increased standard deviation (and as a consequence, higher heave response) at 12 sec. This can be explained with **Figure 6:4**. **Figure 6:4**, shows the variation in standard deviation of catamaran pitch motions with respect to the peak time period, Tp. A high pitch response of vessel is observed at Tp = 12 sec and it hints to the role of pitch motions of catamaran in influencing relative heave responses of the system. Same explanation can be given to the peak in relative surge motions at Tp = 12 sec. As the applied wave direction is parallel to the ship's length, less variations in relative motions in Y directions are expected as shown in **Figure 6:3**.

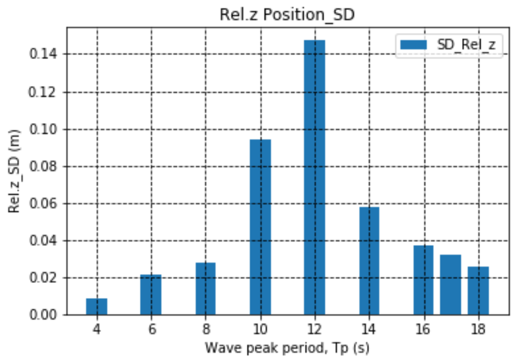


Figure 6:1 Standard deviation of relative heave motion at the mating point for different Tp

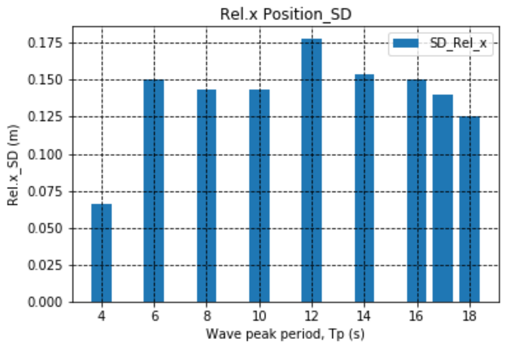


Figure 6:2 Standard deviation of relative surge motion at the mating point for different Tp

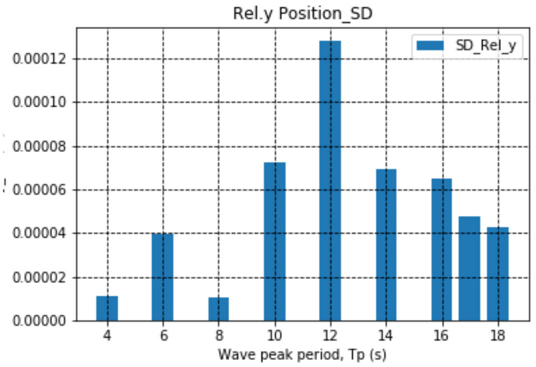


Figure 6:3 Standard deviation of relative sway motion at the mating point for different Tp

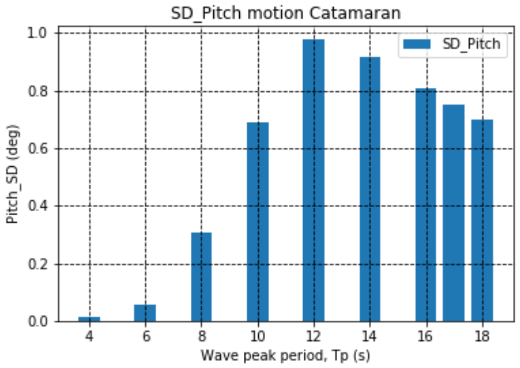


Figure 6:4 Standard deviation of vessel pitch motion for different Tp

Figure 6:5 to **Figure 6:8** shows the standard deviation of total force (resultant of force component in X, Y & Z directions) in the coupling elements such as OWT lifting wires, roller supports (bumper elements) and in wire ropes connecting OWT and spar and the ones connecting spar and catamaran. In SIMO, each coupling between bodies consists of four coupling elements (for example, four simple wire coupling for lifting tower, four bumper elements in each bumper set etc), the coupling element with highest mean force was selected and the standard deviation in it was plotted for comparison.

In all the coupling elements, standard deviation of forces clearly shows a clear peak at Tp = 12 seconds and this can be explained by the similar peak in relative z motion at Tp = 12 sec. **Figure 6:6** shows the standard deviation of forces in the two bumper sets (lower set corresponds to bumper set 1 and upper set corresponds to bumper set 2). Following the plots in figure, the lower bumper set (bumper set 1) has higher responses at Tp = 6 sec in addition to one at Tp = 12 sec. The same trend can be observed in **Figure 6:5** & **Figure 6:7**. This is the result of high relative motions in X direction between spar buoy and lifted OWT at Tp = 6 sec as shown in **Figure 6:2**. It indicates that the horizontal relative motions of the bodies are critical for forces in lower bumper set, lifting wires and wire connecting spar buoy and lifted tower. As expected, tension in wire rope connecting catamaran and spar buoy is more vulnerable to the relative motions in Z direction than that of in horizontal plane.

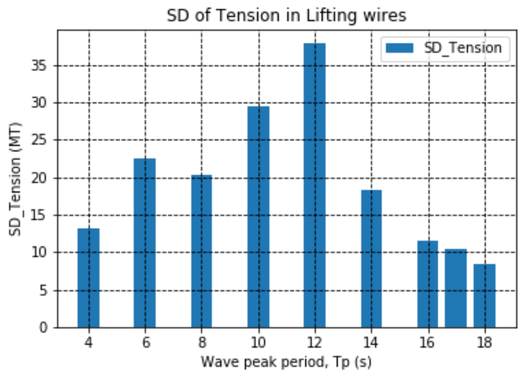


Figure 6:5 Standard deviation of tension in OWT lifting wires for different Tp

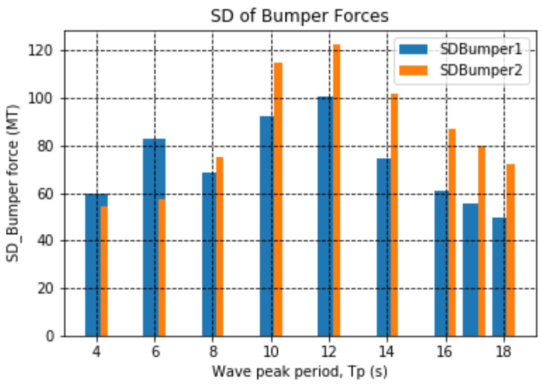


Figure 6:6 Standard deviation of impact forces in roller supports for different Tp

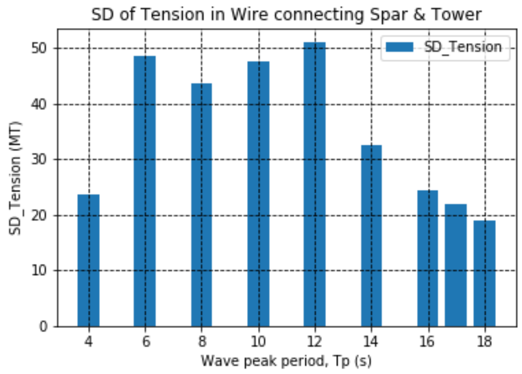


Figure 6:7 Standard deviation of tension in wire between spar and OWT for different Tp

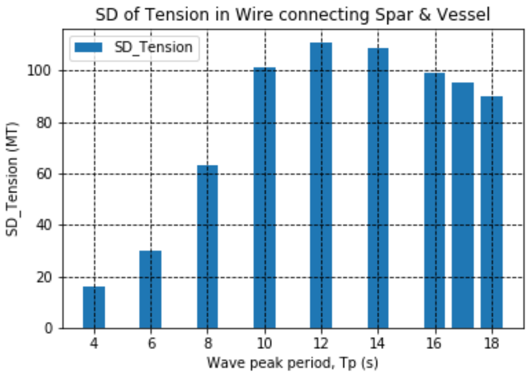


Figure 6:8 Standard deviation of tension in wire between spar and catamaran for different Tp

6.2.2 Variation of significant wave height, Hs

Figure 6:9 to Figure 6:15 shows how recorded system responses behaves for various significant wave height, Hs = 0.5, 1, 1.5, 2, 2.5 & 3 whereas Tp and incoming wave direction are set as 12 sec and 0.0 deg. It is evident from the results that the standard deviation of system responses are getting higher as the incoming wave height is increasing. This was expected as most of the responses are direct result of first order motions and they are proportional to the wave height.

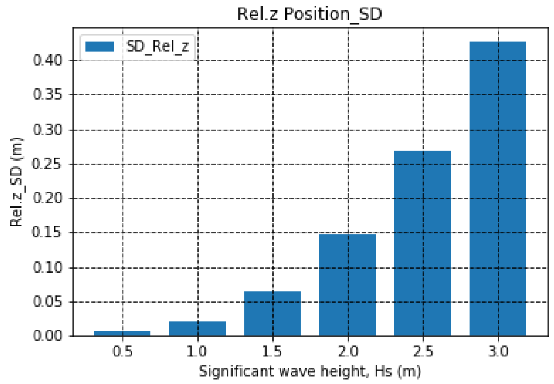


Figure 6:9 Standard deviation of relative heave motion at the mating point for different Hs

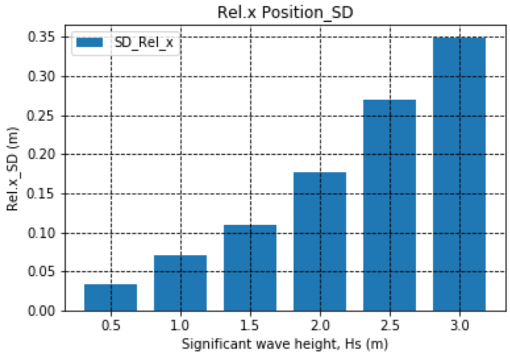


Figure 6:10 Standard deviation of relative surge motion at the mating point for different Hs

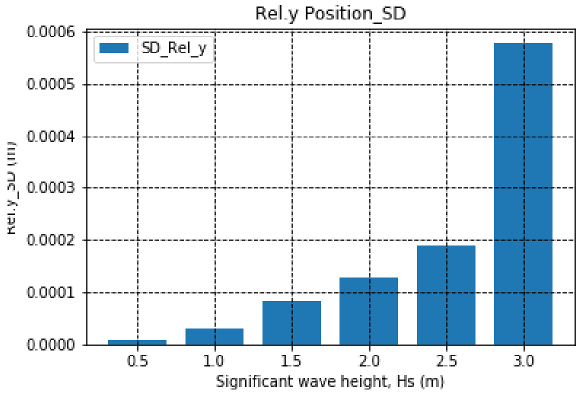


Figure 6:11 Standard deviation of relative sway motion at the mating point for different Hs

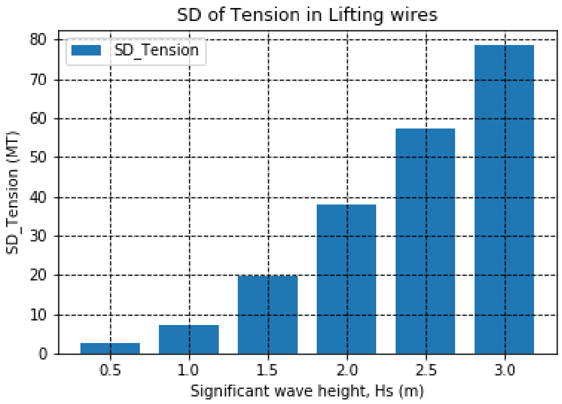


Figure 6:12 Standard deviation of tension in OWT lifting wires for different Hs

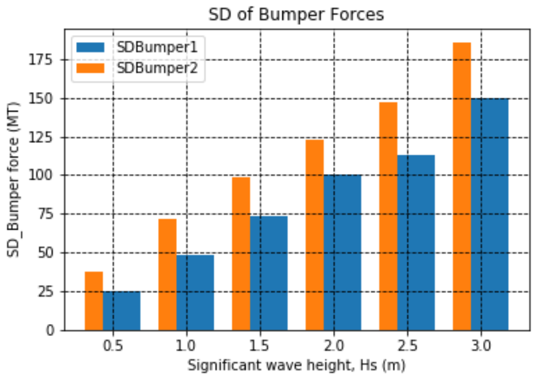


Figure 6:13 Standard deviation of impact forces in roller supports for different Hs

