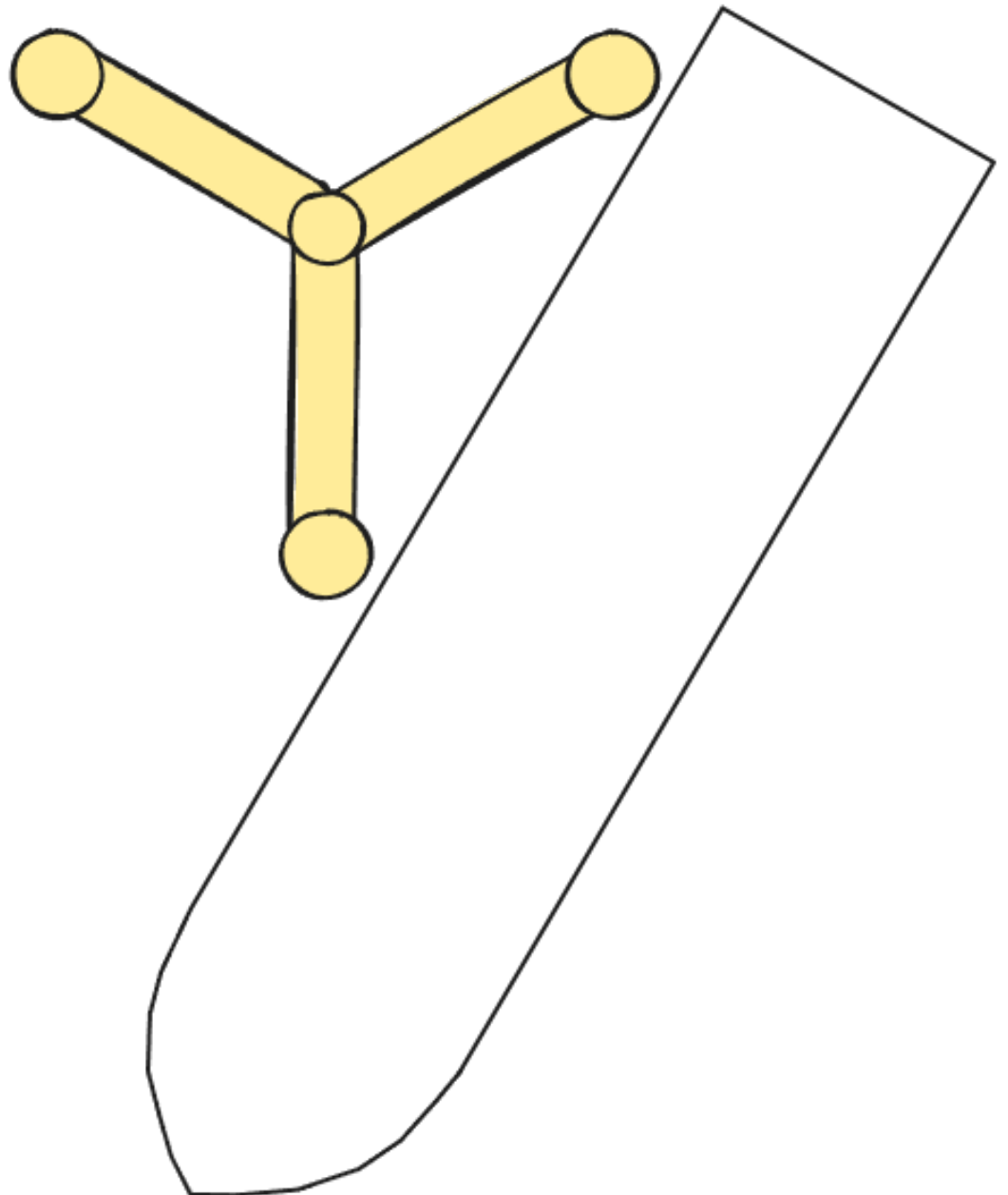


Floating installation of wind turbines on semi-submersible floaters

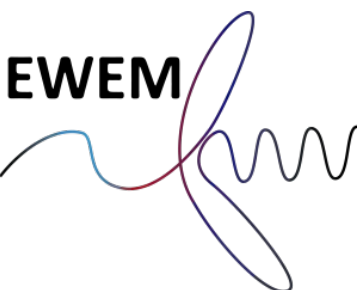
Master thesis

Jin-Jin Yu



 **TU Delft**

 **NTNU**

EWEM


TWD 

Floating installation of wind turbines on semi-submersible floaters

Master thesis

by

Jin-Jin Yu

to obtain the degrees of

Master of Science

in Offshore and Dredging Engineering
at the [Delft University of Technology](#)

and

Master of Science

in Wind Energy Technology
at the [Norwegian University of Science and Technology](#)

under the European Wind Energy Master programme
to be defended publicly on September 26, 2024 at 10:00

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Project Duration:	January, 2024 - September, 2024

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An electronic version of this thesis is available at <http://repository.tudelft.nl/>.

Summary

This research begins with a literature review that examines the current state of floating wind turbine installation methods. This review, combined with a market overview and an analysis of the challenges associated with existing approaches, underscores the need for innovative solutions in floating wind turbine installation. A key proposal is to shift the turbine integration process from traditional onshore marshaling yards to offshore environments, employing floating-to-floating installation techniques. While both industry and academic research have explored various offshore installation concepts, none have specifically addressed the challenges of semi-submersible platforms, highlighting a significant knowledge gap. The primary challenge in this method is effectively managing the relative motions, which is critical for the success of the floating-to-floating installation. To address this, relative motions are first quantified by implementing a multibody model in OrcaFlex, incorporating a heavy lift vessel and the VoltturnUS-S platform.

Following this, four concepts for offshore installation are proposed, each featuring a unique working principle aimed at reducing relative motions. Based on a Multi-Criteria Analysis (MCA), the Gripper Wire Control concept is selected as the most promising. This concept is further refined into a detailed 10-step installation process, incorporating a donut-shaped external platform equipped with winches for horizontal motion compensation. The platform is first secured to the floater, and then the tower, suspended from a crane, is carefully lowered onto the floater, with the winches providing the necessary stiffness in the horizontal plane to control relative motions effectively.

The winch wires are modeled in OrcaFlex as springs between the tower and the floater with specified stiffness in both horizontal directions. Initial validation of this model is performed in MATLAB using an analytical model derived from Lagrangian mechanics. Time-domain simulations under irregular wave conditions ($H_s = 2.5$ m, $T_p = 10$ s, transverse wave direction of 270 deg), revealed a stiffness of 4924 kN/m is required to maintain the horizontal displacement within the predefined limit of 0.2 m. To effectively meet this criterion across various sea states, a higher stiffness value of 8887 kN/m has been selected as the design choice. Additionally, an Active Heave Compensation (AHC) system is assumed, providing 85% compensation for heave motions and thereby reducing the resultant force required in the spring. Further analysis using polar plots illustrates the variability in forces and relative horizontal displacements as a function of wave heading and wave period, offering insights into the system's performance under diverse environmental conditions.

Lastly, a workability study indicates a 92% workability for the compensation step based solely on the metocean data of the proposed area, a maximum crane angle of 2 deg, and the 0.2-meter displacement limit. Ensuring functionality under the simulated sea states reveals a design requirement of 1823 kN for the compensation system in the horizontal direction for $H_s = 2.5$ m and a T_p ranging from 6 to 11 s. While this capacity is expected to be manageable for a compensation system, it is unlikely that four simple winches positioned on both sides of each horizontal axis, as proposed by the concept, would be sufficient.

The findings presented in this report contribute to the development and evaluation of an innovative floating-to-floating installation method for offshore wind turbines on semi-submersible platforms, with a focus on reducing relative horizontal motions between the turbine tower and the floater to enable the successful and feasible integration of the turbine.

Preface

This master thesis report serves as the final deliverable to complete the European Wind Energy Master (EWEM) and to obtain a degree in Offshore Engineering at the Delft University of Technology (TU Delft), and a degree in Wind Energy Technology at the Norwegian University of Science and Technology (NTNU). This research was carried out in collaboration with TWD in Rotterdam, whose involvement played a crucial role in the outcomes of the research.

As I reflect on this journey, I am deeply grateful to those who have supported and guided me. I wish to express my profound thanks to my TU Delft supervisor, Frank Lange, whose insightful brainstorming sessions and steady guidance were crucial in maintaining focus and direction throughout the broad scope of my research. Your encouragement and feedback have been essential to the results achieved. My sincere gratitude also goes to Professor Andrei Metrikine; your critical perspectives during our meetings continued to provoke thoughtful reflection long after our discussions.

At NTNU, I am especially grateful to Professor Erin Bachynski-Polić, who has been a supportive supervisor from the initial stages of my literature review in Trondheim to the final completion of this thesis. Your guidance and ability to steer me in the right direction when faced with challenges have been invaluable. You encouraged me to think critically about my work, challenging me to have a deep understanding of the topic.

The successful completion of this project would not have been possible without the support from TWD. I am especially thankful to Jelmar Termorshuizen for your assistance and valuable input throughout the research process. The expertise and support from TWD's colleagues were vital, particularly in bridging the gap between theoretical research and practical offshore applications. Their willingness to share knowledge and support during challenging moments, along with their encouragement, gave me the energy to keep going.

Lastly, I wish to express my gratitude to my family, especially my mum, my friends and everyone who has supported and encouraged me throughout the years. And lastly, a shoutout goes to my fellow EWEM students, who were not only classmates but also friends and flatmates, whose company made the Scandinavian and Arctic adventures truly unforgettable.

Thank you all, from the bottom of my heart, for your contributions to this significant milestone in my academic journey. I am profoundly grateful for the experiences and knowledge gained along the way.

*Jin-Jin Yu
Rotterdam, September 2024*

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List of Abbreviations

AHC Active Heave Compensation

CoM Center of Mass

DFSC Dynamic Free Surface Condition

DOF Degrees of Freedom

DP Dynamic Positioning

EOM Equation of Motion

EP External Platform

FOWCA Floating Offshore Wind Canarias

FOWT Floating Offshore Wind Turbine

GWEC Global Wind Energy Council

HLV Heavy Lift Vessel

JONSWAP Joint North Sea Wave Project

KFSC Kinematic Free Surface Condition

LCoE Levelized Cost of Electricity

MCA Multi-Criteria Analysis

MPM Most Probable Maximum

NREL National Renewable Energy Laboratory

PC Passive Compensation

POI Point of Interest

RAO Response Amplitude Operator

RNA Rotor Nacelle Assembly

SWATH Small Waterplane Area Twin-Hull

TLP Tension Leg Platform

List of Symbols

Symbol	Description	Unit
A	Amplitude	m
A_w	Waterplane area	m ²
Δz	Reduction in draft	m
d	Water depth	m
D	Diameter	m
ϵ	Random phase	-
E	Modulus of Elasticity	GPa
F	Force	N or kN
f	Frequency	Hz
g	Gravitational acceleration constant	m/s ²
γ	Peak enhancement factor	-
H	Wave height	m
H_s	Significant wave height	m
I	Inertia	t·m ²
k	Stiffness	N/m or kN/m
k	Wave number	1/m
l	Length	m
λ	Wavelength	m
m	Mass	kg or tonnes
n	Number of peaks	-
μ	Mean	Depends on data
ρ	Density of sea water	kg/m ³
r	Radius	m
σ	Standard deviation	Depends on data
σ^2	Variance	Depends on data
t	Time	s
T	Wave period	s
T_n	Natural period	s
T_p	Wave peak period	s
u	Horizontal velocity	m/s
V_{red}	Reduced volume	m ³
w	Vertical velocity	m/s
x_{rel}	Relative surge	m
y_{rel}	Relative sway	m
z_{rel}	Relative heave	m
ω	Angular velocity	rad/s
η	Wave elevation	m
θ	Angle	deg, ° or rad
ϕ	Velocity potential	m ² /s

1

Introduction

1.1. Background

Following the installation of the first offshore wind farm in Denmark in 1991, research initiatives commenced exploring Floating Offshore Wind Turbines (FOWTs) in the late 1990s and early 2000s. This research led to the development of several demonstrator projects during the late 2000s and early 2010s. However, it was not until 2017 that the first pilot-scale floating offshore wind farm, Hywind Scotland, became operational. This pioneering project comprised five 6 MW wind turbines, with a total installed capacity of 30 MW. Subsequently, there has been a significant increase in the number of planned floating wind projects, a trend that will be further elaborated on in the forthcoming section outlining the market forecast.

Typically, floating wind projects are categorized into four distinct types: demonstration projects, pilot projects, pre-commercial projects, and commercial-scale projects. Demonstration projects, often comprising a single unit, primarily aim to validate the feasibility of the technology. Pilot projects, featuring a few FOWTs, focus on studying the interactions between the turbines and are used in attracting larger investments. The subsequent phase involves pre-commercial projects with capacities ranging between 50 and 200 MW. These projects serve to test the supply chain on a larger scale, encompassing the manufacturing and installation of multiple units. Currently, the Hywind Tampen wind farm, consisting of eleven units, is the only project of this size. However, to achieve competitive cost levels, the ultimate goal lies in the realization of large-scale commercial floating wind farms, far surpassing the 200 MW mark (Spearman and Strivens, 2020).

Commercial-scale projects pose numerous challenges, particularly concerning the manufacturing and installation of potentially over thirty floating wind turbines. Addressing these challenges demands substantial upgrades to the supply chain, which is presently not optimized for the production of large structures in significant quantities (Hong et al., 2024).

This research will focus on the installation process, emphasizing first the necessity for large-scale projects and the onshore challenges arising from the installation of numerous FOWTs based on literature. Mitigating these challenges involves exploring alternative installation methods beyond those employed in pilot and pre-commercial projects. As water depths for FOWTs exceed the operational limits of jack-up vessels, these vessels are ruled out for offshore turbine installation. The subsequent literature review will explore various academic investigations and industry concepts into alternative installation methodologies. These methods typically involve using floating vessels, which lack the stability of a jack-up crane vessel fixed to the seabed.

Based on the literature review, a clear framework for the installation concept is defined. Prior to the concept design for floating-to-floating installation, it is essential to identify and quantify the relevant motions in the first modeling part. Subsequently, a design process will be undertaken to explore alternative installation methods, and the proposed concept will be presented. To assess the feasibility of this concept, a second modeling phase will be carried out to demonstrate its viability. Simulation will determine the workability of the critical part of the concept in the applied area, utilizing criteria to

evaluate the performance of the concept, ultimately leading to the establishment of design criteria for the proposed installation method.

1.2. Market overview and forecast

This section, along with section 1.3, chapter 2 and chapter 4 is based on the literature study report written prior to this thesis at NTNU. Additional literature has been incorporated, section 2.2, section 2.3, section 4.4 and section 4.5 are new, and certain sections have been omitted to create a relevant literature review for this report.

This section is intended to highlight the forecasted growth of the floating wind market, to explain the necessity of addressing the challenges associated with the large-scale construction of floating wind farms.

In 2022, the EU generated a total of 2641 TWh of electricity, with renewables accounting for 39.4% of this total, with wind energy contributing 40% of this renewable energy mix. However, the share of electricity in final energy consumption is 21.5% and fossil fuels still make up 38.6% of the electricity produced (Eurostat). These statistics highlight the substantial challenges that lie ahead for the EU in achieving its ambitious targets. Their objectives include reducing carbon emissions by 55% in 2030 and achieving full decarbonization by 2050 (European Commission). According to WindEurope (2023), Europe installed 19 GW of new wind capacity in 2022. This is significantly less than what the EU should be achieving to reach its climate and energy goals. Furthermore, only 13% of the new wind installations were offshore. The EU should be building over 30 GW a year of new wind energy on average to meet its 2030 targets and assuming 25% being offshore, this translates to 7.5 GW of newly installed offshore wind power annually (WindEurope, 2023). On a global scale, the numbers are even more drastic as the current 35 GW offshore wind worldwide should be increased to 270 GW by 2030 and even 2000 GW by 2050 if the global climate goals are to be reached (Díaz et al., 2022). To put it in perspective, Europe's cumulative offshore wind energy capacity increased from 5 GW to 30 GW in the period between 2012 and 2022, meaning an average of newly installed power of 2.5 GW (Statista, 2023).

So far, floating wind has only played a minor role in the wind industry as it is still a young industry with 15 units currently online representing nine projects and a decade of work (Quest Floating Wind Energy, 2021). Nearly all of Europe's existing offshore wind is currently bottom-fixed. However, this foundation type only makes sense commercially for up to 60 m of water depth. Beyond this water depth, it is more cost-competitive to install floating offshore wind turbines (Windeurope, 2023). The Hywind Tampen wind farm is with its 88 MW installed power, the current biggest floating wind farm (Equinor, 2023). DNV predicts that floating offshore wind will generate 264 GW which equals 15% of all offshore wind energy by 2050 (Det Norske Veritas (DNV)). To put this in perspective, this is the equivalent of developing 3000 Hywind Tampen projects.

However, according to the Global Wind Energy Council (GWEC), true acceleration for floating wind projects will not be seen before 2030 due to the higher cost of floating wind energy and supply chain bottlenecks in foundations and port facilities (Williams and Zhao, 2023). As the floating wind industry matures, the Levelized Cost of Electricity (LCoE) will enhance the floating wind's cost competitiveness as witnessed for bottom fixed structures. Since 2016, the LCoE for wind energy reduced over 60% (Quest Floating Wind Energy, 2021). The bottom-fixed project Hornsea One is shown in Figure 1.1 to have a LCoE of \$109/MWh, while EDF's Dunkirk project, which is now expected to be operational by 2028, is projected to be one of the lowest cost wind projects, with an LCoE of \$66.6/MWh.

On average, the costs for floating offshore wind generation are approximately twice as high as those for bottom-fixed offshore wind. Nevertheless, there is optimism that these costs will decline as technology advances and supply chains become more efficient. Research conducted by the National Renewable Energy Laboratory (NREL) indicates that floating turbine projects have the potential to reach cost parity with their bottom-fixed counterparts around 2030 (Musial, 2020).

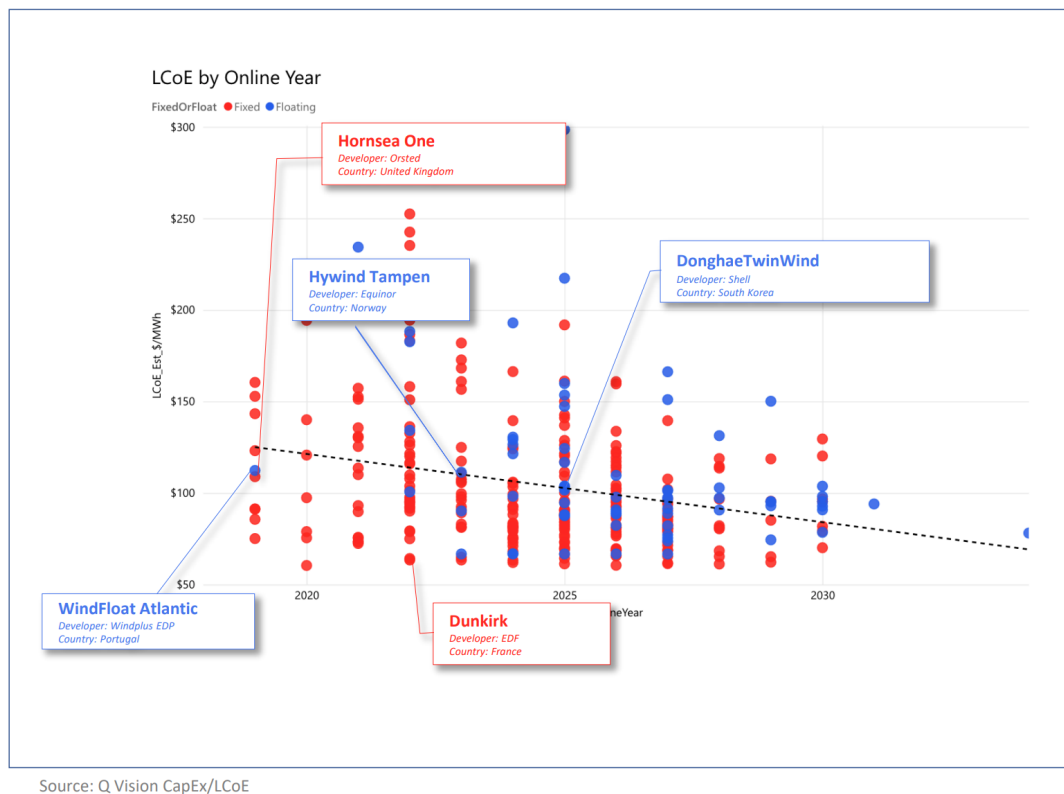


Figure 1.1: Levelized Cost of Energy in \$/MWh for bottom-fixed and floating projects (Quest Floating Wind Energy, 2021)

1.3. Problem statement

As previously mentioned, the GWEC identifies supply chain bottlenecks as a primary factor contributing to the delayed acceleration of the floating wind sector and this is backed up by multiple sources (Durakovic, 2023). This bottleneck will be examined further to define the challenge that needs to be tackled with a focus on the installation process.

1.3.1. Installation vessels

As the previous section clarified, the demand for wind energy is increasing at a high speed. The number of turbines that has to be installed is enormous. The trend of the last ten years showed that the construction duration decreased, whereas the number of MW installed increased as depicted in Figure 1.2. In order to keep up with the installation of all those turbines, the demand for installation vessels will resultingly increase as well.

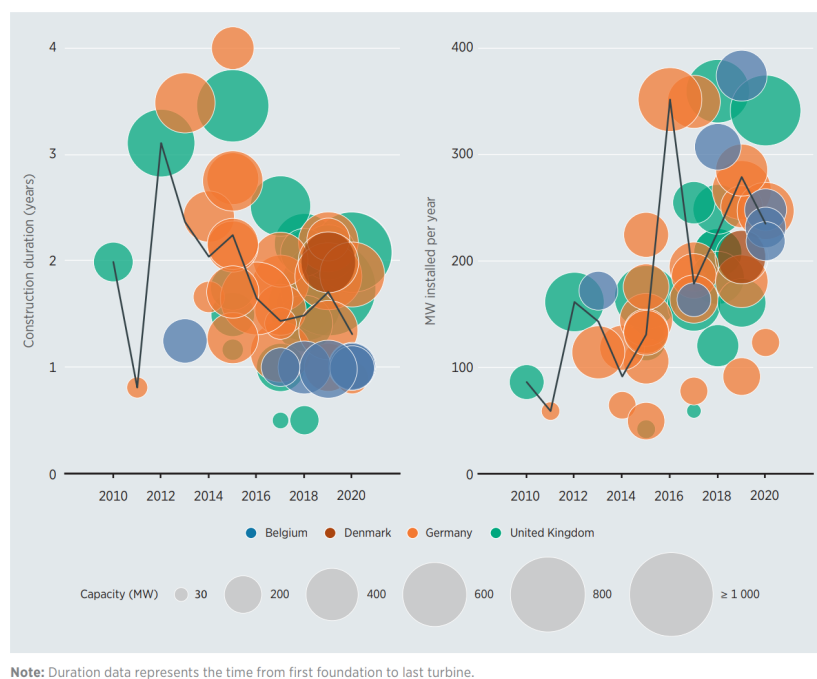


Figure 1.2: Installation time and MW installed per year by offshore wind projects in Europe, 2010 - 2020 (International Renewable Energy Agency, 2023)

The challenge ahead is not solely about the increasing number of turbines that need to be installed in the upcoming years. It also involves addressing the hurdles presented by the trend of continuously growing wind turbine sizes. A new generation of purpose-built vessels is required to meet demand according to Rystad Energy. This holds true for bottom-fixed and floating turbines. Only a handful of vessels worldwide can currently install turbines over 10 MW. According to Rystad Energy, "the demand for offshore wind will outpace the supply of capable vessels as early as 2025, as demand for offshore wind turbine installation vessels worldwide, excluding China will, rocket from 11 vessel years in 2021 to almost 79 vessel years by 2030. The need for installation vessels for turbines larger than 9 MW, which was nonexistent in 2019, will grow significantly by the end of the decade and reach 62 vessel years in 2030." (Buxbaum, 2023). The same shortage in installation vessels is observed by H-BLIX, who investigated for WindEurope the demand and supply of wind turbine installation vessels. The result is presented in Figure 1.3.

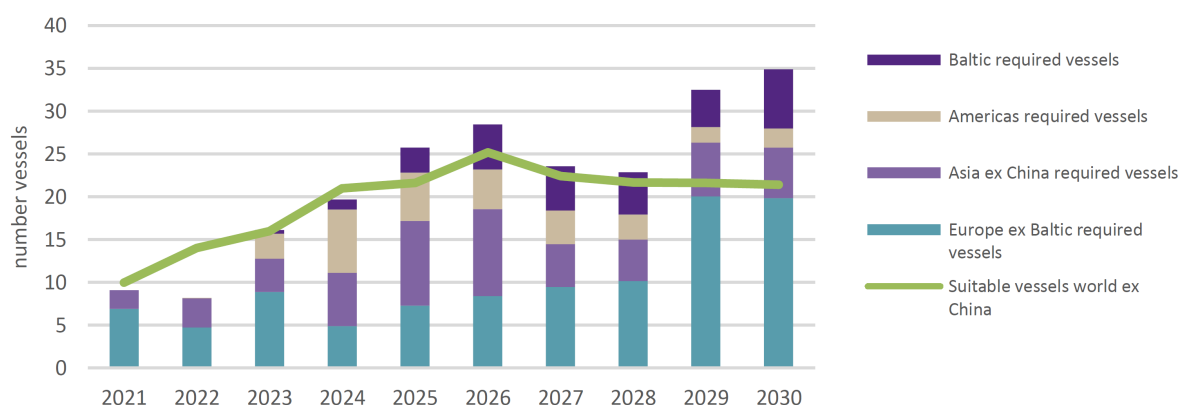


Figure 1.3: Wind turbine installation vessels demand versus supply (H-BLIX and WindEurope, 2022)

Based on research carried out by Spinergie (MClean, 2023), the number of vessel days required for an example project by component type looks like Figure 1.4.

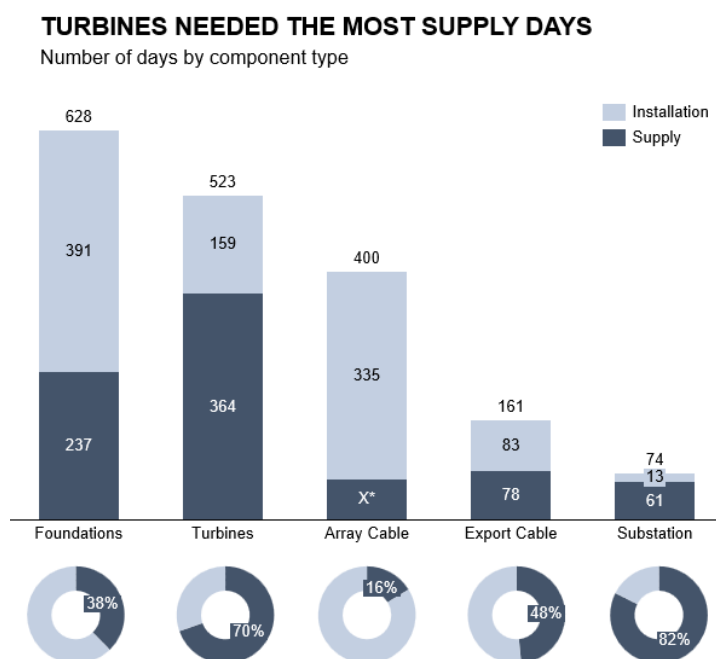


Figure 1.4: Amount of vessel days required for the installation of a wind farm off the coast of France per component type (MClean, 2023)

The turbine and foundation installation takes up the largest number of vessel days. Combined with an undersupply of these vessels, there is a clear bottleneck in the installation process of future wind farms. To meet the installation demand set by the climate goals and reach the commercial-scale project sizes, new installation vessels or methods have to emerge that avoid amplifying this existing bottleneck.

1.3.2. Port area

The huge area that is required for substructure construction imposes the next bottleneck. When the foundations are assembled quayside, they occupy substantial space as expressed in Figure 1.5, but naturally, this depends on the type of FOWT, size of the turbine, number of turbines in the wind farm and the number of turbines to be installed in one summer season.

Wind farm size	25MW pre commercial	300MW commercial
Turbine size	5 MW	10 MW
Water depth	100 m	150 m
Number of units	5	30
Tower manufacture	2 hectares	25 hectares
Nacelle manufacture	3 hectares	15 hectares
Blade manufacture	4 hectares	32 hectares
Dynamic cable storage	2 hectares	12 hectares
Export cable storage	10 hectare	12 hectares
assume 50km length		
Substructure construction	10 hectares	100 hectares

Figure 1.5: Port area estimation for a floating wind farm (Crowle and Thies, 2022)

On an assembly site, all components e.g. the tower, nacelle, blades and substructure come together. Let's take the example of the semi-submersible INO WINDMOOR (Silva De Souza et al., 2021) FOWT as an example. The substructure has a center-to-center distance of 61 m between the 15 m diameter columns. The footprint of the foundation occupies 0.25 hectares and for the UMaine VoltturnUS-S floater (Allen et al., 2020), the value rises to 0.92 hectares.

The quay area has to be huge if the wind farm sizes grow and they have to grow to meet the demand expressed previously. In order to achieve realistic installation periods and follow the trend in Figure 1.2, multiple assembly lines will have to be present to mount the turbine on top of the substructure. The quay area will have to temporarily store blades (> 100 m long), nacelles, tower sections, and hold place for cranes, material and additional equipment, and have a construction area where multiple FOWT are being assembled. "Space is and will become a bigger issue for ports, not just on land but also on water" states WindEurope (WindEurope, 2021). On top of that, "€6.5 bn in investment will be needed by 2030 to enable the effective delivery of offshore targets within the National and Energy Climate Plans and for future growth". The breakdown of the €6.5 bn is presented in Table 1.1. Based on this table, it is evident that huge investments in adapting ports or building new terminals for floating wind are required.

Dry dock facilities are often preferred for the turbine integration process for semi-submersible floaters because they enable the structure to be assembled and launched by flooding the dock, which eliminates the need for costly heavy lift cranes. However, many dry dock facilities were originally designed for the manufacture and repair of vessels, which are typically long and slender structures. This design focus results in the limited availability of dry docks suitable for accommodating wide structures with large beams, characteristic of semi-submersible floaters (Carbon Trust, 2015).

Table 1.1: Overview of investment needs and costs for infrastructure works in European ports (WindEurope, 2021)

Investment item	Cost per investment	Number of investment (No of ports)	Total investment
Upgrading/extending facilities for a port already in the bottom-fixed offshore wind business	€20-80 million	30	€1 billion
Building a new energy port/ terminal for bottom-fixed offshore wind (around 15-20ha)	€80 - 110 million	15-20	€2 billion
Building a decommissioning facility/ refurbishing an existing facility in the port	€5-10 million	5	€50 million
Floating wind port adaptations or new terminal	€200 million	6	€1.5 billion
Infrastructure for renewable hydrogen production in ports	€100 million	10	€1 billion
Accommodating energy island operations, products, and related infrastructure	€500 million	2	€1 billion

In addition to the port area restriction, the weather sensitivity of different installation processes is also a drawback. The weather and sea states have to be favorable for the entire period in which the transportation and collecting of all the components, lifting, mating, etc. take place. Seeing that the industry

is experiencing supply chain issues as demonstrated in the case of Equinor's Hywind Tampen project (Russell, 2022), there is a reasonable chance of delay due to one component being delayed. Such delays can lead to a complete halt in the construction yard, a very costly circumstance. Additionally, after integrating the turbine, a sufficiently long weather window is required not only for towing the FOWT to its designated location but also to ensure it can be safely towed back to port in case of hook-up issues (BVG Associates, 2023).

1.3.3. Opportunities for offshore installation

Many of these challenges can be avoided when the substructure is transported from its fabrication yard to its assigned destination, avoiding the need for a large marshaling yard. It is then moored after which a turbine assembly will be positioned on top, without the complications and potential delays associated with quayside construction. Instead of consolidating all components at a single assembly location, the substructure can be sent directly to the wind farm. The turbine, assembled elsewhere, can be transported later to the pre-installed foundations. This approach shifts the integration of the wind turbine from a marshaling yard to an offshore setting, enabling a floating-to-floating installation.

The primary drawback of offshore turbine installation lies in the offshore mating process between the turbine and the substructure. Unlike monopiles or jackets, the floating structure is not stationary; it has six Degrees of Freedom (DOF). Furthermore, the installation vessel has an additional six DOF since it is a floating vessel. The traditional jack-up vessels are not suitable given that the floating structures are placed in waters too deep for jack-up vessels to handle. Additionally, the location of this operation is not advantageous for the installation process since the wind and therefore wind waves could be rather substantial. While the wind farm benefits from high wind speeds, it increases the motions of both floating bodies which makes this task even more challenging. Nevertheless, offshore turbine installation poses solutions to challenges highlighted in this section, with more advantages explained in section 3.1.

In this chapter, the problem regarding the installation of floating wind turbines is defined. Next, the focus moves to reviewing the current installation methods and exploring ongoing investigations into alternative approaches, to have an understanding of what is currently available before narrowing down the scope of this research.

State-of-the-art installation methods

In this chapter, the current multi-megawatt installed and operational floating wind turbines are presented. Initially, the methods employed by the industry to install floating wind turbines are shown, followed by an exploration of innovative concepts emerging from the industry. Subsequently, the chapter delves into academic research related to the offshore installation of FOWTs. The final section highlights relevant and useful findings for this research.

The recent commissioning of the Provence Grand Large pilot project, using three Tension Leg Platforms (TLPs) mooring systems, marks a milestone (SBM Offshore, 2023). However, due to the substantial differences in the mooring systems and installation procedures between TLPs and spar or semi-submersible floaters, the installation method for TLPs will not be addressed.

2.1. Spar and semi-submersibles

Spar

In 2009, Hywind Demo was installed, which is the world's first multi-megawatt spar FOWT. The installation procedure included wet towing of the spar foundation from Finland to Norway, after which the upending of the spar took place in Stavanger Fjord, followed by solid ballasting and mating the tower and the onshore assembled rotor assembly. The final assembly was then towed to its final destination where the mooring system was connected and lastly, the final ballast adjustment was accomplished. Eight years later, Hywind Scotland, the world's first floating wind farm consisting of five turbines with a spar-type substructure was constructed. The installation procedure is comparable to its Demo case, except that the turbine was fully assembled onshore after which the turbine assembly was lifted by the heavy-lifting vessel Saipem 7000. With a 6 MW turbine suspended from the crane, the vessel then proceeded to the location of the spar foundations for the tower mating process. This installation process is summarized in Figure 2.1 below.

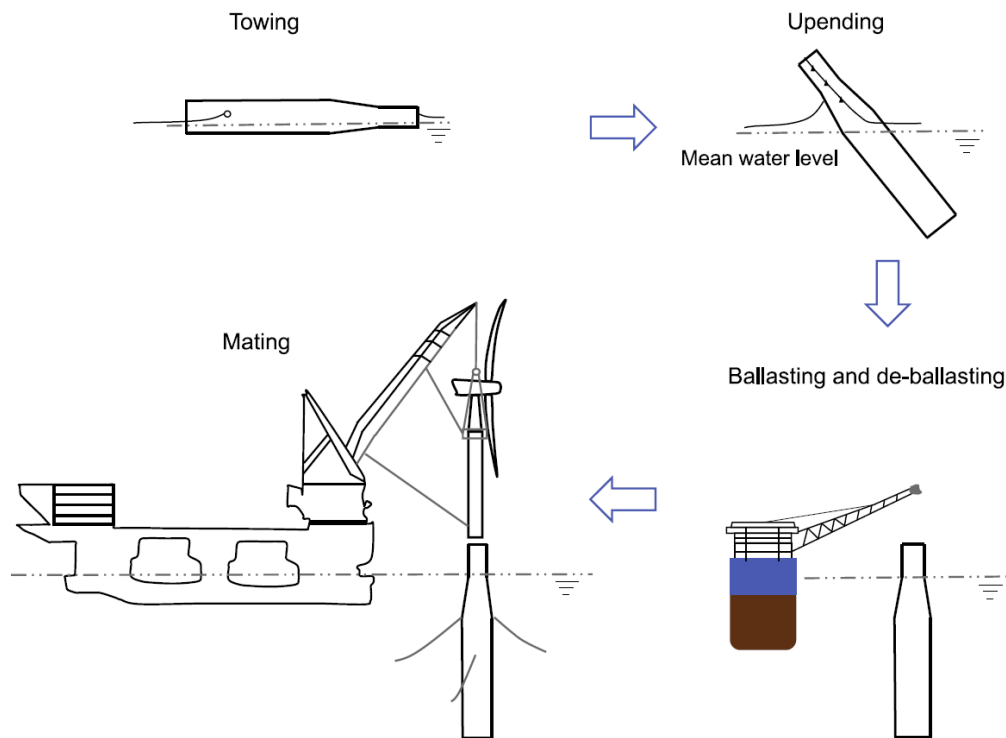


Figure 2.1: Essential stages of the installation process of the Hywind Scotland FOWT (Jiang, 2021)

Currently, Hywind Tampen is the world's largest floating offshore wind farm with a system capacity of 88 MW (Equinor, 2023). The eight wind turbines are installed on floating concrete spar structures. Compared to the previous Hywind projects, the assembly of the wind turbine was carried out by an onshore crane. With such huge 107 m floating spar buoys, the port required an exceptionally large draft, ruling out jack-up vessels, which would be too short to assemble the turbine sections. A spacer barge between the quay and the spar foundation was needed to ensure adequate clearance between the base of the foundation and the seabed. All turbine components would therefore need to be lifted over the quay edge, over the spacer barge, and then onto the foundations themselves, resulting in a distance of around 143 m. The layout of the installation port is visible in Figure 2.2. After assembly, the assembled turbine is towed by three tug boats to the wind farm.



Figure 2.2: Assembly of the Hywind Tampen wind turbines using a spacer barge (Espen Braata, 2022)

Semi-submersible

WindFloat Atlantic, commissioned in 2020, is the first floating wind farm using semi-submersibles as a substructure and the complete assembly was fully assembled onshore in a dry dock. Once completed, the platform is inherently stable and seaworthy meaning that a tug vessel is suitable to tow the platform to its final location where it is connected to its preinstalled mooring system (Principle Power). One of the advantages of this three-column design is that the wind turbine can be positioned adjacent to the quay, minimizing crane outreach requirements (<20 m) in comparison to systems where the wind turbine is centrally located ($40+$ m).

In December 2021, the first pilot anti-typhoon floating wind turbine with a capacity of 5.5 MW was installed in China by Wison (Nick Blenkey, 2021). Due to a lack of public documentation, the installation process remains unclear.

The Kincardine offshore floating wind farm, which began delivering power in 2021, is another project that utilizes semi-submersible floaters for its wind turbines. The farm consists of five 9.5 MW turbines. Similar to the WindFloat Atlantic project, turbine integration for Kincardine took place in a drydock. After assembly, the fully integrated structures were towed to their installation site off the coast of Aberdeen, Scotland.

2.2. Industry concepts offshore installation

Various parties have proposed single transfer solutions, where the fully assembled wind turbine is placed on top of the floating foundation in one operation. Additionally, some concepts involve transporting the turbine with its foundation, while others focus on installing wind turbine components using the floating platform or turbine tower as a working platform. Examples of these three approaches are presented below.

Single transfer

The Huisman concept involves their wind farm installation vessel as depicted in Figure 2.3a. It can carry the components for multiple wind turbines. Once arrived at the site, a wind turbine is assembled directly on the vessel's deck by the installation tower. The installation tower has multiple motion-compensated grippers (in x- y- and z- directions) holding the wind turbine and compensating for the vessel motions. After assembling the wind turbine, the frame then rotates to the aft of the vessel and puts the turbine on top of the fixed or floating foundation.

The turbine installation vessel 'Windlifter,' developed by Ulstein, features a modular mechanical system for skidding turbines from the vessel onto the foundation (Ulstein, 2015), as shown in Figure 2.3b.

The Offshoretronic concept facilitates the transport and installation of two fully assembled wind turbines, each up to 11 MW, in a single round trip. The turbines are held by the ADD-ON Installation Support Tower which can be seen in Figure 2.3c. For larger wind turbines, the vessel can install the turbine tower and nacelle as a single unit, while the blades can be installed separately using a smaller support vessel (Offshoretronic).

Huisman's Wind Turbine Shuttle (Huisman, 2011) depicted in Figure 2.3d is a Small Waterplane Area Twin-Hull (SWATH) type construction vessel and it can also transport two fully assembled wind turbines and install them on both bottom fixed or floating foundations.



(a) The Huisman concept where the turbine is assembled offshore (Huisman Equipment)



(b) The Ulstein concept of the wind turbine installation vessel 'Windlifter' (Ulstein, 2015)



(c) The Offshoretronic installation vessel with their ADD-ON Installation Support Tower (Offshoretronic)



(d) Huisman's Wind Turbine Shuttle using a SWATH type vessel (Huisman, 2023)

Figure 2.3: Different examples for the single transfer concept

Horizontal assembly transfer

Two examples of transporting the fully assembled wind turbine with its foundation horizontally are shown in Figure 2.4.

The Aikido Platform is a semi-submersible platform that can transport a fully assembled Aikido Turbine horizontally. In its transport configuration as depicted in Figure 2.4a, the folded-up platform has dimensions similar to a container ship. Upending the platform only requires ballasting the platform with seawater and their Aikido Turbine is a floating-specific wind turbine with a nacelle designed to be transported horizontally. This approach removes the need for heavy lift operations offshore (Aikido Technologies).

The second example has the wind turbine foundation located on a barge while the tower is resting on a support system. This 'MINT' support system is located at the stern of a mid-size standard offshore support vessel. The MINT is specifically designed for the transport and installation operations allowing relative motions and rotations between the tower and the transport vessel (Haugvaldstad and Gudmestad, 2019). It is pointed out that the large pitch response is of particular concern, creating a considerable bending moment in the tower.