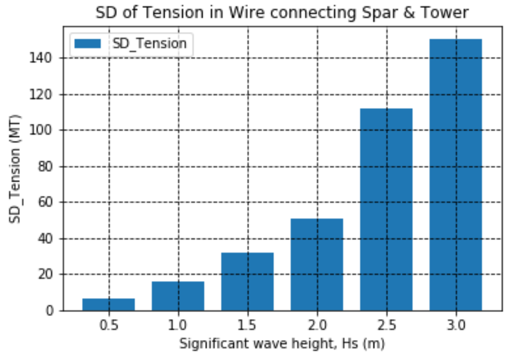


Figure 6:14 Standard deviation of tension in wire between spar and OWT for different Hs

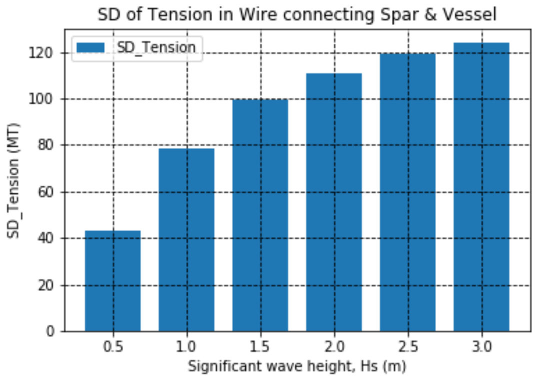


Figure 6:15 Standard deviation of tension in wire between spar and catamaran for different Hs

6.2.3 Variation of input wave direction, β

Figure 6:16 to **Figure 6:22** shows the change in system response as the incoming wave direction is varied from 0 to 30 degrees and at the same time keeping Tp = 12 sec and Hs = 2m. **Figure 6:16** to **Figure 6:18** shows that the standard deviations in relative motions in both X and Z directions are reducing and at the same time standard deviations of relative motions in Y direction is increasing as the wave direction changes from 0 to 30 deg. This trend can be justified by considering the fact that, as the wave direction is changing from 0 to 30 deg, both surge and pitch motion of the bodies are decreasing. Meantime, as bodies are subjected to more wave forces along the Y direction, it causes more motions along Y direction.

As for the total forces in coupling elements(**Figure 6:20** to **Figure 6:22**), the standard deviation of total forces in lifting wires, bumper sets and wire rope connecting spar buoy and vessel are decreasing as the wave direction is varied from 0 to 30 deg. This trend can be explained by examining the **Figure 6:23** to **Figure 6:25**, which shows the how different components of total forces in the listed coupling elements behaves as wave direction is changed. Noticing the trends in **Figure 6:23** to **Figure 6:25**, Z component of total forces in the coupling elements is reducing and at the same time Y components are increasing as wave direction is increasing. However, the increment in magnitude of Y component of total forces is less compared to the decrement in Z component. This explains why the resultant forces in coupling elements are decreasing irrespective of increasing force in Y direction as wave direction changes from 0 to 30 deg.

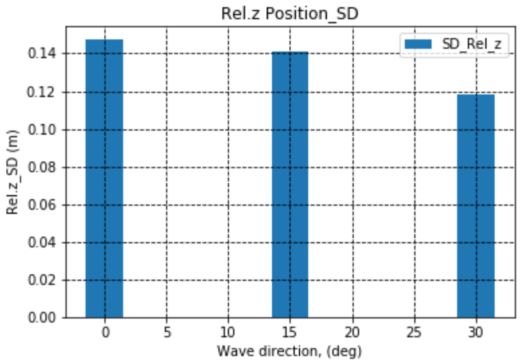


Figure 6:16 Standard deviation of relative heave motion at the mating point for different wave direction

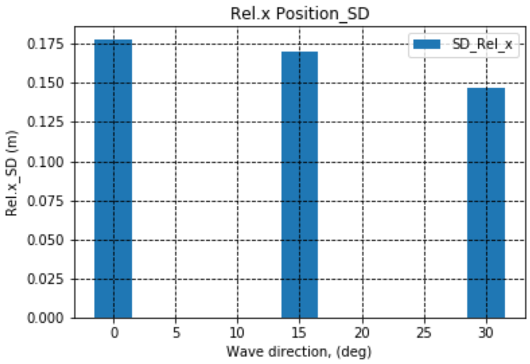


Figure 6:17 Standard deviation of relative surge motion at the mating point for different wave direction

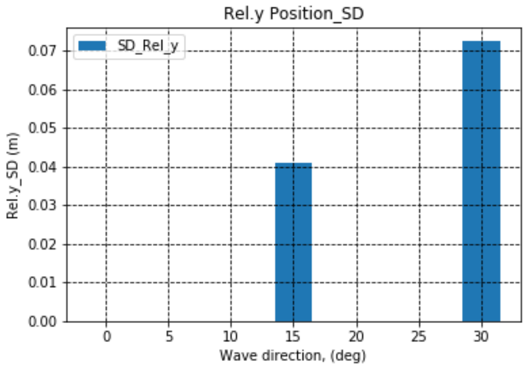


Figure 6:18 Standard deviation of relative sway motion at the mating point for different wave direction

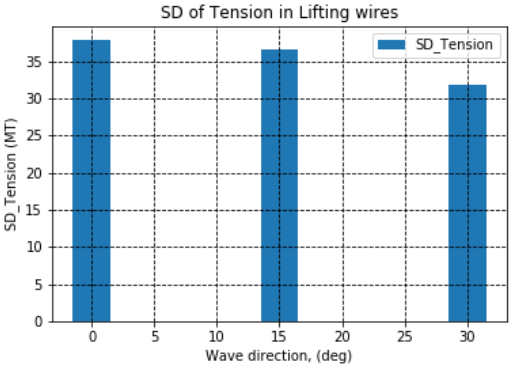


Figure 6:19 Standard deviation of tension in OWT lifting wires for different wave direction

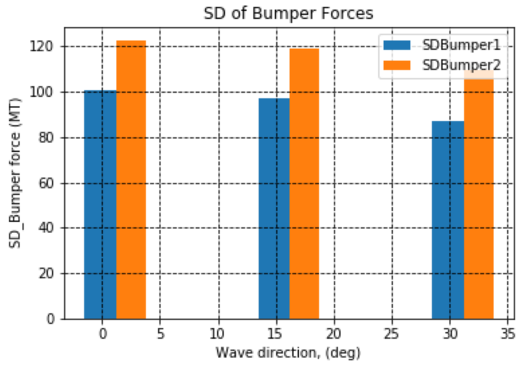


Figure 6:20 Standard deviation of impact forces in roller supports for different wave direction

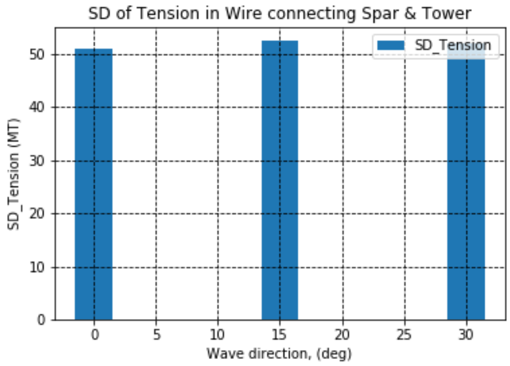


Figure 6:21 Standard deviation of tension in wire between spar and OWT for different wave direction

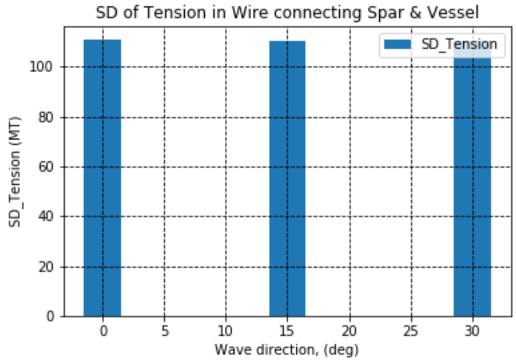


Figure 6:22 Standard deviation of tension in wire between spar and catamaran for different wave direction

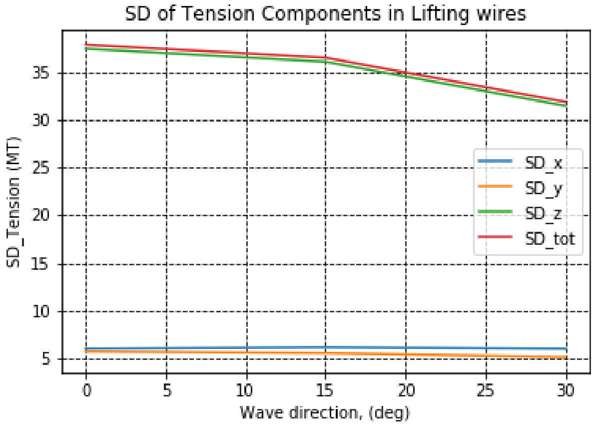


Figure 6:23 Standard deviation of components of tension in OWT lifting wires

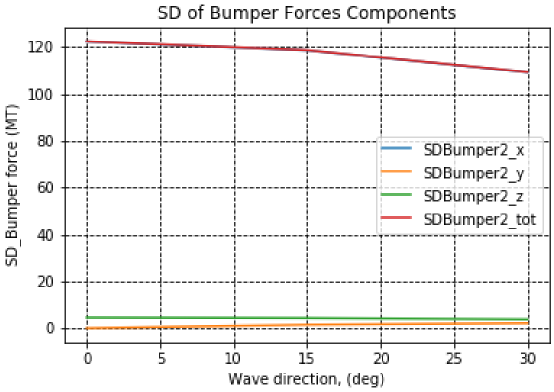


Figure 6:24 Standard deviation of components of impact force in upper bumper element

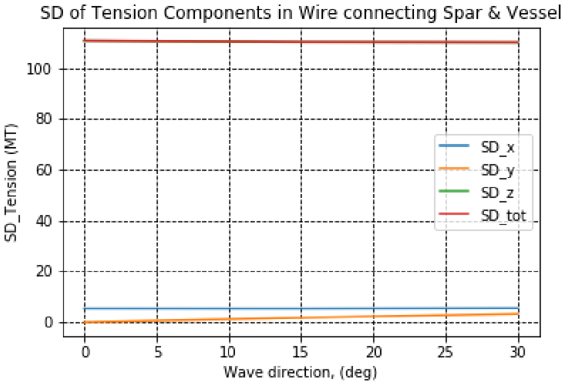


Figure 6:25 Standard deviation of tension components in wire connecting catamaran and spar

6.3 Assessing the performance of recommended modifications

This section measures the effectiveness of the proposed changes to the initial installation concept in terms of relative motions and coupling forces and for that purpose, time domain analysis of the model is done. Throughout this project, many changes were recommended and in the following sections, the advantages of these changes are recorded.

6.3.1 Heave compensation module

The sole reason to include a heave compensation module in the installation concept was to reduce the relative motions between the lifted tower bottom and top spar buoy. As a result. to justify the introduction of heave compensation module, a time domain analysis of two separate scenarios in which one includes the heave compensation module and the one without any heave motion compensation. In both cases, the tower is lifted to 3m above the spar buoy. Considering the applied weather characteristics for the dynamic analysis, a wave condition with Tp = 12 sec and 0-degree wave direction (JONSWAP spectrum) are selected for the simulation. This follows from the fact that it in these conditions, highest relative motions between bodies occur as per the results stated in section 6.2.1. The test results for both cases are compared for a range of significant wave heights, Hs = 0.5, 1.0 1.5, 2.0, 2.5 and 3.0 m.

Figure 6:26 compares the standard deviation in relative vertical motion between spar buoy and lifted tower with and without a heave compensation module. In all wave heights, there is a significant degree of improvement in the performance of the model due to the heave compensation module. It is shown in Figure 6:27 which depicts the percentage improvement achieved by implementing the heave compensation module into the simulation module by comparing both results. On a closer look, there is a trend of decreasing efficiency of the heave compensation module as the significant wave height increases. It was expected because as Hs increases, motions of both bodies increase and hence the heave compensation module has to struggle more to keep a constant distance between them. Consequently, we can derive from the Figure 6:27 that implementing a heave compensation module will benefit in lower significant wave heights.

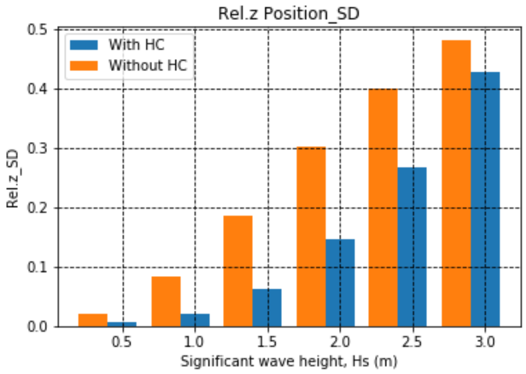


Figure 6:26 Comparison of Standard deviation of relative heave motions at the mating point with and without heave compensator for different Hs

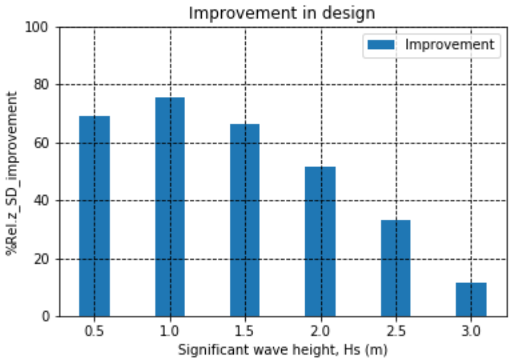


Figure 6:27 Percentage improvement in the performance of proposed installation concept, in terms of relative heave motions, by implementing heave compensator for different Hs

6.3.2 Tensioned wire connecting floating spar buoy and catamaran

Four wires are provided between spar buoy and catamaran and they are tensioned with the help of winches situated in the vessel. These are provided to reduce the horizontal relative motions at the mating point. To check how efficient is this modification while operation, two simulation is performed in SIMO with which one includes the tensioned wire between the bodies and one without tensioned wire. In both cases, the tower is lifted to 3m above the spar buoy. Results from section 6.2.1 clearly points out that a higher response can be observed at Tp = 12 sec and 0-degree wave direction and hence this condition is selected for the simulation. The test results for both cases are compared for a range of significant wave heights, Hs = 0.5, 1.0 1.5, 2.0, 2.5 m (JONSWAP spectrum).

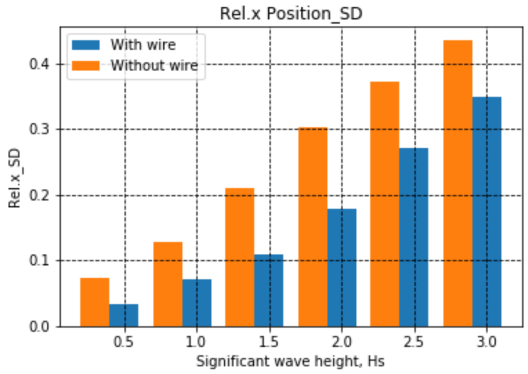


Figure 6:28 Comparison of Standard deviation of relative surge motions at the mating point with and without wire rope between spar & vessel for different Hs

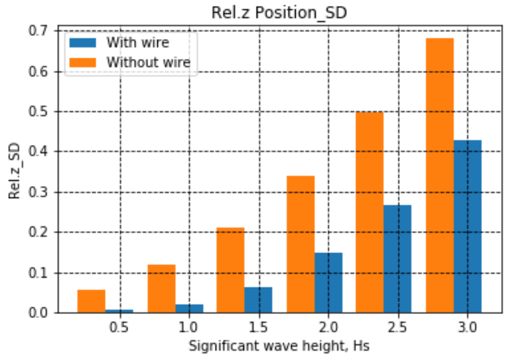


Figure 6:29 Comparison of Standard deviation of relative heave motions at the mating point with and without wire rope between spar & vessel for different Hs

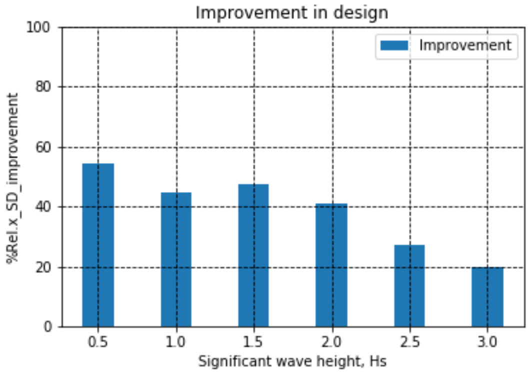


Figure 6:30 Percentage improvement in the performance of the proposed installation concept, in terms of relative surge motions, at the mating point with and without wire rope between spar & vessel for different Hs

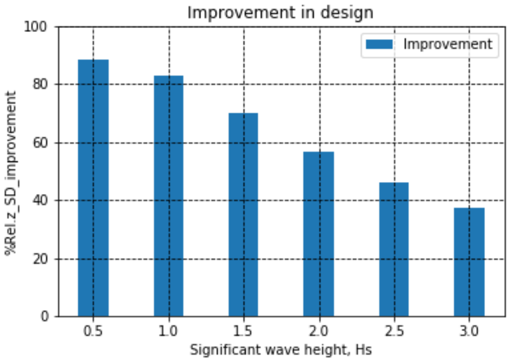


Figure 6:31 Percentage improvement in the performance of the proposed installation concept, in terms of relative heave motions, at the mating point with and without wire rope between spar & vessel for different Hs

Results of the simulation are shown in Figure 6:28 to Figure 6:29. Figure 6:30 and Figure 6:31 compares the standard deviation in relative motions in x and z directions between spar buoy and lifted tower. It can be observed from the graphs that larger motions happen in the absence of the proposed arrangement. When spar is lifted towards catamaran, spar tends to follow the motion of catamaran and hence reduces the differences between the motion of spar and tower as the tower is coupled to the catamaran. This is confirmed by the results plotted in Figure 6:30 and Figure 6:31.

6.3.3 Tensioned wire connecting floating spar buoy and lifted tower

Similar to the tensioned wire between spar buoy and catamaran, four tensioned wires are provided between spar buoy and lifted tower to keep the bodies inline while the mating process is underway. Two simulations are performed in SIMO with which one test includes the tensioned wire between the bodies and one without tensioned wire. In both cases, the tower is lifted to 3m above the spar buoy. The selected environmental parameters are Tp = 12 sec and 0-degree wave direction since this condition results largest tension in the wire connecting spar and OWT as per **Figure 6:7**. The results for both cases are compared for a range of significant wave heights, Hs = 0.5, 1.0 1.5, 2.0, 2.5 and 3.0 m (JONSWAP spectrum).

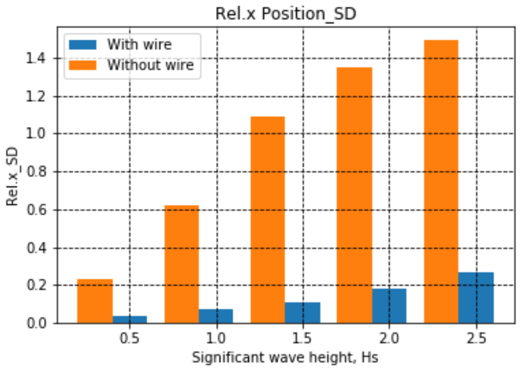


Figure 6:32 Comparison of Standard deviation of relative surge motions at the mating point with and without wire rope between spar & OWT for different Hs

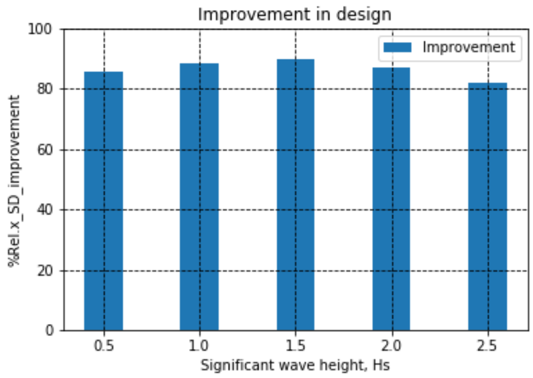


Figure 6:33 Percentage improvement in the performance of proposed installation concept, in terms of relative surge motions, by implementing wire rope between spar & OWT for different Hs

To check the relevance of suggested tensioned wire, standard deviation of relative motions at the mating point in x direction is estimated and plotted for the both cases in **Figure 6:33**. **Figure 6:33** shows that over 80% of the standard deviation of motions in x direction at the mating point are eliminated and it indicates the importance of the proposed arrangement. Even though the tensioned wire between spar and catamaran reduces the relative motions at the mating point by reducing the relative motions between catamaran and spar, it discards the fact that the tower is free to move in six degrees with some flexibility allowed by the coupling. So, by introducing a tensioned wire connecting spar and tower, these relative motions between tower and spar are taken care of.

6.3.4 Docking cone between lifted tower and spar buoy

As explained previously, a docking cone was provided to reduce the excessive relative motions of the tower and spar buoy during the mating process. To check the performance of the suggested docking cone, two tests with and without the docking cones was performed and a JONSWAP spectrum was considered for the simulation. Also, it is to be noted that in these two test cases, the tower is lifted and kept at 0.5 m above the spar buoy whereas in the other cases tower was placed at 3 m above the spar top. This is to make sure that the docking pin is inside the receiver cone and it is taking part during the simulation in SIMO. The selected environmental parameters are Tp = 12 sec and 0-degree and the results for both cases are compared for a range of significant wave heights, Hs = 2.0, 2.5, 3.0, 3.5 and 4.0 m.

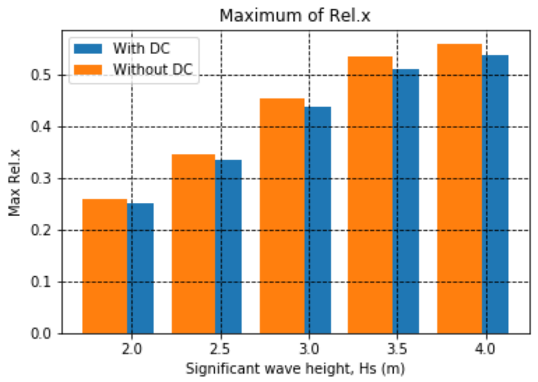


Figure 6:34 Comparison of Standard deviation of relative surge motions at the mating point with and without wire rope between spar & OWT for different Hs

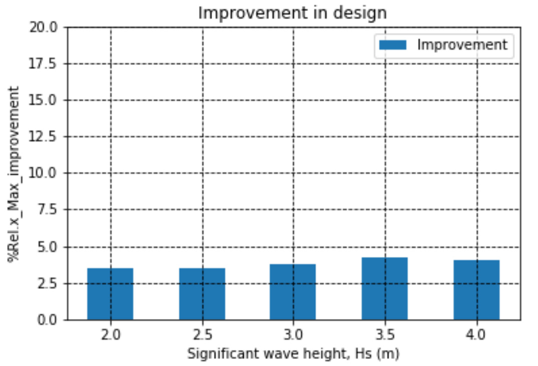


Figure 6:35 Percentage improvement in the performance of proposed installation concept, in terms of relative surge motions, by implementing wire rope between spar & OWT for different Hs

Figure 6:34 and **Figure 6:35** compares the maximum value of relative surge motion at the mating point for both cases and it is evident that even though introducing the docking cone into the model lead to an improved performance, the improvement in the performance is minimal in terms of relative surge. This is the consequence of low stiffness value modelled for the docking cone and once the stiffness value is increased, better performance can be expected. However, increasing the stiffness value can also lead to larger coupling forces and hence the stiffness of the docking cone should be selected after careful iteration.