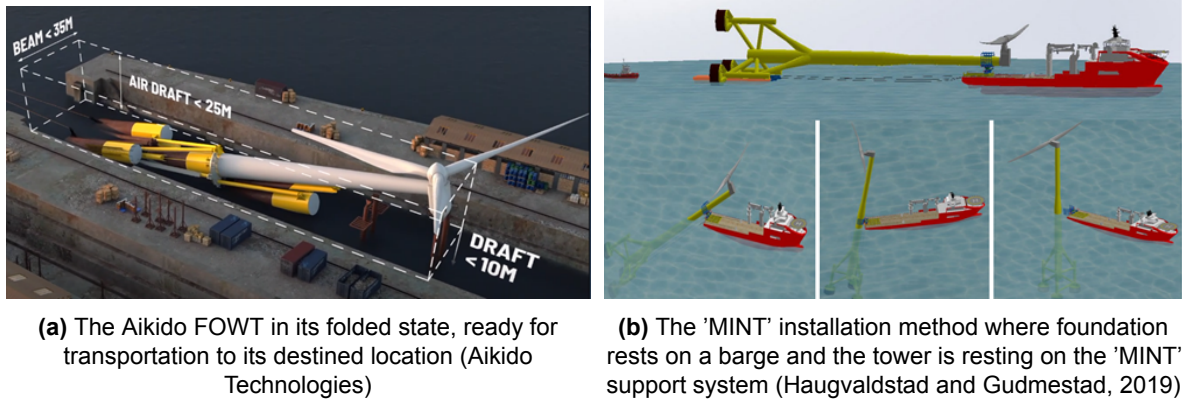


Figure 2.4: Two concepts of transporting the wind turbine with its foundation horizontally and upending it at its designated location

Multiple lifts

Several options for the installation of wind turbines using multiple lifts are shown in Figure 2.5

The WindSpider concept in Figure 2.5a features a modular climbing crane system for assembling and maintaining bottom-fixed and floating wind turbines, eliminating the need for external cranes. It uses aluminum scaffolding around the turbine tower, forming a base for a powerful crane that ascends the structure as it is built (WindSpider, 2024).

The World Forum Offshore Wind (Rattan, 2023) categorized various concepts for wind turbine repairs and installations. Add-on cranes, which can be mounted on FOWTs, facilitate major component replacements directly from the turbine, reducing relative motion between the floater and a vessel crane. Several add-on concepts are under development, featuring different hoisting or climbing capabilities and support system designs as depicted in Figure 2.5b.

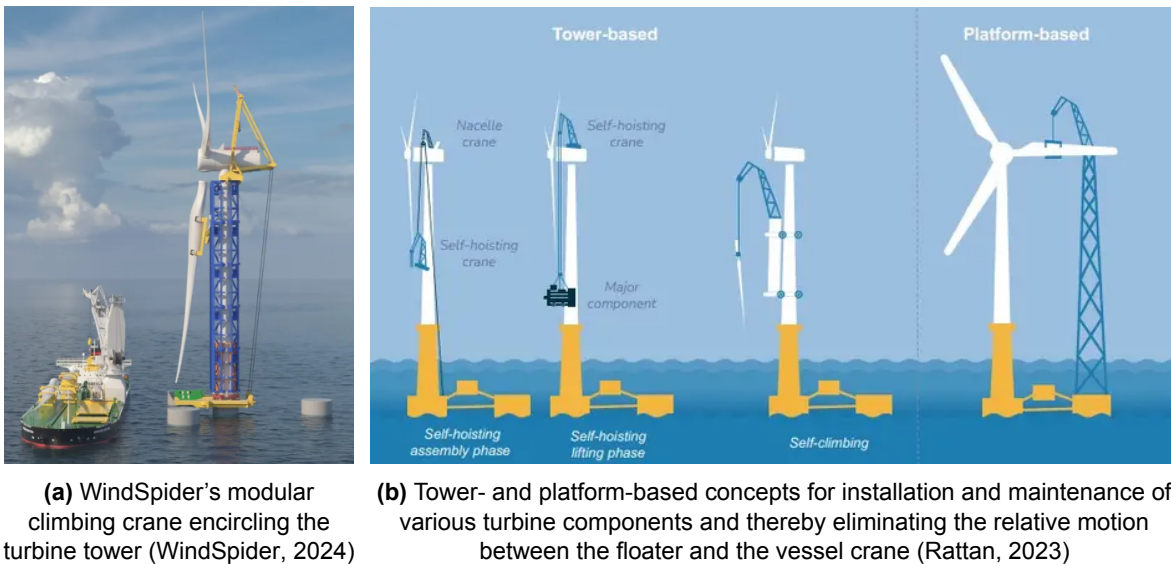


Figure 2.5: Concepts for on-site installation which can also be used for repairs and maintenance

2.3. Guiding mechanism for tower-foundation connection

The examples discussed so far provide a global overview of the installation process. However, attention must also be given to mechanisms that can guide the tower onto the foundation. This is crucial since the relative displacement between the tower and the foundation, or transition piece, will never be zero, even

in non-floating-to-floating scenarios. Human supervision, as often utilized during offshore mating, poses significant dangers in floating-to-floating systems and must therefore be avoided. Both the foundation and the tower are moving, and even a small unforeseen contact with the 1500-ton tower can result in severe injuries. A 'catcher' mechanism can be employed to manage the final centimeters of movement. Two examples are shown in Figure 2.6 and Figure 2.7. The first example was used in the Hywind Scotland project, where the spar foundations were equipped with two pins in the turbine tower and two catchers in the foundation. Workers were present, as seen in Figure 2.6, but this operation was conducted in very calm fjord waters, with minimal waves and by the massive and stable Saipem 7000 vessel with the necessary tugger lines to the turbine assembly, all ensuring minimal relative motions during installation.

As wind turbines continue to increase in size, the traditional L-flange design is reaching its capacity limits. The C1 Wedge Connection in Figure 2.7 is developed to address this issue, aiming to enhance the capacity and reliability of connections in offshore wind structures (Joint Industry Project (JIP), 2024). The connection can be made without any personnel below the suspended load and uses guide plates that are attached to the tower.

These examples will assist in the following chapter in determining the requirements for motion reduction.



Figure 2.6: The Hywind Scotland spar foundations are equipped with two catchers that guide the two pins from the tower onto the foundation (Equinor, 2017)



Figure 2.7: The C1 Wedge Connection uses bent guide plates (in dark blue) to account for the last remaining motions (Joint Industry Project (JIP), 2024)

2.4. Relevant academic research

This section presents different research related to offshore installation methods, categorized into floating-to-fixed or floating-to-floating installation concepts. As this research focuses on floating-to-floating installation, the latter section is the most relevant, but interesting insights into other methods can also be applicable.

Floating to fixed installations

As stated earlier, the use of a jack-up vessel is ruled out for the deep water sites. Consequently, the stable working platform that a jack-up vessel typically provides cannot be utilized. However, the operational weather window using jack-up vessels is limited due to the low sea states required for jacking operations (Li et al., 2013). Compared to the traditional jack-up vessels for the installation of monopiles, floating vessels have more flexibility due to fast transportation between the different foundations as the time the jack-up vessels need to raise and lower their legs is not required. However, the vessel motion will affect the response of the lifted object and it is therefore more difficult to position the object accurately.

Installation of jackets using floating vessel

The dynamic response of the lifting operation of an offshore wind turbine jacket using a floating crane vessel is investigated by Chen et al. (2022). The construction vessel used is a double-arm luffing floating-crane vessel and it is moored by eight mooring lines. Furthermore, the jacket is lifted by four slings as visualized in Figure 2.8.

The tension in the sling and wire, along with the motion of the jacket, are defined as the critical responses. The results indicate that the jacket's motions are primarily influenced by waves and vessel movements. The latter directly affect the jacket, and this influence significantly impacts the lowering operation. On top of that, the vessel and jacket resonate easily in pitch, heave and roll. As this will trigger large motions, avoiding it should be a primary objective.

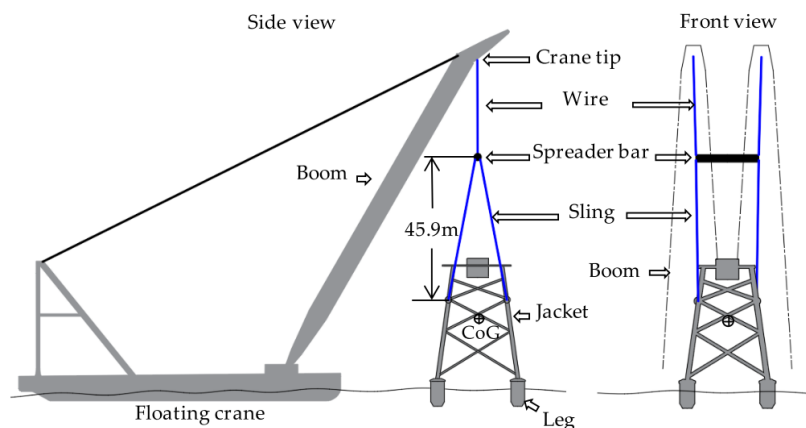


Figure 2.8: Sketch of the lifting operation of a jacket foundation using a floating vessel (Chen et al., 2022)

Installation of monopiles using floating vessel

The installation process of offshore wind turbine monopiles using a mono-hull heavy lift vessel is simulated and compared to the responses to the results of a jack-up vessel by Li et al. (2013). The Heavy Lift Vessel (HLV) is equipped with a Dynamic Positioning (DP) system and an eight-line mooring system. The gripper device controls the horizontal motions of the monopile during the lowering and landing process and is rigidly fixed on the vessel. To guide the landing of the monopile to the intended location, a landing device is mounted in the seabed. The system is depicted in Figure 2.9.

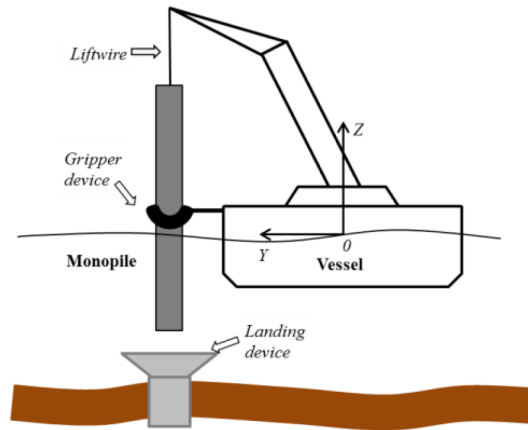


Figure 2.9: Configuration of the monopile installation using a floating vessel system (Li et al., 2013)

The entire process is divided into three phases. In the lowering phase, the monopile is lowered and the lift wire length is increased. The landing phase starts when the contact force between the monopile and docking cone is larger than zero. The steady-state phase starts when the winch stops. After the monopile tip has entered the conical section, the pile enters into the cylindrical part of the landing device and the horizontal motion of the pile tip is constrained.

The critical responses for this system are pointed out to be: the monopile end tip positions, the landing contact force and the lift wire tension.

Installation based on the inverted pendulum principle

A novel installation concept for a fully assembled tower and Rotor Nacelle Assembly (RNA) structure onto a fixed foundation (tripod, monopile or jacket) is developed by Acero et al. (2016). This method is based on the inverted pendulum principle and was shown to be a feasible alternative for jack-up vessels. Moreover, the total installation time can be less than 16 h and this can be even further reduced if a DP system is employed as the mooring activities for the HLV are then not required. Comparing this with the average installation time of 3 days using jack-up vessels, as reported by Herman (2002), or the more recent data showing an average of 1 day for the Hollandse Kust Noord wind farm (CrossWind, 2023), reveals a significant reduction in the installation time.

A medium-sized HLV is required for the upending of the wind turbine. A cargo barge is needed to transport the assembled wind turbine to the site in a horizontal position which is assumed to be feasible. By positioning the HLV parallel to the cargo barge, it can shield the barge from incoming waves resulting in more favorable sea state parameters. To reap this benefit, the foundations need to be installed with a specific heading based on wave spectra statistics. An upending frame is used to lift the tower and a winch with a constant speed lifts the tower from the cargo barge. After mating between the upending frame and the supports on the foundation, the lifting process continues until the tower is standing in an upright position on the foundation supports. Simultaneously, the HLV is moved forward parallel to the lifting points. A locking system is enforced at the final upending stage to avoid any receding motion of the tower. It is favorable to connect the foundation supports and the upending frame at an offset from the centerline of the foundation and the tower, to counterbalance the overturning moment exercised by the blades and hub. Subsequently, the tower is lowered until the bottom flange rests on the transition piece, after which the upending frame can be removed and used to install the next tower.

A summary of this upending installation method is visible in Figure 2.10

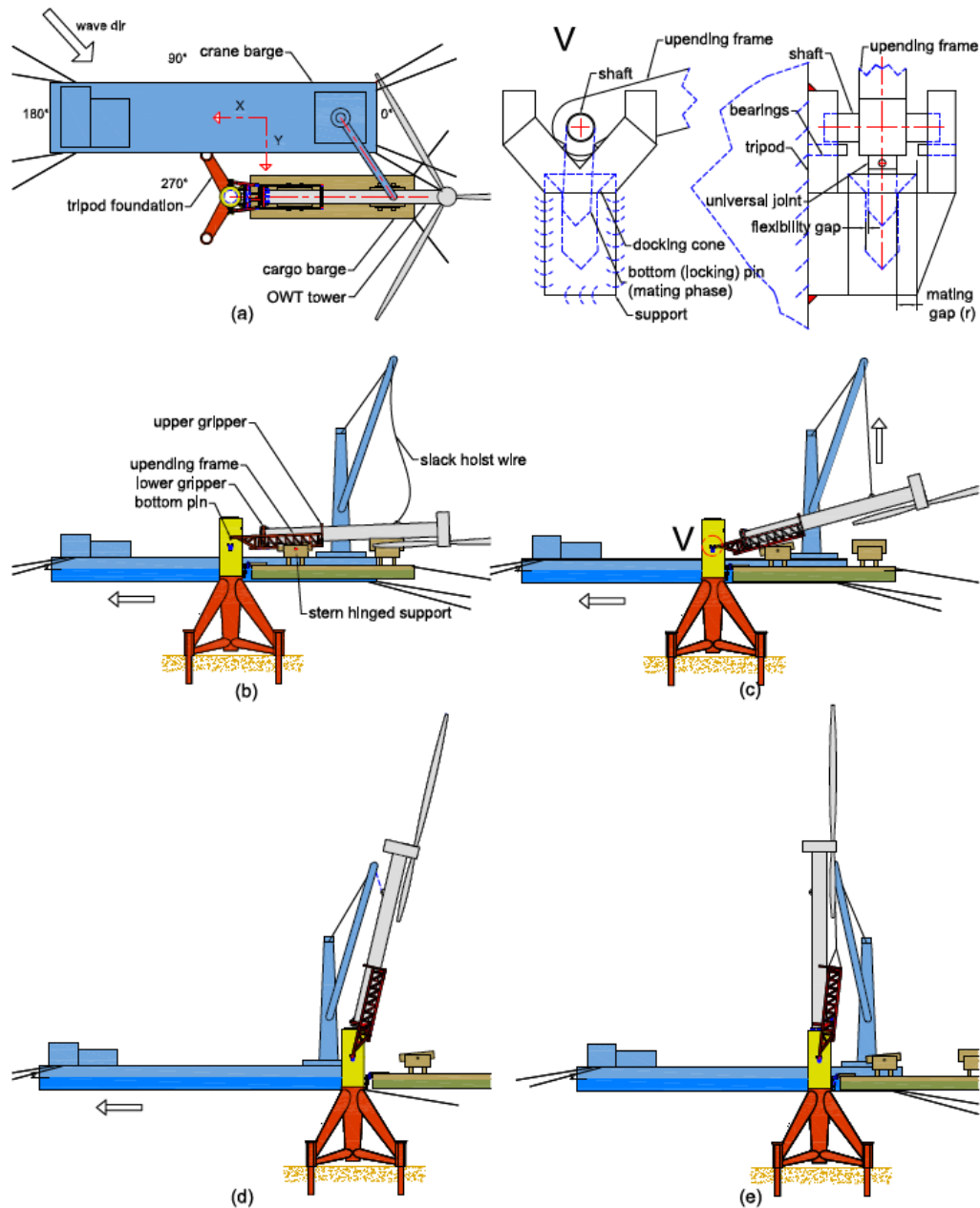


Figure 2.10: Installation stages (a,b) Motion monitoring phase; (c) Mating between the upending frame and foundation supports; (d) Upending of the tower in the final stage; (e) Completion and upending frame removal (Acero et al., 2016)

An important issue with this installation method is that the nacelle is turned 90 deg during transportation which is typically not allowed by the turbine manufacturer, with the exception of the Aikido Turbine. Some of the sub-systems of an offshore wind turbine (bearings, gearbox, generator, etc.) have been designed to operate close to the upright condition (Collu and Borg, 2016).

Blade installation using a mono-hull and semi-submersible vessel

Zhao et al. (2019) performed a numerical study on the feasibility of offshore single-blade installation on a bottom-fixed wind turbine by floating crane vessels. The two vessel types that are considered are the mono-hull and semi-submersible vessels. It is assumed that these vessels are equipped with DP systems capable of effectively mitigating slowly varying horizontal motions.

The three considered vessels are depicted in Figure 2.11 and the same crane is used for all vessels. The DTU 10 MW blade is held by a yoke and lifted by the hook via four slings. The lift wire extends from the crane tip to the hook, while tugger lines, running from the yoke to a trolley on the crane boom, are employed for controlling the heading of the blades. Tugger lines are pre-tensioned to ensure they remain taut and do not become slack.

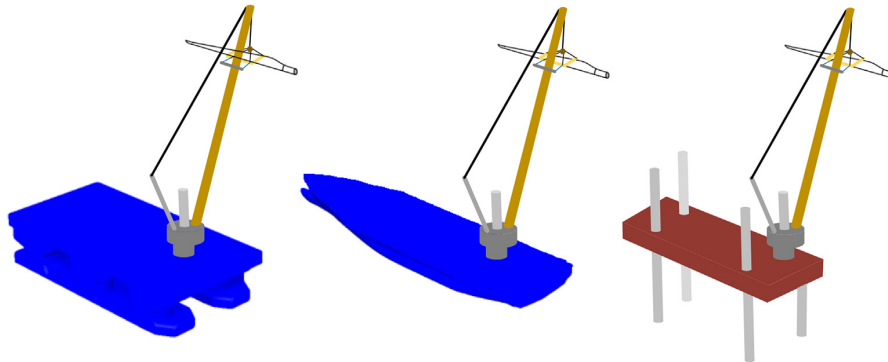


Figure 2.11: Blade installation using a semi-submersible, mono-hull and jack-up vessel (Zhao et al., 2019)

The semi-submersible vessel induces less blade motion and smaller variations in tugger line tension compared to mono-hull vessels and jack-up vessels. However, it must be noted that the displaced volume of the mono-hull vessel is about 40% of the semi-submersible vessel, which provides the mono-hull vessel with less stability compared to the semi-submersible vessel. Furthermore, offshore sites with shorter wave conditions are more suitable for floating vessel installation than those with longer wave conditions.

Floating-to-floating installations

In this section, academically researched floating-to-floating installation methods will be investigated. No papers in the public domain are dedicated to the offshore installation of semi-submersibles using a floating vessel. Instead, research is carried out for spar-typed substructures with a catamaran, SWATH vessel or monohull as installation vessel.

Installation of turbine assembly on a spar substructure using a catamaran

Jiang et al. (2018) investigated the dynamic response of a catamaran installation vessel during the positioning of a wind turbine assembly onto a spar floater. In this concept, the vessel carries a maximum of four fully assembled wind turbines on board. The catamaran is connected to the floating foundation by sliding grippers. These mechanical coupling devices grasp the floating foundation and constrain the relative motions in the horizontal xy-plane. Movement in the z-direction is possible due to the presence of a passive roller at the end tip of a gripper. When the weather allows the operation, the lifting grippers grasp the assembled turbine and lift it up. Thereafter, the assembly is transferred to the catamaran's aft by a rack-and-pinion system. If the relative motion between the tower and the foundation is within allowable limits, the mating process takes place. The mating process is considered successful when all the guiding pins on the tower bottom enter the docking devices inside the floater, after which the catamaran disconnects to the foundation. The different installation steps are depicted in Figure 2.12.

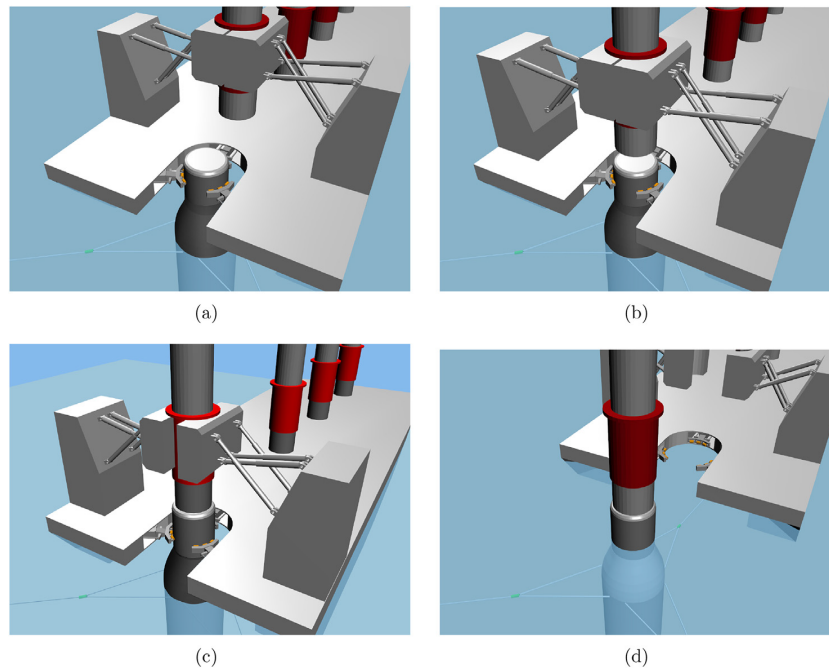


Figure 2.12: Installing a turbine assembly onto a spar foundation using a catamaran; (a) Move the turbine assembly to the catamaran's aft; (b) Monitoring the relative motion (c) Mating process; (d) Releasing the gripper (Jiang et al., 2018)

Installation of turbine assembly on a spar substructure using a SWATH vessel

Liu et al. (2022) used the same spar foundation but used a SWATH as an installation vessel. The SWATH vessel, as its name suggests, has a small water-plane area and as a result, its natural periods are usually larger and located outside the main wave frequency range. This is an advantage as compared to a catamaran vessel. The proposed vessel can accommodate four pre-assembled 10 MW turbines and a sliding gripper is again used as mechanical coupling. The installation process is similar to that of Jiang et al. (2018) depicted in Figure 2.12, but the floating vessel has the configuration depicted in Figure 2.13. The study indicates that careful consideration must be given to selecting the stiffness of the coupling devices. The natural frequencies of the SWATH and the spar could shift into the main wave frequency, potentially causing adverse effects during the installation.

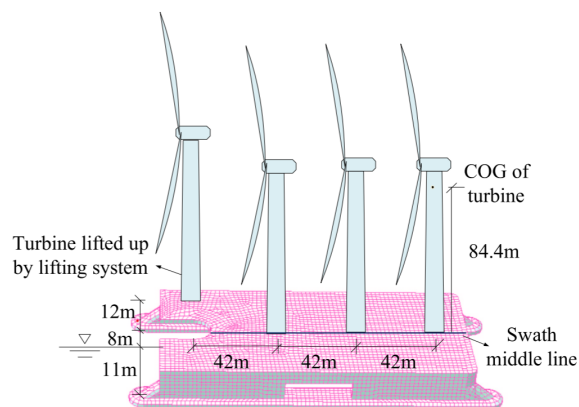


Figure 2.13: SWATH vessel and turbine assembly setup (Liu et al., 2022)

Installation of turbine assembly on a spar substructure using a monohull vessel

The research by Hassan and Guedes Soares (2023) also focuses on the development and analysis of a method for installing floating spar wind turbines. This method employs a layout similar to the one investigated by Jiang et al. (2018) but utilizes a floating mono-hull installation vessel named Nordic Wind, which is designed to transport pre-assembled wind turbines to offshore sites. The components of this system are illustrated in Figure 2.14 where the motion-compensated gripper serves as the mechanism to minimize the horizontal relative motions between the vessel and the floating spar. Additionally, the lifting grippers are equipped with heave compensation to minimize the impact forces experienced during the mating operation. The study demonstrates that multibody interactions influence relative motions within the wave period range of 6 to 9 s, with their effect diminishing as the wave period increases. At the mating point, relative motion is primarily influenced by first-order motions and is particularly sensitive to significant wave height and peak period, while wind and current have a lesser impact.

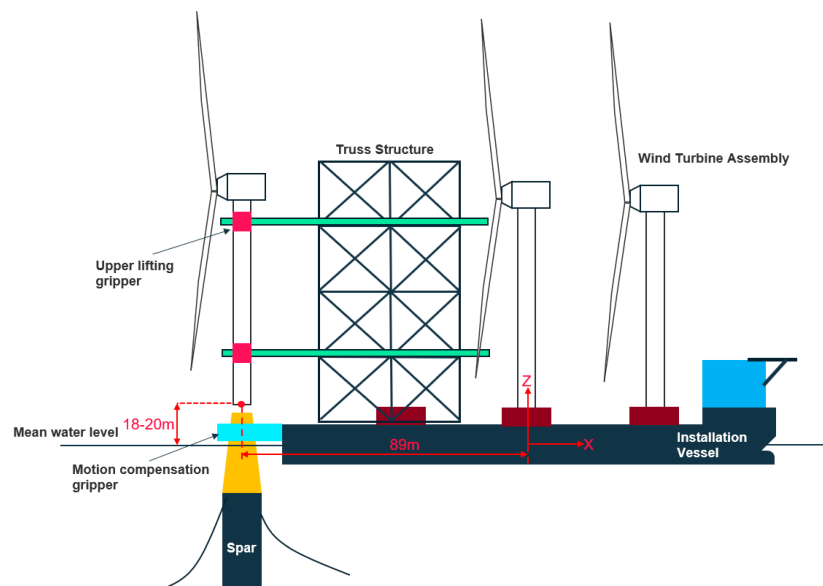


Figure 2.14: Illustration of the installation concept's main components (not to scale) (Hassan and Guedes Soares, 2023)

2.5. Relevant findings and applicability

Industry practices have significantly evolved, showcasing advancements in onshore assembly and offshore deployment techniques through state-of-the-art installation methods observed in projects like Hywind and WindFloat Atlantic. These projects highlight the critical role of specialized ports, advanced lifting vessels, and innovative transport methods in managing the complexities associated with large-scale FOWT installations.

In response to these complexities, the industry has introduced innovative concepts such as single-transfer solutions, modular crane systems, and horizontal towing of the FOWT. Each of these innovations offers unique benefits and demonstrates the industry's commitment to overcoming the logistical and operational challenges in deploying FOWTs.

The findings of the academic research show that when a crane is involved in the installation process, the tension of the wire is one of the critical responses and should always be analyzed. The motion responses of the bodies are influenced by wavelengths, making knowledge about the wave spectrum at the offshore installation site crucial. Whereas lowering and landing the monopile was more critical in shorter waves (Li et al., 2013), the blade installation was preferred at sites with shorter waves (Zhao et al., 2019). Smart positioning of the installation vessel can leverage the wave shielding effect. Furthermore, the forces on two bodies during contact depend highly on the chosen stiffness of the connection such as the monopile gripper (Li et al., 2013) or docking cone (Jiang et al., 2018). This stiffness also influences the natural periods, making it crucial to vary this parameter and investigate its importance and influence, while taking into account the practical feasibility in real-life applications.

The wind forces acting on the turbines situated on the vessel hardly affect the motion of the catamaran, even when the pitch is set at 0 deg (Jiang et al., 2018). The waves are the main contributor (Hassan and Guedes Soares, 2023) which suggests that, for an initial analysis, it may be acceptable to disregard the wind forces acting on the turbines on the vessel. The effect due to wind forces when the turbine assembly is being transported to the substructure cannot be disregarded yet, as this has not been investigated yet.

This chapter shows no academic papers specifically address floating-to-floating installation methods applied to semi-submersible floaters. The focus lies on spar-type substructures, indicating a gap in the academic exploration of semi-submersible floaters in this context. This gap will be the focus of this thesis, aiming to provide new insights and methodologies for the installation of semi-submersible floating wind turbines.

The research conducted on spar-type substructures is still valuable and offers a foundation that can be adapted for semi-submersible floaters. When adapting the approach outlined by Jiang et al. (2018) or Hassan and Guedes Soares (2023) to a semi-submersible floater, several considerations should be accounted for. The gripper, serving as mechanical coupling between the catamaran and the spar, constrains the relative motions in the xy-plane but due to rollers, the spar can move in the heave direction. Semi-submersibles commonly feature braces that connect the different columns. When allowing heave movements, caution must be taken to avoid potential collisions between the gripper and the braces. Furthermore, the spar only consists of one column whereas the semi-submersible has often three columns, increasing the wave loads on the semi-submersible. Moreover, due to the pitch or roll of the floater, larger rotational moments could be exerted on the gripper. If a crane is utilized to hoist the turbine assembly onto the floater, it is crucial to take the crane's reach into account. For a turbine positioned on the center column of the floater, an extensive reach from the crane is required. For this reason, a semi-submersible with the turbine placed on a corner column is preferred for this configuration. This design such as the INO WINDMOOR platform (Silva De Souza et al., 2021), allows for a reduced distance for the crane to reach and facilitates a shorter (grripper) connection distance between the vessel and the floater.

Research focus definition

The research definition begins with a general overview of the envisioned offshore installation process. Building on this overview and the selection of the area, the research objective is refined and defined. Considering the environmental conditions of the site, a framework for the installation concept is established, followed by the methodology employed to achieve the research objective.

3.1. Offshore installation process overview

The envisioned offshore floating-to-floating installation involves these global steps:

1. Load turbine components onto the vessel
2. Sail to location
3. Position vessel next to moored floater using DP system
4. Engage system to reduce relative motions between vessel and floater
5. Transfer turbine components from vessel to floater and secure the components
6. Release the turbine components
7. Disengage system to reduce relative motions
8. Sail away to install next turbines

The literature review shows that offshore installation of a turbine on a floating foundation has not yet been performed. Typically, the towing method is employed as highlighted in Figure 2.1, or alternative floater types are explored in academic papers for floating-to-floating installation scenarios. The advantages of shifting from established methods to the proposed approach will be explained in the following section.

3.1.1. Advantageous of offshore installation

The five main reasons for moving the turbine installation offshore are summarized as:

- No marshaling yard required for turbine integration
- Installation can be performed in phases
- The travel distance of the floater and turbine is decreased
- No tow-out of the FOWT
- No wet storage required

Beginning with the primary motive, shifting the installation process offshore eliminates the need for a marshaling yard to assemble the wind turbine on the floater. Such areas are scarce, not only in Europe but also in the US, where ports and marshaling facilities are recognized as potential bottlenecks for the offshore wind industry. Moreover, the quayside area required for this purpose is substantial, accommodating land cranes, turbine components, tools, and other equipment and large investments are required to adapt ports or build new terminals as shown in section 1.3. While dry dock facilities might be used,

they are typically long and slender, designed to manufacture and repair vessels, and not optimized for accommodating wide structures such as semi-submersibles. By directly transporting the floaters to their designated site, they can be optimized for that location, and their design is not constrained by the assembly port's draft or dry dock facilities and the subsequent tow-out operation.

Installation can be conducted in phases, allowing for the installation of the floater first, followed by the placement of the turbine on top. This phased approach decreases the risk of delays, which is crucial in an industry prone to supply chain issues. For instance, during Equinor's Hywind Tampen project, the final turbine towers faced issues, causing delays, while the floaters were ready. Consequently, these enormous floaters had to be stored over winter, awaiting installation the following summer.

Furthermore, as a result of installation in phases, the floater can be transported directly from its fabrication yard to its final destination. The same holds for the wind turbine, reducing the total travel distance and perhaps the number of vessel days as defined in Figure 1.4, since the additional travel distance to the marshaling yard is eliminated.

The applicability of the towing method of the assembled FOWT is seen as a key advantage of semi-submersibles since offshore operations are minimized. However, the tow-out operation is typically carried out in fair weather conditions, with a maximum significant wave height (H_s) between 1 and 1.5 m and mean wind speeds below 14 m/s. A sufficiently long weather window is required to allow for the safe towing of the assembled FOWT back to port in case of hook-up issues. With transit speeds ranging from 3 to 4 knots (5.6 to 7.4 km/h), the transit distance is a critical factor in the tow-out process, influencing the selection of both construction ports and wind farm sites. Additionally, during transportation and installation, the nacelle acceleration is constrained by the turbine supplier's limit—usually about 0.5 g—to prevent damage to the turbines and to maintain warranty validity (BVG Associates, 2023). These considerations are eliminated when transporting the floater separately. Furthermore, the existing projects showed three vessels were required to tow one assembled FOWT; by eliminating this step, the number of vessel days can also be decreased.

Finally, to minimize potential delays caused by substructure issues, the strategy of wet storage of the substructures near the assembly port is demanded, which involves setting up temporary moorings. Similarly, the assembled FOWT has to wait for a suitable weather window before towing and needs to vacate the quayside to allow for the assembly of the next FOWT. By adopting the proposed installation method, the need for wet storage and the associated actions and the near-shore space requirements can be eliminated.

3.1.2. Challenges in offshore installation

As briefly mentioned in subsection 1.3.3, the primary drawback of offshore turbine installation lies in the offshore mating process between the turbine and the substructure due to both structures having six DOFs each and being heavily dependent on favorable weather conditions. Furthermore, shifting the installation offshore necessitates the use of large, costly vessels. However, with an effective concept, offshore installation may become economically attractive.

The reduction in the relative motion is of utmost important to have a successful installation process according to the steps in section 3.1. While the floating wind farm benefits from high wind speeds, it increases the motions of both floating bodies which makes this task even more challenging compared to performing the task on a marshaling yard.

Since these kind of installations are typically not performed offshore, specialized equipment will be required to compensate for the relative motions. Additionally, due to the novelty of this operation, the risk of accidents and operational failures can be higher, as there are few relevant precedent projects to draw from. The lack of precedents also increases the technical challenges, as there is no established reference project to guide the process.

Furthermore, the environmental impact is greater compared to the traditional towing method, which minimizes offshore activity. Since the installation will now also take place offshore, the extended presence of large vessels, along with their unavoidable pollution and noise, will have a more significant impact on the environment.

However, these disadvantages can partially be countered with rebuttals to strengthen the case. While weather conditions pose challenges, they are generally more predictable further offshore than close to shore, providing clearer operational windows. Furthermore, many existing offshore installations already employ dynamic positioning systems and motion compensation technologies that can be adapted for this type of offshore operation, making it not entirely novel. Additionally, measures can be taken to minimize risks, such as eliminating the need for personnel on the floater during installation by using remote-controlled mechanisms and measuring systems. Moreover, the environmental impact of using floating vessels is notably less severe compared to jack-up vessels, as they do not impact the seabed. Floating foundations typically use anchors, which have a much smaller footprint and are less invasive than traditional monopiles.

3.2. Offshore location

The chosen case study for this installation process is the wind farm on the east coast of the Spanish island Gran Canaria, where Equinor intends to establish a floating wind farm featuring fifteen 15 MW turbines with three-columned semi-submersible foundations (4C Offshore, 2024). This Floating Offshore Wind Canarias (FOWCA) site is selected for this study due to its lack of suitable facilities for a large marshaling yard and its constrained area as an island. Additionally, its economy heavily relies on the tourism industry, which contributes up to 80% of its gross income (Spain Gran Canaria, 2023). Establishing a construction site near its popular beaches could potentially impact tourism negatively. Moreover, the distance of 1200 km to the Spanish coast makes the towing method not realistic. While the African coastline is in closer proximity, still at 200 km, southern Morocco and the Western Sahara region lacks adequate quayside facilities (Ports, 2024). Consequently, offshore installation of the wind turbines would be the preferred approach, aligning perfectly with the objectives of this research.

Metoccean data

According to the Global Wind Atlas (DTU, 2024), the mean wind speed at 150 m above sea level at the specified location in Table 3.1 is 11 m/s and its water depth is 200 m. Figure 3.1 presents the scatter diagram showing the probability of occurrence for various combinations of significant wave height (H_s) and peak periods (T_p). It is evident that the most common waves have an H_s between 1 m and 2 m and a T_p between 6 s and 11 s. The seasonal variations in wave height are minimal as given in Figure 3.2, which is advantageous for the workability study to be conducted later in the study. Then, information about wave directionality relative to the floating bodies will be provided as well.

Table 3.1: The FOWCA wind farm site details and environmental data summarized (DTU, 2024), (4C Offshore, 2024), (WaveClimate, 2023)

Longitude [°]	27.81
Latitude [°]	-15.31
Distance from shore [km]	10
Water depth [m]	200
Significant wave height [m]	< 3
Wave peak period [s]	5 - 13
Mean wind speed [m/s]	11

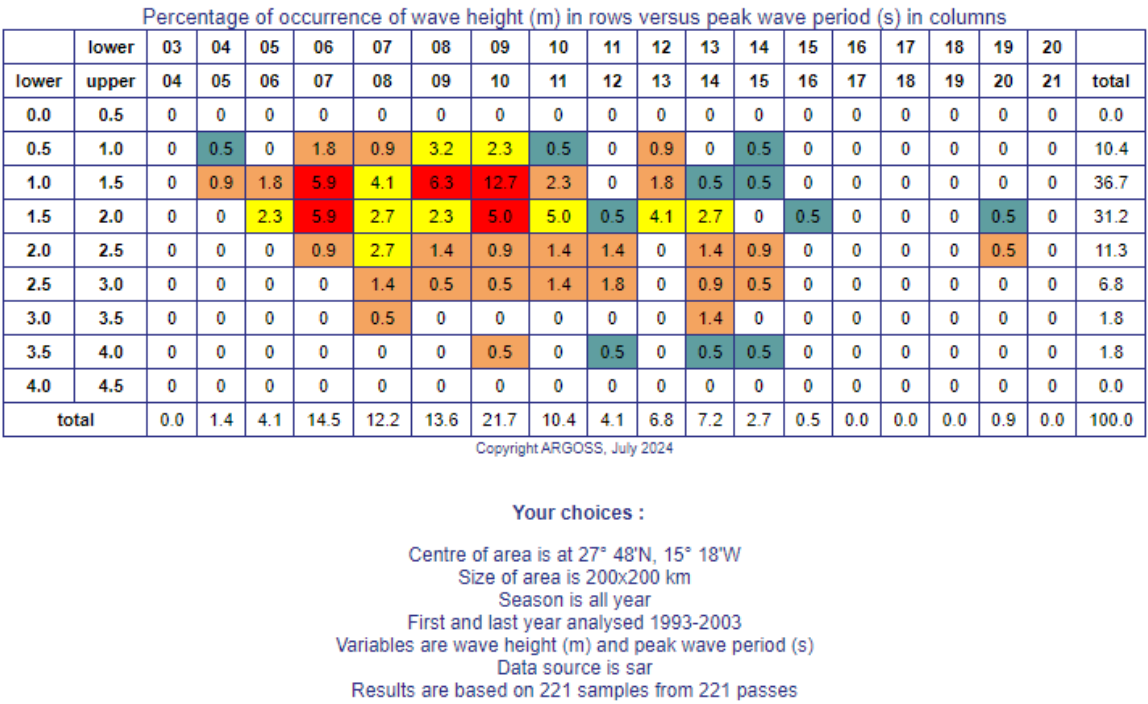


Figure 3.1: 2D scatter diagram of the significant wave height (shortened to wave height in the table) and wave peak period (WaveClimate, 2023). The red cells highlight the most significant values per column, followed by yellow, orange, and turquoise representing progressively lower values

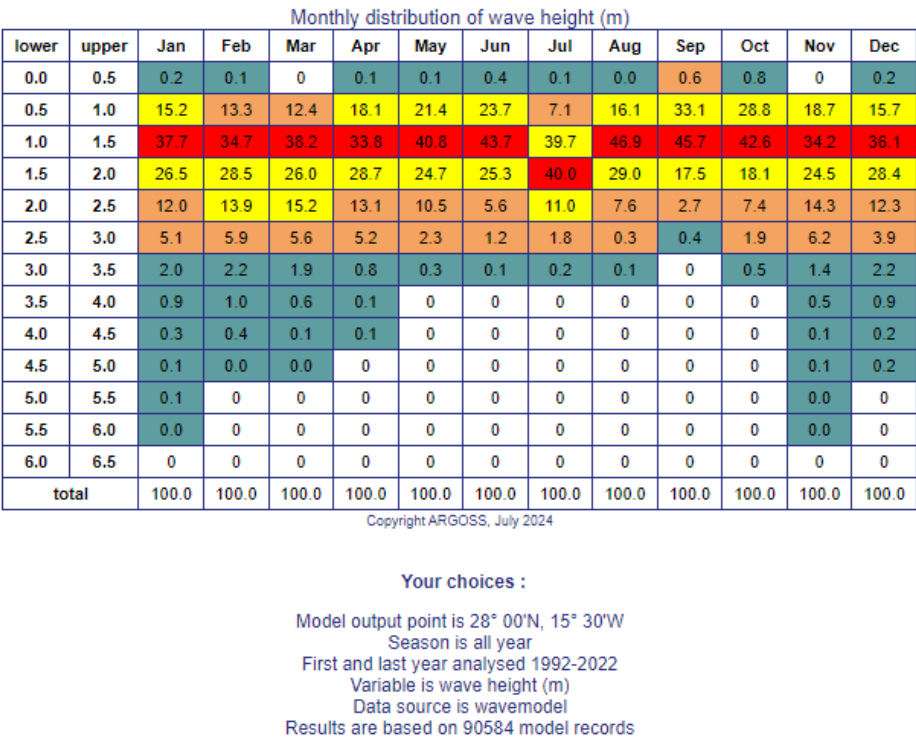


Figure 3.2: Seasonal changes in the significant wave height (WaveClimate, 2023)

3.3. Research focus refinement

The research objective can be narrowed and defined based on the research given so far. Corresponding sub-questions required to achieve the research goal will be stated, followed by the framework within which the operation should take place.

3.3.1. Research objective

Based on the global installation process outlined in section 3.1, this thesis will focus on steps 4 to 7, related to the reduction of the relative motions and developing a method for wind turbine installation. The scope is further refined to cover the installation of the tower only; the installation of the RNA will be addressed in future work and is not within the scope of this thesis. After the tower installation, (a combination of) the concepts illustrated in Figure 2.5 may potentially be applied. The maximum relative displacement is limited to 0.2 m and will be elaborated on in subsection 3.3.3.

The research objective is defined as:

Design an effective concept aimed at reducing the horizontal relative motions between a wind turbine tower base and a semi-submersible floater within 0.2 m, enabling offshore installation of the wind turbine tower using a floating vessel.

3.3.2. Research question

Based on the defined research objective, the research question to be addressed in this study will be formulated. The goal is to develop a new concept rather than to optimize an existing procedure, given that this area is novel and lacks extensive prior research. Additionally, a preliminary feasibility study will be conducted, as it is not feasible within the given timeframe to fully resolve the offshore installation process.

This leads to the following research question:

What concept can be effectively used in an initial feasibility study to reduce the relative motions between a wind turbine tower base and a semi-submersible floater within a 0.2-m radius, enabling the offshore installation of the wind turbine tower using a floating vessel?