6.3.5 Comparison of dynamic system responses with previous works

All of the previous tests looked upon how each of the individual modifications helped to reduce the dynamic response of the system. However, it is important to check how the system as a whole with the recommended modifications will respond to the external environment. In the paper (*jiang_et_al*), many simulations were performed to check how different parameters behave during installation. However, the focus of the previous investigation was restricted to dynamic responses in the horizontal plane and hence the results that is relevant for this study will be a comparison between the relative surge motions at the mating point in both cases. For this matter, a time domain analysis with similar environmental characteristics as applied in (*jiang_et_al*) was done in SIMO and the results were compared to that of the previous works in **Figure 6:36** and **Figure 6:37**. From **Figure 6:36** and **Figure 6:37**, it is clear that most of the relative surge motions are reduced and the percentage improvements achieved by concept design in each case are shown in **Figure 6:38** and **Figure 6:39**.

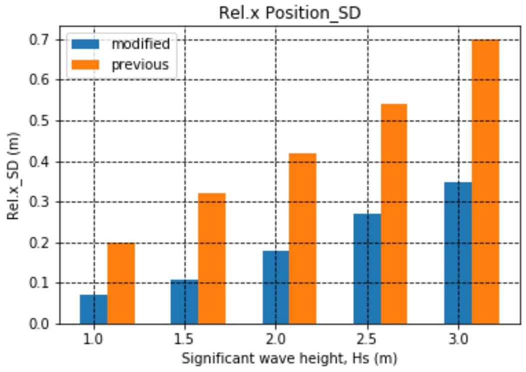


Figure 6:36 Comparison of Standard deviation of relative surge motions at the mating point with the results from previous works for different Hs

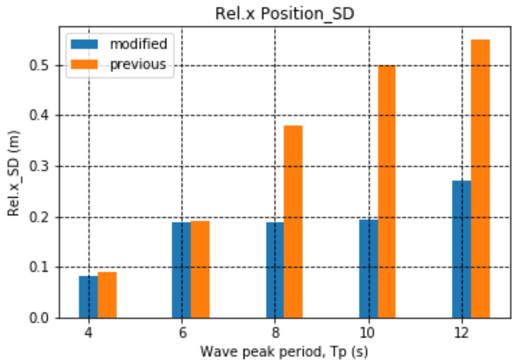


Figure 6:37 Comparison of Standard deviation of relative surge motions at the mating point with the results from previous works for different Tp

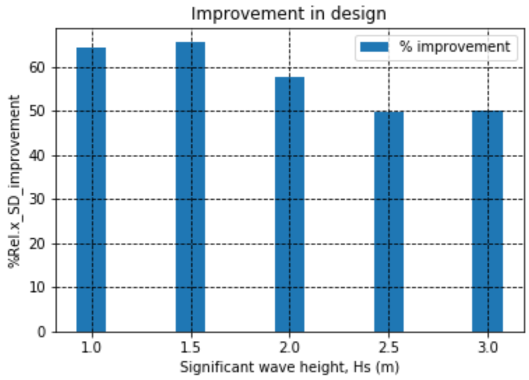


Figure 6:38 Percentage improvement in the performance of proposed installation concept, in terms of relative surge motions, at the mating point with the results from previous works for different Hs

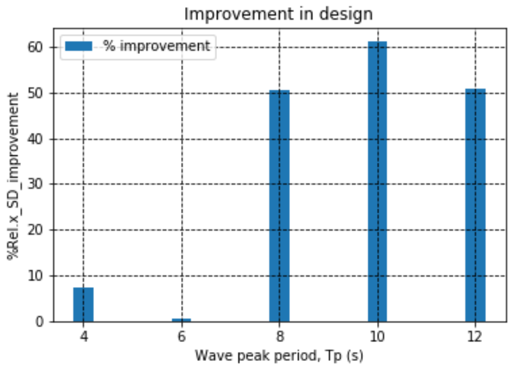


Figure 6:39 Percentage improvement in the performance of proposed installation concept, in terms of relative surge motions, at the mating point with the results from previous works for different Tp

Chapter 7

Estimation of Limiting Weather

This section estimates the maximum allowable sea states for conducting the mating operation of offshore wind tower and spar buoy safely. A series of simulations are performed with different combinations of significant wave height, Hs and peak time periods, Tp and the results are compared with the defined limiting criteria.

7.1 Methodology for Estimating the Limiting Sea States

A systematic approach aided with numerical analysis is implemented to find the operational limits for the mating operation*. The methodology followed for this purpose is derived from the guidelines mentioned in **Acero et al**(21). **Figure 7:1** summarises the steps followed in this process.

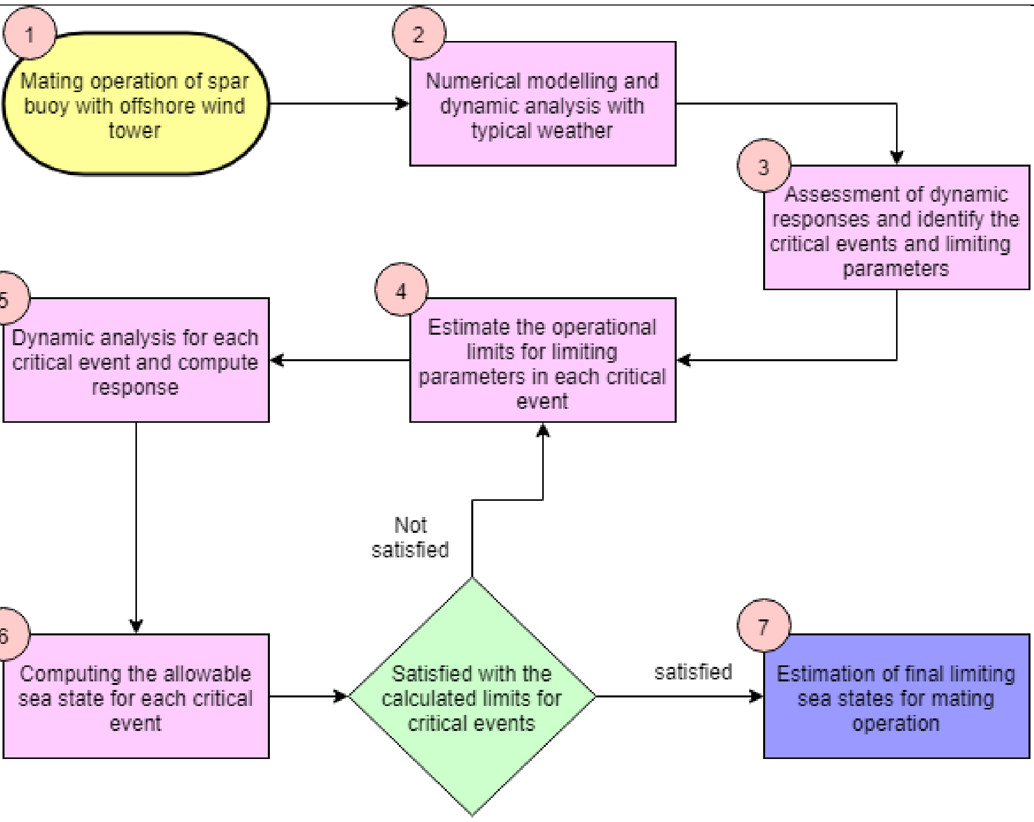


Figure 7:1 Methodology to find the limiting sea state for mating operation

* As stated before, the scope of this thesis is restricted to the events taking place after initiating the mating process and before the transfer of the tower to the top of the spar buoy.

A brief explanation of each of the steps defined in Figure 7:1 is given below.

1. **Mating of spar tower with spar buoy**

   Installation process of wind turbine on top of spar buoy includes many stages of operations as specified in Figure 2:7 and mating operation is just one of them. Prior to actual installation operation, allowable limits for all intermediate operations have to be estimated but due to the limited scope of this project, only the limiting weather conditions for mating operation is calculated here.

   Mating operation* of tower and spar buoy itself can be subdivided into two instances, namely,

   - Starting of operation

     This stage corresponds to the initial phase of mating operation and the tower is kept 3 m above the spar buoy.

   - Completion of operation

     This stage corresponds to the final phase of mating operation and the tower is kept 0.5 m above the spar buoy.

2. **Numerical modelling and global dynamic analysis**

   In SIMO, a numerical model of both of the installation scenarios are created, and a global dynamic analysis of the above operation with a typical weather is performed

3. **Assessment of dynamic responses and identify the critical events and limiting parameters**

   The results from the simulations are investigated for potential critical events which may jeopardise the installation process. Once the critical events are identified, further analysis is done to pinpoint the limiting parameters that initiates the events.

4. **Estimate the operational limits for limiting parameters in each critical event**

   Allowable limits for the limiting parameters in each critical event are investigated based on various factors such as tension in the lifting wire, impact forces etc.

5. **Dynamic analysis for each critical event and compute response**

A time domain analysis is performed for each critical event and the responses are recorded.

6. **Computing the allowable sea state for each critical event**

   On comparing the system responses of the dynamic analysis with allowable limits for each limiting parameter, allowable sea state for each critical event is plotted. If calculated allowable sea states are very low, operational limits for the governing limiting parameter are increased.

7. **Estimating the limiting sea states for mating operation**

   Finally, limiting sea state for the mating operation is decided by comparing the allowable sea states for each of the critical event and finding the lowest allowable wave height for each Tp.

7.2 Calculation of Limiting Sea States

On following the steps depicted in **Figure 7:1**, numerical modelling of the process was completed and detailed in chapter **SIMO Modelling**. In SIMO model, two scenarios are modelled and tested to estimate the limiting sea states. First will be where the tower is lifted by winches from catamaran and kept at a distance of 3 m above the top of spar buoy and in the second case, the tower is kept just above the spar buoy (precisely speaking, 0.5 m above the spar top). In Chapter **Analysis of the Coupled System**, a global analysis of the first case was performed and then explored the dynamic responses of the system for different environment parameters. **Appendix D** details the dynamic response of system when the tower is lifted and placed 0.5 m above spar top. It can be observed that in both cases, generally the system shows similar response pattern and hence same critical events are assumed for both scenarios.

7.2.1 Identification of Critical Events and Limiting Parameters

There are several possibilities that the mating operation of wind tower to the spar buoy can be unsuccessful. A root cause study of the mating operation was performed to recognise the critical events and is shown in **Figure 7:2**.

From the failure root cause study of the mating operation, three main issues that can lead to the failure of the intended operation were identified and they are:

- Excessive motions at the mating point

  Mating operation between tower and spar buoy under dynamic environment requires high precision and during the mating process, both bodies should be vertically aligned for most of the time. Hence it is necessary that excessive motions at the mating point should be avoided. Motions at the mating point can be decomposed to two components namely, motions in the horizontal plane and that of in vertical plane. These responses are a direct result of environmental parameters and their trend was analysed in section 6.2.

- Failure of lifting module

  The wind turbine is lifted by the lifting module using the lifting wires from winches and it is important to have high reliability factor for this component. Considering the restricted scope of this study, three limiting parameters for the successful operation of the winches were established. First one corresponds to the tension in the lifting wires during operation is underway. At any point of time, tension in the lifting wires should not exceed the allowable limits set prior the operation. Similarly, forces in the roller supports are limited to the allowable limits of the shock absorbers installed. Thirdly, it is vital to ensure that the winches have adequate power to cope up with the dynamic responses of the system. High responses demand for more power to keep up with tension requirements in the lifting wires and hence is significant in this regard.

- Failure of horizontal motion compensation system

  Failure of horizontal motion compensation system which includes wire ropes and winches connecting the three bodies can lead to an unsuccessful installation attempt of wind tower. There are several factors that can affect the performance of the system however, only two limiting parameters namely, tension in the wire connecting spar and tower and that of spar and catamaran, are selected due to restricted scope of the report.

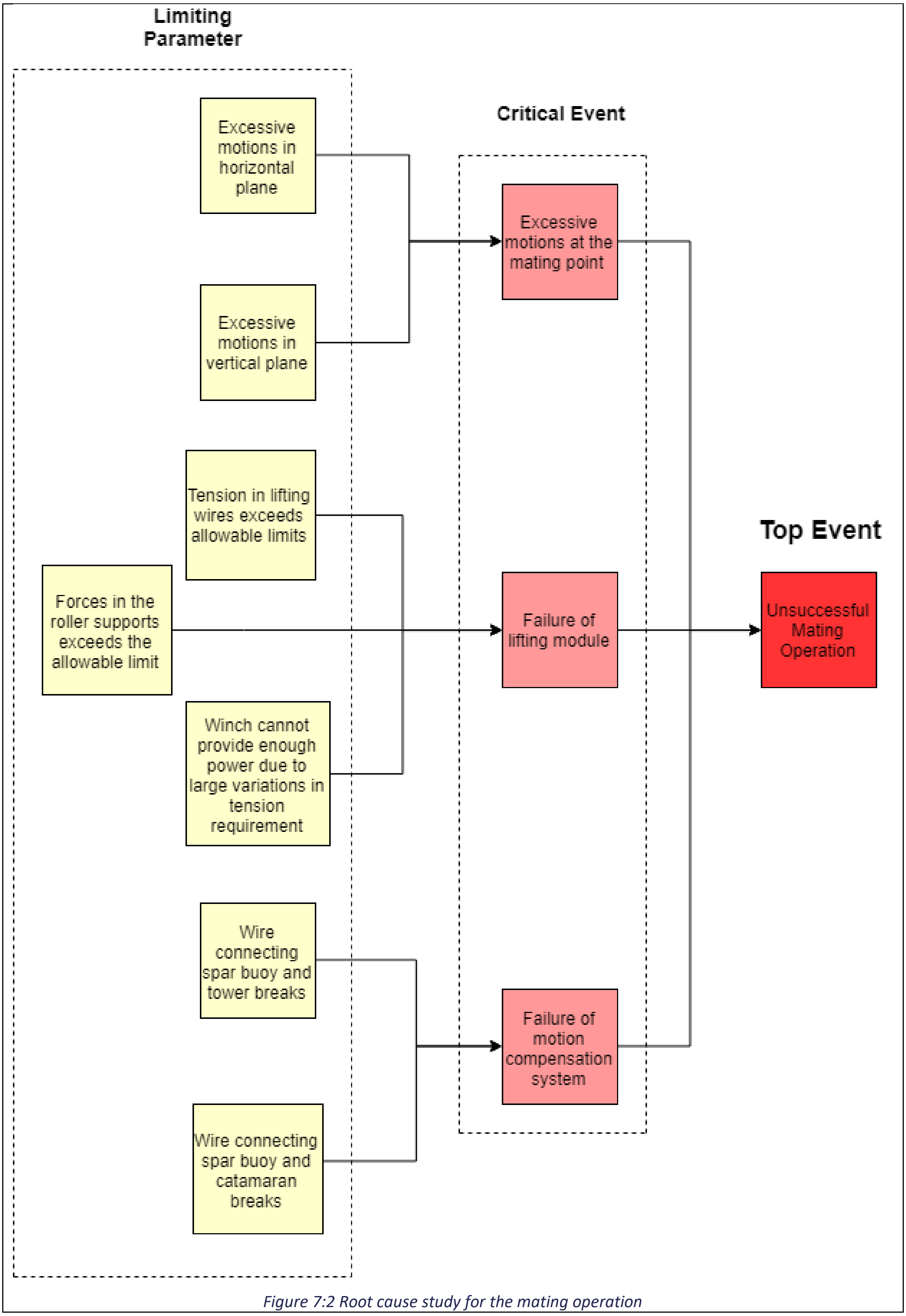


Figure 7:2 Root cause study for the mating operation

7.2.2 Fixing the Allowable Limits for Limiting Parameters

Typically, allowable limits for the limiting parameters depends on the components used in the installation, for example in this case, SWL of the wire rope used for lifting and in the motion compensation system, SWL of the shock absorbers used for roller supports, capacity of the installed winch etc. As a result, it is a prerequisite to define the components that is supposed to be installed in the vessel before estimating the limiting weather. These components are selected based on some samples available in the market. As for the failure of the lifting module due to large variations of tension in the lifting wires, the allowable limits should be expressed in terms of instantaneous power demand on winch. Unfortunately, SIMO does not perform a detailed power calculation for winch nor it is within the scope of this project and hence standard deviation of tension in the lifting wires is used as a benchmark to measure the power requirement in winch. It is to be noted that for both phases of the mating operation, same allowable limits are assumed for the above-mentioned limiting parameters.

Allowable limits for the motions at the mating point has to be decided from the previous experiences and an approximate estimate of these values are selected for this report. Regarding the horizontal motions, the term relative radius, ϑ which is defined as distance between the centres of tower and spar buoy, is used as the criteria. In this project, the maximum allowable relative radius (ϑ) is defined as 0.5 m and 0.3 m for initial and final phases respectively. It is logical to assume that as the tower is lowered towards spar, the operation become more critical and hence the range of allowable maximum motions in horizontal plane will get narrower.

Regarding the motions in vertical direction, it is not possible to explicitly define the maximum allowable limit at this stage of design. Also, the allowable vertical motions tend vary depending on different stages of the operation for example, the range of maximum values get smaller as the distance between the bodies are decreased. However, for the purpose of estimating the limiting sea state, an allowable limit has to be specified. Subsequently, the allowable maximum value for the relative motions at the mating point is set as 0.4 m and 0.2 m for the first and second phases respectively.

Table 7:1 lists the acceptable values for the limiting parameters in each critical event.

Table 7:1 Allowable limits to the limiting parameter of critical events

Stages of Mating Operation	**Critical Event**	**Limiting Parameters**	**Property**	**Allowable Limits**
Initial phase	Excessive motions at the mating point	Excessive motions in horizontal plane	Relative radius, m	0.5
		Excessive motions in vertical plane	Maximum relative vertical motion, m	0.4
Final phase		Excessive motions in horizontal plane	Relative radius, m	0.3
		Excessive motions in vertical plane	Maximum relative vertical motion, m	0.2
Initial & final phase	Failure of lifting module	Tension in lifting wires exceeds allowable limits	Maximum tension in lifting wires, MT	400
		Forces in the roller supports exceeds the allowable limit	Maximum impact force, MT	300
		Winch cannot provide enough power due to large variations in tension requirement	Standard deviation in tension in lifting wires, MT *	40
Initial & final phase	Failure of motion compensation system	Wire connecting spar buoy and tower breaks	Maximum tension in lifting wires, MT	200
		Wire connecting spar buoy and catamaran breaks	Maximum tension in lifting wires, MT	500

* Standard deviation in lifting wires is used as standard for measuring the winch power demand

7.2.3 Dynamic Response Analysis

Before estimating the limiting sea states for the mating operation, it important to choose the site of installation and the weather characteristics at the site. In (ref), ‘Norway 5’ site was chosen for the test condition and same will be followed in this project. Series of simulations lasting 1800 sec and with wave characteristics shown in Table 7:2 were done for estimating the limiting sea state.

Table 7:2 Selected environmental conditions to estimate the limiting sea states

Item	**Wave Spectrum**	**Significant Wave Height, Hs (m)**	**Peak Wave Period, Tp (sec)**	**Direction (deg)**
1	JONSWAP spectrum	0.50	4,6,8,10,12,14,16,17,18	0,30
2		0.75	4,6,8,10,12,14,16,17,18	0,30
3		1.00	4,6,8,10,12,14,16,17,18	0,30
4		1.25	4,6,8,10,12,14,16,17,18	0,30
5		1.5	4,6,8,10,12,14,16,17,18	0,30
6		1.75	4,6,8,10,12,14,16,17,18	0,30
7		2.00	4,6,8,10,12,14,16,17,18	0,30
8		2.25	4,6,8,10,12,14,16,17,18	0,30
9		2.5	4,6,8,10,12,14,16,17,18	0,30
10		2.75	4,6,8,10,12,14,16,17,18	0,30
11		3.00	4,6,8,10,12,14,16,17,18	0,30

In previous section, the allowable limits for the limiting parameters were fixed so that they can be used as a benchmark for further comparisons. However, since the sea environment is defined as a statistical distribution of ocean waves, it is inappropriate to use the maximum response value obtained from one simulation with one wave seed to compare with the limiting parameters. Hence, it is necessary to express the maximum response value in statistical terms. As a consequence, the most probable maximum value is selected as the response of the system to compare with the limiting values and hence estimate the limiting sea states.

Since the waves are Rayleigh distributed, it is safe to assume that the system responses are also Rayleigh distributed and hence the most probable value for the system response for ‘N’ number of amplitudes over the simulation time considered can be defined as

$$R_{max} = \sigma \sqrt{2 \ln(N)} \qquad \text{Eqn 2}$$

Table 7:3 Parameter definitions

Item	Details
R_{max}	Most probable maximum value
σ	Standard deviation of the system response
N	Number of amplitudes in considered simulation time

Even though it is reasonable to use R_{max} to estimate the limiting sea states, the possibility to exceed this value cannot be neglected. A statistical distribution of extreme values can be calculated and the probabilities for waves higher than the most probable maximum value can be estimated. However, considering the restricted scope of this project and inadequate information about the installation setup, it is decided to proceed with the R_{max} value calculated.

For the properties with non-zero mean values such as tension in the lifting wire, forces in roller supports etc, maximum probable value is calculated by summing the mean value with the result of **Eqn 2.**

7.2.4 Computing the allowable sea state for each critical event

After analysing the dynamic response of the system for various limiting parameters, maximum allowable sea state in which the mating operation can be performed without exceeding the allowable limits for different limiting parameters for both 0 and 30 degree wave direction are plotted from **Figure 7:3** to **Figure 7:9**.

On analysing the trend of limiting weather plotted for different limiting parameters, in most of the peak period, Tp, it is the impact forces in the roller supports that is determining the limiting weather for the mating operation. Limiting parameter, “tension in wire connecting spar and OWT”, seems to have low limits of allowable weather in lower periods at 30-degree wave direction.