Sub-questions

1. What are the relative motions between the floater and vessel and which DOF is governing?
2. What are possible concepts to reduce the horizontal relative motions?
3. How do environmental conditions impact the chosen concept with its associated design choices?
4. What is the workability of this concept in the proposed area based on defined limits?
5. Based on the design choices, what are the specifications for the required equipment?

3.3.3. Framework

In the design of a concept, it is crucial to define the constraints and criteria that will guide the assessment of the concepts. These guiding factors are categorized into three key terms: boundary conditions, requirements, and preferences.

First, boundary conditions refer to constraints that establish the framework within which a system must operate. Requirements are the essential specifications and criteria that the system must meet to ensure its functionality. Preferences refer to additional considerations that, while not critical, can enhance the overall performance of the installation process. These are desirable features or conditions that can improve the system's efficiency or effectiveness but are not strictly quantifiable.

Boundary conditions

1. The installation is performed from a floating vessel which also carries the wind turbine components on deck.
2. The wind turbine tower is installed on top of a semi-submersible floater.

3. 15 MW wind turbines are to be installed.
4. The semi-submersible floater is moored using its mooring system, which is designed for the operational state of the wind turbine.
5. Vessel is positioned on DP

Requirements

1. The horizontal relative translation between the tower base and floater center column has to be reduced to a Most Probable Maximum (MPM) of 0.2 m in a 3-hour simulation for $H_s = 2.5$ m and $T_p = 6 - 11$ s

Context: The 0.2 m limit is derived from the figures in section 2.3, estimating that with a maximum relative motion of 0.2 m, a guiding mechanism can manage the final relative displacements effectively. Additionally, Figure 3.1 indicates that 90% of the occurring H_s is below 2.5 m, and the range of T_p between 6 s and 11 s captures over 70% of the wave conditions. Engineering practices confirm that these sea states are compatible with the operational limit of jack-up vessels and facilitate a comparison.

2. The vessel in question should be an existing vessel.

Context: As subsection 1.3.1 highlights, the shortage of installation vessels is expected as early as 2025, and the construction of new, specialized vessels will not be completed in time to address this issue.

3. Measures should be taken to ensure the loads on the turbine tower, the vessel, the floater, and additional equipment during installation do not cause damage.
4. Remote real-time monitoring of the relative displacement should be possible.

Context: As stated in section 2.3, with two floating bodies having six DOFs each, it is dangerous to have people do the monitoring.

5. The installation process should be a safe operation.
6. The installation process should be applicable to different floater geometries, regardless of the installation location of the turbine.

Context: Given the variety of floater concepts currently available and the uncertainty about which will dominate the market and if one concept will dominate, the installation method must be versatile and adaptable to various floater geometries.

7. The installation process should be applicable to a tower diameter of 10 m, corresponding to the tower of the 15 MW reference wind turbine (Gaertner et al., 2020).
8. No changes should be made to the pre-installed mooring system of the floater.

Context: This aligns with the envisioned installation procedure described in section 3.1, where it is assumed that the focus of this study starts once the floaters are moored using their designated mooring system.

Preferences

1. No personnel is required during the installation process.
2. The installation process can be performed by a large fleet.

Context: As subsection 1.3.1 highlights the anticipated expected shortage of installation vessels, the developed method should be compatible with a large fleet. Relying on a single vessel for the operation would significantly diminish the added value of the novel installation method.

3. The installation steps are straightforward and incorporate proven principles and established precedents.

Context: A straightforward process minimizes the risk of human errors and facilitates the adaptation of operators to the new installation procedure. Additionally, proven principles reduce the

need for extensive training, and leveraging precedent operations can help shorten the installation time.

4. The installation process can handle a range of tower diameters.

Context: Although the 15 MW reference turbine has a diameter of 10 m, the versatility of the installation concept would be enhanced if it could accommodate a range of tower diameters. This adaptability would allow the method to be used for wind turbines with capacities slightly lower and higher than the reference turbine.

5. The tools and machinery required for the installation process are widely available.
6. The concept is lightweight.
7. The concept uses affordable equipment.

3.4. Methodology

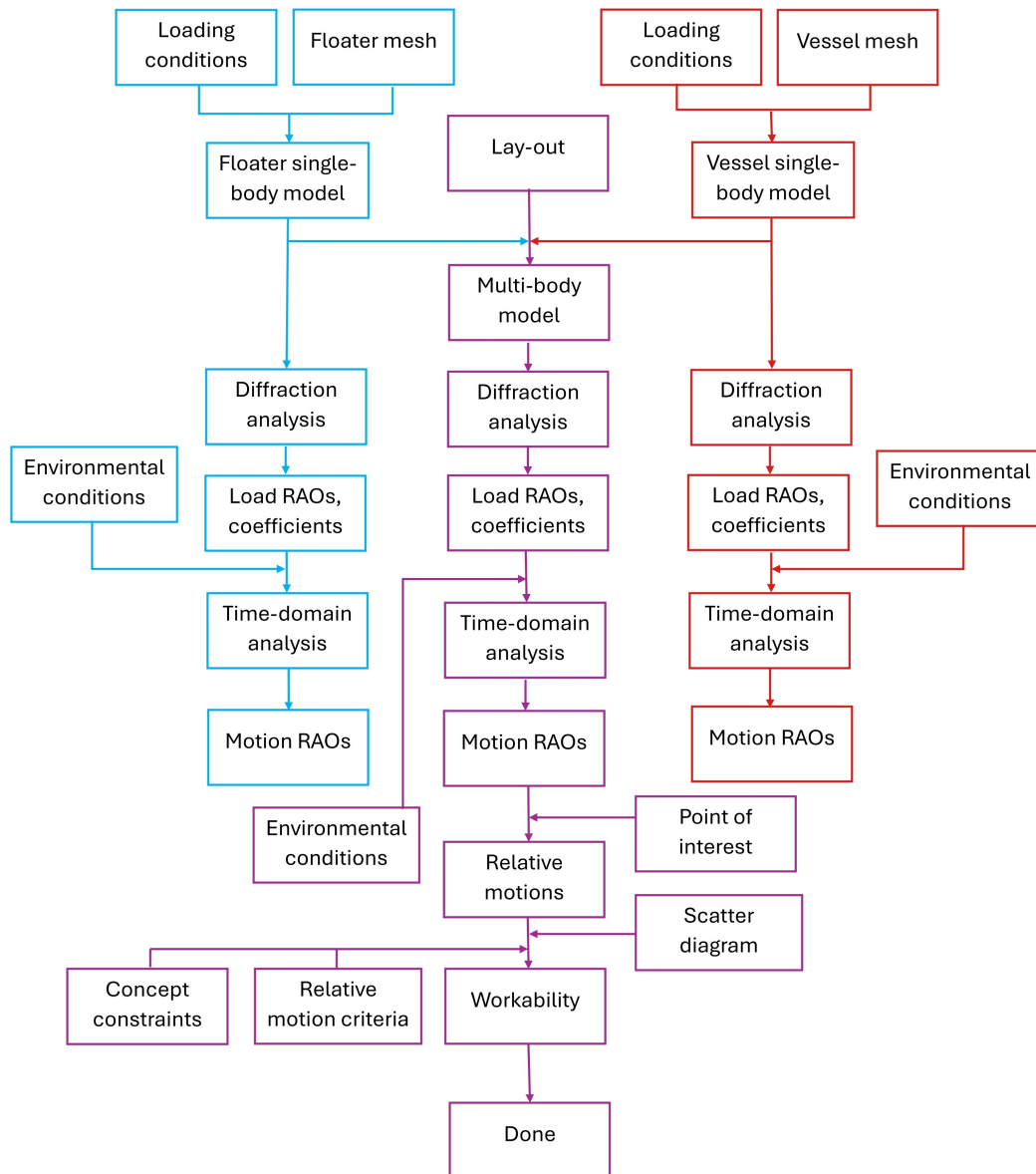
With the defined research objective and established framework, the methodology for achieving this objective is outlined next. This section also details the methods employed to determine the natural periods through decay tests and to obtain motion Response Amplitude Operators (RAOs) using regular wave simulations.

3.4.1. Methodology flowchart

Initially, the single-body models are developed using their meshes and loading conditions. Diffraction analysis is performed on these models to determine the first-order load RAOs and other essential hydrodynamic coefficients in OrcaWave. Additionally, time-domain simulations are conducted in OrcaFlex on the single-body models to investigate the displacement RAOs. This provides the necessary understanding of the behavior of each body individually. As a clarification to OrcaFlex's terminology, the load RAOs describe the wave-induced forces and moments acting on the structure, e.g. the diffraction and Froude-Krylov forces which will be explained in section 4.4, while displacement or motion RAOs describe the amplitude and phase of the structure's motions in response to incident waves.

Following the single-body analysis, the methodology advances to a multi-body diffraction analysis, where the spatial configuration of the floater and vessel is defined to establish a multi-body system. This model incorporates interactions between the individual bodies and undergoes another round of diffraction analysis to derive the load RAOs and hydrodynamic coefficients specific to the multi-body configuration. Time-domain simulations using regular waves are then conducted to obtain the motion RAOs for the multi-body model. Subsequently, based on these time-domain simulations, the relative motions between the floater and vessel under various environmental conditions are evaluated, focusing on points of interest critical for the mating of the tower with the floater. After evaluating the relative motions, concepts to reduce these motions with certain constraints will be developed. The chosen concept with its constraints will be implemented in the model. Finally, the workability analysis integrates the results from the time-domain analysis using irregular waves with operational constraints and relative motion criteria. The scatter diagram, which contains combinations of significant wave height and peak period, is used to determine the workability of the operation by identifying sea states that exceed acceptable limits.

The methodology is summarized in the flowchart depicted in Figure 3.3 and the utilized software for the different steps is listed in Table 3.2.

**Figure 3.3:** Methodology flowchart**Table 3.2:** Software and application used in this research

Description	Software
Mesh	Rhino
Diffraction analysis	OrcaWave
Time-domain analysis	OrcaFlex
Extract OrcaFlex data	Python
Post-processing	MATLAB

3.4.2. Decay tests

For the decay tests, an initial displacement or angle is given to the floater or vessel in a specific DOF. Wave loads are excluded, but added mass, damping, and quadratic damping coefficients are included. The time interval between successive peaks in the oscillation corresponds to the damped natural period, which is the parameter of interest. An example of such a response is plotted in Figure 3.4.

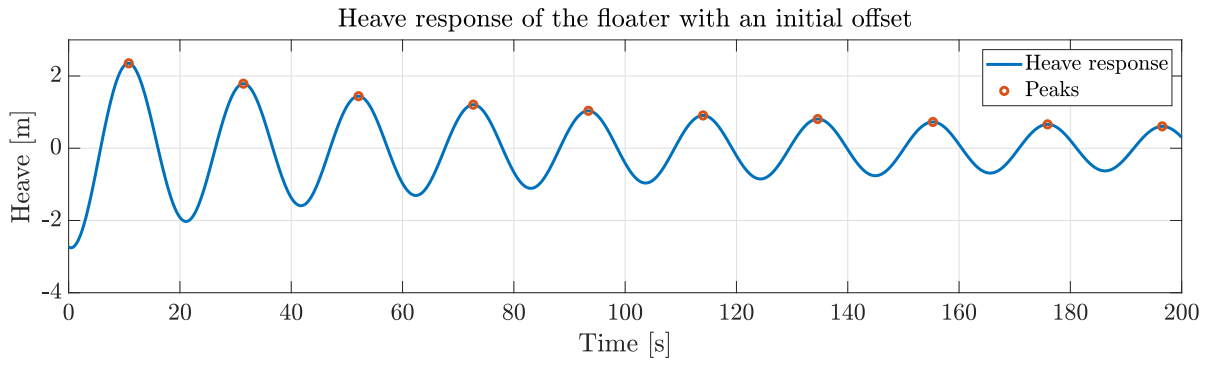


Figure 3.4: The average time between the peaks is the natural period; 20.4 s for the floater's heave

3.4.3. Regular wave tests

The regular wave tests are conducted to obtain the displacement RAOs, while the diffraction results from OrcaWave also provide displacement RAOs. However, OrcaWave does not provide quadratic damping coefficients for the body; only a linear damping matrix can be applied. These damping coefficients are specified in the floater's description (Allen et al., 2020). When damping is not accounted for, the displacement RAOs will be overestimated due to the lack of viscous damping which is not included in potential flow theory. Using this approach, small amplitude waves are assumed, where the response is linearly proportional to the wave amplitude, and nonlinearities are not considered.

The approach is to run regular waves with different periods and obtain the response amplitudes in the postprocessing. The waves approach the body from a single direction, neglecting the effects of wave spreading. An example of the time series of the input wave and the resulting response is given in Figure 3.5. The RAO of a certain wave period is then obtained by dividing the average amplitude of the response over the last 200 s by the amplitude of the exciting wave.

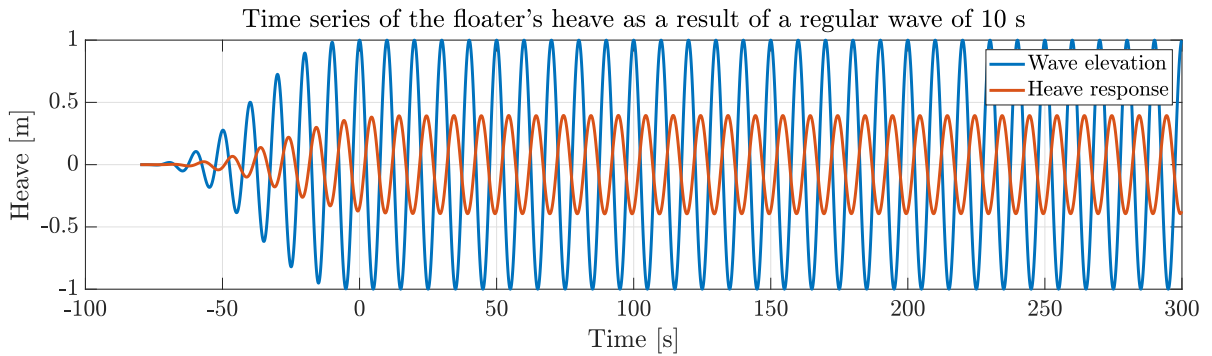


Figure 3.5: Based on this time series, the resulting RAO of this case is 0.4 m/m.

4

Theoretical background

This chapter provides the theoretical foundation for the analysis conducted in this thesis. It begins with a short description of potential flow theory, followed by linear wave theory and the description of irregular waves. The theory given in this section is based on the works of Fredsøe (2008), Journée and Massie (2001), Techet (2003) and Beaume Cedric (2014) and can be consulted to provide elaboration on the theory. An introduction of the theory behind the used software, OrcaWave and OrcaFlex will also be explained.

4.1. Potential flow theory

Potential flow theory can be employed for computationally inexpensive analyses and can yield acceptable results. However, it neglects certain aspects of fluid flow, which can lead to inaccuracies. It is based on the assumption that the fluid is incompressible and inviscid and that the flow is irrotational. Under these assumptions, a velocity potential ϕ is introduced, relating to the fluid velocity $\mathbf{u}$ as:

$$\mathbf{u} = \nabla \phi \quad (4.1)$$

While lacking physical meaning, ϕ facilitates the mathematical analysis. Solving for the velocity potential involves finding a solution to the Laplace equation as given in Equation 4.2, alongside relevant boundary conditions, including the Kinematic Free Surface Condition (KFSC) and Dynamic Free Surface Condition (DFSC). These conditions will be given for linear waves in the next chapter.

$$\nabla^2 \phi = 0 \quad (4.2)$$

4.2. Linear wave theory

Three wave parameters determine which wave theory should be applied in a specific case. These are the wave height H , the wave period T and the water depth d . These parameters are used to calculate three non-dimensional numbers that indicate ranges of validity of different wave theories.

- Wave steepness: $S = 2\pi \frac{H}{gT^2} = \frac{H}{\lambda_0}$
- Shallow water parameter: $\mu = 2\pi \frac{d}{gT^2} = \frac{d}{\lambda_0}$
- Ursell number: $U_R = \frac{H\lambda^2}{d^3}$

Here, g is the gravitational acceleration constant and λ is the wavelength. The three parameters above are not independent. The relation is $U_R = \frac{S}{\mu}$. The range of application of the different wave theories is visualized in Figure 4.1.

With the parameters $d = 200$ m, $T = 10$ s and $H = 1$ m for the proposed area, the variables on the figures's axes are $H/gT^2 = 0.001$ and $d/gT^2 = 0.2$. These values place the scenario right on the border of the validity range for linear wave theory as indicated in Figure 4.1. Given the focus on the installation aspect, linear wave theory will be sufficient and is therefore employed in this research.

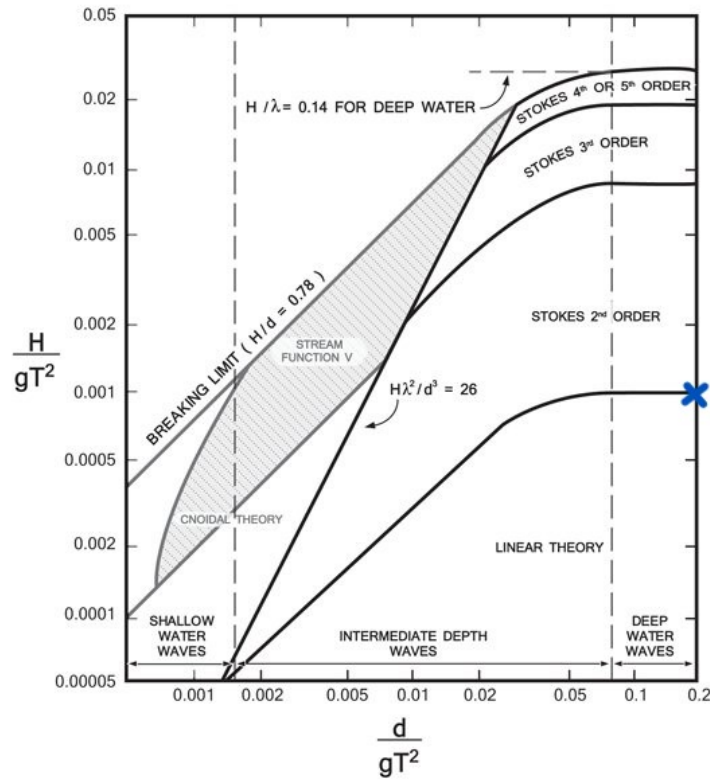


Figure 4.1: Ranges of validity for different wave theories based on the wave steepness and shallowness (Army. Corps of Engineers, 2002), retrieved from Vyzikas et al. (2014)

From the different theories in Figure 4.1, the simplest one is linear wave theory, also known as Airy wave theory. Here it is assumed that the wave height is much smaller than the wave length and water depth. This assumption allows the free surface boundary condition to be linearized by dropping terms that are second-order or higher. It also allows the free surface conditions to be satisfied at the mean water level, rather than at the varying surface elevation. Simplifying into a 2D problem depicted in Figure 4.2, the free surface boundary conditions are reduced to Equation 4.3.

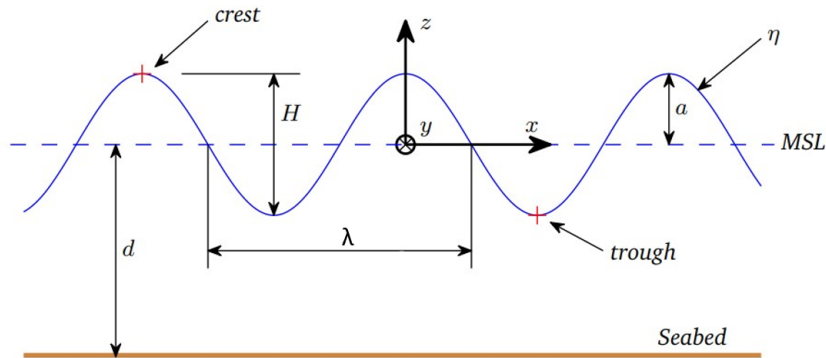


Figure 4.2: Definition of a linear regular wave and the coordinate system, adapted from van der Meulen (2012)

$$\text{KFSC: } \frac{\partial \eta}{\partial t} - \frac{\partial \phi}{\partial z} = 0 \quad \text{at } z = 0 \quad (4.3a)$$

$$\text{DFSC: } \frac{\partial \phi}{\partial t} + g\eta = 0 \quad \text{at } z = 0 \quad (4.3b)$$

Where η is the time- and position-dependent wave elevation, t is the time and z is the direction displaced in Figure 4.2.

Rewriting Equation 4.3b, the elevation profile is given by:

$$\eta = -\frac{1}{g} \left(\frac{\partial \phi}{\partial t} \right) \quad (4.4)$$

and substituting this in Equation 4.3a gives:

$$\frac{\partial^2 \phi}{\partial t^2} + g \frac{\partial \phi}{\partial z} = 0 \quad (4.5)$$

Through separation of variables, Laplace's equation can be solved for η and ϕ . The expression for the linearized velocity potential is:

$$\phi = \frac{gH}{2\omega} \frac{\cosh(z+d)}{\cosh(kd)} \sin(\omega t - kx) \quad (4.6)$$

where ω is the angular velocity and k is the wave number defined as: $\frac{2\pi}{\lambda}$. Substituting Equation 4.6 into Equation 4.4 results in the regular linear wave surface elevation:

$$\eta = \frac{H}{2} \cos(\omega t - kx) \quad (4.7)$$

Substituting the velocity potential from Equation 4.6 in Equation 4.5 gives the linear dispersion relationship Equation 4.8c and the water particle velocities in x and y directions are given by:

$$u = \frac{\partial \phi}{\partial x} = \frac{\omega H}{2} \frac{\cosh k(z+d)}{\sinh kd} \cos(\omega t - kx) \quad (4.8a)$$

$$w = \frac{\partial \phi}{\partial z} = -\frac{\omega H}{2} \frac{\sinh k(z+d)}{\sinh kd} \sin(\omega t - kx) \quad (4.8b)$$

$$\omega^2 = gk \tanh(kd) \quad (4.8c)$$

The dispersion relation in Equation 4.8c is an implicit equation that relates the wavenumber and wavelength to water depth and frequency. For deep water, this equation can be simplified to $\omega^2 = gk$. From the water particle velocities formulas, it is observed that the horizontal velocity is maximum or minimum when the vertical velocity is zero and vice versa. Integrating Equation 4.8a and Equation 4.8b with respect to time gives the particle position. In deep water ($kd > \pi$) the particle paths are circular whereas in shallow water ($kd < \pi/10$) the paths oscillate horizontally. In intermediate water waves, the particles follow an elliptical path, as visualized in Figure 4.3.

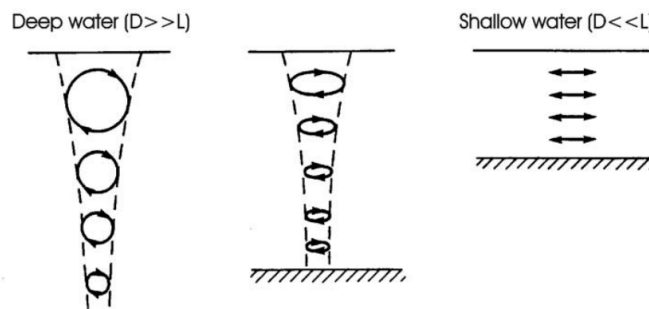


Figure 4.3: Particle trajectory for different water depths (Fredse, 2008)

4.3. Irregular waves and wave spectra

The wave elevation depicted in Figure 4.2 is a regular wave. However, in nature, regular waves are rare, as waves generated by wind or storms are typically irregular. Irregular waves present more challenges for analysis. However, using linear theory and the superposition principle, irregular waves can be decomposed into several regular harmonic waves for simpler analysis.

The surface elevation is made up of a finite sum of waves that can be described by:

$$\eta = \sum_{n=1}^N A_n \sin(\omega_n t - k_n x + \epsilon_n) \quad (4.9)$$

where the subscript n denotes the different individual waves and ϵ is the random phase angle, uniformly distributed between 0 and 2π . ω_n can be calculated for each individual wave using the dispersion relation Equation 4.8c. To generate the amplitudes, it is known that the variance σ^2 of Equation 4.9 is given by:

$$\sigma_\eta^2 = \sum_{n=1}^N \frac{1}{2} A_n^2 \quad (4.10)$$

The power spectrum of the wave elevation defines how energy is distributed among frequencies f . The area under the spectrum S_η is equal to the variance:

$$\sigma_\eta^2 = \int_0^\infty S_\eta(f) df \quad (4.11)$$

Discretize the above equation gives:

$$\sigma_\eta^2 = \sum_{p=1}^N S_\eta(f_p) \Delta f \quad (4.12)$$

Combining Equation 4.12 with Equation 4.10 gives:

$$\frac{1}{2} A_n^2 = S_\eta(f_p) \Delta f \rightarrow A_n = \sqrt{2 S_\eta(f_p) \Delta f} \quad (4.13)$$

A stationary sea state is characterized by the significant wave height H_s and the peak period T_p . The significant wave height is defined as the average wave elevation of the highest one-third of waves in the time period of the sea state. The peak period is defined as the wave period related to the wave frequency at which the energy spectrum reaches its maximum value. The two most widely used spectra are the Pierson-Moskowitz and the JONSWAP spectra.

JONSWAP spectrum

The Joint North Sea Wave Project (JONSWAP) spectrum $S(f)$ is an empirical relationship that describes the distribution of wave energy as a function of frequency f within the ocean.

$$S(f) = \frac{\alpha g^2}{(2\pi)^4} f^{-5} \exp \left[-\frac{5}{4} \left(\frac{f}{f_p} \right)^{-4} \right] \cdot \gamma^{\exp \left[-\frac{\left(\frac{f}{f_p} - 1 \right)^2}{2\sigma^2} \right]} \quad (4.14)$$

where f is the wave frequency, f_p is the spectral peak frequency, α is the generalized Philips' constant which is given in Equation 4.15, σ is the spectral width parameter which is 0.07 for $f \leq f_p$ and 0.09 for $f > f_p$, and γ is the peak enhancement factor and often chosen as 3.3 for simplicity but it can also be calculated using the formula given in Equation 4.16.

$$a = 5 \cdot (H_s^2 f_p^4 / g^2) \cdot (1 - 0.287 \ln \gamma) \cdot \pi^4 \quad (4.15)$$

$$\gamma = \begin{cases} 5 & \text{for } \frac{T_p}{\sqrt{H_s}} \leq 3.6 \\ e^{\left(5.75 - 1.15 \frac{T_p}{\sqrt{H_s}}\right)} & \text{for } 3.6 < \frac{T_p}{\sqrt{H_s}} \leq 5 \\ 1 & \text{for } 5 < \frac{T_p}{\sqrt{H_s}} \end{cases} \quad (4.16)$$

For $\gamma = 1$, the JONSWAP spectrum reduces to the Pierson-Moscowitz spectrum. For a fully developed sea, the Pierson-Moscowitz spectrum can be used, but for a growing wind sea, the JONSWAP spectrum is more suitable. The difference in their spectra is visible in Figure 4.4.

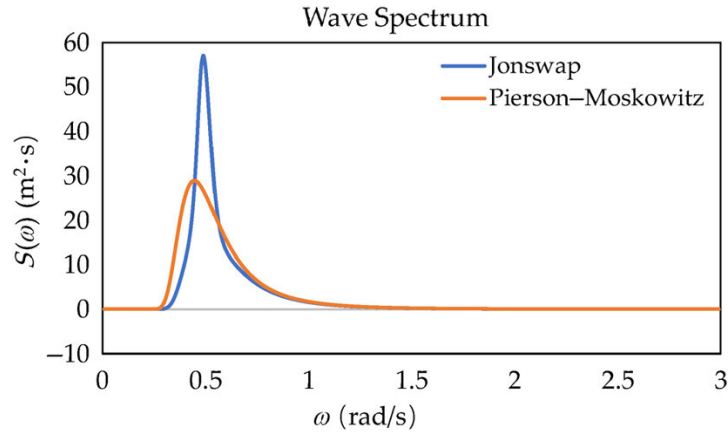


Figure 4.4: Comparison between the JONSWAP spectrum and Pierson-Moscowitz spectrum

4.4. OrcaWave

OrcaWave is a computational tool developed by Orcina (Orcina, 2024) for analyzing wave-structure interactions. It will be used to calculate the hydrodynamic coefficients, including added mass, radiation damping, and first-order wave excitation forces, and these are used for dynamic simulations in OrcaFlex, enabling modeling of the structural response to waves. The diffraction theory in OrcaWave is based on the principles of potential flow theory and satisfies Laplace's equation as introduced in Equation 4.2. This theory serves as the foundation for modeling wave interactions with marine structures. OrcaWave employs this theory to calculate the forces exerted by waves on offshore structures by solving for different potential components: incident, diffraction, and radiation potentials.

The incident wave potential ϕ_i represents the wave field as if the structure were absent. Froude-Krylov forces, derived from ϕ_i , represent the pressure exerted by the undisturbed incident waves directly on the structure. These forces are calculated by integrating this pressure over the wetted surface of the structure.

The diffraction potential ϕ_d on the other hand, represents the modification of the incident wave field due to the presence of a fixed structure. When waves encounter a structure, they are diffracted, altering the wave pattern around the structure. The diffraction potential is obtained by solving the Laplace equation with boundary conditions imposed by the structure's geometry.

Radiation forces are generated when a structure moves, creating waves in the surrounding fluid. These forces are characterized by the radiation potential ϕ_r , which describes the wave field due to the structure's oscillatory motion. It satisfies the Laplace equation and the boundary conditions related to the structure's motion.

The total hydrodynamic force on a structure is then obtained by combining the effects of Froude-Krylov, diffraction and radiation forces. The velocity potential ϕ used in these calculations is the sum of the incident, diffraction, and radiation potentials:

$$\phi = \phi_i + \phi_d + \phi_r \quad (4.17)$$

4.5. Orcaflex

OrcaFlex is a software package developed by Orcina for the analysis and simulation of marine structures and their interactions with the environment. It is widely used in the offshore engineering sector for its robust capabilities in modeling dynamic systems involving floating and submerged structures. The comprehensive documentation for OrcaFlex is available through Orcina (Orcina, 2024), and the following summary highlights key aspects relevant to its use in this research.

In Orcaflex, both the static and dynamic characteristics of the system can be analyzed. The static analysis involves determining the positions and orientations of the bodies in the model, where forces and moments are in equilibrium. These forces and moments facilitate the establishment of local equations of motion, which are then solved to predict the system's response over time.

The dynamic analysis can be split into frequency and time domain analysis, but the latter is used for the simulations in subsequent chapters and will therefore be elaborated.

The equation of motion which OrcaFlex solves in the time domain is:

$$M(p, a) + C(p, v) + K(p) = F(p, v, t) \quad (4.18)$$

where $M(p, a)$ is the system inertia load, $C(p, v)$ is the system damping load, $K(p)$ is the system stiffness load and $F(p, v, t)$ is the external load. p, v, a are the position, velocity and acceleration vectors respectively and t is the simulation time. The added mass, radiation damping and wave excitation forces resulting from OrcaWave's diffraction analysis are included in M , C and F respectively.

In time-domain analysis, the system's mass, damping, stiffness, and loading are calculated at each time interval, considering the instantaneous time-varying geometry. Integration can be performed using either implicit or explicit time-stepping schemes, each with its distinct characteristics.

The explicit scheme is essentially a semi-implicit Euler method with a constant time step. At the start of the time simulation, the initial positions and orientations of all objects in the model, including all nodes in all lines, are known from the static analysis. The time step required for stable integration is typically very short and OrcaFlex gives guidance on an appropriate time step.

Conversely, the implicit scheme involves solving the Equation of Motion (EOM) at the end of each time step. Initial values for position, velocity, and acceleration are unknown, requiring iterative solutions that can significantly increase computational time. However, the implicit scheme is typically stable for much longer time steps than the explicit scheme and often this means that the implicit scheme is faster.

Constraints will be utilized in the model, and a brief explanation is provided here for clarity:

A constraint in OrcaFlex can be assigned a stiffness value when certain DOFs are marked as 'free'. Although the term 'free constraint' is contradictory, it aligns with the terminology used in OrcaFlex and Orcina's documentation. The translational or rotational stiffness in a constraint is isotropic, meaning that these properties are uniform in all translational or rotational directions. For example, if both the x and y directions are indicated as 'free' and given a non-zero stiffness, motion along the x-axis has the same stiffness as motion along the y-axis. To model non-isotropic behavior, where the stiffness varies by direction, one can connect two or more constraint objects in a chain, each with distinct stiffness characteristics (Orcina, 2024).

Floater and vessel descriptions

5.1. VoltturnUS-S floater

The selected floater is the UMaine VoltturnUS-S reference platform (Allen et al., 2020) developed to support the IEA Wind 15 MW offshore reference wind turbine (Gaertner et al., 2020). The steel platform design comprises three 12.5 m-diameter outer columns connected to a 10 m-diameter central column via three rectangular pontoons. Additionally, a central column is integrated to accommodate the wind turbine. These columns provide essential buoyancy and stability, supporting the overall structure. Its dimensions and geometry are visualized in Figure 5.1 and its mass properties along with other relevant parameters are summarized in Table 5.1.

This FOWT is created in OrcaFlex by Orcina as an open-source example project and the turbine represents version 1.1.3 of the 15 MW reference wind turbine (Orcina, 2023). Particularly significant is the increase in tower mass from 1263 t to 1483 t in the OrcaFlex model compared to the original tower configuration described in the technical report. This alteration is attributed to a redesign aimed at enhancing tower stiffness to mitigate resonance excitation arising from the 3P rotor mode (Barter, 2023).

Table 5.1: Relevant turbine and platform properties (Orcina, 2023), (Allen et al., 2020)

Turbine properties		Platform properties	
Hub height [m]	150	Draft (installed state) [m]	20
Rotor mass (inc hub) [t]	275	Freeboard [m]	15
Nacelle mass [t]	675	Steel mass [t]	3914
Tower mass [t]	1483	Seawater ballast [t]	11300
Tower length [m]	133	Iron-ore-concrete ballast [t]	2540
Tower base outer diameter [m]	10	Platform total mass [t]	17854
Tower inertia roll, pitch [$t \cdot m^2$]	1.38e6	Mooring system	Three-line chain catenary
Distance tower bottom to CoM [m]	56.5		

As mentioned in Figure 2.1, the advantage of the installed three-column designs is that the turbine is located on the periphery of the platform. This minimizes the crane reach required for installation, in contrast to centrally located platforms such as the VoltturnUS-S floater. Therefore, in comparison to platforms like the INO WINDMOOR 12 MW floater, the VoltturnUS-S floater presents a less favorable geometry.

Nevertheless, for the present analysis using the VoltturnUS-S floater, the transfer mechanism to transfer the tower to the floater has not been determined yet. When using a crane, there is typically a minimum working radius, which for the crane in question is approximately 30 m. Assuming the nearest distance to the vessel is the layout in which two columns are adjacent alongside the vessel, this results in an additional distance of only approximately 2 m, since the minimum distance from the vessel's hull to the center column is 32 m. However, if a frame similar to the concepts in Figure 2.3 were used, the reach of the frame would be at least 32 m. This would impose a substantial moment, making the transfer quite challenging.

Despite the less favorable geometry, the chosen floater also has a distinct benefit. Due to its symmetry, it does not require changes in ballast during installation. In contrast, platforms with a corner turbine are ballasted for their installed state, and when the turbine is absent, these platforms must be reballasted to eliminate static tilt during the tower installation. This reballasting is not necessary for the VoltturnUS-S platform, as it will only move upwards in heave when the turbine is not yet installed.

Unless otherwise specified, the term floater or platform will refer to the UMaine VoltturnUS-S reference platform henceforth.

5.2. Heavy lift vessel

The installation vessel is a general monohull heavy lift installation vessel equipped with a DP system. Due to confidentiality reasons, the exact properties of the vessel cannot be shared. Instead, the approximate dimensions are given an asterisk in Table 5.2. With multiple vessels in the industry possessing these approximate dimensions, the analysis is applicable to a range of existing vessels. Furthermore, the crane is positioned approximately one-quarter from the stern of the vessel and according to its load chart, it has the capacity and reach to position the tower above the center column.

Table 5.2: Approximation of the relevant vessel parameters

Length overall [m]*	225
Breadth [m]*	50
Draft [m]	10
Lightship mass [t]*	$40 \cdot 10^3$
Deck components mass [t]	$8.3 \cdot 10^3$
Ballast mass [t]	$41 \cdot 10^3$
Displaced volume [m ³]	$87 \cdot 10^3$

A simplified ballast plan and deck layout consisting of components of three wind turbines and sea fastening systems are devised to determine the mass properties of the vessel. The vessel is segmented into eight equal tanks, and these tanks are filled to align the Center of Mass (CoM) coordinates in the x- and y-directions with the center of buoyancy to ensure zero trim and heel. Additionally, the total displacement matches the displaced volume of the vessel's hull. This reversed plan is used because the mesh of the vessel provided by TWD has a draft of 10 m, and therefore, the prescribed displaced volume could not be changed.

5.3. Floater-vessel orientation

Two orientations are considered; a stern-to-floater orientation and a side-to-floater orientation, both with their own advantages and disadvantages. With a crane positioned on the aft, lifting heavy objects over the stern side of a vessel is generally considered safer due to the increased stability along the longitudinal axis of the ship. Conversely, lifting over the side, which aligns with the transverse axis, can introduce more movement and instability. From an operational perspective, it is more common to lift heavy objects over the side because this area is typically more accessible and offers a larger working area. Additionally, the crane is often positioned on the side, enhancing the crane capacity since the reach required is typically less compared to lifting over the stern. Moreover, the side-to-floater

orientation can potentially reduce wave loads on the floater during installation due to the shielding effects of the vessel.

Based on the outlined advantages of the side-to-floater orientation, it is chosen for this layout. Despite the drawback of reduced stability in roll compared to pitch, the advantages outweigh this disadvantage.

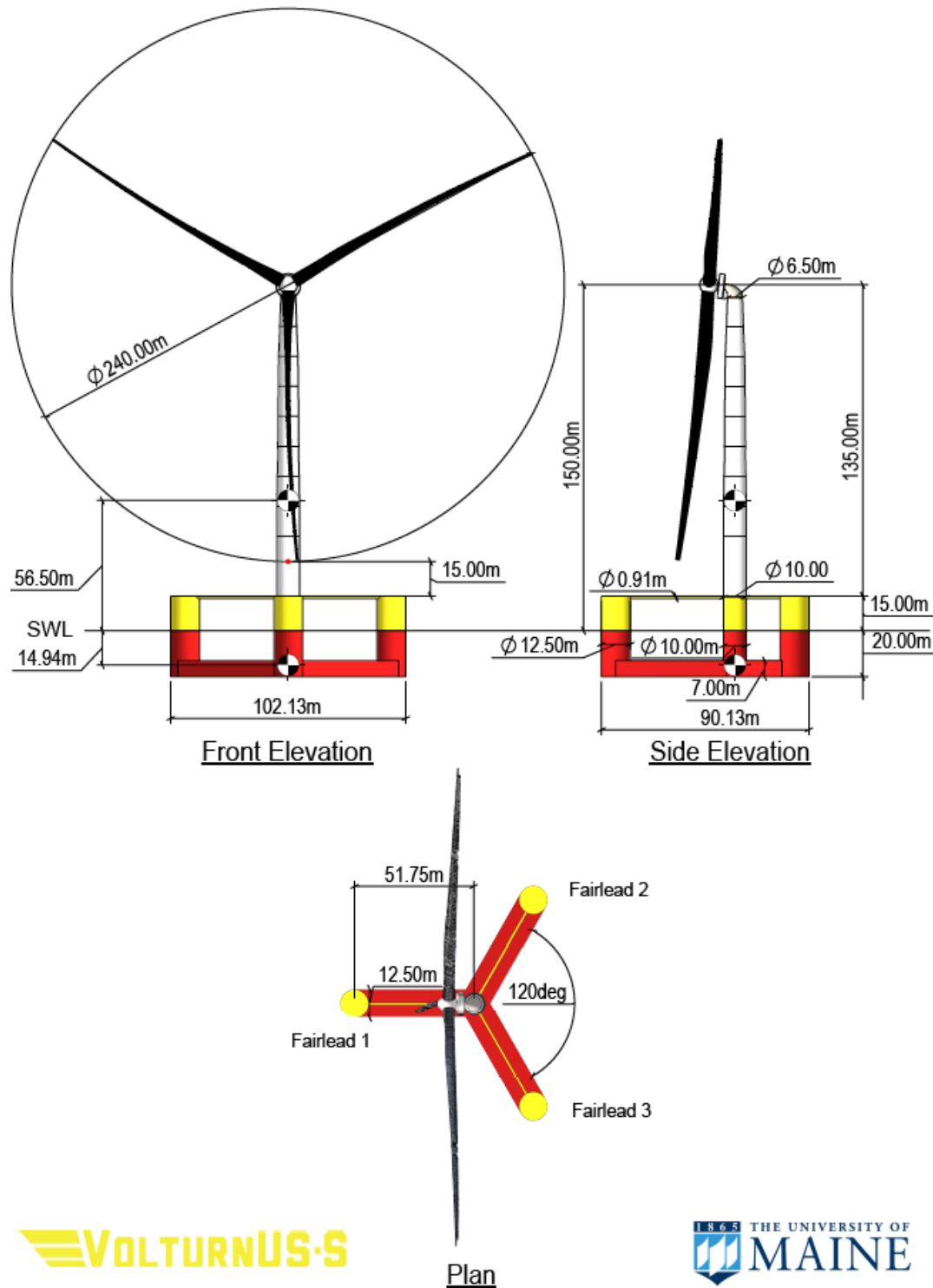


Figure 5.1: General arrangement of the UMaine VoltturnUS-S FOWT (Allen et al., 2020)

Single body model motions

6.1. Model assumptions

The most important assumptions of the single body model are listed below and these are also applicable to the multibody model.

- The floater and vessel move as rigid bodies.
- The vessel is assumed to be equipped with a DP system compensating for second-order wave drift forces, so only first-order wave excitation forces are included. ¹
- Potential flow is assumed.
- Only first-order wave excitation forces are applied to the floater.
- No current forces.
- No wind forces ²
- The pre-calculated hydrodynamic coefficients are accurate and applicable
- The quadratic damping coefficients of the floater are provided by Allen et al. (2020).
- The quadratic roll damping coefficient of the vessel is provided by TWD.
- The provided mesh has a size appropriate for the analysis.