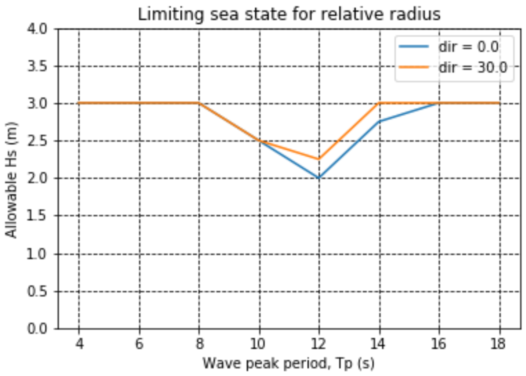


Figure 7:3 Limiting sea state for limiting parameter – relative radius between bodies

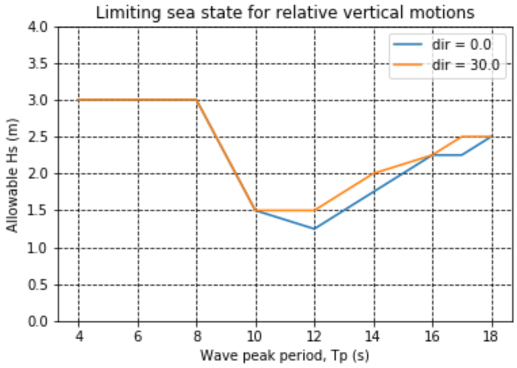


Figure 7:4 Limiting sea state for limiting parameter – relative vertical distance between bodies

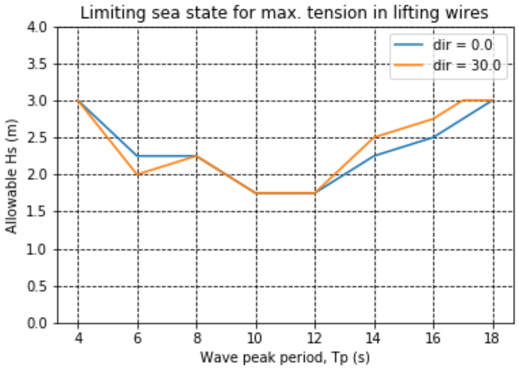


Figure 7:5 Limiting sea state for limiting parameter- maximum tension in OWT lifting wire

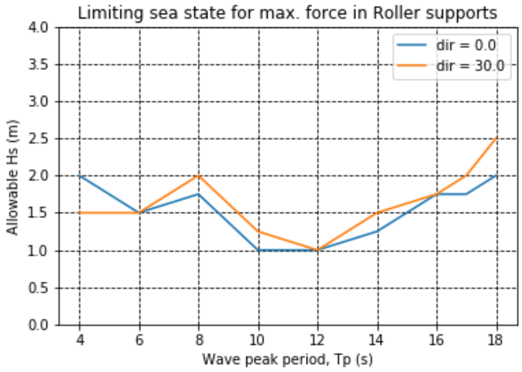


Figure 7:6 Limiting sea state for limiting parameter- maximum impact force in roller

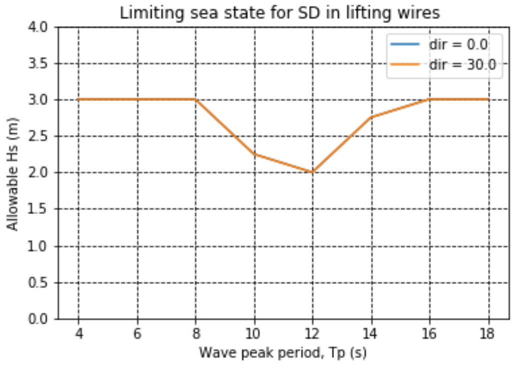


Figure 7:7 Limiting sea state for limiting parameter- maximum standard deviation of tension in OWT lifting wire

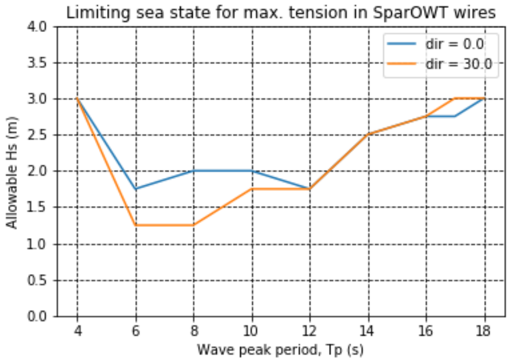


Figure 7:8 Limiting sea state for limiting parameter- maximum tension in wire connecting spar buoy and OWT

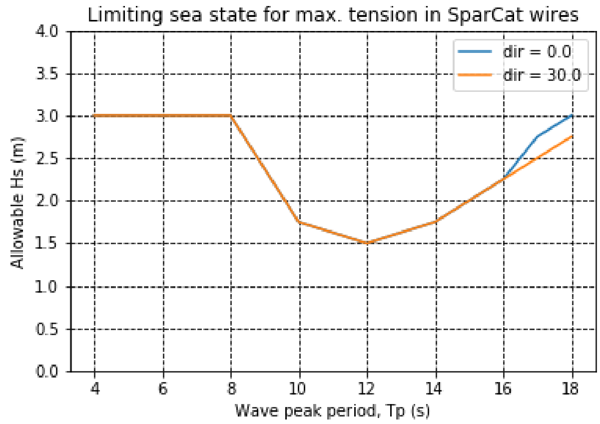


Figure 7:9 Limiting sea state for limiting parameter-maximum tension in wire connecting spar buoy and catamaran

7.2.5 Estimating the limiting sea states for mating operation

Limiting sea states for different limiting parameters of critical events are compared and the allowable sea state for conducting the mating operation safely was calculated based on the governing value (lowest value of Hs for each Tp) among all the limiting parameters. **Figure 7:10** plots the limiting sea state for the mating operation.

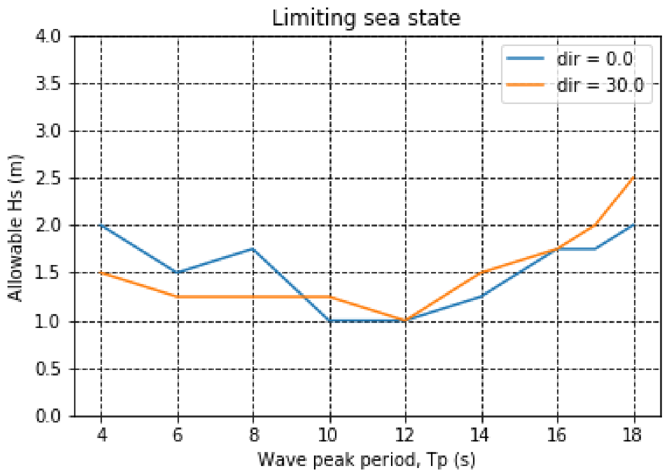


Figure 7:10 Final limiting sea state estimated for proposed mating operation

On analysing **Figure 7:10,** the lowest allowable limits are in the range of peak periods 10 and 12 sec which is a consequence of higher motion responses of the system in these peak period as documented in section **6.2.1**. As for the direction of the incoming waves, it is observed that lower periods are more vulnerable to 30 degrees wave direction whereas at higher periods, 0-

degree direction seem to have a greater effect on determining the limiting Hs for the mating operation.

Chapter 8

Discussions and Conclusion

It was a novel proposal from NTNU to utilize catamaran for the installation of wind turbines instead of proceeding with existing solutions such as weather sensitive heavy lift cranes or with jack-up barges with depth restrictions. This thesis was focussed on analysing the dynamic behaviour of the recommended system during the mating stage of the installation procedure and also in suggesting possible modifications to improve the overall performance of the coupled system. Subsequently, a numerical model of the installation scenario was modelled in SIMO environment and several adjustments to base model was tested and later modelled in SIMO environment to analyse the response of the system.

After a series of tests and trials, final configuration of the installation setup was determined where it includes both horizontal and vertical motion compensation systems to reduce the dynamic responses. The installation setup was modelled in SIMO with the recommended changes and numerous tests were performed to assess the improvements in the design concept, in terms of relative motions, by incorporating the modifications. Time domain analysis of the modelled coupled system was performed and the trends in dynamic response of the coupled system under varying environmental conditions were investigated. Later, based on previous results, limiting sea states for mating operations were estimated after executing a series of tests in SIMO.

Examining the results obtained from this project, following conclusions can be reached:

- Incorporating heave compensation and horizontal motion compensation systems have improved the overall performance of the system in terms of relative motions.
- The proposed system was tested under varying environmental conditions (peak wave period (Tp), Significant wave height (Hs) and wave direction (β)). Generally, the proposed system exhibits higher responses at Tp = 12 sec and response amplitudes increases as the significant wave height (Hs) increases. Dynamic

response of the system generally reduces as the incoming wave direction deviates from 0 to 30 degrees (wave direction parallel to stern is assumed to be 0 degree).

- It was observed that pitch motions of the catamaran have a significant influence on the relative motions at the mating point especially, regarding the relative heave and surge motions between the bodies.
- It was observed that the vertical component of the coupling force is significantly higher than the other two components (**Figure 6:23, Figure 6:24, Figure 6:25**) and hence the variations in vertical component influences the total coupling force the most. Therefore, to reduce the coupling forces in the connection elements between the bodies, efforts must be concentrated to reduce the relative motions in vertical direction between the bodies.
- Three critical events were selected and limiting sea states for 2 incoming wave directions (0 & 30 deg) were estimated based on the allowable limits of the limiting parameters for the mating operation. It was observed that the mating operation is limited by the forces in coupling elements rather than the relative motions criteria. In most of the cases, it is possible to increase the allowable limits for the coupling element by implementing a ‘bigger’ equipment for the installation whereas, it is complicated and difficult to increase the performance of the coupled system in terms of relative motions compared to the coupling forces. Hence, there exists a possibility to improve the weather limitations of the mating operation with this proposed concept by selecting different components for the OWT installation.

Throughout this project, attempts were made to comprehend the dynamic behaviour of the proposed installation concept of using catamaran as installation vessel. As previously explained, different approaches were tried during the process to reach the goal. Many assumptions were made along the process due to the lack of available information as the concept is still in initial stages and is developing. Some of the key points regarding the numerical modelling and installation concept are listed below:

- The stiffness and damping values for lifting wires, roller supports and docking cones are critical in determining the natural frequencies of the coupled system and affects the dynamic responses of the model. Hence the response and trends shown in this thesis are specific to this modelled system and one cannot expect similar responses with different parameters.

- To reduce the vertical relative motions, a heave compensation winch module based on PID controller was incorporated into the model and its parameters were tuned to have a decent response. However, considering the scope and objectives of this project, tuning of the PID controller was a secondary task and hence limited time was invested in this regard. Consequently, it may be possible to obtain better results if more time and efforts were put to tune the controller or even change to different controller such as PD + feed forward controllers.
- The heave compensation module developed as part of SFI project was focussed in controlling the lifted object and following the motion of the spar buoy and thereby reducing the relative heave motions between them. However, it is inappropriate to not to acknowledge the fact that the developed heave compensation module almost entirely neglects the internal mechanism of the lifting winches such as the hydraulic properties, stroke length, cylinder cross section area etc
- A detailed design of the different components proposed in this thesis was out of the scope of this project and hence some of the minor challenges were overlooked during the design. One of them is the design of the roller supports were a shock absorber consisting of spring and damper was suggested. From the numerical analysis, it was observed that impact forces on the roller supports while correcting the tower angle are not completely along the x axis, but rather was making an angle with the vertical axis. This is a serious issue regarding the design of the roller supports especially considering the large amount of forces involved during the installation process. If not properly corrected, it can lead to metal to metal contact and later structural failures.
- The limiting sea states were established based on the allowable limits of limiting parameters for each critical event. However, at this stage, it is unrealistic to decide the safe working load (SWL) or the capacity of the lifting modules etc. Therefore, further modifications in the allowable limiting weather should be expected as the design progresses.

Chapter 9

Future Works

The preliminary intention of this thesis was to lay the foundation for the further research works on using catamaran as an installation vessel for the offshore wind turbines. Taking this into account, some of the tasks that can be persuaded in future is listed below.

- This project was concentrated on designing, modelling and analysing the dynamic responses of the involved bodies during the mating operation. Nonetheless, after the mating operation, total weight of the tower will be transferred to the top of the spar buoy and it causes for the sudden large increment in the draft of the combined system and complex dynamic responses can be expected during this transient stage. Therefore, further studies on this intermediate stage must be conducted and responses should be documented.
- Characteristics of the station keeping components such as tension in mooring lines, arrangement of the mooring lines, DP control forces etc were not discussed in this report. It is worth to invest efforts in this regard especially the mooring arrangement of spar buoy as the ultimate objective is to achieve lowest possible relative motions between the involved bodies.
- The environmental properties considered for this project consists of only waves. Modelling the wind characteristics in the simulation model can bring the modelled system closer to the actual installation scenario at site.
- In current installation concept, roller supports were used to keep the tower upright during the mating operation. Even though it is feasible to use roller supports for this purpose, less sophisticated options have to be explored. One of the potential alternatives will be to use an additional set of tensioned wires from the winches in the lifting module to keep the lifted tower stable. More research works have to be done in this regard to determine how satisfactory is the suggested alternative.

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Appendix A – Tuning of Heave Compensator

One of the objectives of the thesis was to implement a heave compensation module to reduce the relative heave motions between the lifted tower and spar buoy. For this purpose, an external controller based on the PID controller was incorporated into the SIMO model. It is important to tune the PID controller parameters (namely, proportional gain (k_p), integral gain (k_i) and derivative gain (k_d)) to obtain satisfactory results and hence the following strategy was implemented. The tuning strategy was borrowed from reference (20)

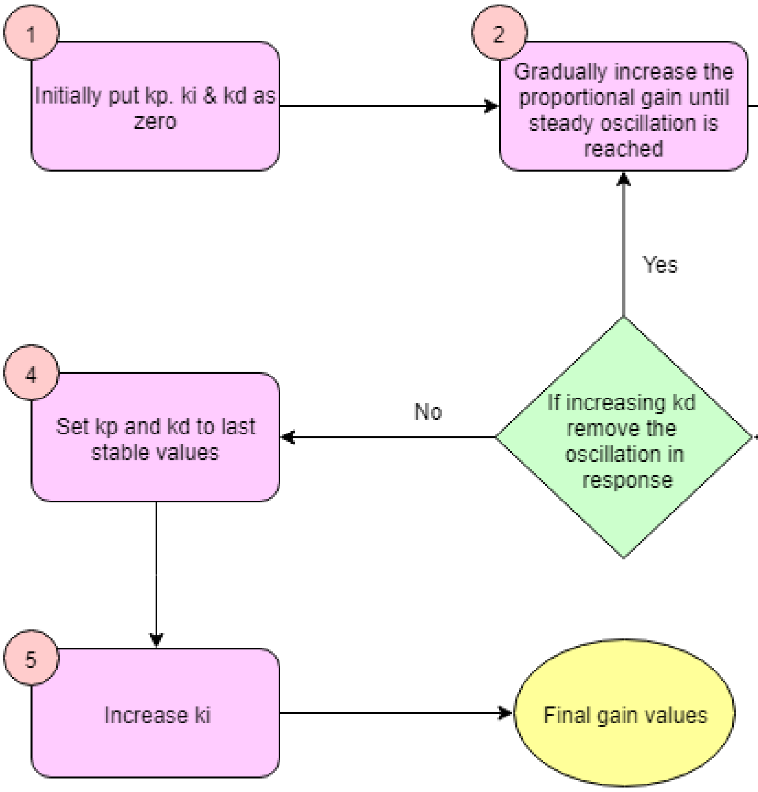

Figure A.:1 Methodology for tuning the heave compensator

A brief explanation of each of the steps defined in **Figure A.:**1 is given below.

1. Initially put k_p, k_i and k_d as zero

In step 1, the gain factors are set to zero and a simulation is run and the relative motion between the bodies in vertical direction is recorded.

2. Gradually increase the proportional gain until steady oscillation is reached

The proportional gain is increased slowly so that steady oscillation can be observed.

3. Increase the derivative gain so that the oscillations due to $\boldsymbol{k_p}$ are removed

In this stage, slowly increase the magnitude of the $\boldsymbol{k_d}$ so that the motion is critically damped, and the oscillations are gone.

4. Check if increasing $\boldsymbol{k_d}$ remove the oscillation in response

Steps 2 and 3 are performed again until the oscillation are not removed by further increasing the $\boldsymbol{k_d}$.

5. Increasing $\boldsymbol{k_i}$

The integral gain is increased to check if there is any reduction in the response of the system. $\boldsymbol{k_i}$ and $\boldsymbol{k_d}$ are set to previous stable values.

Appendix B – Pretensioning of Wire Connecting Spar Buoy and Catamaran

To reduce the relative motions between spar buoy and tower, one of the proposed methods was to lift the spar buoy using a pretensioned wire from catamaran and in this way, the spar buoy follows the motion of catamaran and hence less relative motions between spar and tower.

In SIMO, there is no explicit method to pretension the simple wire coupling and hence tp tension the wires connecting the spar and catamaran, the length of the wires is defined as a smaller value than the required value (8 m) calculated based on the initial distance between the connection points on spar buoy and catamaran. This allows the wires to be pre-tensioned and thereby lifts the spar buoy to a certain distance above the water. This replicates the action of a winch providing the tension to the wire ropes. Series of tests were performed to determine the amount of pretension in the wires connecting spar buoy and catamaran. In all the tests, Hs, Tp and wave direction are set to 2 m, 12 sec and 0 degrees and the pretension is varied by changing the length of wire coupling from 2 m to 10 m. The results of the simulations are shown in **Figure 1** to **Figure 4**.

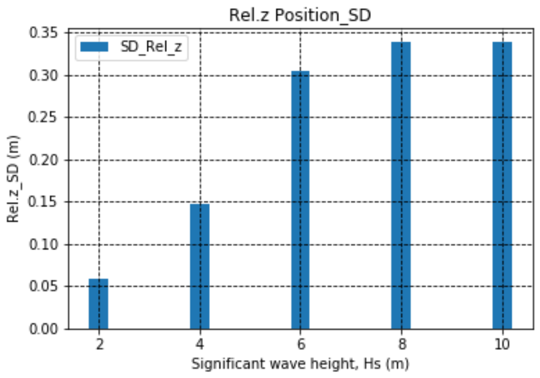

Figure 1 Standard deviation of relative heave motion at the mating point for different pretension values (length of wire)

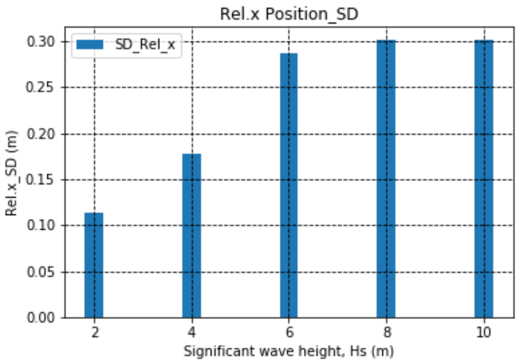

Figure 2 Standard deviation of relative surge motion at the mating point for different pretension values (length of wire)

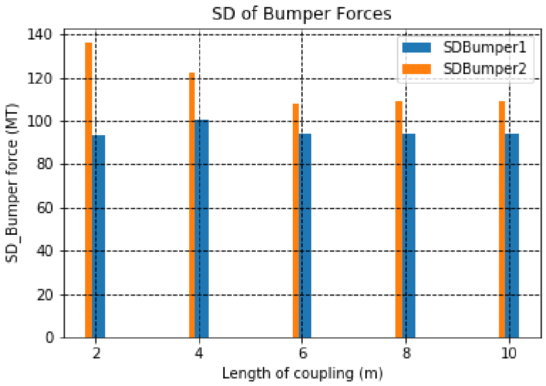

Figure 3 Standard deviation of forces in bumper eleent for different pretension values (length of wire)

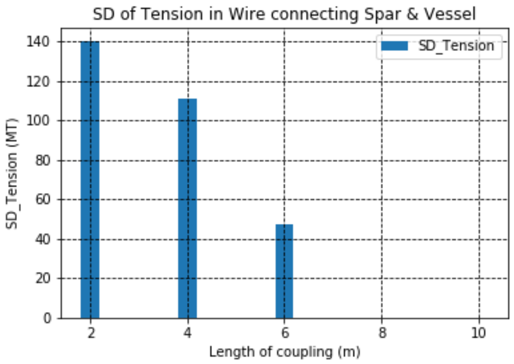

Figure 4 Standard deviation of tension in wire connecting spar and catamaran for different pretension values (length of wire)

Examining the results, it is clear that setting a high pretension in the coupling element can lead to lower relative motions between the spar buoy and tower, but on the other hand, it can also cause to increase the variations in the magnitude of the coupling forces in bumper and wire elements. Once the length of the wire coupling crosses the required length (8 m) calculated based on the initial distance between the connection points on spar buoy and catamaran, the responses become constant as there is no pretension in wires and hence loses its significance. The length of the wire was selected as 4 m as choosing a smaller length can lead to higher coupling forces whereas choosing longer wire length can results to unacceptable relative motions between the bodies.

Appendix C – Eigen values

```
SIMO_EIG_FILE
26-MAY-2019 15:02
'FILEPART
EIVA
'Natural periods in top row with corresponding eigen vectors below
'
Body    Mode  Excursion    0.73      0.73      1.21      2.44      3.99      4.17
'------------ --------- -------   -------   -------   -------   -------   -------
Catmrn  SURGE 1.00(m)      0.00      0.00      0.00      0.28     -0.00     -0.00
Catmrn  SWAY  1.00(m)     -0.00     -0.00     -0.00     -0.02     -0.00     -0.00
Catmrn  HEAVE 1.00(m)     -0.00     -0.00      0.00     -0.22     -0.00      0.00
Catmrn  ROLL  1.00(deg)   -0.00      0.00     -0.00     -0.03      0.00     -0.00
Catmrn  PITCH 1.00(deg)    0.00     -0.00      0.00     -1.00      0.00      0.00
Catmrn  YAW   1.00(deg)   -0.00      0.00     -0.00     -0.10     -0.00     -0.00
OWT     SURGE 1.00(m)      0.03     -1.00      0.00     -0.00      0.01      0.31
OWT     SWAY  1.00(m)     -1.00     -0.03      0.00      0.00      0.02     -0.09
OWT     HEAVE 1.00(m)     -0.00     -0.00     -1.00      0.00      0.00      0.00
OWT     ROLL  1.00(deg)   -0.38     -0.01     -0.00      0.00      0.06     -0.29
OWT     PITCH 1.00(deg)   -0.01      0.38     -0.00      0.00     -0.02     -1.00
OWT     YAW   1.00(deg)    0.43      0.00      0.06     -0.00      1.00     -0.03
Spar    SURGE 1.00(m)      0.00      0.00     -0.00      0.08      0.00     -0.00
Spar    SWAY  1.00(m)      0.00      0.00      0.00      0.01     -0.00     -0.00
Spar    HEAVE 1.00(m)     -0.00     -0.00      0.00      0.80     -0.00      0.00
Spar    ROLL  1.00(deg)   -0.00     -0.00     -0.00     -0.02      0.00     -0.00
Spar    PITCH 1.00(deg)    0.00      0.00      0.00      0.09      0.00     -0.00
Spar    YAW   1.00(deg)    0.00      0.00     -0.00     -0.11     -0.00     -0.00
'
Body    Mode  Excursion    4.63      6.46      6.59      7.77      8.04      9.56
'------------ --------- -------   -------   -------   -------   -------   -------
Catmrn  SURGE 1.00(m)     -0.00     -0.01      0.00     -0.00     -0.17     -0.00
Catmrn  SWAY  1.00(m)     -0.00     -0.03      0.02     -0.00      0.01     -0.21
Catmrn  HEAVE 1.00(m)     -0.00     -0.66     -0.33     -0.00     -0.28     -0.00
Catmrn  ROLL  1.00(deg)    0.00     -0.51      0.46     -0.01     -0.01     -1.00
Catmrn  PITCH 1.00(deg)    0.00      0.53      0.20     -0.00     -0.03     -0.00
Catmrn  YAW   1.00(deg)   -0.00     -0.58      0.48     -0.01      0.01      0.20
OWT     SURGE 1.00(m)      0.00     -0.00      0.00     -0.00      0.00      0.00
OWT     SWAY  1.00(m)      0.01      0.00     -0.00      0.00     -0.00      0.00
OWT     HEAVE 1.00(m)     -0.00     -0.00     -0.00     -0.00     -0.00      0.00
OWT     ROLL  1.00(deg)    0.03      0.00      0.00     -0.00     -0.00      0.00
OWT     PITCH 1.00(deg)   -0.01      0.00      0.00      0.00     -0.00     -0.00
OWT     YAW   1.00(deg)   -1.00     -0.00     -0.00      0.00      0.00     -0.00
Spar    SURGE 1.00(m)      0.00     -0.79     -0.35      0.00      0.82      0.01
Spar    SWAY  1.00(m)     -0.00     -0.84      0.83     -0.00     -0.06      0.41
Spar    HEAVE 1.00(m)     -0.00      0.09      0.02     -0.00     -0.42     -0.00
Spar    ROLL  1.00(deg)    0.00      1.00     -1.00      0.00      0.07     -0.47
Spar    PITCH 1.00(deg)    0.00     -0.95     -0.43      0.00      1.00      0.01
Spar    YAW   1.00(deg)    0.00     -0.93      0.78      1.00     -0.15     -0.14
```

```
'
Body    Mode  Excursion   15.91     31.49     35.78    229.65    260.10     35.80
'------------ --------- -------   -------   -------   -------   -------   -------
Catmrn  SURGE 1.00(m)     -0.44      0.32     -0.57     -0.81      0.96      0.06
Catmrn  SWAY  1.00(m)     -0.04      0.23      0.18     -0.82     -0.78      0.44
Catmrn  HEAVE 1.00(m)     -0.05      0.01      0.01      0.01     -0.01     -0.03
Catmrn  ROLL  1.00(deg)   -0.00     -0.06     -0.03     -0.02     -0.02      0.05
Catmrn  PITCH 1.00(deg)    0.67     -0.09     -0.05     -0.03      0.04      0.13
Catmrn  YAW   1.00(deg)   -0.37     -0.37     -0.09      0.13     -0.08      1.00
OWT     SURGE 1.00(m)     -0.00      0.00     -0.00     -0.00     -0.00      0.00
OWT     SWAY  1.00(m)     -0.00      0.00     -0.00     -0.00     -0.00     -0.00
OWT     HEAVE 1.00(m)      0.00      0.00     -0.00      0.00     -0.00     -0.00
OWT     ROLL  1.00(deg)   -0.00      0.00     -0.00     -0.00     -0.00     -0.00
OWT     PITCH 1.00(deg)    0.00     -0.00      0.00      0.00      0.00     -0.00
OWT     YAW   1.00(deg)    0.00     -0.00      0.00      0.00     -0.00      0.00
Spar    SURGE 1.00(m)      0.81     -0.05     -0.10     -0.84      1.00      0.20
Spar    SWAY  1.00(m)      0.36      0.28      0.06     -1.00     -0.63     -0.77
Spar    HEAVE 1.00(m)      0.91     -0.16     -0.10     -0.02      0.04      0.26
Spar    ROLL  1.00(deg)   -0.53     -1.00     -0.50      0.02      0.01      0.54
Spar    PITCH 1.00(deg)    1.00      0.23     -1.00     -0.02      0.06      0.26
Spar    YAW   1.00(deg)   -0.20     -0.26     -0.07      0.09     -0.05      0.64
```