6.2. Floater single body model

The floater model is based on the open-source Orcina model where the entire platform and turbine are modeled in Orcaflex, including diffraction results from OrcaWave (Orcina). Here below, the essential changes made between Orcina's model to obtain the used floater model are shown. Further details of the platform and wind turbine can be consulted in Orcina's documentation (Orcina, 2023) and its technical report (Allen et al., 2020).

Coordinate system

The platform's origin is positioned at the center of the center column at the still water level. The original floater is rotated -90 deg to match the coordinate system of the vessel which is convenient for the multibody model. This results in the x- and y-directions pointing in the direction as depicted in Figure 6.1 with the positive z-direction pointing outward from the waterplane into the air and symmetry is present in the yz plane.

¹The DP of a vessel is achieved using thrusters to maintain the desired positioning. For a vessel, the DP system eliminates unwanted surge, sway, and yaw motions by counteracting mean wave, current, and wind loads. It should be noted that DP systems are not designed to respond to high-frequency waves and these motions are filtered out of the thruster forces, as these rapid changes are beyond the reaction capabilities of DP systems. Therefore, DP systems primarily address slowly varying motions of the vessel.

²Jiang et al. (2018) and Hassan and Guedes Soares (2023) demonstrated that wind forces acting on the turbines situated on the vessel and the vessel itself have minimal impact on the vessel's motion when the vessel is on-site.

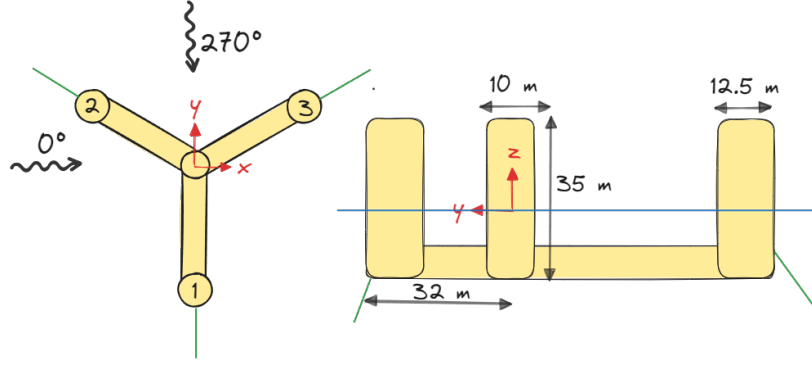


Figure 6.1: Coordinate system of the floater and the direction of the waves

Henceforward, surge, sway, and heave will be referred to as the translational motions of the floating body along the x -, y -, and z -axis, respectively. The corresponding rotational motions around these axes are referred to as roll, pitch, and yaw.

Floater model setup

Diffraction analysis is performed in OrcaWave with a translational shift in the z -direction to account for the draft reduction resulting from the removal of the turbine mass $m_{turbine}$. The reduction in submerged volume V_{red} is calculated as:

$$\begin{aligned} V_{red} &= m_{turbine} / \rho = A_w \cdot \Delta z \\ \Delta z &= 5.31 \text{ m} \end{aligned} \quad (6.1)$$

where ρ is the seawater density and A_w is the waterplane area. The reduction in draft Δz is calculated to be 5.31 m.

New values for CoM, mass and inertia are computed accounting for the contribution of the floater only. The roll inertia I_{xx} and pitch inertia I_{yy} are decreased as the distance d between the CoM and the still water level is reduced. Using the parallel axis theorem, also called Steiner's theorem, the new reduced mass moment of inertia $I_{red,draft}$ is given by:

$$I_{red,draft} = I_{original} - m_{floater} \Delta z^2 \quad (6.2)$$

where $m_{floater}$ is the mass of the floater given in Table 5.1 and $I_{original}$ is the original mass moment of inertia. The changed values are summarized in Table 6.1

Table 6.1: Parameter changes between the original model and the new reduced draft model

	Original model	Reduced draft model
Draft [m]	20.0	14.7
I_{xx} [t·m ²]	$1.25 \cdot 10^7$	$1.20 \cdot 10^7$
I_{yy} [t·m ²]	$1.25 \cdot 10^7$	$1.20 \cdot 10^7$

The floater model in OrcaFlex is obtained by removing all turbine-related components from the original Orcina model. Only the platform with the shifted draft and the three catenary mooring lines remain. The fairlead positions of the mooring lines are also shifted in the z -direction with the same Δz such that they are attached to the same location on the floater column as the original model.

No mesh refinement study is performed since it is not possible to modify the mesh file. Nonetheless, validation of Orcina's model against the VoltturnUS-S floater documentation (Allen et al., 2020) assures that panel sizes within the mesh are deemed sufficiently small for this analysis.

6.2.1. Natural periods

Decay tests are performed to obtain the natural periods of the floater. Initially, the decay tests are performed for the entire FOWT with the turbine installed to compare with the provided rigid body natural periods in the reference report (Allen et al., 2020). The differences observed are due to modifications made to the FOWT after the reference report was written. Orcina's model is based on version 1.1.3 of the 15 MW reference wind turbine with the changes stated in (Barter, 2023).

For the individual DOF, an initial displacement or angle is assigned to the platform and the time between the peaks of the oscillation after its release defines the natural period of the system, as defined in subsection 3.4.2. Due to the turbine mass removal, the natural period T_n is expected to decrease according to:

$$T_n = 2\pi\sqrt{\frac{m}{k}} \quad (6.3)$$

where k is the stiffness and m is the mass. Moreover, the hydrostatic stiffness in roll and pitch has increased due to a lower center of gravity as a result of removing mass at the top, also decreasing the natural period

The shift in natural period can be seen in Table 6.2.

Table 6.2: Rigid body natural periods of the floater with and without turbine

	Surge	Sway	Heave	Roll	Pitch	Yaw
VoltturnUS-S FOWT [s] (Allen et al., 2020)	143	143	20.4	27.8	27.8	90.9
VoltturnUS-S FOWT simulation [s]	132	132	20.6	28.4	28.4	84.3
VoltturnUS-S platform simulation [s]	118	118	20.4	14.3	14.3	76.5

6.2.2. Displacement RAOs

The rigid-body wave-induced motion RAOs of the floater are obtained by conducting time domain simulations in OrcaFlex using Airy waves as explained in subsection 3.4.3. For a wave heading of 0 deg, the RAOs relating to surge and pitch are considered, while the RAOs relating to sway, heave, roll and yaw are shown for a wave heading of 270 deg shown in Figure 6.4. The Point of Interest (POI) is taken at the origin of the floater. The natural periods identified in Table 6.2 are evident in Figure 6.4, with a peak at 14 s for roll and pitch, corresponding to its natural period of 14.3 s.

The natural period for heave is 20.4 s, which is just outside the simulated wave period range, and the heave RAO shows a sharp decrease at 20 s. This decrease is also visible in the diffraction force and attributed to the wave cancellation effect caused by the floater's geometry. When calculating the heave forces resulting from pressures on the tops and bottoms of the submerged braces and the bottoms of the columns, there is a specific frequency at which these forces become zero. A derivation of this effect is given in Appendix C in the thesis by Kall  k (2020), though it is based on a different floater design and includes heave plates. The wave period at which this cancellation occurs is strategically placed just before the natural period is reached, thereby reducing the resonance effect.

Irregular waves

To capture the floater's interactions with different wave frequencies, irregular wave simulations of 1 h are conducted. The results for three different peak periods and a wave heading of 0 deg and a $H_s = 2.5$ m, are depicted in Figure 6.2. The peak observed at 0.17 Hz for $T_p = 6$ s aligns with the small local peak in the surge RAO at this period. This peak diminishes for $T_p = 8$ s, as there is less wave energy in this frequency range. Additionally, a new peak emerges between 0.08 and 0.12 Hz, corresponding to the local peak in the pitch RAO between 8 and 12 s. For a peak period of 11 s, the peak between 0.06 and 0.11 Hz results from contributions from both surge and pitch, with significant responses observed between 9 and 16 s.

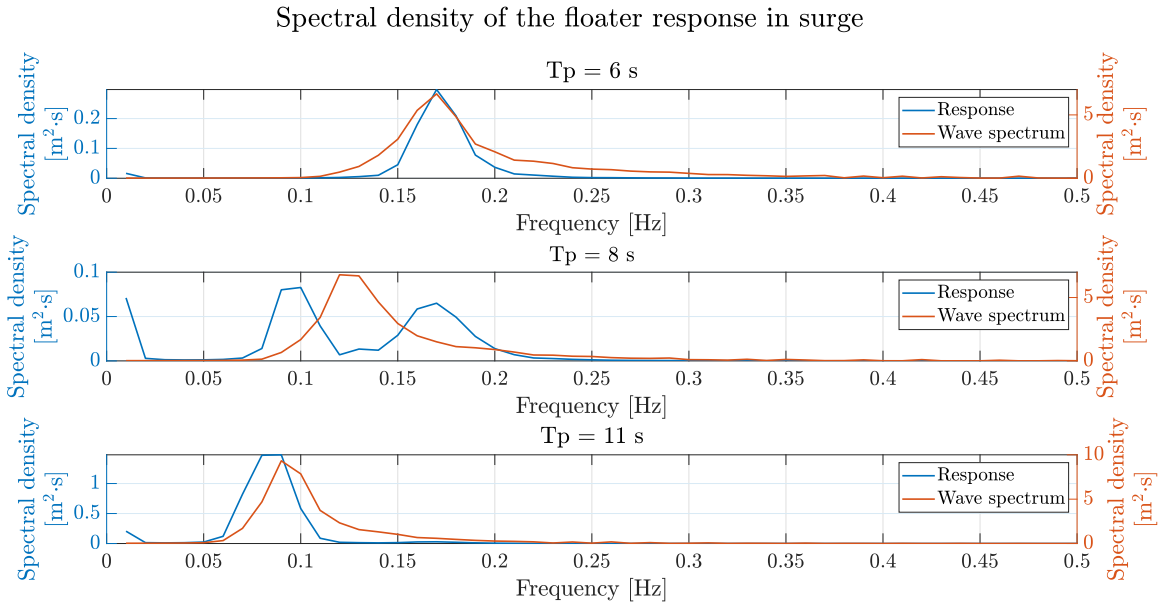


Figure 6.2: Spectral density for three different wave peak periods with a wave heading of 0 deg and $H_s = 2.5$ m

6.3. Vessel single body model

While for the floater all parameters were given due to Orcina's open-source model, only the mesh and the quadratic roll damping coefficient were available for the vessel. The mass matrix is constructed based on the ballast plan, and the same decay tests and regular wave tests that were performed for the floater are also conducted for the vessel.

Coordinate system

The origin of the vessel is on the center line, at the baseline and at the aft perpendicular of the ship. The x-direction corresponds to the longitudinal axis, the y-direction to the transverse axis and the z-coordinate represents the vertical direction, pointing upwards from the keel as depicted in Fig-ure 6.3,

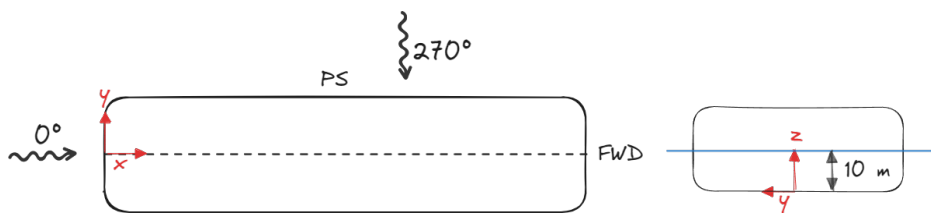


Figure 6.3: Vessel coordinate system and the direction of the waves

Vessel model setup

The draft of the vessel is 10 m and the mesh was provided by TWD. Similar to the floater, the diffraction analysis of the installation vessel is performed using OrcaWave. The mass properties are incorporated into the OrcaFlex model using what is referred to as 6D buoys. It is separated into three components, accounting for the lightship weight, ballast and deck components separately. Moreover, four low-stiffness springs are added between the vessel and a fixed location. These springs serve solely to facilitate a static solution within the model.

6.3.1. Natural periods

The decay tests result in the natural periods stated in Table 6.3.

Table 6.3: Rigid body natural periods of the vessel

	Surge	Sway	Heave	Roll	Pitch	Yaw
Natural period [s]	140	164	9.8	14.1	8.4	90

6.3.2. Displacement RAOs and comparison

Employing the same methodology as for the floater, the displacement RAOs of the vessel are determined and subsequently plotted in Figure 6.4, enabling a motion comparison between both bodies. The response amplitude of the vessel is taken at the CoM coordinates and on the still water level.

The natural period for surge and sway are again significantly outside the simulated wave period range. The peak of the heave RAO corresponds to the heave natural period of 10 s, after which the heave RAO stabilizes at a steady state value of 1. This behavior is expected since, for longer waves, the vessel can "ride" on the waves. The distinct peak at 14 s in the roll RAO corresponds to its natural roll period, while a local peak of the pitch RAO is showing at 8.4 s.

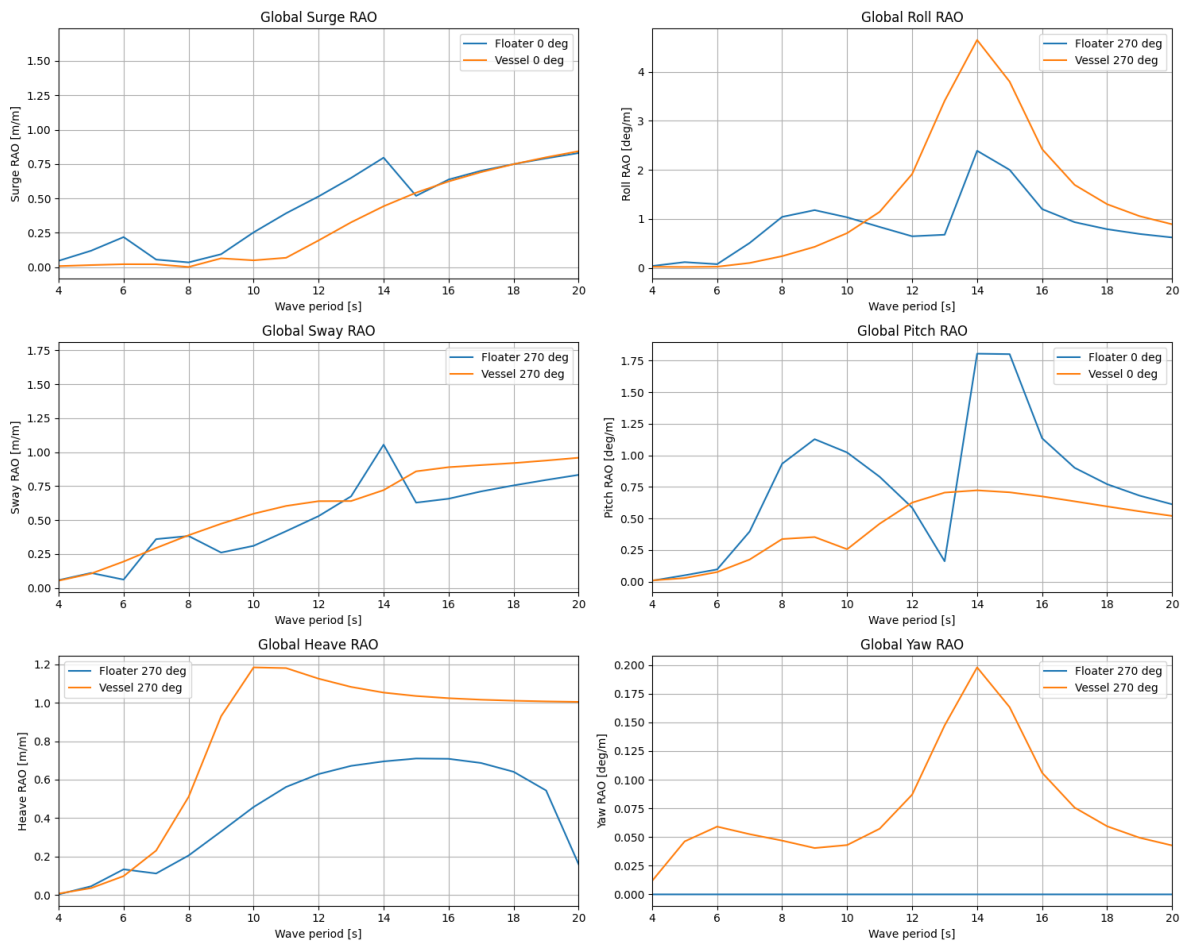


Figure 6.4: Single body floater and vessel rigid-body RAOs

When examining the motions of the floater and the vessel, notable differences are observed, particularly in heave, roll and pitch. The vessel's heave amplitude has an overshoot at its natural period of 10 s and decreases to 1 m/m for longer wave periods as expected. Due to the wave cancellation effect of the floater, its heave RAO features a trough of around 20 s and reaches 1 m/m at even longer waves. Regarding the roll RAO, a significant peak is visible for the vessel at its natural period of 14 s with an amplitude twice that of the floater. This large amplitude is due to the vessel's relatively narrow width, providing less stability in the transverse direction. The pitch RAO of the vessel generally exhibits lower amplitudes compared to the floater's roll RAO, primarily due to the vessel's significantly larger pitch inertia. While the vessel's resonance peak shows a larger amplitude in roll, the floater exhibits larger roll and pitch responses for wave periods below 11 s which coincide with wave periods of interest.

For the installation process, it is crucial to consider the interaction between both bodies. Therefore, a multibody model is essential to examine the relative motions between the floater and the vessel.

Floater-vessel multibody model motions

The floater-vessel model refers to the configuration that includes both the vessel and the floater. The same steps used in obtaining the displacement RAOs in the single-body models are followed for the multibody model as outlined in the methodology flowchart. This allows the observation of interactions between the two bodies when they are in close proximity. This multibody model enables the first sub-question stated in subsection 3.3.2 to be answered, relating to the relative motions between both bodies.

7.1. Multibody model layout

The floater is positioned adjacent to the starboard side of the vessel, in accordance with the side-to-floater layout determined in section 5.3. In this configuration, columns 2 and 3 from Figure 5.1 are aligned parallel to the vessel, as sketched in Figure 7.1. A distance of 3.5 m separates the vessel from the floater, a configuration designed to accommodate a sizable fender capable of shielding both structures from potential impact damage. The floater's center column aligns with the crane base center, ensuring a minimal crane radius and the global origin of this model coincides with the origin of the vessel.

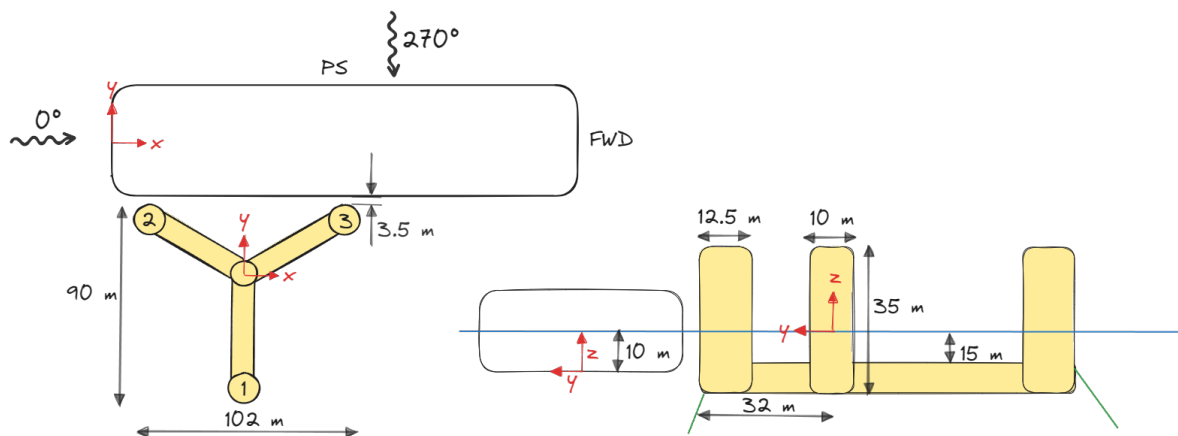


Figure 7.1: Position of the floater with respect to the vessel, with the relative sizes of both bodies maintained in the sketch

7.2. Diffraction

Similar to the single-body simulations of the floater and vessel, the diffraction analysis of the floater-vessel model is again performed in OrcaWave to obtain the load RAOs and the required hydrodynamic coefficients of this multibody model.

When performing multibody diffraction, strong hydrodynamic interaction between two floating bodies may occur. An important non-linear interaction effect is a trapped standing wave between the floating bodies that can excite sway and roll motions (Det Norske Veritas). However, the necessity for such mitigation is negligible in this model due to the absence of actual wave entrapment between the vessel and columns 2 and 3, despite the appearance of a confined space. The bottom braces' height covers only about half of the draft, allowing surface waves to propagate further and preventing them from being trapped, as would occur when two vessels are positioned adjacent to each other.

7.3. Displacement RAOs

The displacement RAOs of the multibody model are plotted in Figure 7.2.

At first sight, the RAOs for the multibody model show the same trend as for the single-body models as shown in Figure 6.4. The resonance peaks are at the same periods and the differences at larger wave periods are minimal. However, distinctions become apparent at lower wave periods, where the presence of the vessel is anticipated to impact the floater's motions. To illustrate this effect, the motions of the floater in both single- and multibody simulations are compared next.

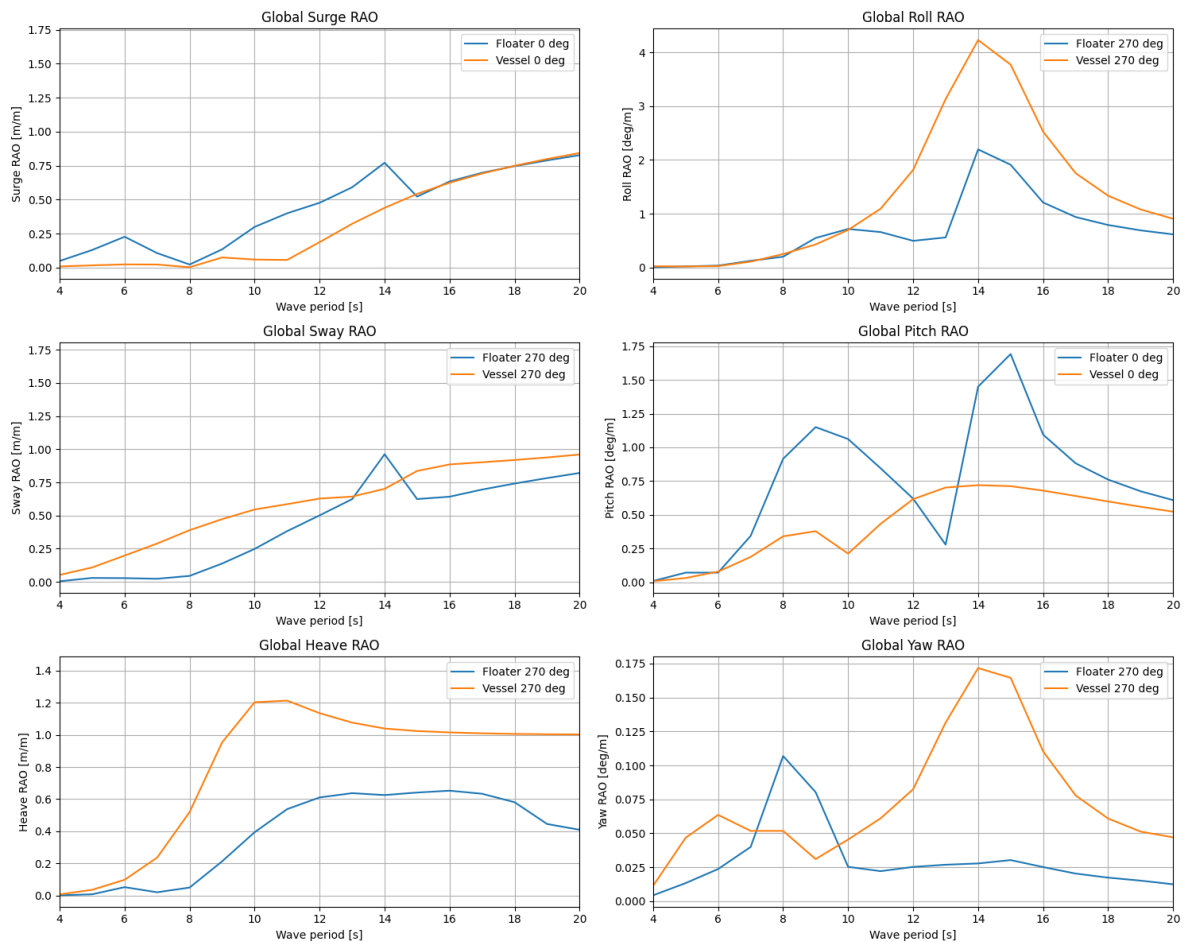


Figure 7.2: Displacement RAOs of the floater and vessel of the multibody model in all six DOFs

7.4. Shielding effects on the floater

Shielding effects are expected as the vessel will be able to shield off the incoming waves partially. This effect is most visible when the wave heading is 270 deg, such that the transverse wave first encounters the vessel and then the floater. These shielding effects for sway, heave and roll are plotted in Figure 7.3, Figure 7.4 and Figure 7.5 respectively. The solid line represents the single-body results, while the dotted line presents the multibody case.

The wave periods of interest that are described in subsection 3.3.3 vary from 6 to 11 s. In this range, the shielding effect is quite substantial, and strategically positioning the installation vessel can maximize this effect, consistent with the conclusions of several studies referenced in section 2.5. This effect decreases with longer wave periods as expected, as the vessel is more capable of following the wave motions, thereby transferring energy rather than deflecting it.

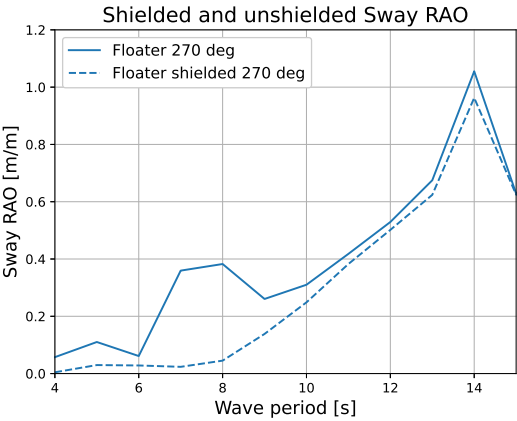


Figure 7.3: Sway shielding effects

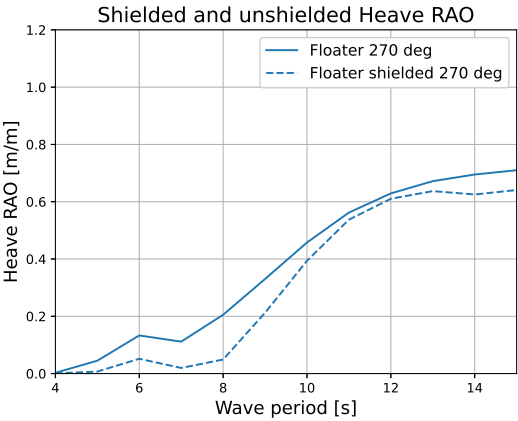


Figure 7.4: Heave shielding effects

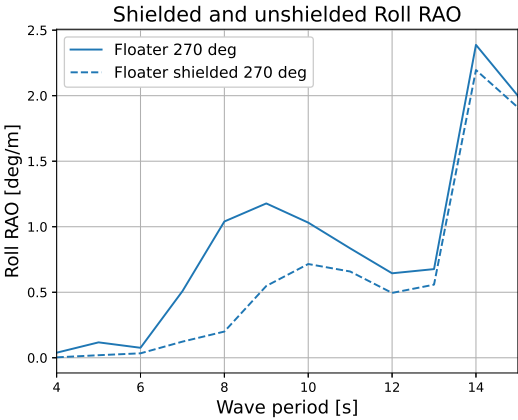


Figure 7.5: Roll shielding effects

7.5. Relative motions

The RAOs provide information about the motion of both bodies separately. For the installation process, however, the relative motion between the vessel and the floater is the crucial parameter. To determine the relative motion between the floater and the vessel, the POI of the floater is taken at the center column top, while for the vessel, two POIs are investigated: one at a point 3 m above the center column top of the floater and another at the crane tip, defined as 178 m above the water line and above the center column of the floater. This 178 m is an estimation based on a 20 m freeboard distance of the floater, a 3 m initial distance between the tower bottom and the floater, a tower length of 135 m and an assumed crane wire of 20 m. The first POI represents a rigid connection between the turbine tower bottom and the vessel, such as the concepts in Figure 2.3 employing a frame. The second POI provides insight into the relative motion between the floater and the crane tip if an assumed rigid crane were to be employed. The three POIs are depicted in Figure 7.6. The relative motion is calculated by subtracting the vessel's time series response from the floater's time series response, their motions taken at their corresponding POIs. The results are plotted in polar plots for the wave periods of interest and different wave headings.

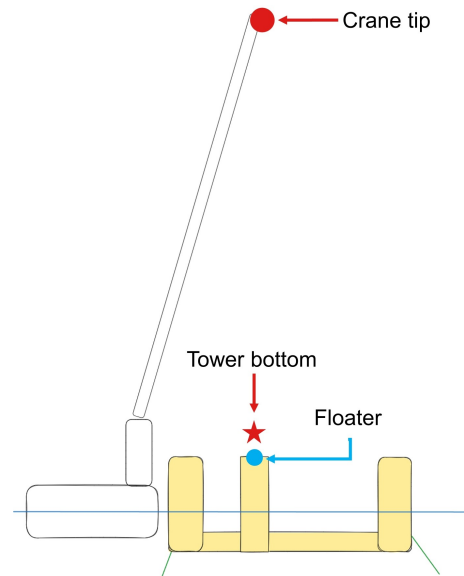


Figure 7.6: The points of interest used for relative motions assessment

Simulations using regular waves with a wave height of 2 m in the wave period range of 6 to 11 s and a coarse wave heading range of 0, 45, 90, 135, 180, 210, 225, 270 and 315 deg are performed to investigate the relative motions. As a clarification, Figure 7.10 shows how these wave headings relate to the multibody model. The magnitude of the relative motion depends on the individual motions of both bodies, as well as if they move in or out of phase with each other. The plotted results depict the maximum of the relative motion time series after subtracting the mean of the corresponding time series (which is close to zero).

7.5.1. Vessel's POI: tower bottom

The results for surge, sway and heave are plotted in Figure 7.7, Figure 7.8 and Figure 7.9 respectively for the vessel's POI located at 3 m above the floater, representing a rigid connection between the vessel and that location.

When examining the horizontal plane, the relative motion in both the x- and y-directions remains below 1 m. In the x-direction, waves with headings of 135 deg and 45 deg are the most critical. In contrast, waves from 270 deg and 90 deg produce the largest responses in the y-direction. This significant response in the y-direction is primarily driven by the vessel's roll, induced by the transverse waves. The peak observed for the 7-second wave period and 90-degree wave heading is due to the combination of large roll and exactly out-of-phase motions at the POIs.

The largest response in the x-direction occurs for a wave period of 8 s and a wave heading of 135 deg, primarily driven by the floater, whose amplitude reaches a maximum of 1 m. In contrast, the vessel's maximum amplitude of 0.1 m contributes insignificantly. The maximum relative motion in the x-direction does not exceed 1.1 m due to the slightly in-phase motion of the two bodies. The significant floater's motion at 8 and 9 s corresponds to a local peak value in its pitch RAO. Furthermore, these 8 or 9-second waves do not dominate for wave headings of 225 deg and 315 deg, as the floater's motion is effectively shielded by the vessel.

Conversely, the vessel is the primary contributor to the maximum relative y displacement, which can also be inferred from the figure due to its elongated shape. Due to the vessel's reduced stability in the transverse direction, the largest responses are observed for waves from 270 deg and 90 deg. In contrast, the floater, being symmetrical in its yz-plane, is expected to exhibit symmetry along the 90-270 deg axis, which is also (approximately) reflected in the relative x displacement. This demonstrates

that the relative displacement in the horizontal plane is highly influenced by the environment, with both the floater or the vessel potentially becoming the main contributor depending on the specific circumstances.

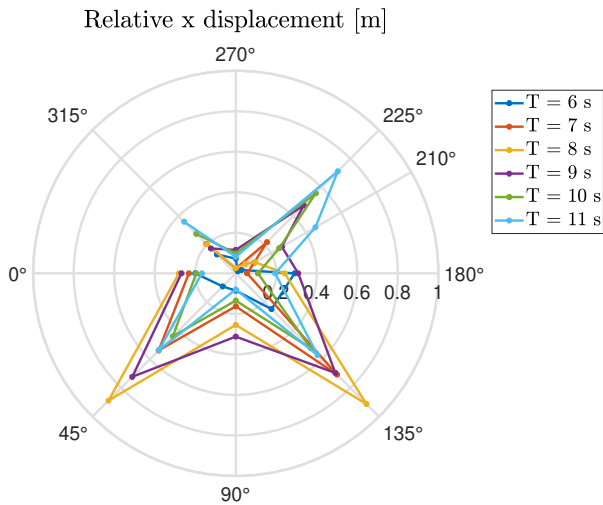


Figure 7.7: Maximum relative surge amplitude for different wave periods and wave heading at the vessel's POI located at 3 m above the floater

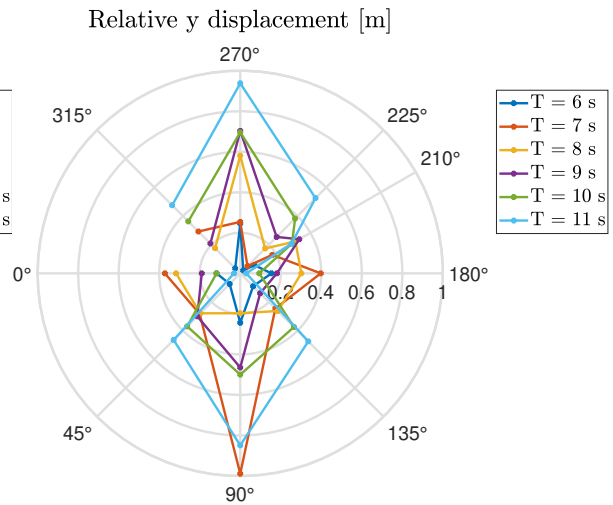


Figure 7.8: Maximum relative sway amplitude for different wave periods and wave heading at the vessel's POI located 3m above the floater

When examining the relative heave in Figure 7.9, it is evident that the relative z motion increases with longer wave periods. The vessel is the main contributor to this motion, which aligns with the shape of the graph and the significantly larger heave RAO for the vessel compared to that of the floater. However, the maximum value is observed for the 90-degree case, despite the load RAOs in heave and roll being larger for the 270-degree wave. This discrepancy originates from the roll motion of the vessel, which becomes significant due to the large distance between the center of the vessel and the point of interest (60 m). The vessel's roll motion induces heave, and this heave motion is out of phase with the vessel's own heave motion, amplifying the resulting heave motion used to determine the relative motion.

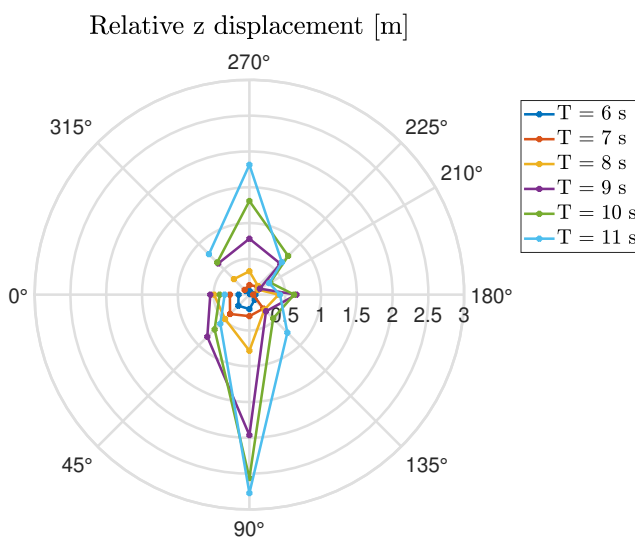


Figure 7.9: Maximum relative heave amplitude for different wave periods and wave heading at the vessel's POI located at 3 m above the floater.

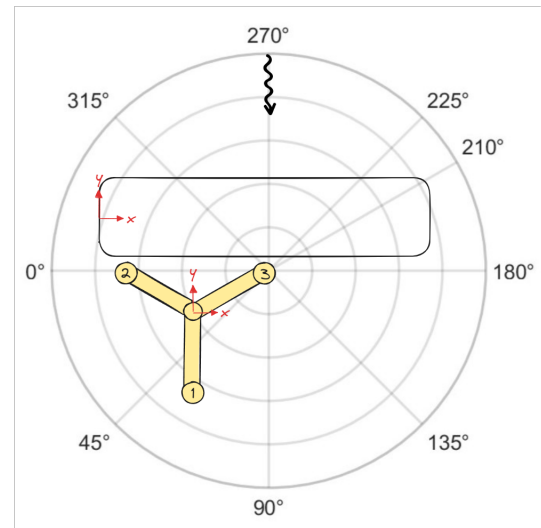


Figure 7.10: Visualization of the polar plot angles with respect to the system's orientation. The headings indicate waves that are 'coming from' that direction.

7.5.2. Vessel's POI: crane tip

While the first POI of the vessel was only 3 m above the center column of the floater, the crane tip is positioned 135 m (tower length) + 20 m (crane wire) = 155 m higher. This substantial increase in the z-coordinate significantly alters the relative displacement in the horizontal directions. With the floater's POI remaining the same, these changes are driven by the vessel's movements.

Starting with the relative surge in Figure 7.11, compared to Figure 7.7, there is an overall increase in relative displacement for all data points. This effect is more pronounced for longer waves, with the 10- and 11-second waves surpassing the 7- and 8-second waves. While the shielding effect of the floater was noticeable in Figure 7.7, it is no longer apparent, and the figure now displays a star-shaped pattern, further confirming that the vessel's motion is governing. The large increase at 180 deg is due to the pitch of the vessel. Given the crane tip's much larger height, the surge is significantly influenced by the pitch, and according to the displacement RAOs, the vessel's pitch increases with longer wave periods in this range.

In Figure 7.12, the relative motions have also increased significantly, with the 270-degree and 90-degree waves now showing even greater dominance. Similar to the relative surge, this increase is attributed to the larger distance to the crane tip. The primary contributor remains the roll of the vessel, which is consistent with the observed symmetry in the figure. While Figure 7.8 shows the maximum relative sway at a 7-second wave period, the current figure highlights longer wave periods as the critical ones. This observation aligns with the displacement RAOs, where larger wave periods (up to 14 s) lead to increased vessel roll.

The relative heave plot in Figure 7.13 is practically identical to the one shown in Figure 7.9. This consistency implies that the roll-induced heave due to the increased distance to the crane tip is negligible.

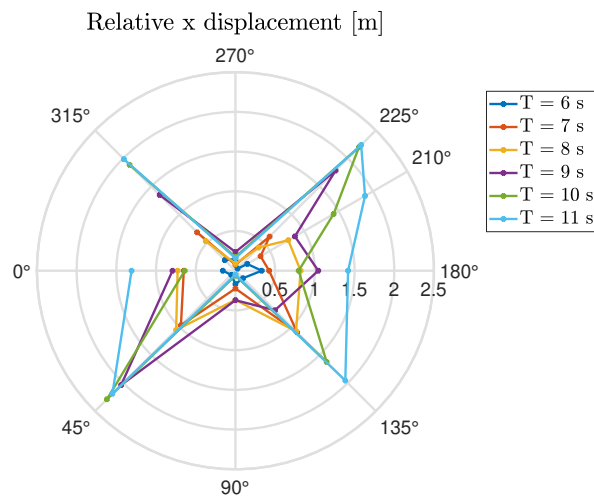


Figure 7.11: Maximum relative surge amplitude for different wave periods and wave heading at the vessel's POI located at the crane tip

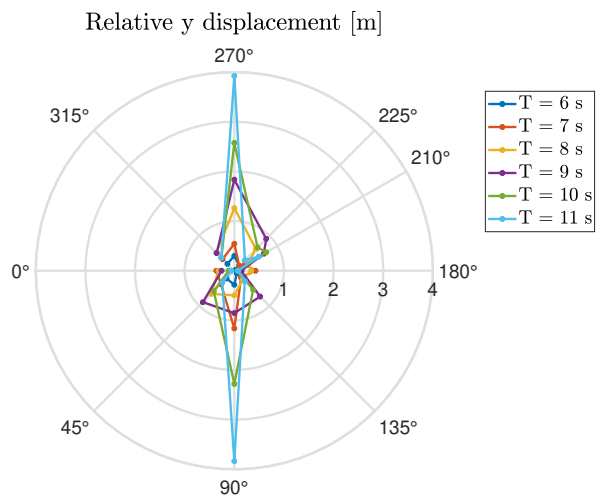


Figure 7.12: Maximum relative sway amplitude for different wave periods and wave heading at the vessel's POI located at the crane tip

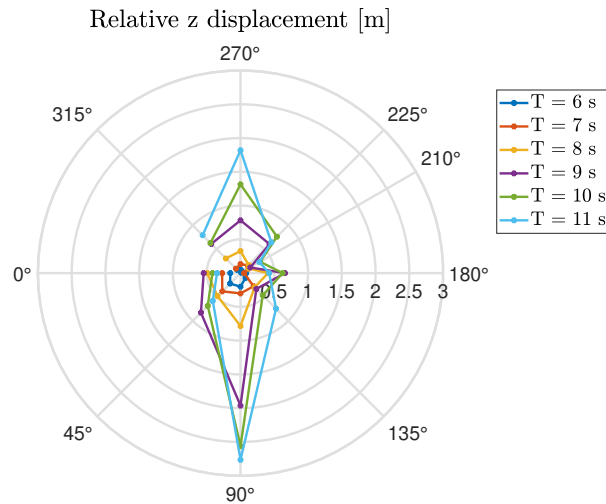


Figure 7.13: Maximum relative heave amplitude for different wave periods and wave heading at the vessel's POI located at the crane tip.

While the vessel's shielding effect significantly reduces the floater's motions, its positive impact is less apparent when examining the relative sway motion as the vessel's roll motion dictates the relative sway. Consequently, the benefit of shielding is overshadowed by the vessel's dominant roll, making the improvement in relative sway negligible. Instead of the configuration depicted in Figure 7.1, assuming a prevailing wind and wave heading of 270 deg, which would ensure maximum shielding but also maximum roll, the vessel could be rotated such that it is adjacent to columns 1 and 3, while still maintaining a minimum crane reach. This layout corresponds to 210 deg waves in the Figure 7.14 configuration due to the symmetry of the floater. The difference in relative motions between the 270-degree wave and the 210-degree wave is rather substantial and is therefore the desired configuration during the installation process. While opting for this configuration may lead to a slight increase in relative surge motion according to Figure 7.7 and a somewhat larger increase according to Figure 7.11, this outweighs the substantial decrease in sway direction. For this reason, the 210 deg results are also added in the polar plots above. While having a 210-degree wave direction is beneficial for reducing relative motions, prioritizing maximum shielding of the floater would enhance safety for personnel who need to secure the tower.