Appendix D – Dynamic Response Analysis of System When Tower is 0.5m Above Spar Buoy

Similar to the coupled analysis of the system performed in section **6.2.1**, time domain analysis of the coupled system when the tower is lifted and placed 0.5 m above the spar buoy is performed. The chosen environmental parameters are Hs=2 m and wave direction = 0 degrees. The results of the simulation are shown in **Figure 5** to **Figure 12**.

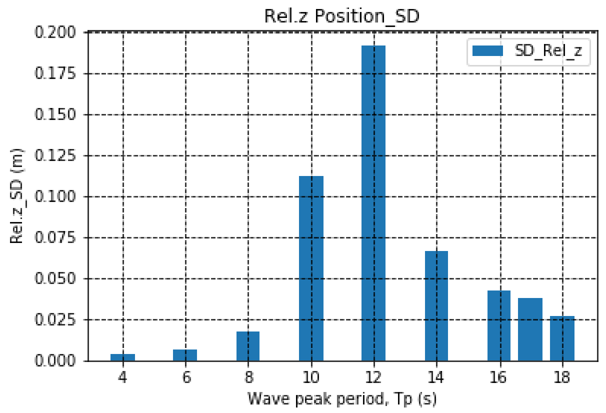

Figure 5 Standard deviation of relative heave motion at the mating point for different Tp

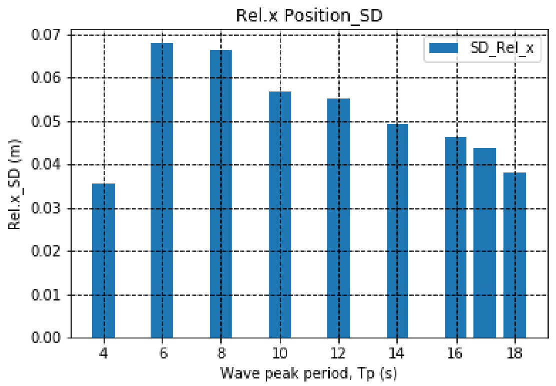

Figure 6 Standard deviation of relative surge motion at the mating point for different Tp

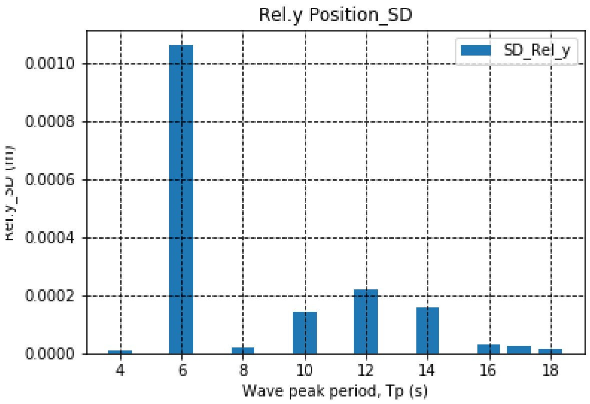

Figure 7 Standard deviation of relative sway motion at the mating point for different Tp

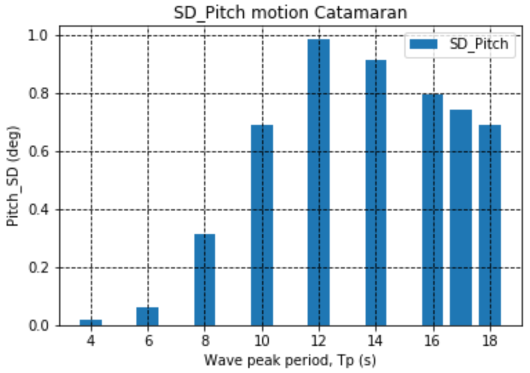

Figure 8 Standard deviation of vessel pitch motion for different Tp

Observing the results of the simulation, it is clear that most of the responses are following the same pattern as the case described in section **6.2.1**. However, a change in peak value of the relative surge and sway motions was observed. This is possibly due to the increased stiffness along the horizontal plane as now tower is just above the spar buoy (0.5 m) and in this configuration, docking cone is interacting with the tower motions in horizontal directions.

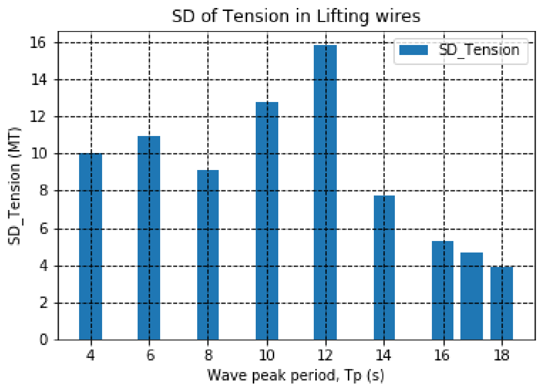

Figure 9 Standard deviation of tension in OWT lifting wires for different Tp

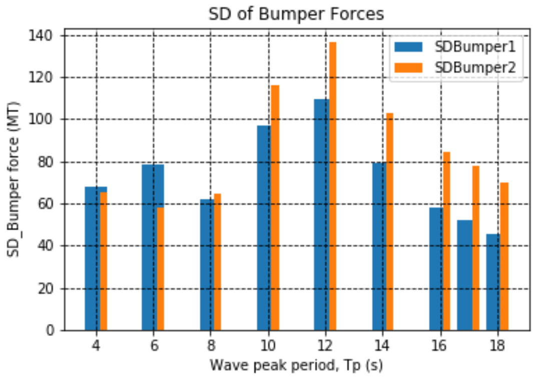

Figure 10 Standard deviation of impact forces in roller supports for different Tp

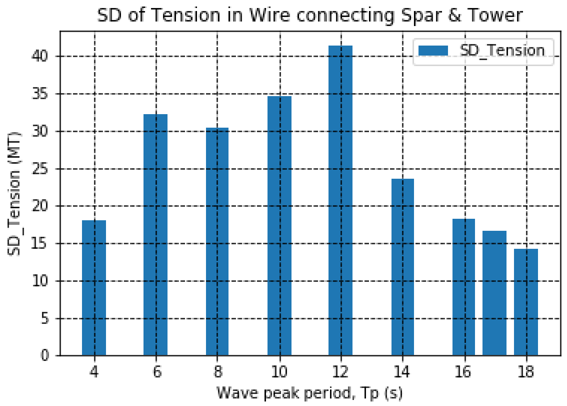

Figure 11 Standard deviation of tension in wire between spar and OWT for different Tp

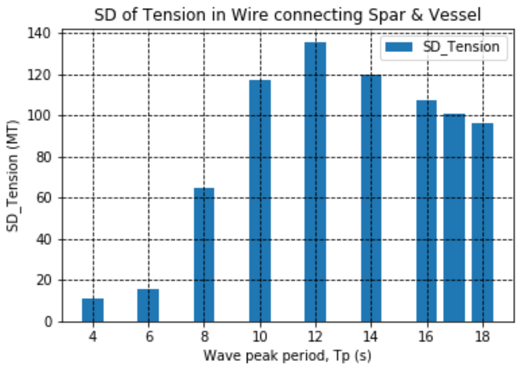

Figure 12 Standard deviation of tension in wire between spar and catamaran for different Tp

Regarding the coupling forces, it was stated previously that it is the vertical component that influences the variation of the forces in coupling elements. Following that, a peak in response is identified at Tp = 12 sec which is the consequence of similar trend in relative heave motion between the bodies.

Appendix E–Post Processing

One of the most underestimated part of numerical simulation is post processing of the immense quantity of the data produced after the simulations. During the course of this thesis, number of simulations were performed, and huge quantity of data were produced. It was humanly impossible to manually check all the generated data and then later make sense out of it. Hence a clear strategy for postprocessing the generated data was planned and is shown in fig xxx.

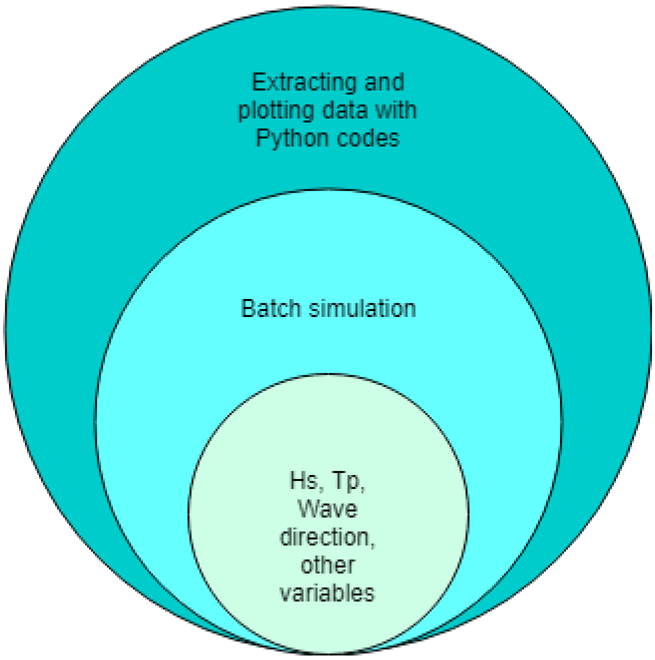

Figure 13 Workflow of SIMO analysis

Figure 13 Workflow of SIMO analysisshows how the workflow was modelled in SIMO for this thesis. Initially, parameters for each of the tests (for example, Hs, Tp, wave direction etc) are modelled and once the input data for all the intended tests are modelled, a batch simulation of all the tests are done in SIMO and a single result file is emitted in HDF format. Python codes were developed for reading the emitted file from SIMO and results were plotted as required.

NTNU
Norwegian University of
Science and Technology