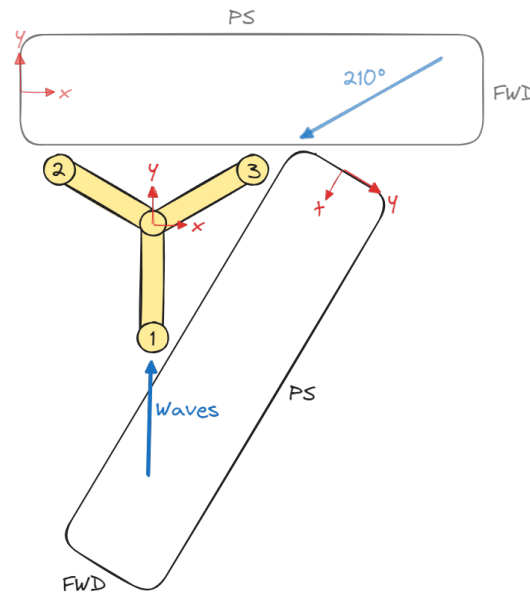


Figure 7.14: The vessel's preferred position relative to the floater provides partial shielding and reduces roll motion, aligning with the 210 deg wave results.

7.6. Key findings

The displacement RAOs of the multibody model largely align with those observed in single-body models. However, differences are observed at lower wave periods, where the presence of the vessel impacts the floater's motions. This shielding effect is most effective for wave periods between 6 and 11 s, where the vessel can deflect wave energy, reducing the impact on the floater. However, the effectiveness of this shielding decreases with longer wave periods as the vessel is more capable of following the waves, transferring rather than deflecting energy.

The analysis of the relative motions at the vessel's POIs located at the tower bottom, shows that relative motion in the horizontal plane is influenced by wave direction, wave period and the movement of both bodies. For instance, 8- and 9-second waves originating from 135 deg and 45 deg induce the largest relative motions in the x-direction, largely governed by the floater's movement. In contrast, waves from 270 deg and 90 deg produce the largest relative motions in the y-direction, driven primarily by the vessel's roll motion. Additionally, the relative heave motion increases with longer wave periods, predominantly due to the vessel's heave and roll, aligning with their displacement RAOs. Waves from 90 deg induce larger motions than those from 270 deg, attributed to the in-phase interaction of roll-induced heave and the vessel's inherent heave motion.

Shifting the POI to the crane tip, located 155 m higher, the horizontal motions of the vessel increase significantly, dominating its contribution to the relative surge and sway, making this the less attractive vessel POI due to larger relative displacements. This is caused by the larger distance between the POIs, increasing the roll- and pitch-induced translations. For this POI, the shielding effect of the floater is not visible anymore as the vessel's roll motion dictates the relative sway, reducing the shielding's effectiveness. Thus, it is advantageous to position the vessel as depicted in Figure 7.14, corresponding to a 210-degree wave heading in the original configuration, to substantially decrease relative sway.

The findings in this chapter provide the answer to the following first sub-question:

1. What are the relative motions between the floater and vessel and which DOF is governing?

The maximum relative motions for surge, sway and heave are summarized and presented in Table 7.1, along with the corresponding environmental conditions under which these maxima occur. Please note that the results presented are based solely on regular wave conditions, providing an initial indication of the magnitude of relative displacements and the critical sea states. These findings should not be overgeneralized, as they do not account for all possible influences.

Table 7.1: Maximum relative motions for the simulated environmental conditions and both POIs

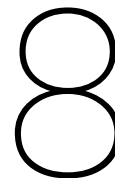
Location	DOF	Maximum relative displacement [m]	Wave heading [deg]	Wave period [s]
Tower bottom POI	Surge	0.9	135	8
	Sway	1	90	7
	Heave	2.7	90	11
Crane tip POI	Surge	2.2	225	11
	Sway	4	270	11
	Heave	2.7	90	11

For the proposed wave heading of 210 deg, the relative motions are given in Table 7.2.

Table 7.2: Maximum relative motions for a wave heading of 210 deg for the simulated wave periods and both POIs

Location	DOF	Maximum relative displacement [m]	Wave heading [deg]	Wave period [s]
Tower bottom POI	Surge	0.5	210	11
	Sway	0.3	210	9
	Heave	0.4	210	11
Crane tip POI	Surge	1.9	210	11
	Sway	0.8	210	10
	Heave	0.4	210	10

The results indicate that there is no consistent underlying pattern that can be directly addressed to minimize relative motions. Therefore, the design phase should be entered with the following aspects in mind: The compensation system needs to effectively address both surge and sway directions, as either could be dominant depending on the sea state. Additionally, a low POI of the vessel is preferred to reduce relative motions. Furthermore, implementing a capture system on the floater is recommended rather than relying on a system situated on the vessel, as the floater's motions differ from those of the vessel in magnitude and phase.



Vessel and floater coupling

Following the determination of relative motions between the floater and the vessel, and drawing inspiration from the work of Hassan and Guedes Soares (2023) and Jiang et al. (2018), constraints are introduced into the multibody model to connect the foundation to the vessel. These constraints are applied to assess the forces imposed on them to minimize relative motions by allowing the floater and the vessel to move as a single body. This investigation provides insight into the feasibility of using this method to reduce relative motions during the mating process.

8.1. Connection implementation

A constraint connecting the vessel and the floater is applied, with the translational z-direction and the three rotational DOFs marked as free, with zero stiffness, in accordance with the terminology outlined in section 4.5. This configuration creates a rigid connection in the horizontal plane while permitting independent rotation between the two bodies. The constraint is positioned on the starboard side of the vessel at a distance from the stern that aligns with the center of the floater and at the vessel's deck height in the z-direction. Regular waves with a wave height of 1.5 m are used, and the statistics are assessed after the transient period has passed. Given the sinusoidal nature of the time-domain output, the peak values can be estimated by multiplying the given standard deviation by the square root of 2.

8.2. Forces acting on the connection

Figure 8.1 and Figure 8.2 show the results for the x- and y-direction respectively.

The polar plot in the x-direction shows a similar pattern to the plot in Figure 7.7 as anticipated. Although the POIs used in Figure 7.7 do not precisely coincide with the locations where the constraint is applied, the relative motions are expected to be similarly influenced by wave heading and wave period. Consequently, the larger the relative displacement, the greater the force required to restrain it.

Since the constraint is placed on the starboard side of the vessel, the y-distance from the constraint to the center of the floater is significant (36 m). This roll-induced sway, combined with the significant roll of the vessel in transverse waves and the lack of shielding from the floater for waves at 90 deg, leads to an expected peak at the 90-degree wave heading. However, it is the wave period of 7 s that generates the largest force, consistent with the greatest relative sway displacement observed in Figure 7.8. As previously outlined, for the 7-second wave period and 90-degree wave heading, the sway motion at the connection points of the two floating bodies is exactly out of phase, resulting in the highest force required to maintain the connection.

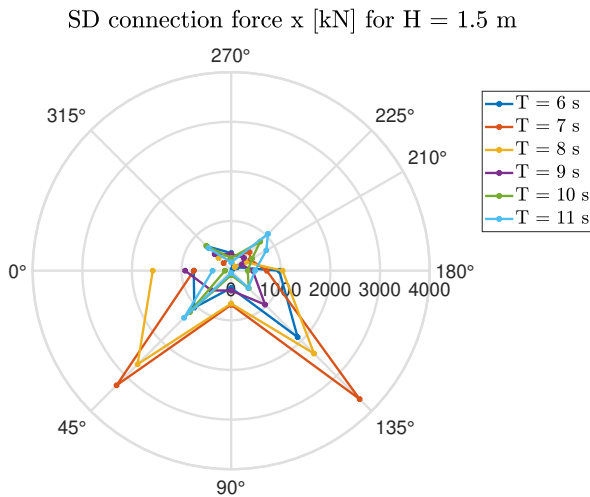


Figure 8.1: The standard deviation of connection forces in the x-direction for different wave periods and headings

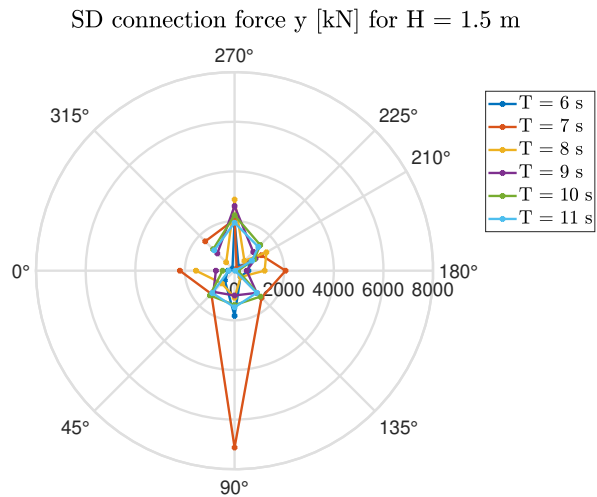


Figure 8.2: The standard deviation of connection forces in the y-direction for different wave periods and headings

8.3. Force comparison with literature

Hassan and Guedes Soares (2023) also modeled a rigid (infinite stiffness) connection between the floating foundation and the monohull installation vessel, but applied it to a spar foundation instead of a semi-submersible one, as mentioned in Figure 2.4. The standard deviation of the gripper force for an H_s of 2.5 m and a wave heading of 180 deg (longitudinal direction, first encountering the spar foundation and then the stern of the vessel) was shown to reach 550 kN in the x-direction at a wave period of 11 s and 500 kN in the y-direction at a wave period of 9 s. In the worst-case scenario, with a wave heading of 330 deg, the surge force reached up to 920 kN, and at 210 deg, the sway force reached up to 560 kN.

In the study by Jiang et al. (2018), which also modeled a spar foundation but coupled with a catamaran vessel at the stern, a mechanical coupling stiffness of $1e5$ kN/m is applied. This configuration results in a maximum standard deviation coupling force of 1150 kN for an H_s of 2.5 and a heading of 30 deg. The headings used in both papers correspond to the headings of the semi-submersible model. The coupling is modeled as a continuous docking cone¹ encircling the spar's circumference, so the forces are not specified separately in the x- and y-directions.

Comparing these results to the values obtained for the semi-submersible, the forces are significantly larger, with a maximum standard deviation reaching 3700 kN for 135-degree waves in surge and 7100 kN for 90-degree waves in sway. The vessels used in the three studies vary, and the differing vessel motions significantly impact the connection force. For a fair comparison, the same vessel in each study should be used.

8.4. Conclusions on floater-vessel coupling analysis

While the study by Hassan and Guedes Soares (2023) concludes that the resulting gripper forces are within reasonable limits for compensation, and the paper by Jiang et al. (2018) assumes that three hydraulic actuators can handle somewhat larger forces, the forces required to rigidly connect the vessel with the VoltturnUS-S floater are several times greater. These forces, resulting from regular waves, are already substantial, making it less practical to reduce the relative motions by rigidly connecting the two floating bodies.

¹A docking cone is a spring-damper system with a specified relationship between relative radial offset and radial restoring force.

Concept development, selection and detailing

After the initial modeling phase, the subsequent design phase outlines the process through which the selected concept for motion reduction is developed. This concept is then further evaluated and refined in the detailing phase.

9.1. Concepts overview

This section presents four concepts derived from an array of ideas, providing the answer to the second sub-question formulated as:

2. *What are possible concepts to reduce the horizontal relative motions?*

Each concept is introduced and its working principle is highlighted. Subsequently, the criteria utilized for the Multi-Criteria Analysis (MCA), which is used to select the winning concept based on previously defined requirements and preferences, are briefly outlined. The MCA results are then presented and the winner is highlighted. The justification section elaborates on the values assigned to the winning concept, focussing on the relative values between the different concepts.

Similar to the earlier sketches, the yellow structure represents the floater, while the white structure, outlined in black, denotes the vessel. These two bodies, along with the tower, are drawn to scale relative to each other. However, the additional components drawn in blue, illustrating the concept, are not to scale and are depicted to ensure the concept's visibility. In addition, the coordinate system corresponds to the sketch in Figure 7.1.

1. Co-floatation

The Co-floatation concept requires positioning the floater at the aft of the vessel instead of the starboard side. The vessel maneuvers between the floater's columns, subsequently establishing a connection with the bottom braces. Increasing the vessel's draft by ballasting the vessel then exerts downward pressure on the floater. Assuming both bodies move as a single body, the relative motions would be omitted. The sketches in Figure 9.1 depict three points of contact between the vessel and the floater. This arrangement prevents overconstraining that could result from additional contact points and mitigates pitching or rolling that could occur with fewer contact points.

Since the VoltturnUS-S floater allows only two points of contact on its braces, an additional one is added that wraps around the center column as visible in Figure 9.1. The presence of an u-stern vessel provides an advantageous geometry to accommodate the third point of contact.

As the system moves as a single entity, the distance between the floater's center column and the crane base remains constant. A crane is then subsequently used to place the tower on the floater.

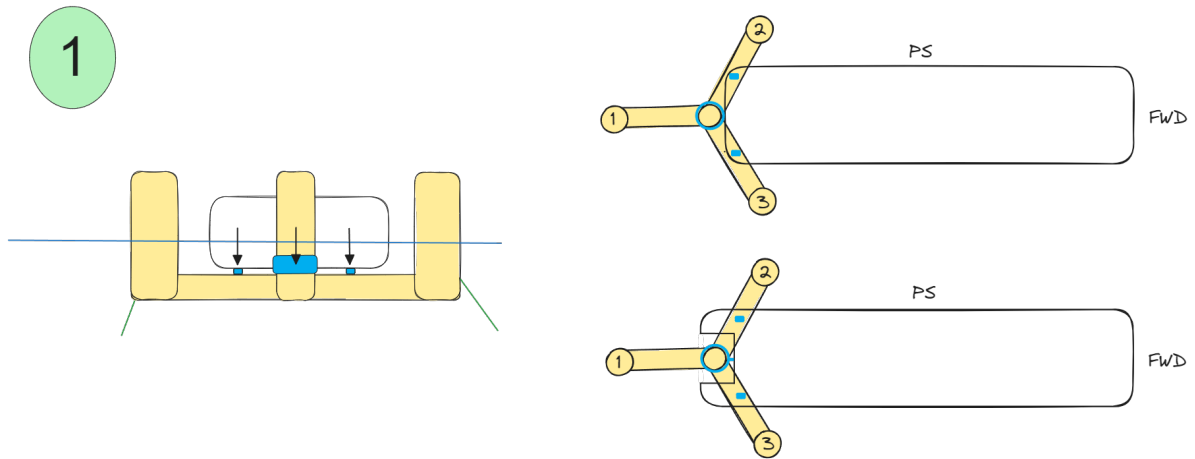


Figure 9.1: Concept sketch of the Co-floatation concept

2. Motion-compensated twin gripper

The motion-compensated twin gripper employs two grippers capable of movement independently from each other, allowing for not only compensation of the horizontal x and y motions but also for aligning the angle of the tower relative to the floater. The frame standing on the vessel holds the tower and necessitates a heave compensation system to prevent collision between the tower bottom and column top. Furthermore, to minimize relative velocities, a damping system is incorporated between the tower and the column, which is attached to an external pedestal encircling the floater column as shown in Figure 9.2.

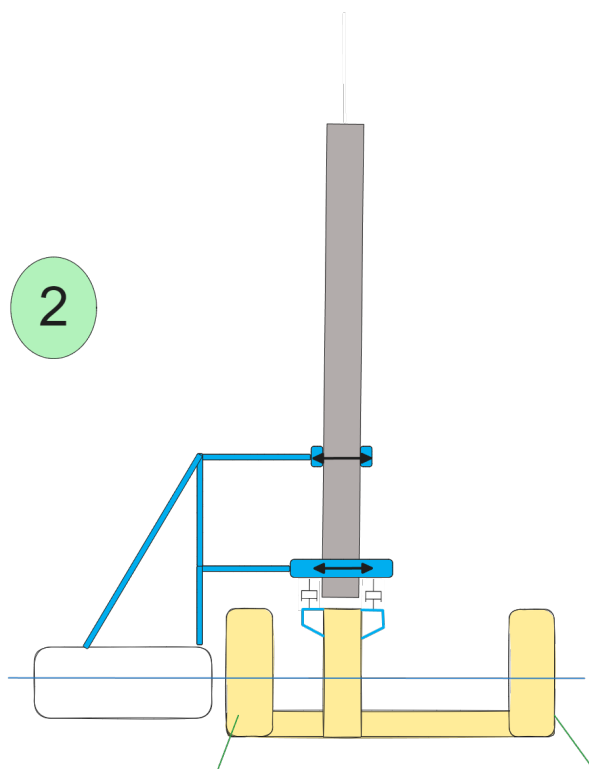


Figure 9.2: Concept sketch of the Motion-compensated twin gripper concept

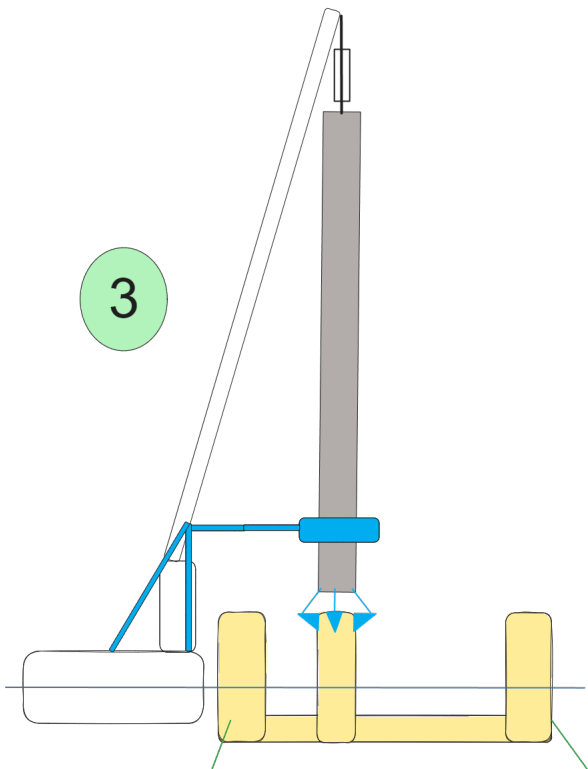


Figure 9.3: Concept sketch of the Gripper wire control concept

3. Gripper wire control

The Gripper wire control concept as depicted in Figure 9.3 employs a single gripper designed to restrain the horizontal x and y movements caused by the pendulum motion of the tower suspended from the crane. A heave compensation system integrated into the crane minimizes the heave motions induced by the vessel motions and pendulum effects. While the gripper secures the tower in place, wires extending from the tower bottom to the floater column can be tensioned to achieve the correct horizontal alignment of the tower. The gripper releases during the tensioning of the wires to prevent bending of the tower which could occur due to loading on the tower at two different locations and in different directions.

4. Passive control

The Passive control concept reduces the relative motions, mainly in sway direction, through the implementation of two Passive Compensation (PC) systems as depicted in Figure 9.4. The two columns adjacent to the vessel are connected to the PC system at two different height levels, thereby minimizing relative roll motion. Fenders positioned between the floater and the vessel serve to prevent collision while also providing stiffness and damping between both bodies. Additionally, slings configured in a crossed pattern ensure stiffness in the horizontal plane. The constraint imposed by adding the PC system and the slings will result in the floater and vessel moving approximately as a single body. This synchronization makes it feasible to use a standard crane to position the tower on top of the floater.

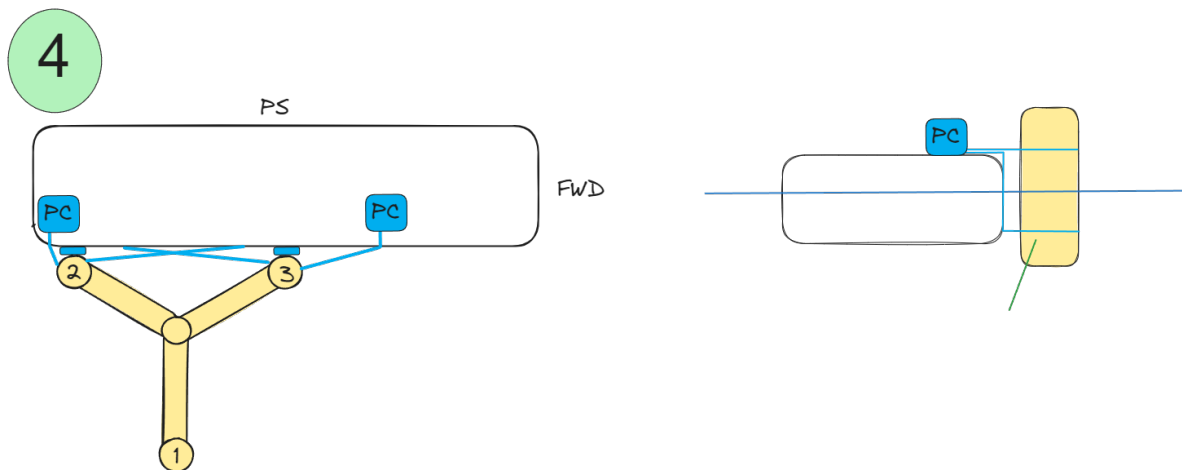


Figure 9.4: Concept sketch of the Passive control concept

9.2. Multi-criteria analysis

The criteria used for the MCA are listed below and a short description is given.

1. Applicable to different floater geometries

This criterion is considered significant due to the absence of one favored geometry among semi-submersible floaters within the industry.

2. Applicable to different tower diameters

The industry features different wind turbine sizes with varying tower diameters. To ensure versatility, the concept must be capable of accommodating a range of tower diameters.

3. Forces on the floater

Efforts should be made to minimize the forces acting upon the floater to mitigate potential structural damage. During the installation phase, it is necessary to limit loading on the floater and its mooring system to ensure that forces remain within their designed capacity.

4. Applicable to existing vessels

The shortage of installation vessels is expected as early as 2025 as highlighted in subsection 1.3.1 thereby precluding the feasibility of constructing a new, bespoke vessel. Consequently, it is assigned a value of 0 when deemed inapplicable, and a value of 10 when deemed applicable.

5. Forces required on vessel/from the concept

The findings presented in chapter 8 demonstrate the substantial forces necessitated during the connection of both floating bodies and the vessel should withstand these significant forces. Therefore, it is advantageous to avoid the implementation of a rigid connection between the bodies.

6. Applicable to a large fleet

The applicability of a concept to an existing vessel does not necessarily imply a widespread availability of vessels capable of accommodating the concept. With the anticipated vessel shortage, the applicability to a large fleet is an attractive feature.

7. Precedent/mature technology

The maturity of the applied technology indicates the extent to which installation operations have been refined through previous projects. Greater experience with the technology enhances security and certainty in its application.

8. Fabrication complexity

Assessing fabrication complexity considers factors such as material type and availability, manufacturing precision, and assembly techniques.

9. Mass

The mass of the concept serves as an indication of the costs. Additionally, this criterion extends to whether the concept entails a significant mass that must be accommodated on or transported to either the vessel or the floater.

10. Operational complexity

Operational complexity reviews the ease and efficiency with which a concept can be utilized or executed. A complex concept poses challenges in persuading operators to undertake the operation, while also increasing the likelihood of errors.

11. Operation duration

Operation duration assesses the timeframe required for a concept to complete the tower installation process. Extended durations are unfavorable due to elevated vessel costs and susceptibility to weather-dependent operational windows.

Each criterion is assigned a weight factor to indicate its relative importance. These weight factors are chosen such that the sum of all eleven factors equals 100, assisting in a clear overview of each criterion's significance within the total evaluation.

Each concept is assigned a value ranging from zero to ten, representing its performance relative to the other concepts for each criterion. This value is then multiplied by the corresponding weight factor, and the sum of these products is stated in the bottom row of Table 9.1. The concept with the highest cumulative score is deemed the most favorable among the four concepts, based on the described criteria. Emphasis is placed on the relative values between the concepts rather than the absolute values. This MCA serves to compare the concepts rather than ascertain their overall quality. While this assessment is rather subjective, it serves as a transparent evaluation tool and can be easily communicated.

Table 9.1: Multi-criteria analysis table

	Weight factor	Concept 1	Concept 2	Concept 3	Concept 4
1. Applicable to different floater geometries	12	4	8	9	9
2. Applicable to different tower diameters	12	10	8	9	10
3. Forces on the floater	11	1	10	9	7
4. Applicable to existing vessels	9	0	10	10	10
5. Forces required on vessel/from the concept	9	5	7	8	6
6. Applicable to a large fleet	7	0	9	8	8
7. Precedent/ mature technology	8	1	7	7	8
8. Fabrication complexity	8	8	4	8	7
9. Mass	8	8	4	7	7
10. Operational complexity	8	7	7	7	8
11. Operation duration	8	6	7	8	7
Sum	100	464	750	829	801

9.3. Concept selection and justification

When examining the cumulative results in Table 9.1, it is evident that Co-floatation, Concept 1, scores significantly lower than the other three concepts, which show less pronounced differences. The Co-floatation concept requires a novel type of vessel and has limited applicability to different floater types due to geometrical restrictions and the prohibition of cross braces on the floater. Additionally, submerging operations associated with this concept are not mature practices, and a large force is imposed on the floater by the vessel. These criteria, which carry relatively high weight factors, contribute to the notably low total score of Concept 1, making it the least favorable option among the four concepts.

The comparison then primarily focuses on Concept 2, Concept 3 and Concept 4, with the most significant differences in the fabrication complexity and mass criteria. Concept 2 scores the lowest in both criteria due to the need for a large frame that can move independently and support the heavy tower, which requires substantial hydraulics to align the tower with the floater column. Additionally, Concept 2 is limited by the maximum tower diameter and mass it can handle due to the Twingripper frame's capacity constraints. In contrast, the gripper in Concept 3 only restricts horizontal motions without needing to hold the tower, allowing it to accommodate larger tower dimensions than Concept 2.

Concept 3, utilizing tension wires performs slightly better compared to Concept 4 which employs PC systems. While the absence of a gripper in Concept 4 makes it suitable for a wider range of tower diameters, Concept 3 imposes lower forces on the floater. This is because the mooring system experiences forces when the PC systems pull on the floater, causing it to move along with the vessel. The findings of chapter 8 underscore the large forces to be endured when both bodies are interconnected. Consequently, Concept 4 scores lower due to the presence of a stiff connection, whereas Concept 3 benefits from a gripper that softens during tensioning, mitigating a rigid connection between the floater and the vessel. This results in Concept 3 being the winning concept and will be developed in greater detail in the following section.

While Concept 3 emerged as the preferred option through this MCA, this does not diminish the feasibility of the other concepts. Based on the current knowledge and analysis, Concept 3 has been selected as the most suitable choice.

9.4. Detailing concept steps

The Gripper wire control concept is developed in greater detail and divided into ten steps for the installation process. These steps will be shown below, supported by sketches to clarify the procedure with the corresponding legend provided in Figure 9.5.

The ten steps are explained below and their corresponding sketches can be found in Figure 9.6, Figure 9.7, Figure 9.8, Figure 9.9, Figure 9.10.

- **Step 1: Initial rest position**
The tower and External Platform (EP) are fastened on the vessel and the wires and cables are connected but soft. The EP is a donut-shaped structure that can be opened and closed and provides space for the winches and other additional materials for the turbine integration process. Furthermore, a gripper surrounds the tower and this gripper can move to the required deck location. Fenders or something similar (not sketched) are attached to the vessel to avoid structural damage due to collision between the two bodies.
- **Step 2: Lift up**
The gripper becomes stiff and the tower is lifted by the crane, with the EP suspended from the gripper due to the cables. The Active Heave Compensation (AHC) system is on and it is capable of keeping a desired distance between the tower bottom and the vessel deck ensuring the tower bottom does not collide with any objects beneath it.
- **Step 3: Positioning**
The crane and gripper rotate simultaneously to position above the floater's center column. The gripper restricts horizontal motions but is equipped with rollers to allow heave motions.
- **Step 4: Lowering EP**
The EP is being lowered on top of the floater column by extending the cables while the gripper restricts the pendulum motion of the tower. The conical shape of the EP ensures that the EP slides on top of the floater column. Bumpers or similar protective features (not sketched) are incorporated into the EP to avoid structural damage during this lowering process.
- **Step 5: Secure EP**
The EP is placed on top of the column and fastened to the floater after which the cables are slackened. This locking mechanism operates without the need for manual intervention.
- **Step 6: Tensioning**
As the wires are tensioned, the gripper gradually reduces its hold, enabling the horizontal motion constraints to transition from the gripper to the wires, which then take over the role of restricting movement. This ensures that no rigid connection exists between the vessel and floater, thereby avoiding the large forces that such a connection would need to withstand. The horizontal motions of the tower are then maintained within 0.2 m through the tensioning of the wires. The tower is subsequently lowered, with the winches ensuring that horizontal motions are kept within 0.2 m, while the AHC system tracks and compensates for the heave motions.
- **Step 7: Secure tower**
The tower is placed on top of the floater and is held in place by an initial support system and workers access the floater. Workers then access the floater to fully secure the tower. Once the tower is secured, the AHC system is turned off, and the tower is released from the crane.
- **Step 8: Release EP**
The winch wires are disengaged from the tower by workers and hauled back, after which the personnel leave the platform. Subsequently, the cables between the gripper and the EP are tensioned again and the floater-EP connection established in Step 5 is automatically released.
- **Step 9: Pull up EP**
The EP is pulled up to the gripper and the gripper and EP open simultaneously to release the tower. After releasing the tower, the gripper and EP close again and retract back to the vessel.
- **Step 10: Return EP**
The EP is placed back on the vessel, disconnected from the gripper and the 10 steps can then be repeated for the next turbine.

9.5. Installation process evaluation

This installation process will be evaluated by discussing its advantages and disadvantages. One major disadvantage involves the need for a comprehensive gripper capable of moving in the three translational degrees of freedom. Omitting the gripper would make the installation process economically more attractive, but its two main functions would need to be addressed differently.

The first function of the gripper is to reduce the tower bottom motions caused by pendulum effects and excitation at the crane tip. As shown in subsection 7.5.2, the crane tip motions are significant, even without considering the pendulum effects of the tower. These motions could potentially be managed using tugger lines, which provide stiffness primarily in one direction, whereas the gripper provides stiffness in both horizontal directions. The second advantage of the gripper is its ability to retract the EP back to the vessel. While releasing the EP into the water could be an option, this approach is complicated by the presence of the floater's braces, which are also found in other floaters with different geometries. Another possibility is to lift the EP using the crane; however, this would require lifting the EP above the tower, necessitating an even greater crane height capacity. These challenges highlight the necessity of employing a gripper, although they could potentially be solved in future work.

Another disadvantage is the large reach required by the gripper, which could be mitigated by using a floater with a different geometry. In floater geometries such as the INO WINDMOOR or WindFloat platforms, the turbine is mounted on a corner column strategically positioned adjacent to the vessel. This configuration significantly reduces the required length of the gripper's arm, making it a more favorable geometry for this installation process. Given that the WindFloat Atlantic and Kincardine floaters already use this preferred geometry, it is reasonable to assume the potential adoption of such floaters in future installations.

The inclusion of the EP may raise questions, as it introduces an additional step in the process. However, it is advantageous to have a system that allows for the retrieval of winches and additional equipment back to the vessel for reuse in the installation of future turbine towers. The use of short cables, a rigid gripper, and the conical shape of the EP all facilitate its positioning atop the floater column. With the gripper located at the tower bottom, this setup corresponds to the POI used in the relative motions analysis in subsection 7.5.1 and it shows a maximum relative displacement of 1 m in the horizontal plane for a regular wave height of 2 m. This concept is only viable if placing the EP is significantly easier than placing the tower on the floater.

One of the advantages of this approach is that it avoids any rigid connection between the floater and the vessel during the tower installation process. Initially, the gripper rigidly holds the tower, but as the process continues, the horizontal constraints are transferred from the gripper to the winch wires. Since the tower is connected to a crane wire, it maintains a limited degree of rotation, permitting controlled motion during the integration process.

Other considerations for this concept include reinforcing the tower bottom to withstand tensioning without damaging the tower which has a small wall thickness-to-diameter ratio. The AHC system's capabilities are expected to manage the necessary stroke and mass, akin to the Seaqualize system eventually handling up to 2000 t with a 3.5 m stroke, sufficient for the maximum observed relative heave of 2.7 m as seen so far in Figure 7.9. The focus of the modeling effort will, therefore, be on minimizing horizontal motions.

9.5.1. Modeling Step 6: Tensioning

From the various steps described above, Step 6: Tensioning will be modeled. This step is selected because it represents the novel aspect of the installation process and is crucial for evaluating the feasibility of the winch-based tensioning concept. Although the transient lowering process will not be simulated, the focus will be on the starting position with the tower suspended 3 m above the floater's column top. The winch wires must restrain horizontal motions to maintain the 0.2-m displacement limit, with no motion compensation provided by the gripper. The subsequent modeling part will determine the required stiffness and the forces imposed on the winch wires.

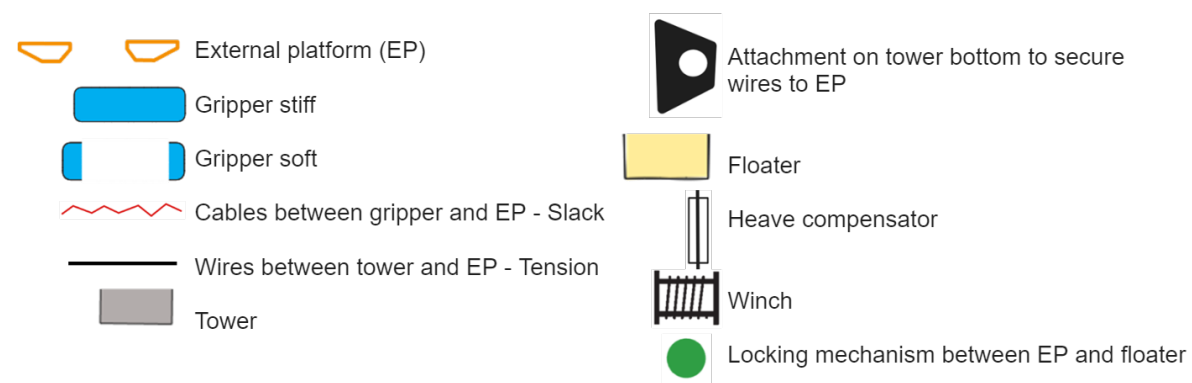


Figure 9.5: Legend of the sketches below. Here, red cables will be used to indicate the cables between the gripper and EP while black wires will be used to indicate the wires between the tower and the EP.

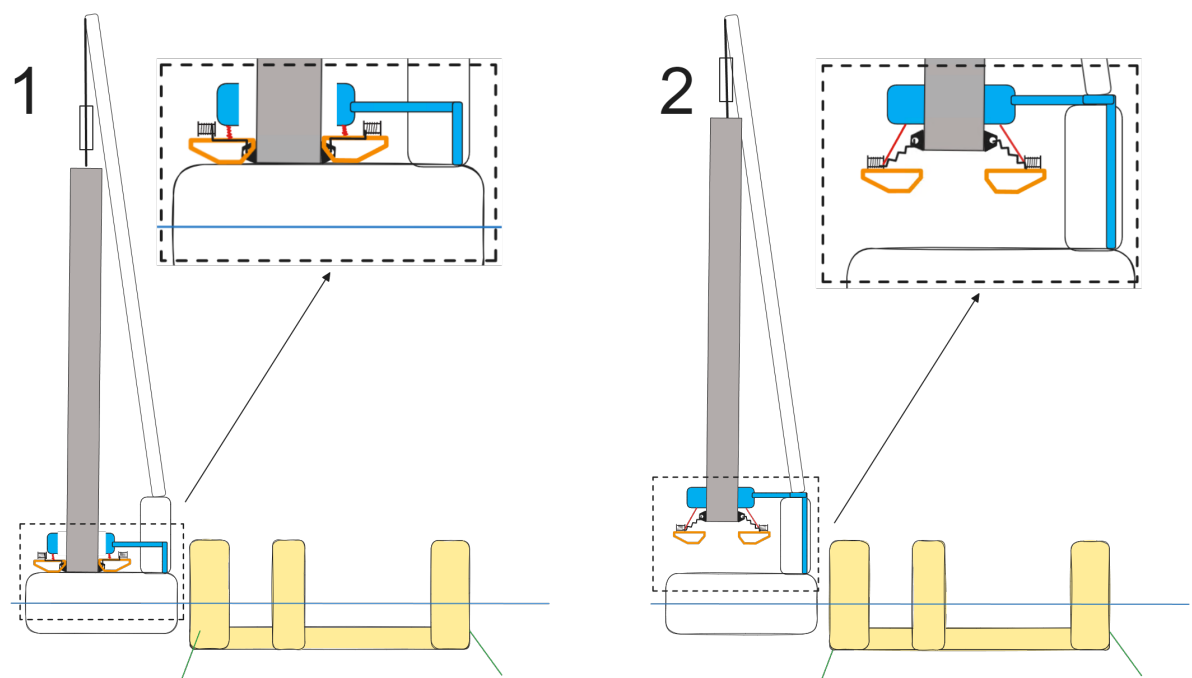


Figure 9.6: Step 1: Initial rest position; The tower and EP are fastened on the vessel. Step 2: Lift up; the gripper is stiff and the EP is suspended from the gripper, below the tower

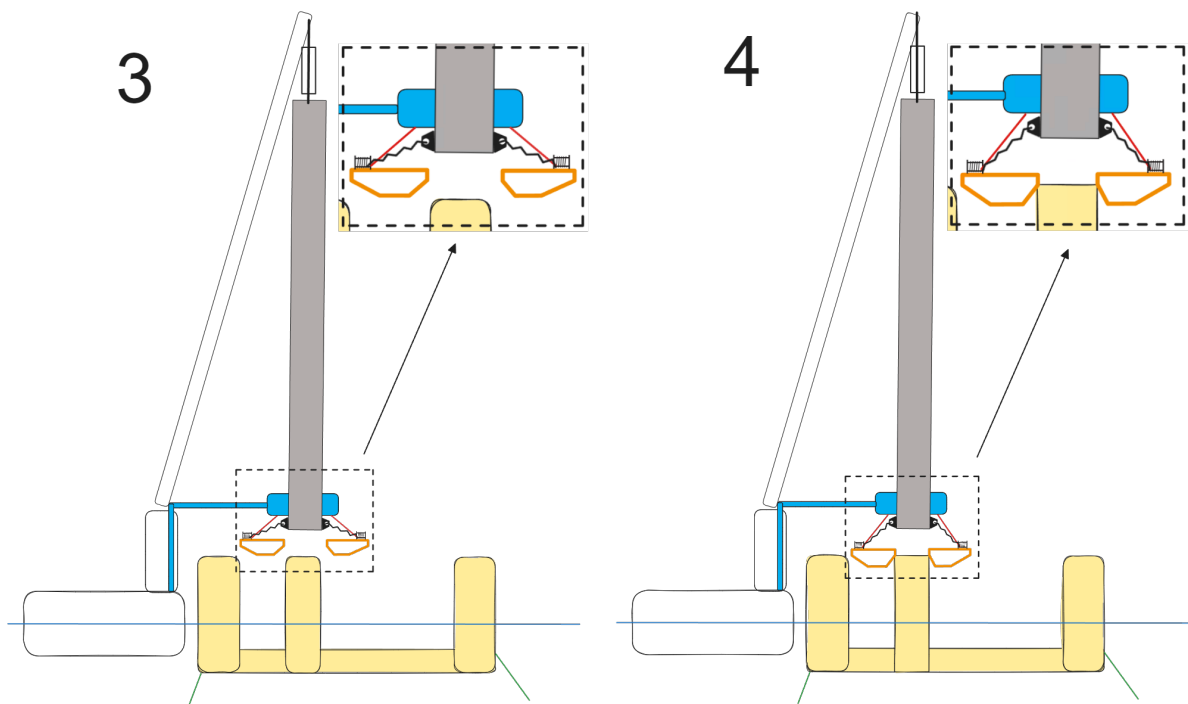


Figure 9.7: Step 3: Positioning; The crane and gripper rotate to the floater center column. Step 4: Lowering EP; The gripper restricts pendulum motions while the conical-shaped EP is lowered.

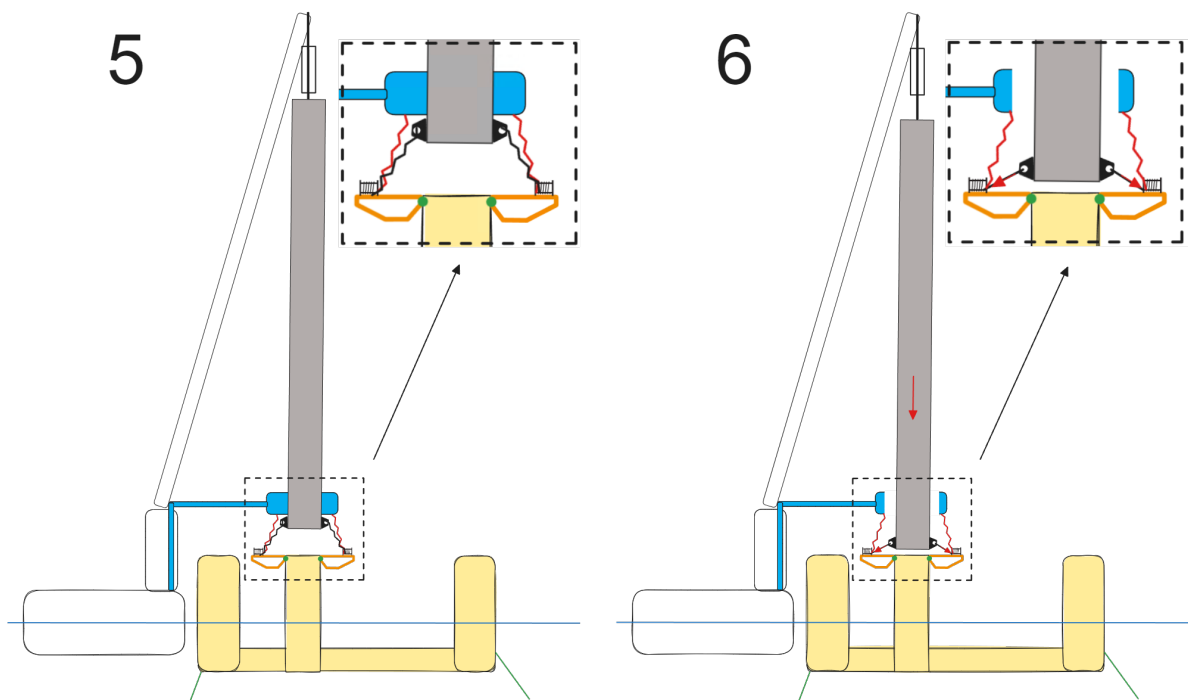


Figure 9.8: Step 5: Secure EP; The EP is fastened to the floater. Step 6: Tensioning; The gripper opens while the wires are being tensioned by the winches. The wires compensate for the horizontal motion during the lowering of the tower.

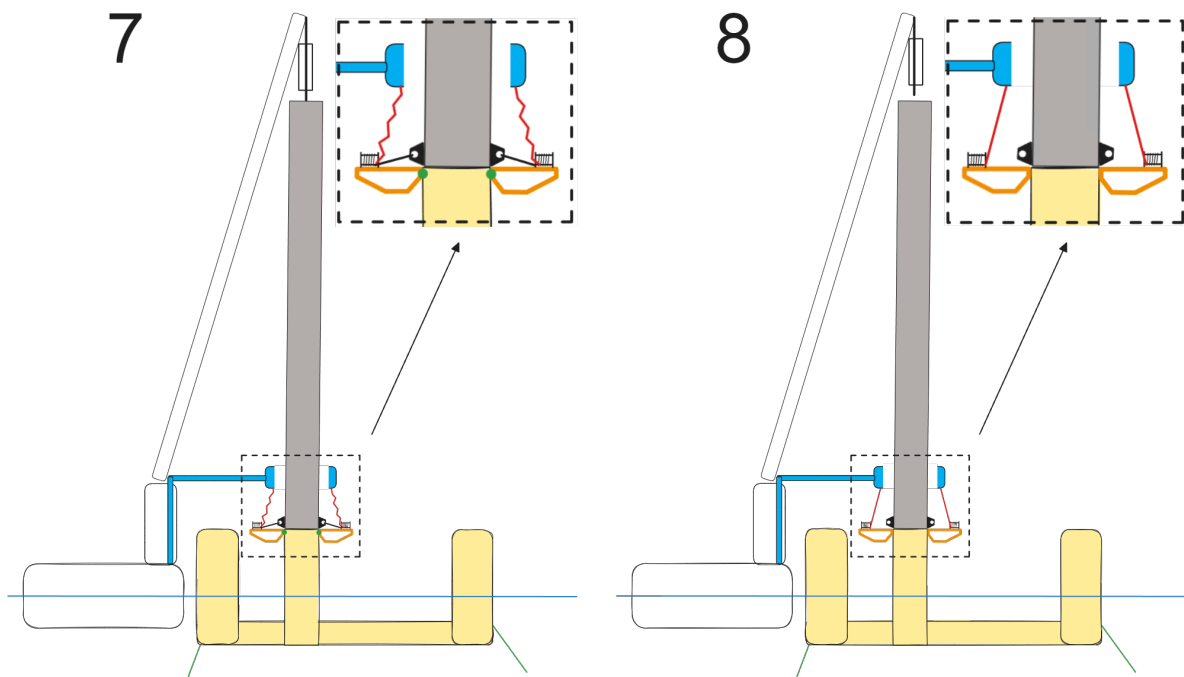


Figure 9.9: Step 7: Secure tower; The tower is secured on top of the floater and the heave compensator is turned off. Step 8: Release EP: Cables between the gripper and EP are tensioned and the wires between the EP and tower, as well as the floater-EP connection are disengaged.

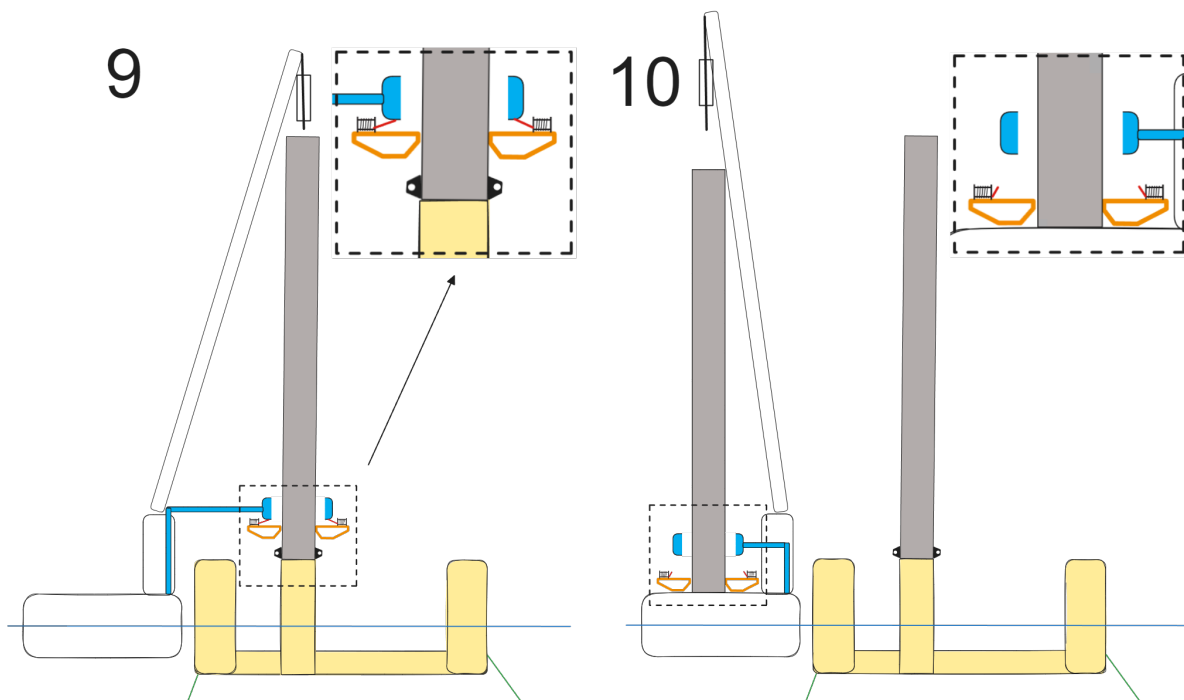


Figure 9.10: Step 9: Pull up EP; The EP is pulled up to the gripper and both open simultaneously and retract to the vessel. Step 10: Return EP; The EP is placed back on the vessel and disconnected from the gripper.

10

Modeling the motion reduction step

The design phase is followed by a second modeling phase to evaluate the performance of the tensioning step. An analytical model of the tower is developed to validate the OrcaFlex simulations, which simulate the tower's motions using the previously employed multibody model, now incorporating the tower suspended from the crane. With the validated model, time-domain simulations are conducted to determine the required stiffness needed to limit horizontal relative motions to within 0.2 m.

10.1. Analytical model

Using Lagrangian mechanics, the equation of motion for the system represented by a double pendulum model is derived and the resulting second-order differential equation is solved using MATLAB. Additionally, a driven pendulum model is solved to confirm the results of the double pendulum model, as the latter is prone to (coding) errors.

10.1.1. Assumptions and simplifications

The analytical model is a variation of a double pendulum with driven displacements at both the crane tip and the tower bottom. The tower bottom is attached to a horizontal spring to simulate the wires. The winch wires, originally angled from the tower's outer radius to the EP, are modeled as a horizontal spring with zero force in its initial state. In practice, this setup implies that the winch would be positioned 3 m above the External Platform.

As mentioned in the previous chapter, it is assumed that an AHC system will effectively handle the relative heave motions between the two floating bodies. Therefore, the analytical model includes one horizontal spring to investigate the novel aspect of this system which is the restriction of the relative horizontal motions. With winches attached on both sides of the tower, as depicted in the sketches in section 9.4, this is simplified into one spring, considering that they are arranged in series.

The additional assumptions and simplifications are given below and applied to the Orcaflex model presented in the next section as well.

The list below applies to Step 6 only.

1. The EP is rigidly connected to the floater column.
2. The increase in mass of the total floater due to the addition of the EP is considered negligible.
3. The gripper is rigidly connected to the vessel.
4. The gripper, in its soft state, remains disengaged from the tower during the alignment process, and thus it is not represented in the model.
5. The crane is rigidly connected to the vessel.
6. The tower is a rigid body.
7. The winches and wires have a negligible mass.

8. The wires connect the center of the tower bottom to the floater, at a location 3 m above the center column top. These wires are set to have zero force when the relative displacement between these two locations is zero.
9. The attachments on the tower used to connect the wires between the EP and tower are rigidly connected to the tower and have a negligible mass.
10. The AHC is assumed to be capable of keeping the tower at a fixed distance of 3 m above the floater center column (not valid from section 10.3 onwards), neglecting the heave motion at the top.
11. The mass of the AHC and the dynamics it induces is also neglected

The analytical tower model is shown below in Figure 10.1 with an overview of the variables next to it. The model consists of a massless crane wire that is assumed to be rigid and driven at the top with a response corresponding to the y_{CT} displacement of the vessel at that location. It has a length L_{wr} and it makes an angle θ_1 with the vertical. The tower has a mass m_T , inertia I , length L_T and a distance of L_{CoM} between the center of mass to the tower top. It makes an angle θ_2 with the vertical and at the bottom, a spring with a stiffness k is attached which is driven with a response corresponding to the floater's displacement at a vertical distance of 3 m from the floater top.

10.1.2. Equation of Motion

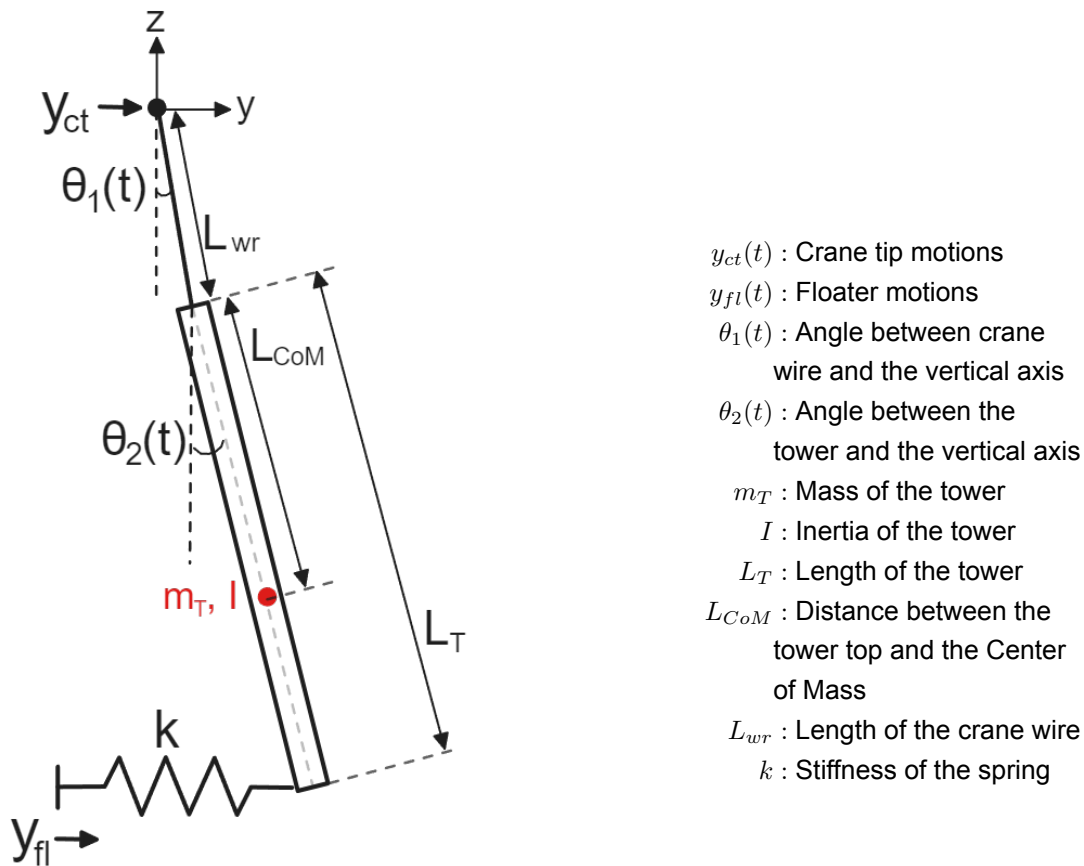


Figure 10.1: Sketch of the analytical tower model which resembles a double pendulum model

Lagrangian mechanics is used to obtain the expression of the equation of motion of this system. The Euler-Lagrange equations are defined as (Morin, 2012):

$$\frac{d}{dt} \frac{\delta L}{\delta \dot{q}_j} - \frac{\delta L}{\delta q_j} = 0 \quad (10.1)$$

where q_j and $\dot{q}_j$ are the generalized displacement and velocity for the j^{th} degree of freedom. The Lagrangian L is defined as:

$$L = T - V \quad (10.2)$$

where T and V represent the kinetic- and potential energy of the system.

The point of interest is chosen as the center of mass of the tower with the y and z coordinates being y_{CoM} and z_{CoM} respectively. This position can be described using the angles θ_1 and θ_2 :

$$\begin{aligned} y_{CoM} &= y_{ct} + l_{wr} \sin \theta_1 + L_{CoM} \sin \theta_2 \\ z_{CoM} &= z_{ct} - L_{wr} \cos \theta_1 - L_{CoM} \cos \theta_2 \end{aligned} \quad (10.3)$$

Taking the time derivative of Equation 10.3, the velocities in y and z can be written as:

$$\begin{aligned} \dot{y}_{CoM} &= \dot{y}_{ct} + L_{wr} \dot{\theta}_1 \cos \theta_1 + L_{CoM} \dot{\theta}_2 \cos \theta_2 \\ \dot{z}_{CoM} &= \dot{z}_{ct} + L_{wr} \dot{\theta}_1 \sin \theta_1 + L_{CoM} \dot{\theta}_2 \sin \theta_2 \end{aligned} \quad (10.4)$$

where the dot indicates the time derivative of the respective variable. For the system in Figure 10.1, the kinetic energy T is described as:

$$T = \frac{1}{2} m_T (\dot{y}_{CoM}^2 + \dot{z}_{CoM}^2) + \frac{1}{2} I \dot{\theta}_2^2 \quad (10.5)$$

And the potential energy is defined as:

$$V = m_T g z_{CoM} + \frac{1}{2} k y_s^2 \quad (10.6)$$

where y_s is the elongation of the spring which is defined as:

$$y_s = y_{ct} + L_{wr} \sin \theta_1 + L_T \sin \theta_2 - y_{fl} \quad (10.7)$$

Combining Equation 10.5 and Equation 10.6 into Equation 10.2 results in the following Lagrangian formulation:

$$L = \frac{1}{2} m_T (\dot{y}_{CoM}^2 + \dot{z}_{CoM}^2) + \frac{1}{2} I \dot{\theta}_2^2 - m_T g z_{CoM} - \frac{1}{2} k y_s^2 \quad (10.8)$$

Substituting Equation 10.8 into Equation 10.2 and applying small angle assumption results in the following operations: $\sin \theta_1 = \theta_1$, $\sin \theta_2 = \theta_2$, $\cos \theta_1 = 1$ and $\cos \theta_2 = 1$. Moreover, by assuming the variables θ_1 and θ_2 to be small enough that higher-order terms are significantly smaller than the linear term, this results in θ_1^2 , θ_2^2 , $\dot{\theta}_1^2$, $\dot{\theta}_2^2$ and $\theta_1 \cdot \theta_2 = 0$, resulting in the following two equations:

$$\begin{aligned} k L_{wr} y_{ct} - k L_{wr} y_{fl} + L_{wr} m_T \ddot{y}_{fl} + k L_{wr}^2 \theta_1 + L_{wr}^2 m_T \ddot{\theta}_1 + g L_{wr} m_T \theta_1 + L_{CoM} L_{wr} m_T \ddot{\theta}_2 + k L_T L_{wr} \theta_2 &= 0 \\ I \ddot{\theta}_2 + L_{CoM} m_T \ddot{y}_{ct} + L_{CoM}^2 m_T \ddot{\theta}_2 + k L_T y_{ct} - k L_T y_{fl} + g L_{CoM} m_T \theta_2 + L_{CoM} L_{wr} m_T \ddot{\theta}_1 + k L_T L_{wr} \theta_1 &= 0 \end{aligned} \quad (10.9)$$

Writing Equation 10.9 in matrix form results:

$$\begin{aligned}
& \begin{bmatrix} L_{wr}^2 m_T & L_{CoM} L_{wr} m_T \\ L_{CoM} L_{wr} m_T & m_T L_{CoM}^2 + I \end{bmatrix} \begin{bmatrix} \ddot{\theta}_1 \\ \ddot{\theta}_2 \end{bmatrix} + \begin{bmatrix} k L_{wr}^2 + g L_{wr} m_T & k L_T L_{wr} \\ k L_T L_{wr} & k L_T^2 + g L_{CoM} m_T \end{bmatrix} \begin{bmatrix} \theta_1 \\ \theta_2 \end{bmatrix} \\
& = - \begin{bmatrix} L_{wr} m_T \\ L_{CoM} m_T \end{bmatrix} \ddot{y}_{ct} - \begin{bmatrix} k L_{wr} \\ k L_T \end{bmatrix} y_{ct} + \begin{bmatrix} k L_{wr} \\ k L_T \end{bmatrix} y_{fl}
\end{aligned} \quad (10.10)$$

Equation 10.10 is solved in MATLAB using the ode45 solver with:

$$\begin{aligned}
y_{fl} &= A_{fl} \sin(\omega t + \phi_{fl}) \\
y_{ct} &= A_{ct} \sin(\omega t + \phi_{ct}) \\
\ddot{y}_{ct} &= -A_{ct} \omega^2 \sin(\omega t + \phi_{ct})
\end{aligned} \quad (10.11)$$

with a floater amplitude of A_{fl} , crane tip amplitude A_{ct} and ϕ_{fl}, ϕ_{ct} the phase of the floater and crane tip resulting from OrcaFlex simulations

Equation 10.10 can be rewritten in matrix form according to:

$$\mathbf{M} \begin{bmatrix} \ddot{\theta}_1 \\ \ddot{\theta}_2 \end{bmatrix} + \mathbf{K} \begin{bmatrix} \theta_1 \\ \theta_2 \end{bmatrix} = \mathbf{F}(t) \quad (10.12)$$

Where $\mathbf{M}$, $\mathbf{K}$ and $\mathbf{F}$ represent the mass matrix, stiffness matrix and external force vector respectively.

The relative displacement y_{rel} is defined as the misalignment between the response of the tower bottom y_{TB} and the floater motions according to:

$$\begin{aligned}
y_{TB} &= y_{ct} + L_{wr} \sin \theta_1 + L_T \sin \theta_2 \\
y_{rel}(t) &= y_{TB}(t) - y_{fl}(t)
\end{aligned} \quad (10.13)$$

The spring force is then calculated using:

$$F_s = k y_{rel} \quad (10.14)$$

The tower top moves in phase with the imposed crane tip motion as visible in the top figure of Figure 10.2. The tower bottom moves out of phase in its transient phase with a period that can be calculated by solving:

$$(-\omega^2 \mathbf{M} + \mathbf{K}) \mathbf{X} = 0 \quad (10.15)$$

where $\mathbf{X}$ is the eigenvector.

Solving the homogeneous Equation 10.15 results in the natural frequencies stated in Table 10.1. The analytical model provides a first natural frequency of 0.30 rad/s which equals the period of 21 s between the peaks of the transient tower bottom response in Figure 10.2, corresponding to mode 1. After reaching a steady state (around 400 s), the tower bottom moves with the same period as the crane tip, which characterizes the particular solution of the differential equation.

Table 10.1: Natural periods of mode 1 and mode 2; the mode shape is normalized by setting the largest coefficient to 1

Mode	Natural frequency ω (rad/s)	Natural period (s)	Normalized mode shape
1	0.30	20.9	$\begin{bmatrix} 0.89 \\ 1 \end{bmatrix}$
2	2.12	2.97	$\begin{bmatrix} 1 \\ -0.227 \end{bmatrix}$

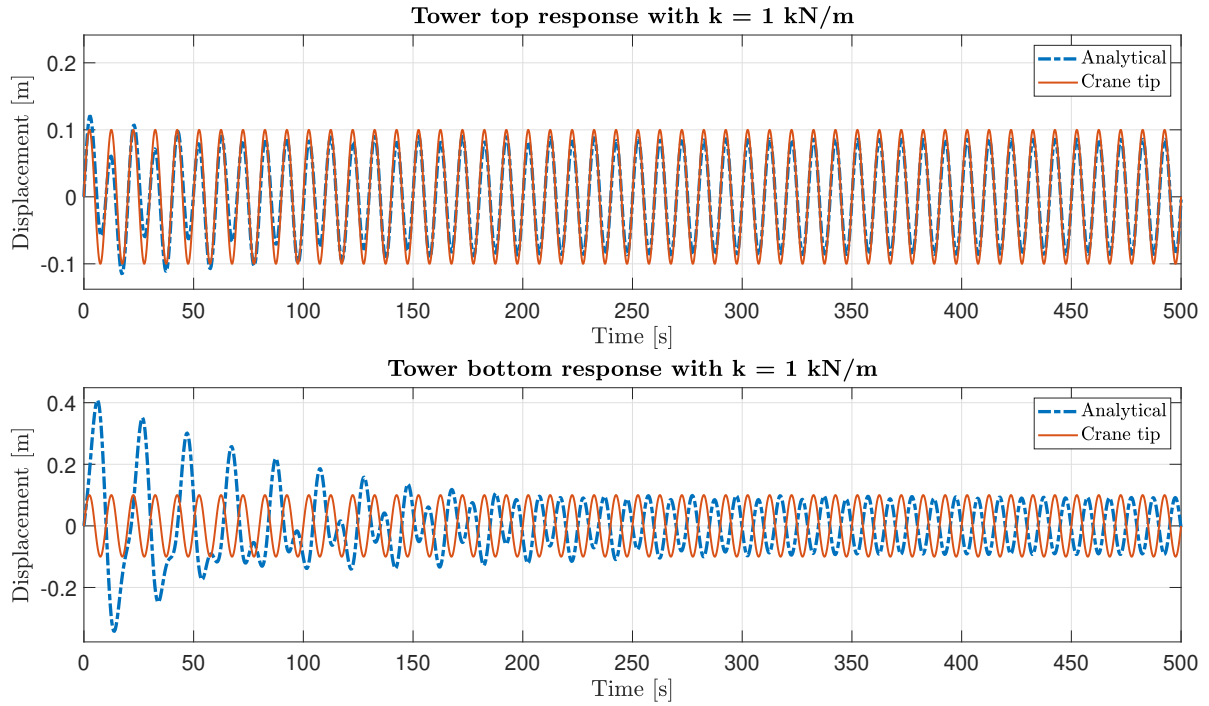


Figure 10.2: Response of the tower using $A_{fl} = 0$ m and $A_{ct} = 0.1$ m using an arbitrarily chosen stiffness of 1 kN/m, a period of 10 s and considering 5% critical damping.

10.1.3. Driven pendulum

As a validation step of the derived equations above, a separate validation model is written to solve for the case of a driven pendulum as depicted in Figure 10.3. This model mimics the model in Figure 10.1 when:

1. $k = 0$
2. L_T is small to simulate a point mass and is set to 1 m
3. L_{CoM} is set to 0.5 m

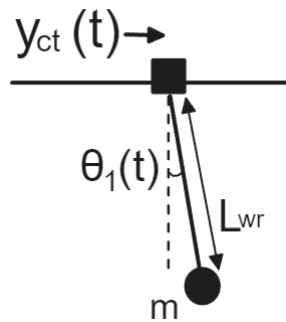


Figure 10.3: Sketch of the driven pendulum model with $y_{ct} = A \sin(\omega t)$

The equation of motion of the driven pendulum model (also based on Lagrangian mechanics) can be described by (Hill, 2017):

$$\ddot{\theta}_1 = -\frac{g}{L_{wr}} \sin(\theta_1) + \frac{\omega^2}{L_{wr}} A \cos \theta_1 \sin(\omega t) \quad (10.16)$$

Solving the differential equation in Equation 10.16 and the double pendulum model from Equation 10.10 using the three assumptions above results in the time response visible in Figure 10.4.

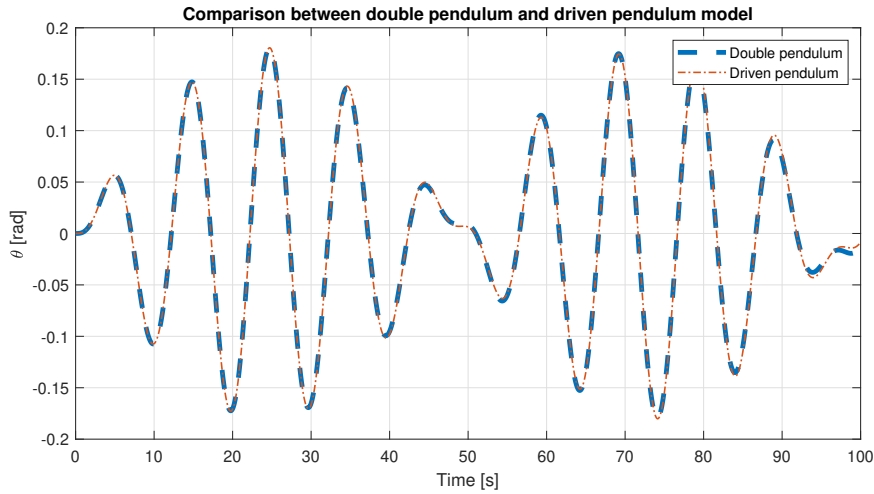


Figure 10.4: Time series of θ_1 using the double pendulum and driven pendulum model with a driven oscillation of $\sin \omega t$ for both models

Both graphs overlap which provides confidence that the double pendulum is implemented correctly. When increasing the length of the tower L_T and L_{CoM} , deviations between the double and driven pendulum become visible as the point mass assumption becomes less valid.

10.2. OrcaFlex separate tower model validation

Initially, a separate validation model is created in OrcaFlex to compare its results with the dynamic system depicted in Figure 10.1. This step ensures the correct solving of both the analytical model and the OrcaFlex implementation. This section serves the sole purpose of verification, the discussion of the responses and forces is reserved for the subsequent section.

The separate tower model includes a crane wire, represented as a spring with a large stiffness to maintain a constant length, aligning with the analytical model. The crane wire connects the imposed motion constraint with the tower and the tower is assigned the mass properties listed in Table 5.1. The imposed motion constraint at the top applies a sinusoidal displacement in the y-direction, with the other DOFs having zero imposed displacement. The bottom of the tower includes a constraint that mimics a spring, fixed in space at one end and connected to the center of the tower at the other, thereby neglecting the floater motions y_{fl} in this case.

The double pendulum response of the tower without the influence of the spring is shown in Figure 10.5. The imposed motion with a small amplitude of 0.1 m ensures the small angle assumption is valid. The results based on the analytical model and the OrcaFlex model show good correspondence indicating that both models are implemented correctly. The slight difference in the tower bottom response between both models is caused by the build-up phase ($t < 0$ s) in the OrcaFlex model which causes a small difference in the initial conditions at $t = 0$ s compared to the analytical model. By having a slow build-up phase, the correspondence is even better which will be shown in the next section.

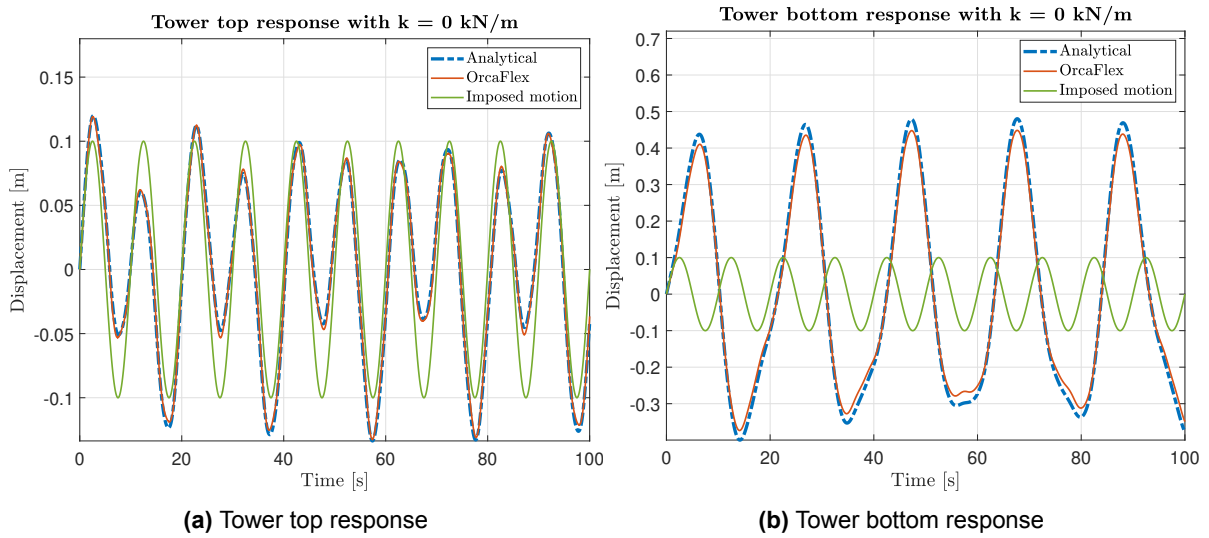


Figure 10.5: Tower response based on the analytical model and OrcaFlex simulations without a spring and using an imposed motion for $y_{ct}(t)$ of $0.1 \sin(\omega t)$

The next step is to incorporate the spring in both models and the correspondence between both models is shown in Figure 10.6 for an arbitrarily chosen stiffness of 100 kN/m. Yet again, both models show matching results with a maximum difference in the tower bottom displacement of 0.02 m. As mentioned before, the correspondence when using a slow build-up phase in OrcaFlex will be even better.

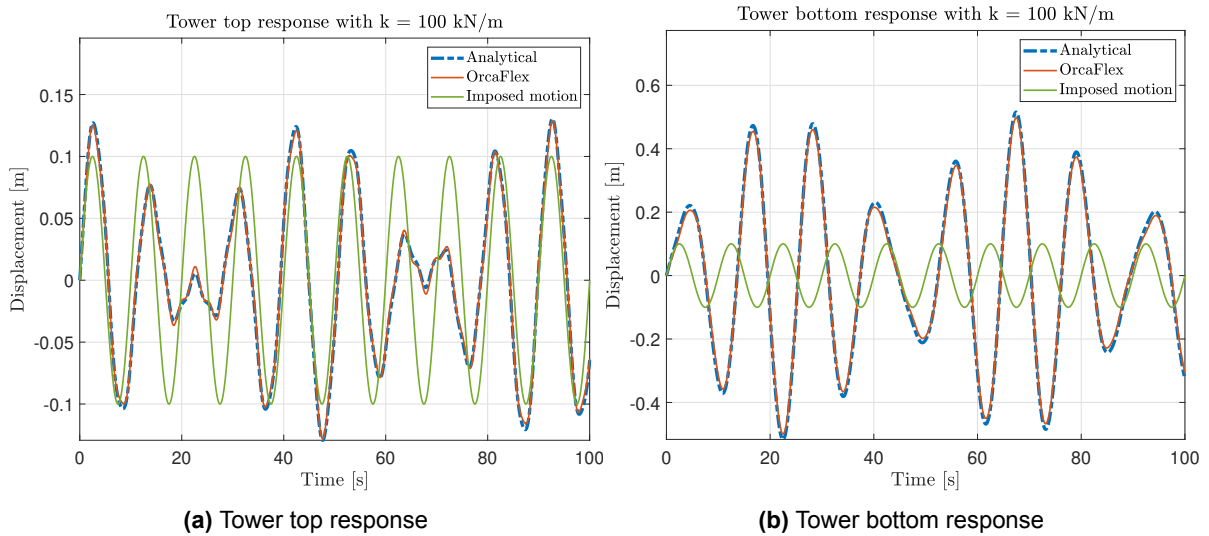


Figure 10.6: Tower response based on the analytical model and OrcaFlex simulations using a spring stiffness of 100 kN/m with an imposed motion of $0.1 \sin(\omega t)$

10.3. Tower response in multibody model validation

The tower model is integrated into the multibody model such that the crane tip moves rigidly with the vessel, replacing the previously imposed motion constraint used in the separate tower model. The bottom spring is again modeled as a constraint, now connected to the floater, with a non-zero stiffness in surge and sway, and a zero stiffness in the roll and pitch directions, consistent with the analytical model. An additional constraint is required and connected to the bottom spring to free the heave movement, as dictated by how OrcaFlex handles constraints (as explained in section 4.5). This ensures that the floater's heave, in combination with roll or pitch, does not exert additional forces on the tower by pulling

on the tower through the spring; only the floater's horizontal movements should be considered as the imposed motion, to be consistent with the analytical model.

One notable difference between the two models is that the analytical model does not account for the heave motion of the crane tip, whereas the OrcaFlex model includes it. Additionally, in the OrcaFlex model, the floater is free to move in the heave direction, which is also neglected in the analytical model.

To show the correspondence between the analytical and the multibody OrcaFlex model, the sway response of the crane tip is exported and used as input for the crane tip motion in y direction $y_{ct}(t)$ for the analytical model. The response of the tower top and tower bottom is plotted in Figure 10.7 demonstrating that the OrcaFlex results closely match the analytical results. This correspondence supports the earlier statement that, with a proper build-up phase, the OrcaFlex results align even more accurately with the analytical results. The floater motions are negligibly small and therefore not exported and used as input $y_{fl}(t)$ for the analytical simulation.

This validation check represents the final step in validating the OrcaFlex model. Subsequent simulations will utilize this validated model, with variations made solely to the environmental conditions or spring stiffness.

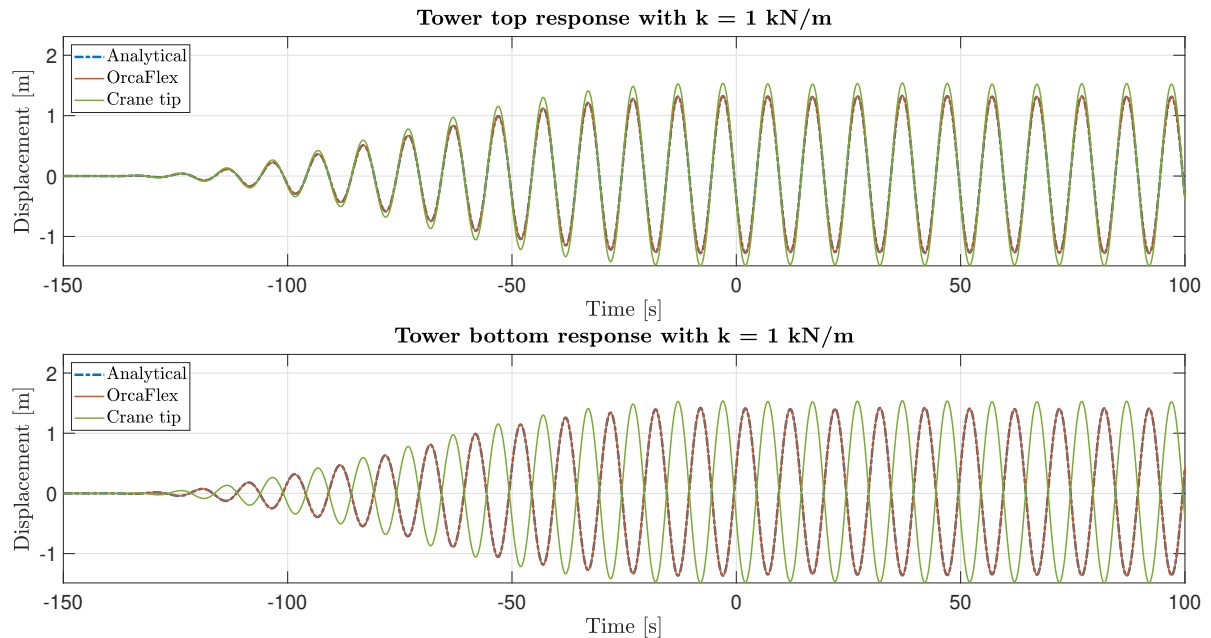


Figure 10.7: Tower response based on the analytical model and OrcaFlex's multibody simulations resulting from an arbitrary regular wave height of 1 m, a wave direction of 270 deg and a spring stiffness of 1 kN/m

10.4. Regular waves results

To initially estimate the required stiffness to maintain relative motions within 0.2 m and to determine the resulting forces in the spring, simulations are conducted with increasing stiffness applied equally in both the x- and y-direction, but no stiffness in the z-direction is applied. The results, shown in Figure 10.9 with a wave height of 1 m and a wave direction of 270 deg, are presented exclusively for the y-direction, as this direction dominates due to significantly smaller displacements in the surge direction. The stiffness array includes values at intervals of 10^a N with a ranging from 0 to 4, followed by 40 evenly spaced values on a logarithmic scale between 10 kN/m and $1e6$ kN/m. For every stiffness, a 200-second period, excluding the transient phase, is simulated using waves with a period of 10 s.

Note that in this second part of modeling, the relative motions include the swinging motions of the tower, in contrast to the first modeling part, which only considered the relative motions between the vessel and the floater.

Point of Interest

Figure 10.9 illustrates the maximum misalignment and the force components based on the relative distances. The tower's POI is located at the bottom edge and on its centerline, while the floater's POI is also on its centerline but positioned 3 m above the floater top. The horizontal relative distance is calculated as the y-coordinate of the tower's POI minus the y-coordinate of the floater's POI. The relative heave z_{rel} is measured by the difference in the z-coordinates between the floater's POI and the tower's POI. The resultant length l_{yz} as depicted in Figure 10.8 is then computed using Pythagoras' theorem.

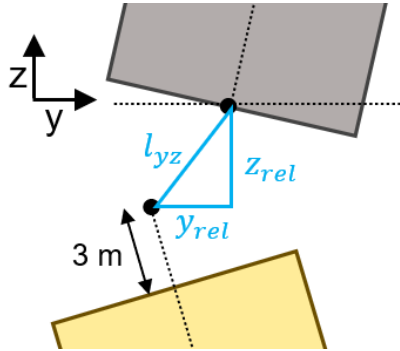


Figure 10.8: Sketch to clarify the parameters extracted from OrcaFlex

Misalignment curve

The shape of the horizontal misalignment curve can be explained by examining the effects of varying stiffness on the system. At low stiffness levels, the tower is not (significantly) influenced by the spring, resulting in no change in relative displacement until a stiffness of 10 kN/m is reached. Furthermore, a resonance peak is observed at 143 kN/m. Solving Equation 10.15 with this stiffness shows that the first mode occurs at a natural period of 10 s, which matches the wave and excitation period. Beyond the resonance peak, the relative displacement decreases as the spring increasingly restricts the tower's motions.

Force curves

The graphs also illustrate the maximum spring force for every 200-second steady-state period. The maximum horizontal displacement is multiplied by the applied spring stiffness to obtain the horizontal force component. The resultant force in the x-direction $F_{res,x}$ and y-direction $F_{res,y}$, uses the 2D length l_{xz} and l_{yz} of the spring and is determined by considering the contributions from both the horizontal and vertical displacement components, as depicted in Figure 10.8 and expressed in the following equations:

$$\begin{aligned} F_{res,x}(t) &= k\sqrt{x_{rel}^2(t) + z_{rel}^2(t)} = kl_{xz} \\ F_{res,y}(t) &= k\sqrt{y_{rel}^2(t) + z_{rel}^2(t)} = kl_{yz} \end{aligned} \quad (10.17)$$

Remember that the relative heave z_{rel} referred to here does not represent the actual distance between the floater top and tower bottom. Instead, it is the distance minus the static distance of 3 m that is set between the structures. For example, if $z_{rel} = -0.1$ m, it does not imply that the tower and floater 'overlap'; rather, the actual distance is 2.9 m as illustrated for clarity in Figure 10.8.

For each 200-second simulation with a given stiffness, the maximum values of $F_{res,y}(t)$ are identified and plotted as the resultant force in Figure 10.9. Note that these maximum values do not correspond

to $k\sqrt{\max|y_{rel}^2(t)| + \max|z_{rel}^2(t)|}$ as the time at which the maximum horizontal and vertical relative displacement occurs do not necessarily coincide.

The vertical force component is obtained by multiplying the stiffness with the relative vertical distance z_{rel} . On a log-log scale, the curve appears as a linear line since $\max(z_{rel}(t))$ is a constant value due to the application of only a horizontal spring. This curve is described mathematically as follows:

$$F_{max,z} = z_{rel} \cdot k$$

$$\log(F_{max,z}) = \log(z_{rel}) + \log(k) \quad (10.18)$$

When comparing the contributions of the horizontal and vertical components to the resultant force in the spring, it is evident that the primary contribution originates from the horizontal component for stiffness values below 464 kN/m in sway. Conversely, for higher stiffness values, the relative heave becomes the dominant contributor, as it remains constant while the horizontal misalignment decreases. The location at which this transition occurs is not arbitrary. The relative heave for all stiffness values, excluding those near the resonance peak, is 0.6 m and the horizontal misalignment at this stiffness of 464 kN/m is also 0.6 m. Considering Equation 10.17, the contributions of both components are expected to be comparable when the horizontal and vertical displacements are nearly equivalent.

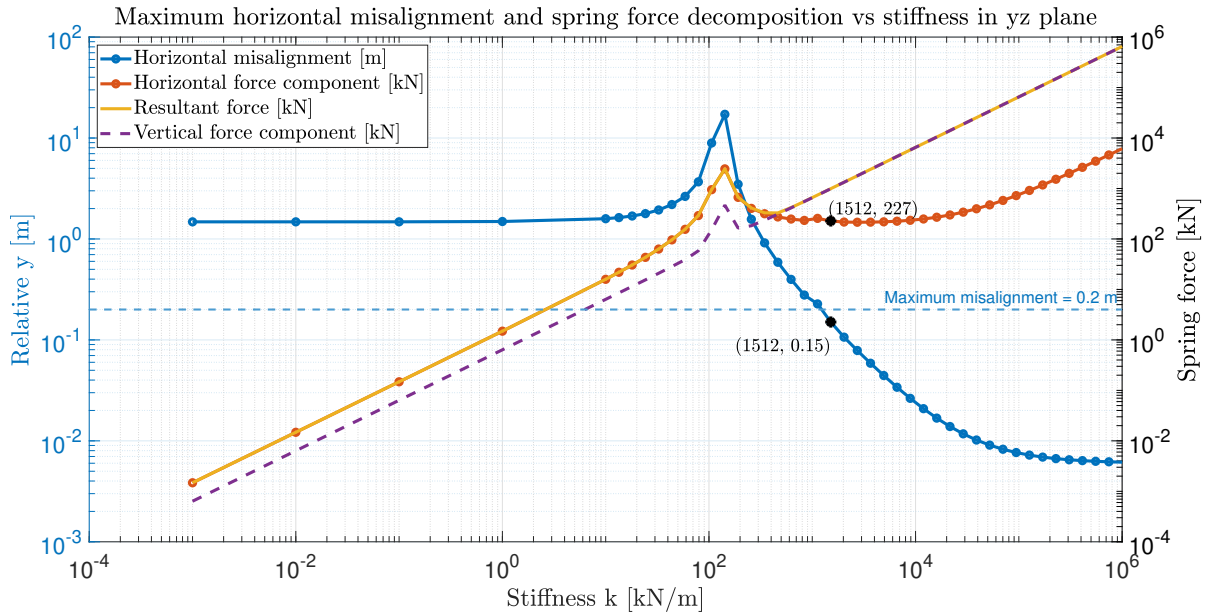


Figure 10.9: Maximum y (sway) misalignment and spring force components using different stiffnesses for regular waves of 1 m approaching from 270 deg with a wave period of 10 s

10.4.1. Influence of stiffness on the natural period

For increasing spring stiffness, the natural period decreases when solving Equation 10.15. This change in the natural period for both the first and second mode is illustrated in Figure 10.10. Focusing on mode 1, it can be observed that, for low stiffness values, the period is 20.9 s, which matches the result in Table 10.1. A sharp transition occurs between 10 kN/m and 1000 kN/m, eventually reaching a plateau at 4.3 s for very high stiffness. The natural period is quite sensitive to the selected stiffness in the transition region. Moreover, the natural period in this region aligns directly with the wave period range, which is undesirable for the system, making the application of damping necessary. A stiffness below 1000 kN/m would resonate with the waves, while higher stiffnesses are harder to achieve in design.

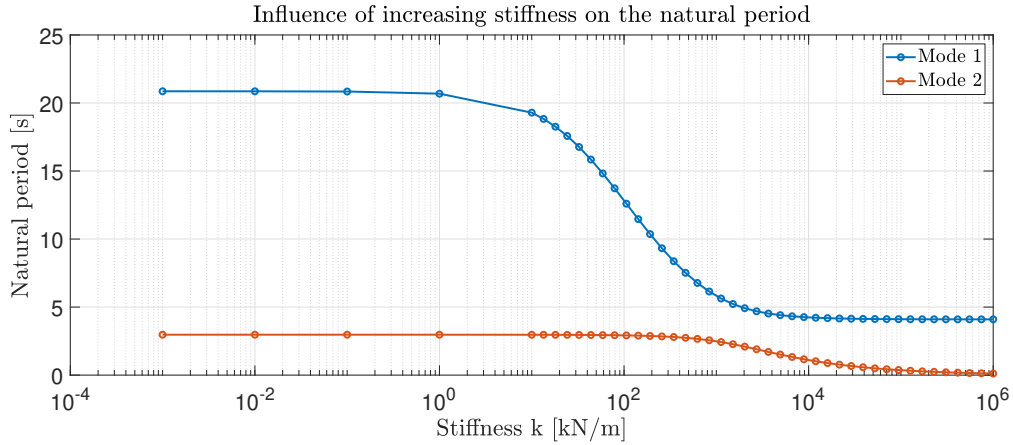


Figure 10.10: Natural period of the model described in subsection 10.1.2 for various stiffness values

10.5. Irregular waves results

Up to this point, only regular waves have been used to analyze the system's behavior. However, the next step towards assessing workability involves utilizing irregular waves to represent real wave conditions better. For this purpose, a JONSWAP spectrum as given in Equation 4.3 is assumed for the specific location, with a peak enhancement factor γ of 3.3. The input peak period and significant wave height are determined from the scatter diagram in section 3.2. While JONSWAP spectra are not tailored specifically to conditions in the Atlantic Ocean, this choice is made because it produces sufficiently acceptable waves for the purpose of the thesis.

Similar to the regular wave analysis, simulations with increasing stiffness are conducted to estimate the required stiffness and the corresponding force. The resulting plot for $H_s = 2.5$ m, $T_p = 10$ s and a heading of 270 deg is visible in Figure 10.11. These parameters are chosen to represent a severe circumstance. According to Figure 3.1, 89.6% of the recorded significant wave heights are below 2.5 m. Additionally, as shown in the figures in subsection 7.5.2, longer wave periods tend to induce larger relative displacements. The 270-degree wave heading is again selected because it results in the greatest vessel roll, thereby causing significant displacement in sway at the crane tip. Consequently, only the results in the sway direction are presented.

In contrast to the regular wave analysis, Figure 10.11 presents the MPM values of the relative displacement and spring force rather than the absolute maximum value. It is calculated for a duration T , 3 h in this study, using Equation 10.19. where $n = T/T_z$ is the number of peaks, μ is the mean which is close to zero for the outputs and σ and T_z are the standard deviation and mean up-crossing period respectively. Using the MPM value considers the likelihood of occurrence within a distribution, providing a more realistic estimate of the peak force that the irregular waves could induce on the spring.

$$MPM = \mu + \sigma \sqrt{2 \cdot \ln n} \quad (10.19)$$

10.5.1. Required stiffness

According to Figure 10.11, the minimum stiffness required is 4924 kN/m to keep the relative MPM sway displacement within 0.2 m. with the same resonance peak occurring around 150 kN/m.

To get an estimate of the required wire diameter and if it would be realistic, the following formula can be used to calculate the stiffness of a uniform wire:

$$k_{wire} = \frac{E \cdot A_{wire}}{l} = \frac{E \cdot 0.25 \cdot \pi \cdot D_{wire}^2}{l} \quad (10.20)$$

Given a modulus of elasticity E of 132 GPa (Arcus Wire Group, 2023) and a length l of 3 m, a wire diameter D_{wire} of 12 mm is required to obtain a stiffness of 4924 kN/m. However, this formula assumes

linear elastic behavior and one wire with a uniform cross-sectional area and tends to underestimate the required diameter. Typically, winch wires are composed of multiple strands, but this calculation provides a realistic order of magnitude for initial design considerations.

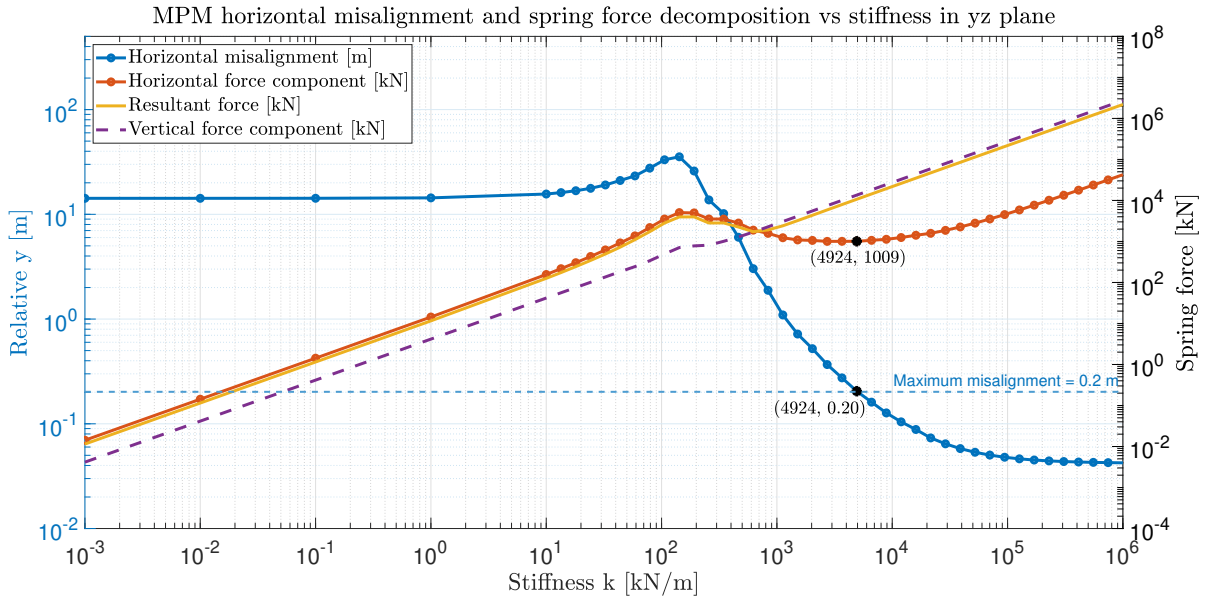


Figure 10.11: MPM of y (sway) misalignment and spring force components using different stiffnesses for irregular waves of $H_s = 2.5$ approaching from 270 deg with a wave period of 10 s

According to the figure above, the relative sway between the tower bottom and floater top reaches 18 m when no spring is present. This displacement is caused primarily by the crane tip and pendulum motions rather than by the floater, which is also shielded in this wave heading. This significant displacement of the tower bottom underscores the necessity of a gripper (or an alternative mechanism) to stabilize the tower's swinging motion before attempting to position it close to the floater column.

10.5.2. Influence of the AHC system

The relative heave contributes significantly to the resultant force for large stiffnesses, as seen in the stiffness versus spring force plots above and in section 10.4. Since the focus of this study is to analyze the horizontal force that the winch cables must withstand, the horizontal force component is the primary curve of interest. However, it is insufficient to assume that the required force is solely the horizontal component because the relative heave contribution will never be zero. As mentioned in section 9.4, an active heave compensation system ensures the desired distance between the two bodies by synchronizing the heave motion of the tower with the floater. This system, exemplified by Seaqualize's HeaveChief, can reduce the relative heave motion by up to 95% (Seaqualize, 2024). Therefore, for further analysis, the forces considered are based on the horizontal spring length and 15% of the vertical component, assuming it compensates for 85% rather than the full 95% to provide a safety margin.

The effectiveness of the AHC system is displayed in Table 10.2, where including the AHC system, the spring force reduces from 10677 kN to 1617 kN for the stiffness of 4924 kN/m. The MPM spring force including the AHC system is obtained by taking the standard deviation in Equation 10.19 from the time series of the resultant force according to Equation 10.17, but replacing $z_{rel}(t)^2$ by $(0.15 \cdot z_{rel}(t))^2$.

Table 10.2: MPM resultant force based on different contributions of z_{rel} for $k = 4924$ kN/m

	$z_{rel} = 0\%$ (Only horizontal component)	$z_{rel} = 15\%$ (AHC system)	$z_{rel} = 100\%$ (no AHC system)
$F_{res,y,mpm}$ [kN]	1009	1617	10677

10.5.3. Wave headings and peak periods

The polar plots presented in this section display the MPM values from the 3-hour simulations for various wave headings and peak periods. The wave headings indicate the direction from which the waves are coming, using the same headings as the relative motions plots in section 7.5.

Zero stiffness

First, the case where the spring has zero stiffness in surge and sway is shown in Figure 10.12 for $H_s = 2.5$ m. This figure demonstrates that, in the worst cases of relative surge, the responses are less severe than in the previously analyzed 270 deg, 10-second wave for sway. Although it was assumed that the stiffness required to restrict sway motion within 0.2 m for the 270 deg, 10-second wave represented the severe scenario, this stiffness is insufficient to keep the relative surge close to the 0.2-m limit for 135 deg waves which will be shown next.

Non-zero stiffness

Figure 10.13 presents the relative displacements for a stiffness of 4924 kN/m. It is evident that the displacements at 135 deg and 0 deg significantly exceed the 0.2-m limit for various wave periods, while in the sway direction, only the 270 deg, 11-second wave significantly exceeds the limit. This indicates that a stiffness of 4924 kN/m is inadequate, leading to the decision to use a higher stiffness of 8887 kN/m in subsequent analysis, which corresponds to the next available stiffness data point.

The results obtained with $k = 8887$ kN/m are presented in Figure 10.14. Unlike the case with $k = 4924$ kN/m, this stiffness is more effective in maintaining the maximum relative motions close to the limit. To evaluate the performance of this model, a workability study will be conducted, focusing on the design decision to utilize a stiffness of 8887 kN/m.

It is important to recognize that the primary goal of this analysis was not to determine the optimal stiffness of the springs, it was intended to provide an estimation of the necessary magnitude of stiffness required. Therefore, the specific stiffness value of 8887 kN/m represents a flexible range and may be rounded up for practical purposes. The analysis indicates that the stiffness should exceed 4924 kN/m to maintain acceptable maximum relative motions. However, a slightly lower stiffness than 8887 kN/m could be advantageous, as it would result in reduced resultant forces. Keep in mind that this high stiffness is required to effectively restrict motions up to an H_s of 2.5 m. However, this level of stiffness might not be necessary in other areas or if the operation is limited to periods with lower H_s values.

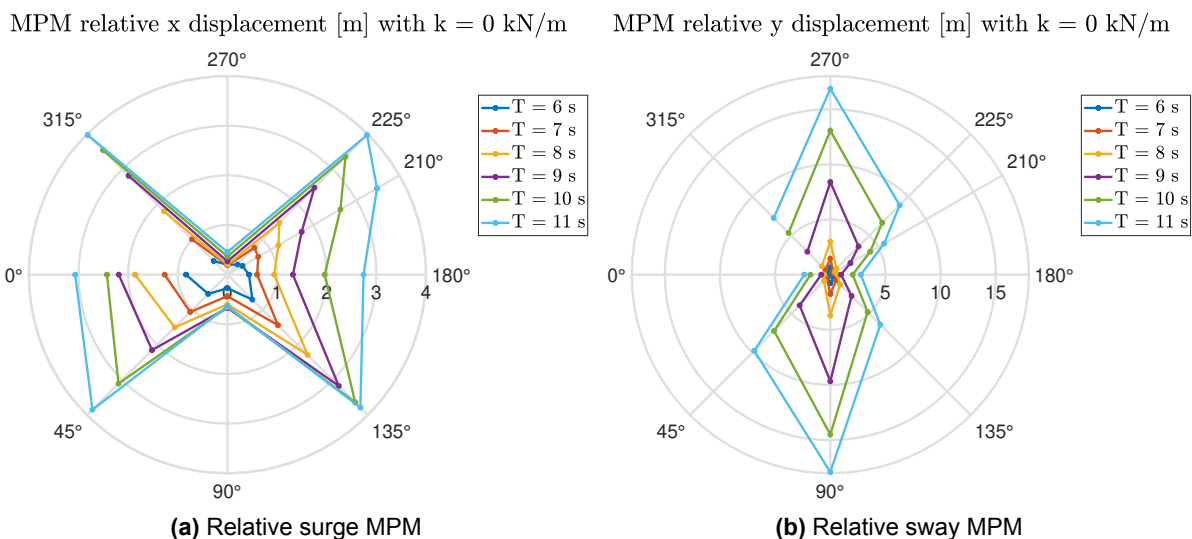


Figure 10.12: Relative displacement for $k = 0$ kN/m and different wave headings and peak periods

MPM relative x displacement [m] with $k = 4924 \text{ kN/m}$ MPM relative y displacement [m] with $k = 4924 \text{ kN/m}$

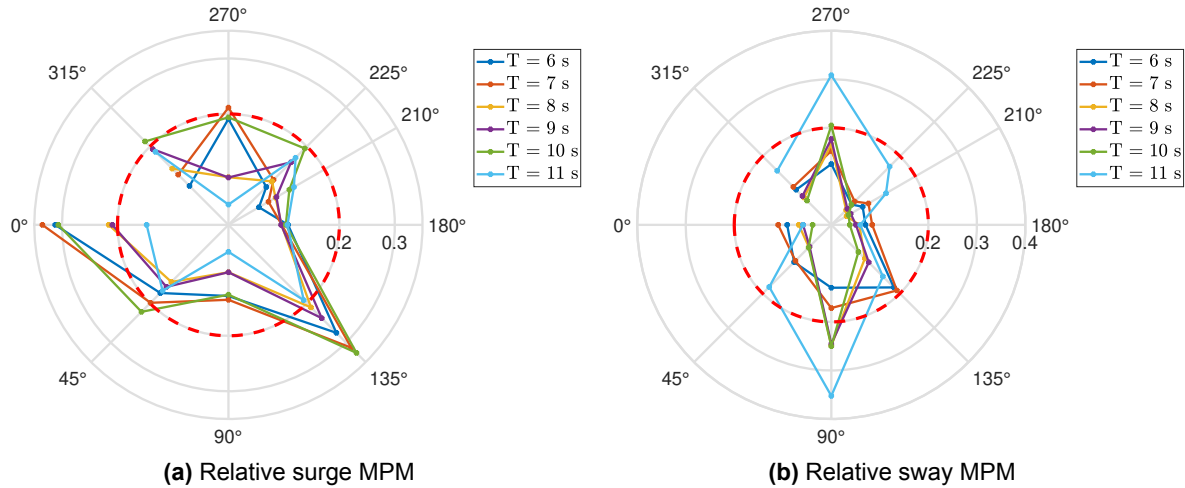


Figure 10.13: Relative displacement for $k = 4924 \text{ kN/m}$ and different wave headings and peak periods

MPM relative x displacement [m] with $k = 8887 \text{ kN/m}$ MPM relative y displacement [m] with $k = 8887 \text{ kN/m}$

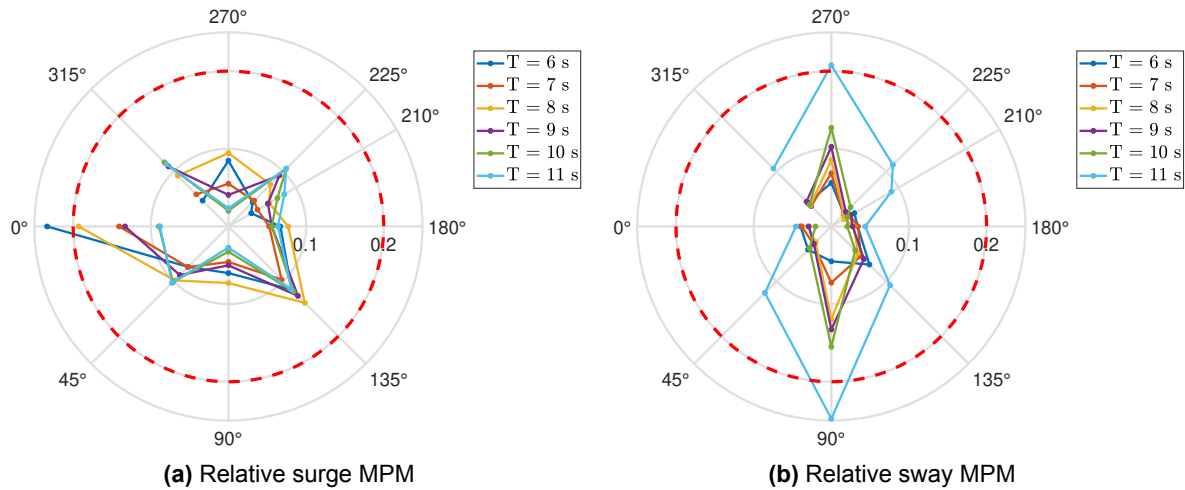


Figure 10.14: Relative displacement for $k = 8887 \text{ kN/m}$ and different wave headings and peak periods

Wave seed influence

The phases associated with each wave component (the ϵ_n component in Equation 4.9) are pseudo-random and OrcaFlex uses a random number generator and the user-defined seed to assign phases (Orcina, 2024). A sensitivity study is performed on the influence of different seed numbers and shown in Figure 10.15. This graph presents the MPM spring force data derived from simulations with varying wave seeds over a 3-hour period. The resulting MPM spring force values show small variations across these nine seed numbers. All time-domain simulations using irregular waves use OrcaFlex's default seed number 12345.

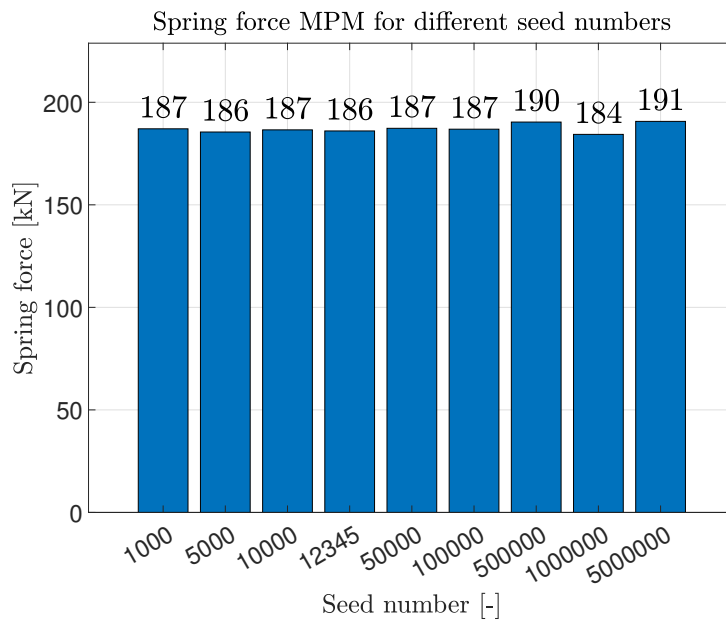


Figure 10.15: Variations in the spring force based on a 3h simulation using eight arbitrarily chosen different seed numbers and OrcaFlex's default 12345 seed number

11

Workability study

The workability of the tensioning step of the concept will be determined using two criteria, namely the relative horizontal displacement and the wire angle. These criteria will be explained first, after which the results of the workability study of this step will be shown.

11.1. Limiting criteria

1. Horizontal relative displacement

This criterion requires that the MPM values from 3-hour simulation data, as plotted in the following polar plots, remain below the 0.2-meter limit for all relevant wave headings. If either the surge or sway direction exceeds this limit, the corresponding Hs-Tp combination in the scatter diagram is marked as unfeasible. This analysis evaluates the x- and y-directions separately. However, the combined 2D distance could exceed the specified limit, but this Euclidean distance is not investigated here.

2. Crane wire angle

When suspending a tower from a crane, the angle of the crane wire must be limited, as cranes are designed to carry loads in a vertical orientation. Based on industry practices, the maximum permissible angle of the crane wire is taken as 2 deg.

3. (Relative angle)

This criterion becomes relevant during the lowering process where the relative distance between the tower bottom and floater is decreasing. Although it is mentioned here, it is not a determining criterion at this stage of the installation process. It relates to the imposed heave due to the angle of the tower and floater according to Equation 11.1 and displayed in Figure 11.1. The relative heave should be larger than this minimum value $h_{rel,min}$ to avoid collision. Nevertheless, protective measures must be in place to ensure the structural integrity of both the tower and the floater.

$$h_{rel,min} = |r_t \cdot \sin(\theta_t) - r_{fl} \cdot \sin(\theta_{fl})| \quad (11.1)$$

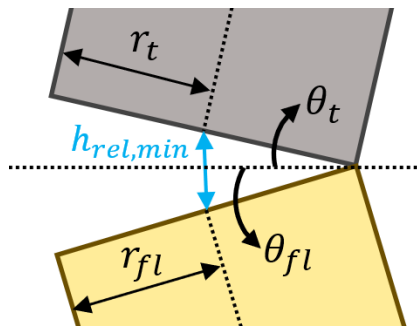


Figure 11.1: Clarification of the minimum relative heave

11.2. Wave headings

The workability study is conducted based on the wave rose data provided for the specified area, defined in section 3.2. The orientation of the multibody system relative to the main wave direction is depicted in Figure 11.2. This configuration results in the primary waves originating from the north, corresponding to the 210-degree wave direction in the OrcaFlex model. The wave range of interest is defined from $210 - 22.5 = 187.5$ deg to $210 + 45 = 255$ deg. The workability study will be performed for wave headings increasing from 180 deg to 260 deg, covering all the possible wave directions for this site. If the wave direction of a specific peak period exceeds the defined limits, the workability is marked as unfeasible in the Tp-Hs scatter diagram. This method of handling the wave headings is rather conservative, as it may rule out workability even if only one wave direction, with a very low probability of occurrence, exceeds the limit.

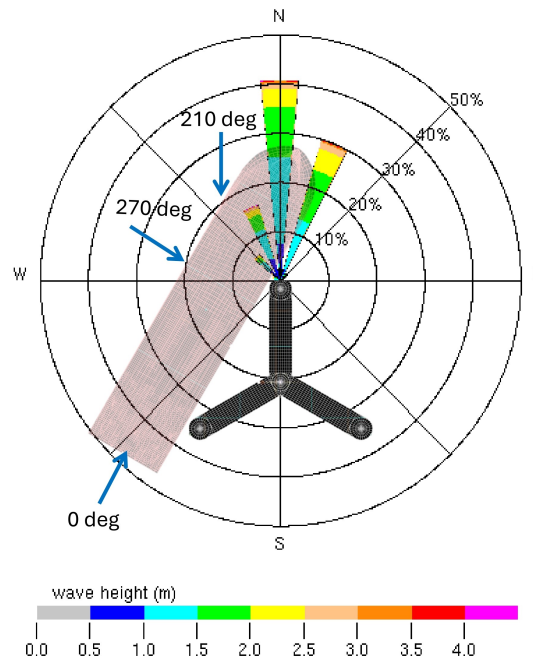


Figure 11.2: Wave rose of the area defined in section 3.2 with the directions indicate where the waves are 'coming from'. It shows the waves relative to the OrcaFlex headings. The waves originate mainly from the north due to the influence of the north-northeast trade winds, which generate wind waves in that direction.

11.3. Workability

Based on the scatter diagram provided in section 3.2, the wave rose, and the defined limits, the workability can be determined using the polar plots. For $H_s = 2.5$ m, the results are plotted in Figure 11.3 and Figure 11.4 for the horizontal alignment in surge and sway respectively. The results of other wave heights can be found in Appendix A.

11.3.1. Relative displacement and resultant forces

In those figures, the right polar plot indicates the relative displacement with a red circle highlighting the 0.2-m limit. The red circle on the left polar plot corresponds to the force when the elongation reaches the 0.2-m limit. Figure 11.3 shows refined wave headings which causes the surge peak at 240 deg to emerge. For this heading, it is evident that shorter periods result in larger responses compared to longer periods. This is related to the first natural period of the double pendulum, which is 4.3 s, as determined by Equation 10.15, with $k = 8887$ kN/m in Equation 10.10. Consequently, within the wave period range from 6 to 11 s, the shorter periods are closer to the natural period, leading to greater displacements.

It can be concluded that the chosen stiffness of 8887 kN/m performs adequately in restricting the relative motions. However, due to its relatively high stiffness, the resultant spring force is quite substantial. This is primarily due to the relative heave, even with 85% compensation. The force plot for surge and sway reveals a similar pattern, with the maximum forces occurring during long waves and waves impacting the vessel nearly perpendicularly, particularly in the 260 deg case. This alignment causes significant roll, leading to roll-induced heave at the crane tip, pendulum-induced heave, and a contribution from the out-of-phase heave of the floater, all of which add to the total heave and are therefore dominating the resultant spring force. Incidentally, if the heave contribution were negligible and the springs were primarily stretched in the horizontal direction, the resultant force plot would exhibit a shape identical to that of the relative motions plot, scaled by a factor of 8887, consistent with the relationship $F = k \cdot x_{rel}$. Under these conditions, the force data points would be expected to cluster within the left red circle, analogous to their near containment within the right red circle.

When quantitatively assessing the forces, the design criteria for the required forces to ensure full workability of this system across the simulated wave periods of 6 to 11 s and wave headings for 180 to 260 deg are outlined in Table 11.1 below and these values are calculated without the inclusion of any safety factors. A more elaborate overview including the corresponding T_p and headings is given in Table A.1. No linear relationship is evident for the horizontal forces in Table 11.1 as the maxima occur at different sea states and are further complicated by nonlinearities within the system.

Table 11.1: Maximum horizontal and resultant spring fore for different significant wave heights for wave periods from 6 to 11 s and a heading from 180 to 260 deg

	Hs = 1 m	Hs = 1.5 m	Hs = 2 m	Hs = 2.5 m
Horizontal x force [kN]	797	925	1477	1823
Horizontal y force [kN]	789	1078	1363	1655
Resultant force [kN]	1961	2638	3267	3877

Polar plots for Hs = 2.5 m and different peak periods and $k = 8887$ kN/m

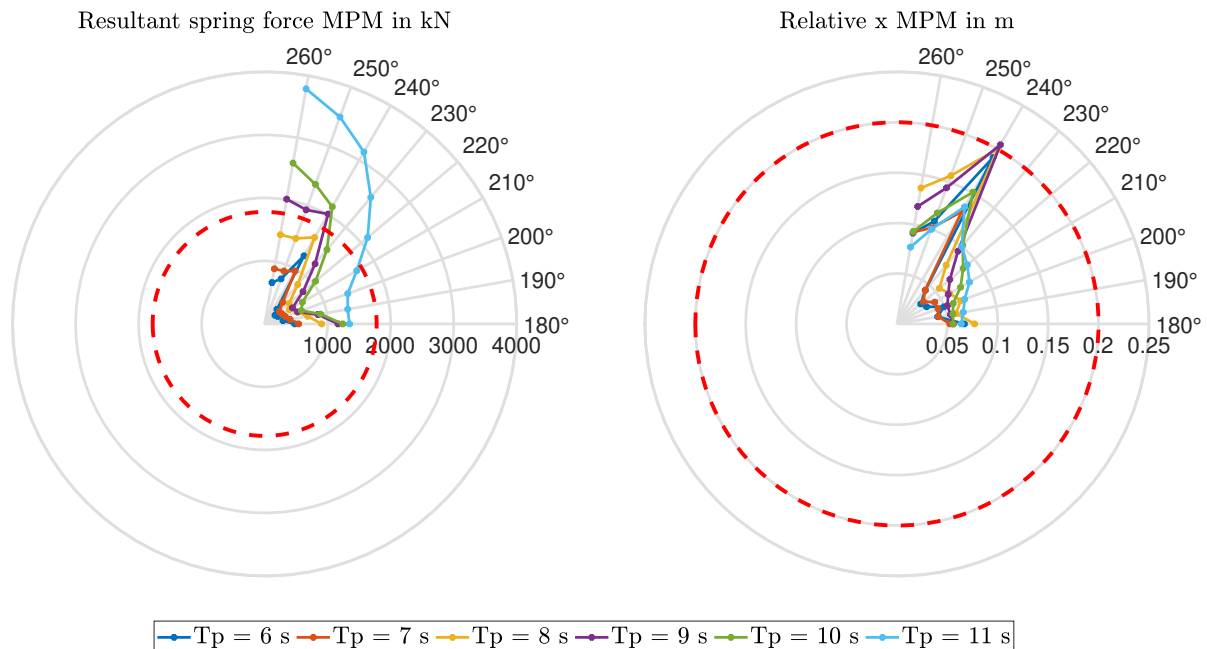


Figure 11.3: Polar plot displaying the relative surge and the resultant force using a stiffness of 8887 kN/m and 85% heave compensation. The red circle on the left indicates the magnitude of the force with an elongation of the 0.2-m limit.

Polar plots for $H_s = 2.5$ m and different peak periods and $k = 8887$ kN/m

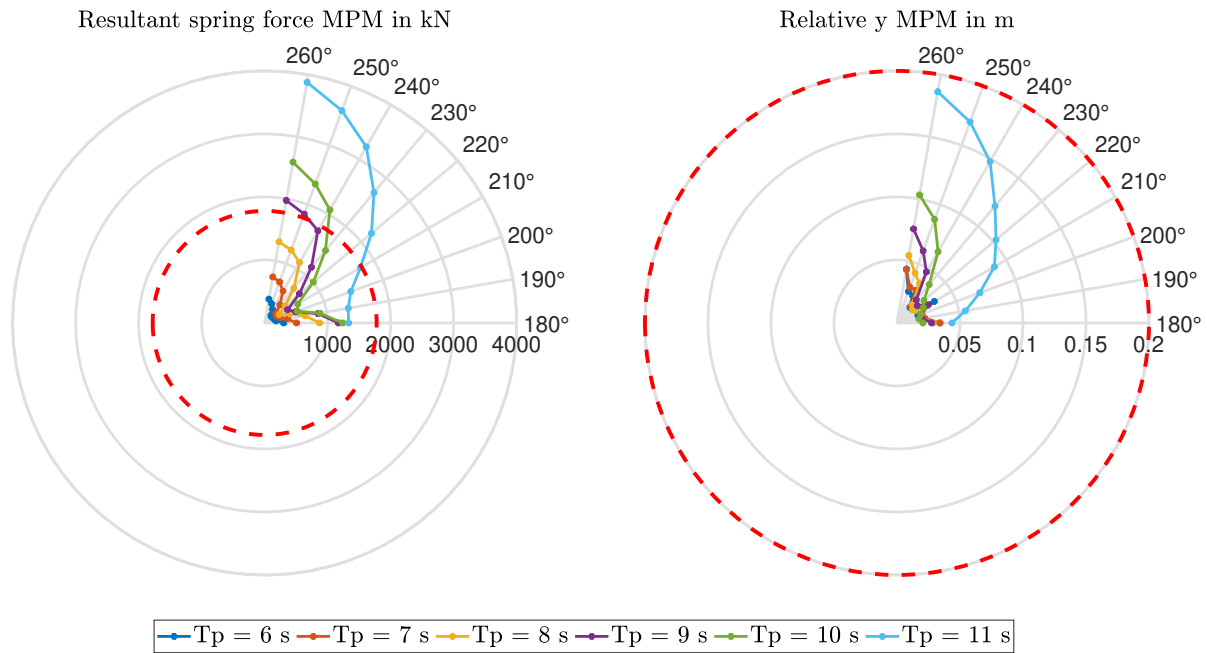


Figure 11.4: Polar plot displaying the relative sway and the resultant force using a stiffness of 8887 kN/m and 85% heave compensation. The red circle on the left indicates the magnitude of the force with an elongation of the 0.2-m limit.

11.3.2. Crane angle

The second criterion focuses on the crane wire angle and is investigated next. For the highest significant wave height of 2.5 m, this limit is exceeded in the x-direction for short waves originating from 240 deg. This corresponds to conditions where the largest surge relative displacements are observed, as shown in Figure 11.5a. While the x-direction dictates this criterion, the values in the y-direction remain within acceptable limits and are not the cause for concern. For lower significant wave heights, the crane wire angle does not exceed the 2-degree limit; those polar plots are also provided in Appendix A.

The figures in this section can now address the third sub-question:

3. *How do environmental conditions impact the chosen concept with its associated design choices?*

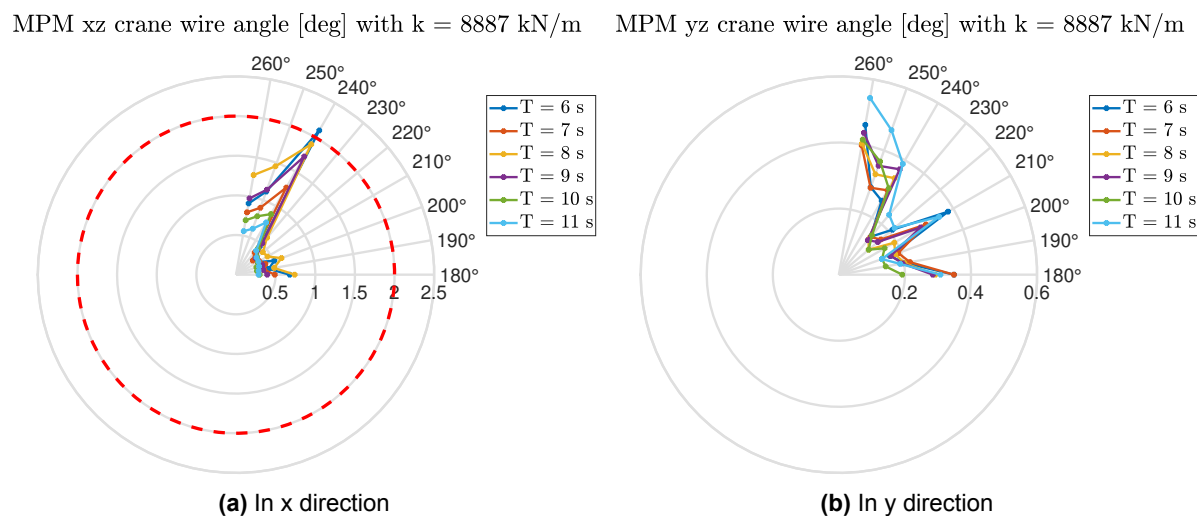


Figure 11.5: MPM crane wire angle for $H_s = 2.5$ with the indicated limit of 2 deg

The two limits under consideration, the crane angle limit and the horizontal relative displacement limit, illustrate how different environmental conditions can cause these thresholds to be exceeded. Longer wave periods result in larger sway displacement due to increased roll-induced sway motion, up to a period of 14 s, as indicated by the vessel's roll RAO. In contrast, intermediate wave periods (8 and 9 s) generate the largest relative surge motion. This is due to a combination of the wave period being relatively close to the natural period of 4.3 s of the pendulum system and the significant pitch of the floater during these wave periods, as shown in Figure 7.2. Conversely, shorter wave periods cause the crane wire angle to exceed the acceptable limit, as these periods closely align with the double pendulum system's natural period of 4.3 s. These observations are supported by the spectral density plots of the tower bottom response in surge for peak periods of 6, 8, and 11 s, as shown in Figure 11.6. The peak at $T_p = 6$ s corresponds to the natural period of the pendulum system of 4.3 s, while the 8-second period also shows responses within the wave energy range. This is linked to a local peak in the pitch RAO of the floater, as shown in Figure 7.2. Additionally, the main peak at a peak period of 11 s aligns with the floater's natural period in pitch, which is 14.3 s (0.07 Hz), as indicated in Table 6.2.

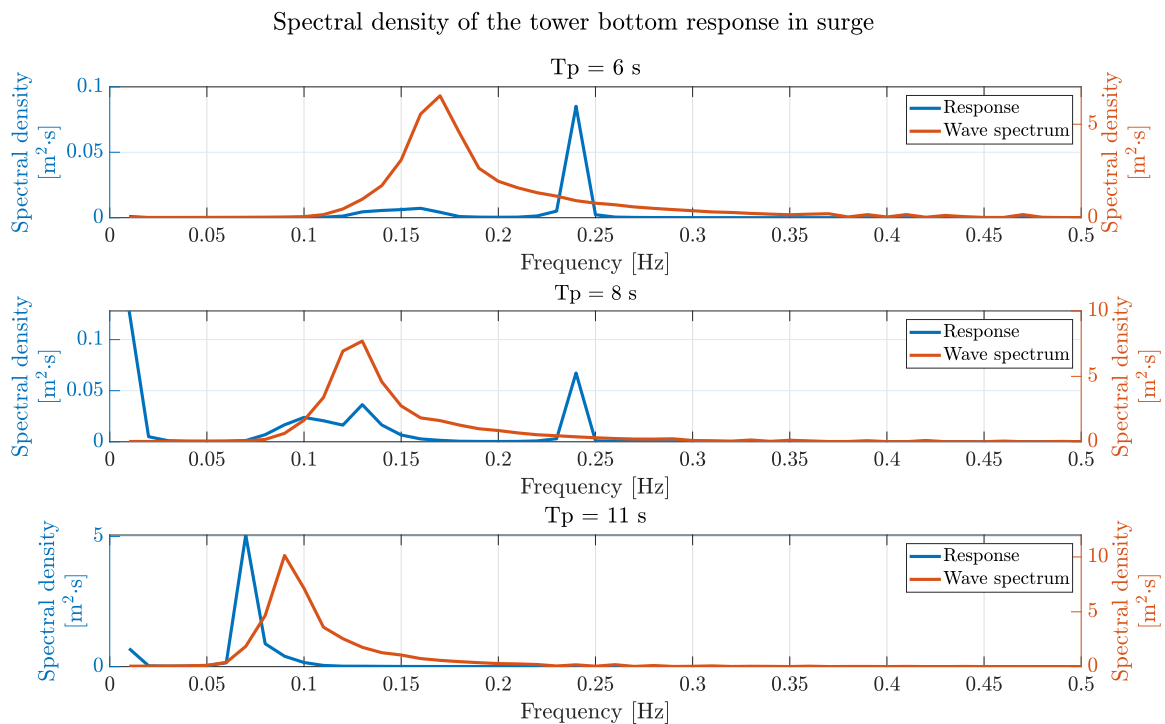


Figure 11.6: Spectral density for three different wave peak periods with a wave heading of 240 deg and $H_s = 2.5$ m and the input wave spectrum

11.3.3. Results

The last two sub-questions can now be addressed:

4. *What is the workability of this concept in the proposed area based on defined limits?*
5. *Based on the design choices, what are the specifications for the required equipment?*

The scatter diagram in Figure 11.7 displays blue crosses, which mark the T_p - H_s combinations that exceed the crane angle limit. The black crosses denote the T_p - H_s combinations that exceed the horizontal relative displacement limit, even if this limit is exceeded for only one of the wave headings. The workability for this step in the installation process is 92% based on these two limits, with a design criterion for the resultant force of 3877 kN, dictated by $H_s = 2.5$ m, $T_p = 11$ s and a wave heading of 260 deg. In the x-direction, the largest MPM force observed is 1823 kN, while in the y-direction, it is 1655 kN. When focusing solely on the horizontal contribution, the surge direction governs the design for ≥ 2 m, whereas for lower H_s , their difference in magnitudes decreases.

Percentage of occurrence of wave height (m) in rows versus peak wave period (s) in columns

	lower	03	04	05	06	07	08	09	10	11	12	13	14	15	16	17	18	19	20	
lower	upper	04	05	06	07	08	09	10	11	12	13	14	15	16	17	18	19	20	21	total
0.0	0.5	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0.0
0.5	1.0	0	0.5	0	1.8	0.9	3.2	2.3	0.5	0	0.9	0	0.5	0	0	0	0	0	0	10.4
1.0	1.5	0	0.9	1.8	5.9	4.1	6.3	12.7	2.3	0	1.8	0.5	0.5	0	0	0	0	0	0	36.7
1.5	2.0	0	×	2.3	5.9	2.7	2.3	5.0	5.0	0.5	4.1	2.7	×	0.5	0	0	0	0.5	0	31.2
2.0	2.5	0	0	×	0.9	2.7	1.4	0.9	1.4	1.4	×	1.4	0.9	0	0	0	0	0.5	0	11.3
2.5	3.0	0	0	0	×	1.4	×	×	1.4	1.8	×	0.9	0.5	0	0	0	0	0	0	6.8
3.0	3.5	0	0	0	0	0.5	0	0	0	0	0	1.4	0	0	0	0	0	0	0	1.8
3.5	4.0	0	0	0	0	0	0	0.5	0	0.5	0	0.5	0.5	0	0	0	0	0	0	1.8
4.0	4.5	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0.0
total		0.0	1.4	4.1	14.5	12.2	13.6	21.7	10.4	4.1	6.8	7.2	2.7	0.5	0.0	0.0	0.0	0.9	0.0	100.0

Figure 11.7: The scatter diagram displays blue crosses, which mark the Tp-Hs combinations that exceed the crane angle limit. Black crosses indicate the Tp-Hs combinations that exceed the relative displacement limit, even if the limit is surpassed by just one wave heading. The thick black line marks the boundary where Tp-Hs combinations are acceptable.

11.3.4. Limitations to workability study

This workability study focuses solely on the tensioning step of the entire installation concept. However, the actual workability of the full installation process is expected to be lower due to several additional factors. The lowering of the EP will also face limitations based on restricted sea states, and long swell waves were not accounted for in this analysis. For this specific location, swell waves are limited because they originate from the west and the island, situated to the west of the wind farm, helps reduce their impact. However, in other areas, long swell waves could exacerbate the conditions.

Additionally, the performance of the AHC is limited by its maximum stroke. Other factors that can exacerbate the situation, such as wind forces on the vessel and tower, as well as the flexibility of the crane, were not considered in this model. Furthermore, several papers in section 2.4 emphasize that the tension in the crane wire is a critical response, yet this aspect is not investigated in this study.

11.4. OrcaFlex findings to practice

Since the OrcaFlex model approximates the practical concept, the interpretation of the results needs to be translated into their practical implications and appearances.

Notably, as depicted in section 9.4, the concept uses two wires in each of the horizontal directions to compensate for the relative motions. In the OrcaFlex analysis, this is modeled by a single spring, implying that the required stiffness can be halved since the springs are in series. This assumption holds only if the wires are pretensioned, ensuring they are never slack and both wires contribute to the stiffness. However, the force calculated in the OrcaFlex spring should be handled by a single wire in practice.

Further examination of offshore winches suggests that the required force exceeds the capacity of an average offshore winch. This implies that to manage these forces effectively, the use of multiple winches may be necessary. Alternatively, other methods such as a hydraulic system or pulleys could be employed to handle these forces successfully, while considering the limited working area on the EP. Moreover, the analysis demonstrated that the relative heave significantly contributes to the resultant force. Therefore, it would be more beneficial to design the system such that elongation occurs primarily in the horizontal direction. A potential solution could involve fully decoupling the horizontal and vertical stretching of the spring. However, addressing these challenges falls outside the scope of this research and may be considered in future work.

12

Conclusion, reflection and recommendations

12.1. Conclusion

The installation of floating wind turbines presents a range of significant challenges, including the extensive area required for turbine integration and the substantial investments necessary to modify ports for these operations. The assembly of all components at a single site demands vast quay space and precise coordination, with the process further complicated by weather sensitivity, which can lead to delays, not only during assembly but also in the towing of semi-submersibles. To mitigate these challenges, an alternative approach has been proposed: shifting turbine integration offshore by utilizing floating-to-floating installation methods, where the semi-submersible is moored at the wind farm and the turbine is subsequently positioned on top.

This offshore installation method is still in its early stages of exploration within both the industry and academia. However, the specific challenge of floating-to-floating installation for semi-submersibles has not been thoroughly investigated, highlighting the knowledge gap that this research aims to address. First, the relative displacements between the floating bodies are identified by implementing a multibody model in OrcaFlex, incorporating the VolturnUS-S floater and the installation vessel. The results from this model, using a regular wave height of 2 m and wave headings ranging from 0 to 315 deg in 45-degree increments, along with an additional heading of 210 deg, indicate maximum relative horizontal motions of 2.2 m in surge and 4 m in sway between the floater top and the crane tip. The larger sway motion is driven by the vessel's roll due to transverse waves. This analysis demonstrated that the vessel's orientation during installation is crucial, with a proposed alignment corresponding to a main wave direction of 210 deg, which partially shields the floater and significantly reduces the vessel's roll motion, resulting in a maximum relative displacement of 1.88 m for an 11-second wave in surge and 0.82 m in sway for a 10-second wave.

Among the four concepts evaluated through a Multi-Criteria Analysis, the Gripper Wire Control concept emerged as the most promising. Its strengths include applicability to various floater geometries, compatibility with multiple existing vessels, and the avoidance of a rigid connection between the vessel and floater. Furthermore, this concept has the potential to operate without personnel on the floater, enhancing safety through remote monitoring and measurement systems. The installation process begins with the tower and the donut-shaped External Platform (EP) on the vessel. The EP holds the necessary equipment, such as winches, to control horizontal motions. The tower is then lifted with the EP suspended from the gripper, and the assembly, along with the gripper, is moved above the floater's center column. An Active Heave Compensation (AHC) system manages the relative heave during this process. The EP is gradually lowered and secured onto the floater, with the gripper restricting pendulum motions during this phase. Once the EP is in place, the tower can be lowered onto the floater. In this step, the gripper disengages, ceasing to restrain any motions, while the winches take over, controlling the horizontal displacement within 0.2 m by tensioning the wires. After the tower is secured on the floater, the EP is released and pulled up to the gripper, they then both open up and return to the ves-

sel. The EP is subsequently placed back on the vessel, ready to be used for the next batch of turbine towers.

The implementation of the tensioning of the winch wires in OrcaFlex involves modeling the tower with a rigid crane wire and a spring connected to the floater. Validation is performed using an analytical model derived from Lagrangian mechanics and solved in MATLAB. Initial time-domain simulations with regular waves and varying stiffness reveal a resonance peak, after which horizontal relative displacement decreases until it is within the target of 0.2 m. The relative heave, however, remains constant, as no stiffness is applied in the heave direction. To address this, an Active Heave Compensation system is assumed (not modeled), significantly reducing the resultant force in the spring by reducing the relative heave by 85%.

Further simulations with irregular waves confirm a stiffness of 8887 kN/m performs effectively in restraining relative horizontal motions up to $H_s = 2.5$ m. The 0.2-m horizontal displacement limit and the crane angle limit are employed as criteria for the workability study. This study, based on a scatter diagram for the selected area off the east coast of Gran Canaria, suggests a workability of 92% for this tensioning step using this stiffness and considering the region's wave directions. To ensure functionality under all sea states that meet the two criteria, the compensation system must be capable of handling a resultant force of 3877 kN for $H_s = 2.5$ m. When focusing solely on horizontal motions, this force requirement is reduced to 1823 kN. While the force in the surge direction is influenced by the floater's pitch and resonance with the pendulum's natural period, the force in the sway direction is dominated by the vessel's roll. The forces identified exceed the capacity of a single winch wire, but they remain within a realistic range for a compensation system to manage.

This research provides an initial foundation for developing a floating-to-floating installation method for offshore wind turbines, presenting an alternative to traditional onshore integration. While it addresses the critical issue of relative horizontal motions caused by the offshore environment, there remain many aspects that require further exploration. However, before recommending future work, a reflection on two decisions made during this research that in hindsight could have been improved is discussed, as well as some more general considerations.

12.2. Reflection

The choice to use Orcina's floater model at the start may not have been the most suitable considering the use of a gripper in the concept. The centrally located turbine results in a much larger distance this gripper has to reach. A platform with a corner-mounted turbine would have been the preferred geometry. However, when the floater choice was made, the installation process was still unknown. Furthermore, with a corner-mounted turbine, it becomes more feasible for the EP to be suspended from the gripper without inducing a significant moment.

Furthermore, one of the key decisions made in the modeling process was to represent the winch wires as constraints with a specific stiffness in OrcaFlex. This approach required precise ballasting of the vessel, as even a small deviation of the center of gravity from the center of buoyancy could introduce a slight initial angle to the vessel. Given the 60-meter distance from the centerline to the floater's center, this small angle led to an initial relative displacement between the tower's bottom center and the floater center. Due to the way constraints function in OrcaFlex, this initial relative displacement created an initial force in the spring, which became increasingly dominant at higher stiffness levels. This initial horizontal displacement was significantly larger than the maximum relative displacement expected during the dynamic simulations, potentially compromising the accuracy of the results if the ballasting was not sufficiently precise.

Instead, a more accurate approach might have been to model the winches using OrcaFlex's 'Winch' feature, which allows for specific payout rates and can be controlled by either length or tension. This would have enabled the investigation of the exact force the winch needs to exert and the necessary payout or haul-in velocities. This could better capture the real-world dynamics of this installation step, assessing whether the required haul-in or payout velocities are realistic while controlling the tension and length of the winch wires.

The primary aim of this study was to explore the feasibility of shifting the installation of semi-submersible wind turbines offshore, specifically to avoid the need for a large marshaling yard. Although the initial findings demonstrate the technical feasibility of this approach, the economic viability remains undressed. Given that financial considerations often drive project decisions, it is important to assess whether the costs associated with renting a large installation vessel to install numerous turbines and the additional tools required outweigh the investment needed for onshore facilities.

The proposed installation steps focus solely on the installation of the tower, leaving the challenge of installing the remainder of the turbine unresolved. Given the significant height of the tower, even minor pitch or roll movements of the floater can lead to considerable horizontal translations at the top of the tower. Given this consideration, it may be more advantageous to have a single transfer solution for the entire assembled turbine. Furthermore, while this study focused on compensating the vessel-induced motions on the tower, another approach could involve minimizing these imposed motions in the first place, rather than addressing the issues they create. Additionally, the stability of the floater could be improved, or the compensation systems could be placed on top of the other columns, eliminating the need for an EP; there are multiple approaches to addressing the relative motions.

12.3. Recommendations

This research has laid an initial foundation for the development of a new floating-to-floating installation method; however, much work remains to be done. The following recommendations are proposed to address the remaining challenges and further enhance the feasibility and efficiency of this installation approach.

Alternatives for the gripper: As discussed in the evaluation of the installation process, the gripper adds significant mass to the concept, reducing its economic attractiveness. A more elegant solution is needed to reduce the horizontal motions caused by the crane tip and pendulum effects, as well as to improve the method for retrieving the EP. The current gripper design, although functional, is complex and capable of moving in three translational directions, open and close and adjusting stiffness as required by different steps in the process. An alternative approach worth considering is moving the tower to the gripper, rather than having the gripper move to the tower on the vessel. Eliminating or simplifying the gripper would make the concept more economically viable.

Modeling of transient lowering processes: The current analysis focuses on Step 6: Tensioning, particularly the initial stage of this step. However, the transient process of lowering the tower onto the floater has not been modeled, which is critical to understanding the interplay with the Active Heave Compensation system. Furthermore, as the crane wire lengthens, the natural period of the pendulum increases, influencing the system's dynamics. Investigating this process in detail to assess the dynamic behavior during this critical phase of the installation is therefore recommended.

Workability and feasibility of other installation steps: While the current study has provided insights into the early stages of the installation process, the workability and feasibility of other steps, particularly Step 4: Lowering EP, remain uncertain. This step involves lowering the external platform onto the floater, which should be considerably easier than lowering the tower itself. If this step proves to be complex, the benefit of first placing the platform on the floater and then positioning the tower may not justify the effort.

Further design of installation components: A more detailed analysis of the various components required for the installation process is necessary to fully assess the feasibility of the method. This includes the development of a self-locking EP-floater mechanism and the strengthening of the tower to withstand the forces exerted by the winch wires. Additionally, the method should be designed to eliminate the need for personnel during the installation process until the tower is securely placed on the floater. Remote monitoring and measuring systems should be developed to ensure safety and precision throughout the process. When personnel are required to secure the tower, their safety must be guaranteed, and they should be able to effectively perform their tasks despite the floater's motion in six DOFs.

More accurate OrcaFlex model: To enhance the accuracy of predictions, future modeling should incorporate the effects of wind, current, and second-order wave loads. The spring model should also be refined to include damping effects, and the impact of adding pre-tension in the spring should be

evaluated. Developing an appropriate control mechanism for the winches is necessary, ensuring that the required velocities are realistic while also preventing high snapping loads.

Minimizing crane tip motions: The relative motions are significantly influenced by the imposed motion at the crane tip. Instead of compensating for the motion it induces, it may be worth investigating the possibility of eliminating or minimizing this imposed motion. This could for example be achieved by implementing a compensation system that allows the crane tip to follow the floater's column, ensuring it remains directly above the required tower position throughout the lowering process. Whereas low wave periods exceeded the crane angle limit in this study, this would no longer be a limiting factor, as the horizontal translations at the top of the tower would also be reduced under such conditions.

These recommendations are intended to guide the further development of the floating-to-floating installation method, addressing the remaining technical challenges and ensuring its practical application in the industry.

Bibliography

- 4C Offshore. Floating Offshore Wind Canarias (FOWCA), 2 2024.
- Wilson Guachamin Acero, Zhen Gao, and Torgeir Moan. Numerical Study of a Novel Procedure for Installing the Tower and Rotor Nacelle Assembly of Offshore Wind Turbines based on the Inverted Pendulum Principle. *J. Marine Sci. Appl*, 15:1, 2016. doi: 10.1007/s11804-016-0000-0.
- Aikido Technologies. Aikido Platform. URL <https://www.aikidotechnologies.com/technology>.
- Christopher Allen, Anthony Viselli, Habib Dagher Andrew Goupee, Evan Gaertner, Nikhar Abbas, Matthew Hall, and Garrett Barter. Definition of the UMaine VoltturnUS-S Reference Platform Developed for the IEA Wind 15-Megawatt Offshore Reference Wind Turbine Technical Report. Technical report, 2020. URL www.nrel.gov/publications.
- Arcus Wire Group. Stainless steel wire rope catalogue, 2023. URL https://arcuswire.com/wp-content/uploads/2023/05/5324_wire_catalogue_march_2023_web.pdf.
- Army. Corps of Engineers. *CEM: Coastal Engineering Manual*. 2002.
- Garrett Barter. IEA Wind 15-MW Release Notes, 6 2023. URL <https://github.com/IEAWindTask37/IEA-15-240-RWT/blob/master/ReleaseNotes.md>.
- Beaume Cedric. Fundamentals of Fluid Mechanics. Technical report, Department of Aeronautics Imperial College London, 2014. URL <https://cbeaume.com/download/FFM.pdf>.
- Peter Buxbaum. Offshore wind installation vessels – a coming shortage. *American Journal of Transportation*, (753):4, 5 2023.
- BVG Associates. Tow-out, 3 2023. URL <https://guidetofloatingoffshorewind.com/guide/i-installation-and-commissioning/i-6-floating-offshore-wind-turbine-installation/i-6-1-tow-out/>.
- Carbon Trust. Floating Offshore Wind: Market and Technology Review. Technical report, 6 2015. URL <https://ctprodstorageaccountp.blob.core.windows.net/prod-drupal-files/documents/resource/public/Floating%20ffshore%20Wind%20Market%20Technology%20Review%20-%20REPORT.pdf>.
- Mingsheng Chen, Guibo Yuan, Chun Bao Li, Xianxiong Zhang, and Lin Li. Dynamic Analysis and Extreme Response Evaluation of Lifting Operation of the Offshore Wind Turbine Jacket Foundation Using a Floating Crane Vessel. *Journal of Marine Science and Engineering*, 10(12), 12 2022. ISSN 20771312. doi: 10.3390/jmse10122023.
- M. Collu and M. Borg. Design of floating offshore wind turbines. In *Offshore Wind Farms: Technologies, Design and Operation*, pages 359–385. Elsevier Inc., 3 2016. ISBN 9780081007808. doi: 10.1016/B978-0-08-100779-2.00011-8.
- CrossWind. Hollandse Kust Noord Frequently asked questions, 2023. URL <https://www.crosswindhkn.nl/about/faq/#:~:text=Building%20one%20wind%20turbine%20at,one%20day%20per%20wind%20turbine>.
- A P Crowle and P R Thies. Floating offshore wind turbines port requirements for construction. 236(4): 1047–1056, 2022. doi: 10.1177/14750902221078425.
- Det Norske Veritas. DNV-RP-C205 Environmental Conditions and Environmental Loads. Technical report.
- Det Norske Veritas (DNV). Floating Offshore Wind: The next five years. URL <https://www.dnv.com/focus-areas/floating-offshore-wind/floating-offshore-wind-the-next-five-years.html>.

- Hugo Díaz, José Serna, Javier Nieto, and C. Guedes Soares. Market Needs, Opportunities and Barriers for the Floating Wind Industry. *Journal of Marine Science and Engineering*, 10(7):934, 7 2022. ISSN 2077-1312. doi: 10.3390/jmse10070934.
- DTU. Global Wind Atlas, 2024. URL <https://globalwindatlas.info/en>.
- Adnan Durakovic. Overcoming Floating Wind Challenges Is Key to Global Energy Transition – Houlder. *offshoreWIND*, 1 2023. URL <https://www.offshorewind.biz/2023/01/27/overcoming-floating-wind-challenges-is-key-to-global-energy-transition-houlder/>.
- Equinor. Full story of Hywind Scotland – world's first floating wind farm, 10 2017. URL https://www.youtube.com/watch?v=PULfvXaISvc&ab_channel=Equinor.
- Equinor. Hywind Tampen: the world's first renewable power for offshore oil and gas, 2023. URL <https://www.equinor.com/energy/hywind-tampen>.
- Espen Braata. Verdens største pakkes ned, 10 2022. URL <https://www.at.no/anlegg/verdens-storste-pakkes-ned/704549>.
- European Commission. 2050 long-term strategy. URL https://climate.ec.europa.eu/eu-action/climate-strategies-targets/2050-long-term-strategy_en.
- Eurostat. Net electricity generation by type of fuel - monthly data. URL https://ec.europa.eu/eurostat/databrowser/view/NRG_CB_PEM__custom_5180368/default/table?lang=en.
- Jørgen Fredsøe. *Hydrodynamics*. 2008. URL https://www.researchgate.net/publication/335620750_HYDRODYNAMICS.
- Evan Gaertner, Jennifer Rinker, Latha Sethuraman, Frederik Zahle, Benjamin Anderson, Garrett Barter, Nikhar Abbas, Fanzhong Meng, Pietro Bortolotti, Witold Skrzypinski, George Scott, Roland Feil, Henrik Bredmose, Katherine Dykes, Matt Shields, Christopher Allen, and Anthony Viselli. Definition of the IEA Wind 15-Megawatt Offshore Reference Wind Turbine Technical Report. Technical report, 2020. URL www.nrel.gov/publications.
- H-BLIX and WindEurope. Offshore wind vessel availability until 2030: Baltic Sea and Polish perspective. Technical report, 6 2022. URL https://proceedings.windeurope.org/biplatform/rails/active_storage/disk/eyJfcjFpYmHMj0nsibWVzc2FnZSI6IkJBaDddVG9JYTJWNVNTSWhlSEI1TkhwZW50aG1hZGZURReWJHVMxh--68961cf787f72b9c99d26b16dc530039bfecdeed/Offshore-wind-vessel-availability-until.pdf.
- Mohamed Hassan and C. Guedes Soares. Dynamic Analysis of a Novel Installation Method of Floating Spar Wind Turbines. *Journal of Marine Science and Engineering*, 11(7), 7 2023. ISSN 20771312. doi: 10.3390/jmse11071373.
- J. Haugvaldstad and O. T. Gudmestad. Testing of a new transport and installation method for offshore wind turbines. In *IOP Conference Series: Materials Science and Engineering*, volume 700, 2019. doi: 10.1088/1757-899X/700/1/012004.
- S A Herman. OFFSHORE WIND FARMS Analysis of Transport and Installation Costs. Technical report, 2 2002.
- Christian Hill. The harmonically-driven pendulum, 7 2017. URL <https://scipython.com/blog/the-harmonically-driven-pendulum/>.
- Sunghun Hong, Jade McMorland, Houxiang Zhang, Maurizio Collu, and Karl Henning Halse. Floating offshore wind farm installation, challenges and opportunities: A comprehensive survey. *Ocean Engineering*, 304:117793, 7 2024. ISSN 0029-8018. doi: 10.1016/J.OCEANENG.2024.117793.
- Huisman. Huisman Wind Turbine Shuttle, 11 2011. URL https://www.kivi.nl/uploads/media/5644bee53d3b1/Huisman-Wind_Turbine_Shuttle.pdf.
- Huisman. Radical change in installation floating windfarms, 2 2023. URL <https://floatingwindsolutions.com/wp-content/uploads/2023/02/Husiman-Joop-Roodenburg.pdf>.

- Huisman Equipment. Windfarm installation vessel.
- International Renewable Energy Agency. Renewable Power Generation Costs in 2022. Technical report, IRENA, Abu Dhabi, 2023.
- Zhiyu Jiang. Installation of offshore wind turbines: A technical review, 4 2021. ISSN 18790690.
- Zhiyu Jiang, Lin Li, Zhen Gao, Karl Henning Halse, and Peter Christian Sandvik. Dynamic response analysis of a catamaran installation vessel during the positioning of a wind turbine assembly onto a spar foundation. *Marine Structures*, 61:1–24, 9 2018. ISSN 09518339. doi: 10.1016/j.marstruc.2018.04.010.
- Joint Industry Project (JIP). The C1 Wedge Connection, 2024. URL <https://c1connections.com/technology/>.
- J M J Journée and W W Massie. OFFSHORE HYDROMECHANICS First Edition. Technical report, 2001.
- Vetle Kallåk. *Parametric Design and Analysis of Wave-Induced Responses of a Semi-Submersible Floating Wind Turbine Platform*. PhD thesis, NTNU, 6 2020. URL <https://ntnuopen.ntnu.no/ntnu-xmlui/handle/11250/2780121>.
- Lin Li, Zhen Gao, and Torgeir Moan. NUMERICAL SIMULATIONS FOR INSTALLATION OF OFFSHORE WIND TURBINE MONOPILES USING FLOATING VESSELS. Technical report, ASME, Nantes, 6 2013.
- Ting Liu, Karl H Halse, Bernt J Leira, Zhiyu Jiang, Wei Chai, Hans-P Brathaug, and Hans P Hildre. Dynamic response of a SWATH vessel for installing pre-assembled floating wind turbines. 2022. doi: 10.1016/j.marstruc.2022.103341. URL <https://doi.org/10.1016/j.marstruc.2022.103341>.
- Sarah MClean. Challenges lie ahead in the race to meet 2030 offshore wind targets. *Spinergie*, 2 2023. URL <https://www.spinergie.com/blog/challenges-lie-ahead-in-the-race-to-meet-2030-offshore-wind-targets>.
- David Morin. The Lagrangian method. In *Introduction to Classical Mechanics*. 2012. doi: 10.1017/cbo9780511808951.007. URL <https://scholar.harvard.edu/files/david-morin/files/cmchap6.pdf>.
- Walt Musial. Overview of Floating Offshore Wind, 2 2020. URL <https://www.nrel.gov/news/video/overview-of-floating-offshore-wind-text.html>.
- Nick Blenkey. Wison delivers China's first floating wind platform. 6 2021.
- Offshoretronic. Offshoretronic new concept. URL <https://offshoretronic.tech/new-concept>.
- Orcina. OrcaFlex Examples: Diffraction. URL <https://www.orcina.com/resources/examples/?key=1>.
- Orcina. K03 15MW semi-sub FOWT. Technical report, 2 2023. URL <https://www.orcina.com/wp-content/uploads/examples/k/k03/K03%2015MW%20semi-sub%20FOWT.pdf>.
- Orcina. Orcina webhelp, 2024. URL <https://www.orcina.com/webhelp/OrcaFlex/Default.htm>.
- Ports. Map of ports in Africa, 2024. URL <http://ports.com/browse/africa/map-view/>.
- Principle Power. The WindFloat advantage. URL <https://www.principlepower.com/windfloat/advantage/installation>.
- Quest Floating Wind Energy. Global Floating wind - Market and Forecast Report 2021 - 2034. Technical report, 2021. URL https://questfwe.com/wp-content/uploads/2021/03/GFLF_2021VOL3_Samp_Brochure.pdf.
- Charley Rattan. Onsite Major Component Replacement Technologies for Floating Offshore Wind: the Status of the Industry World Forum Offshore Wind (WFO), 2 2023. URL <https://energycentral.com/c/gn/onsite-major-component-replacement-technologies-floating-offshore-wind-status>.

- Tom Russell. Hywind Tampen delayed due to supply chain struggles. *4coffshore*, 7 2022. URL <https://www.4coffshore.com/news/hywind-tampen-delayed-due-to-supply-chain-struggles-nid25934.html#:~:text=Equinor%20revealed%20that%20it%20has,will%20be%20installed%20next%20spring>.
- SBM Offshore. SBM Offshore announces the successful installation of the 3 floating wind units for the Provence Grand Large pilot project, 10 2023. URL <https://www.sbmoffshore.com/newsroom/news-events/sbm-offshore-announces-successful-installation-3-floating-wind-units>.
- Seaqualize. The HeaveChief: Hook based Balanced Heave Compensation, 2024. URL <https://www.seaqualize.com/>.
- Carlos Eduardo Silva De Souza, Andreas Berthelsen, Sintef Ocean, Lene Eliassen, Erin Bachynski, Espen Engebretsen, and Herbjørn Haslum. *OC2020 A-044-Unrestricted Definition of the INO WIND-MOOR 12 MW base case floating wind turbine*. 2021. ISBN 9788271744076. URL www.sintef.no.
- Spain Gran Canaria. Economy & Industries in Gran Canaria, 2023.
- Dan Kyle Spearman and Sam Strivens. Phase ii summary report - floating wind joint industry project. Technical report, Carbon Trust, 7 2020.
- Statista. Cumulative offshore wind power capacity installations in Europe from 2012 to 2022, 9 2023. URL <https://www.statista.com/statistics/271055/cumulative-european-offshore-wind-power-capacity-installations/>.
- Alexandra H. Techet. Linear free surface waves. 2003.
- Ulstein. Winner of Statoil Challenge, 9 2015. URL <https://ulstein.com/news/winner-of-statoil-challenge>.
- Michiel van der Meulen. *Influence of Nonlinear Irregular Wave Modeling on the Dynamic Response of an Offshore Wind Turbine*. PhD thesis, Delft University of Technology, Delft, 9 2012.
- Thomas Vyzikas, Deborah Greaves, Dave Simmonds, Christophe Maisondieu, Helen Smith, and Lisa Radford. *Application of numerical models and codes - Task 3.4.4 MERiFIC project*. 2 2014.
- WaveClimate. WaveClimate database, 4 2023.
- Rebecca Williams and Feng Zhao. Global Offshore Wind Report 2023, 8 2023.
- WindEurope. A 2030 Vision for European Offshore Wind Ports Trends and opportunities. Technical report, 5 2021. URL https://proceedings.windeurope.org/biplatform/rails/active_storage/disk/eyJfcMfPbHMiOmsibWVzc2FnZSI6IkJBaDdVVG9JYTJWNVNTSWNhbnUptWlRNd2FHUTRkbVZyTORNM1luUjFjM2hrZDNOcmFHeH https://proceedings.windeurope.org/biplatform/rails/active_storage/disk/eyJfcMfPbHMiOmsibWVzc2FnZSI6IkJBaDdVVG9JYTJWNVNTSWNhbnUptWlRNd2FHUTRkbVZyTORNM1luUjFjM2hrZDNOcmFHeH https://proceedings.windeurope.org/biplatform/rails/active_storage/disk/eyJfcMfPbHMiOmsibWVzc2FnZSI6IkJBaDdVVG9JYTJWNVNTSWNhbnUptWlRNd2FHUTRkbVZyTORNM1luUjFjM2hrZDNOcmFHeH https://proceedings.windeurope.org/biplatform/rails/active_storage/disk/eyJfcMfPbHMiOmsibWVzc2FnZSI6IkJBaDdVVG9JYTJWNVNTSWNhbnUptWlRNd2FHUTRkbVZyTORNM1luUjFjM2hrZDNOcmFHeH https://proceedings.windeurope.org/biplatform/rails/active_storage/disk/eyJfcMfPbHMiOmsibWVzc2FnZSI6IkJBaDdVVG9JYTJWNVNTSWNhbnUptWlRNd2FHUTRkbVZyTORNM1luUjFjM2hrZDNOcmFHeH 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A

Polar plots for different H_s

$H_s = 2 \text{ m}$

Polar plots for $H_s = 2 \text{ m}$ and different peak periods and $k = 8887 \text{ kN/m}$

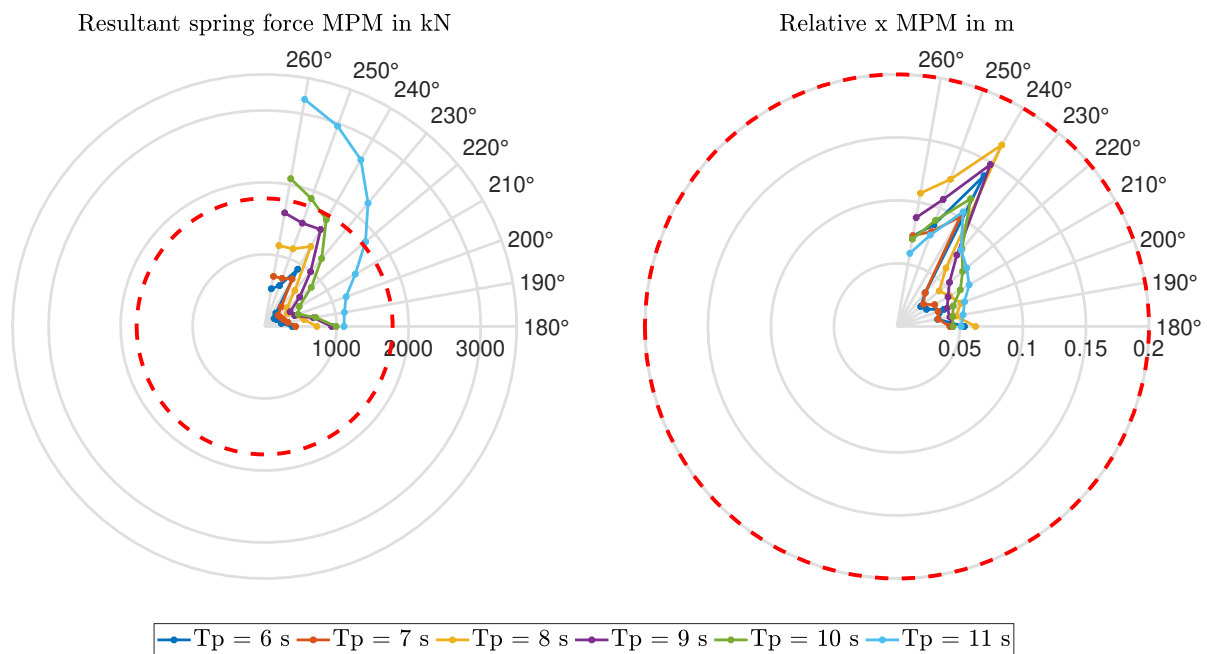


Figure A.1: Surge polar plot for $H_s = 2 \text{ m}$ and $k = 8887 \text{ kN/m}$

Polar plots for $H_s = 2$ m and different peak periods and $k = 8887$ kN/m

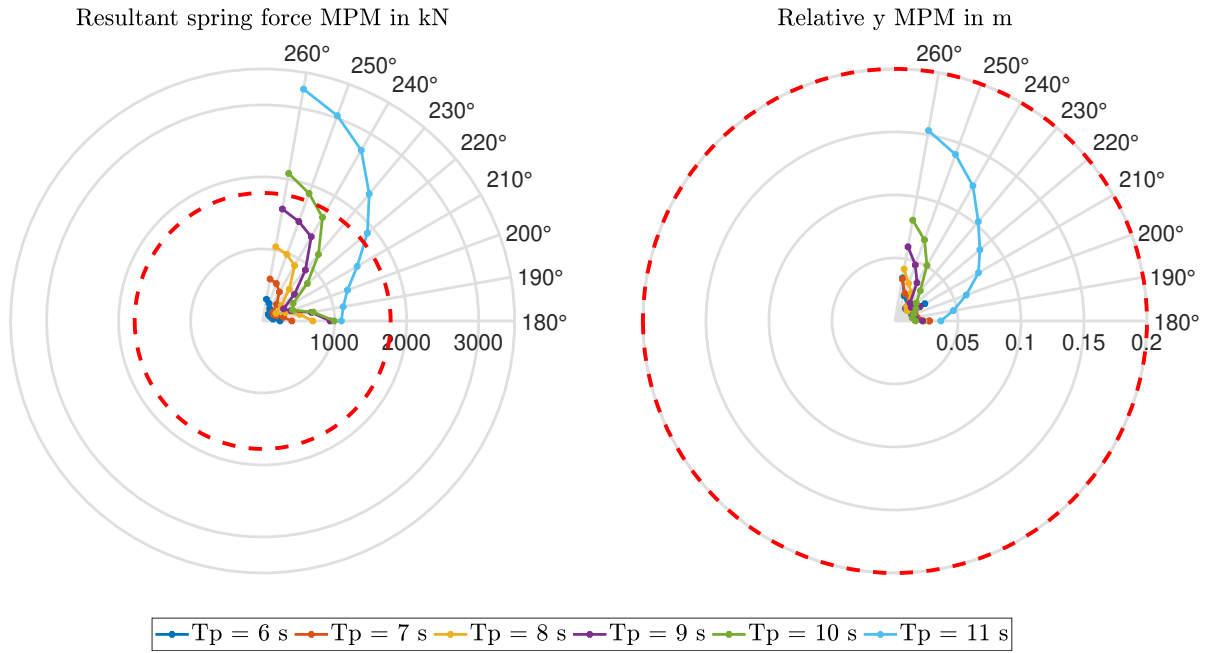


Figure A.2: Sway polar plot for $H_s = 2$ m and $k = 8887$ kN/m

MPM xz crane wire angle [deg] with $k = 8887$ kN/m MPM yz crane wire angle [deg] with $k = 8887$ kN/m

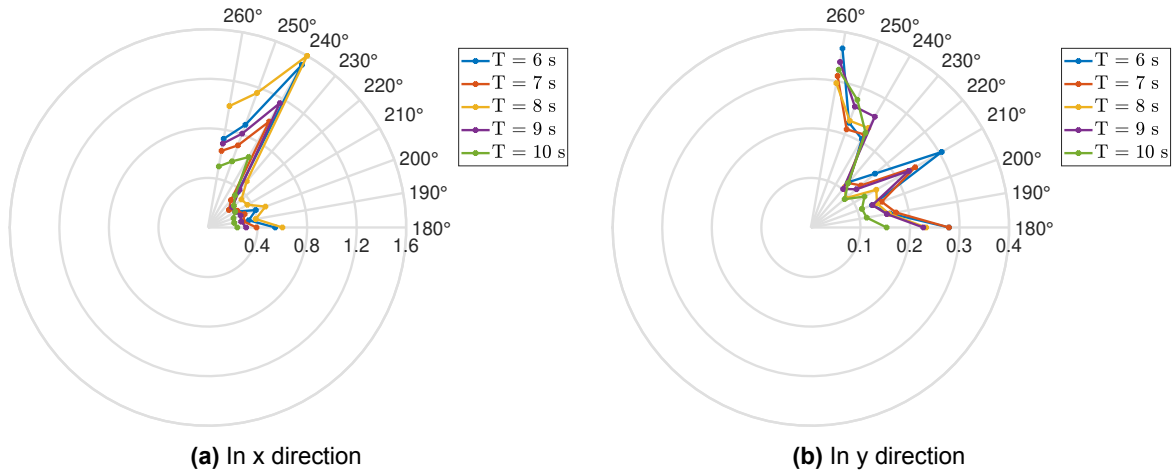


Figure A.3: MPM crane wire angle for $H_s = 2$ and $k = 8887$ kN/m

$H_s = 1.5$ m

For $H_s = 1.5$ m, the simulated wave period increased to 13 s, investigate the limit.

Polar plots for $H_s = 1.5$ m and different peak periods and $k = 8887$ kN/m

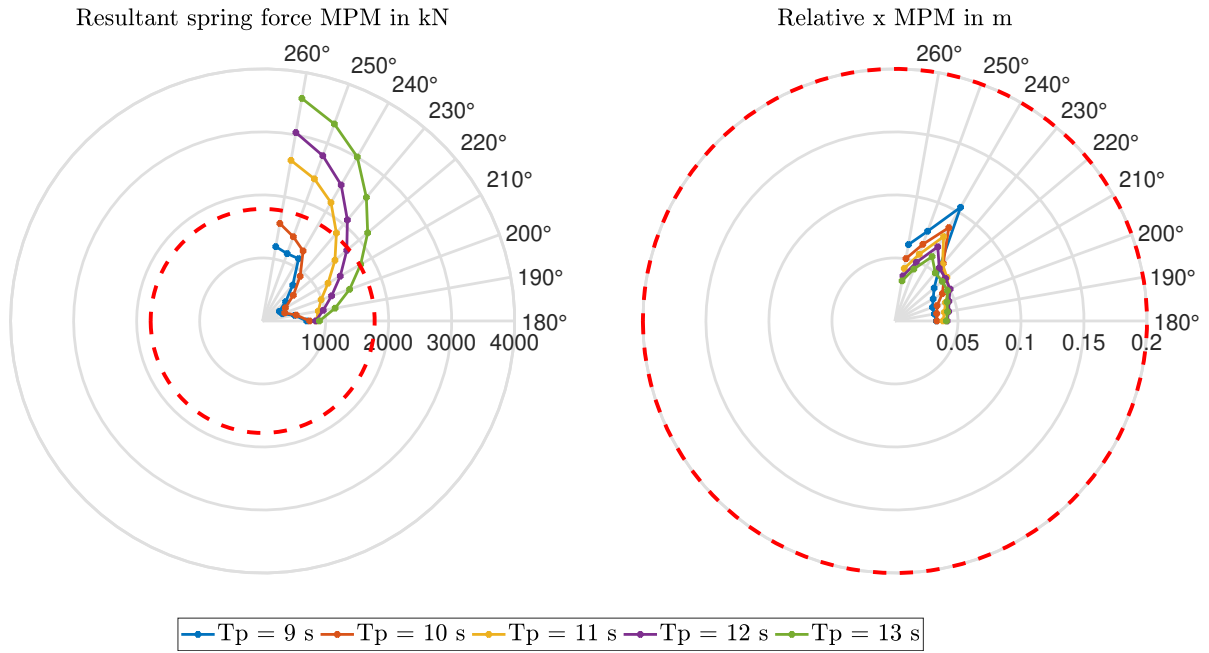


Figure A.4: Surge polar plot for $H_s = 1.5$ m and $k = 8887$ kN/m

Polar plots for $H_s = 1.5$ m and different peak periods and $k = 8887$ kN/m

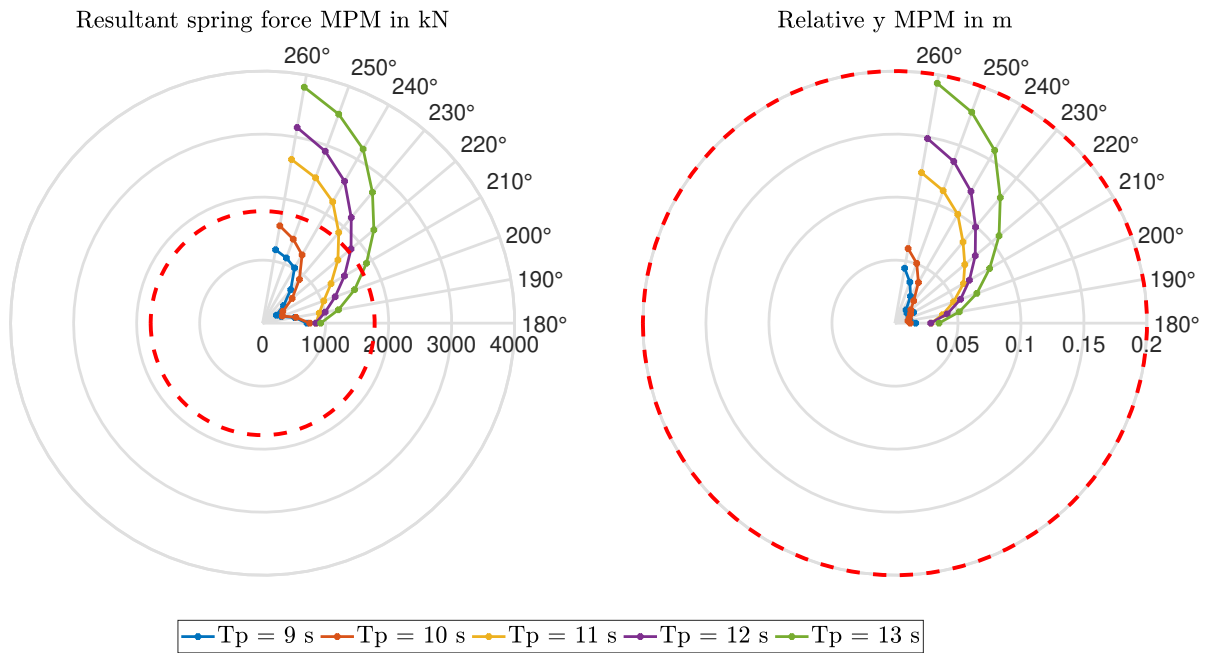
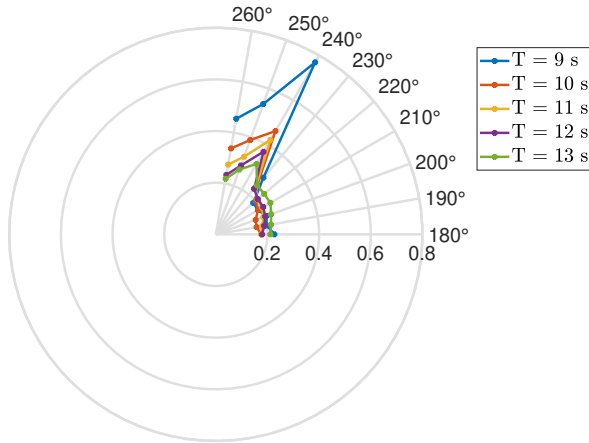
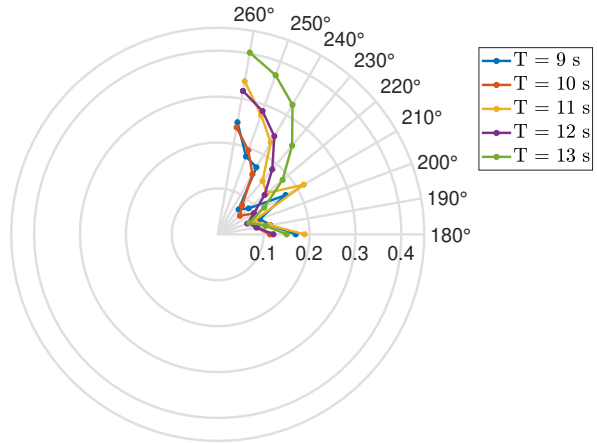


Figure A.5: Sway polar plot for $H_s = 1.5$ m and $k = 8887$ kN/m

MPM xz crane wire angle [deg] for $H_s = 1.5$ m

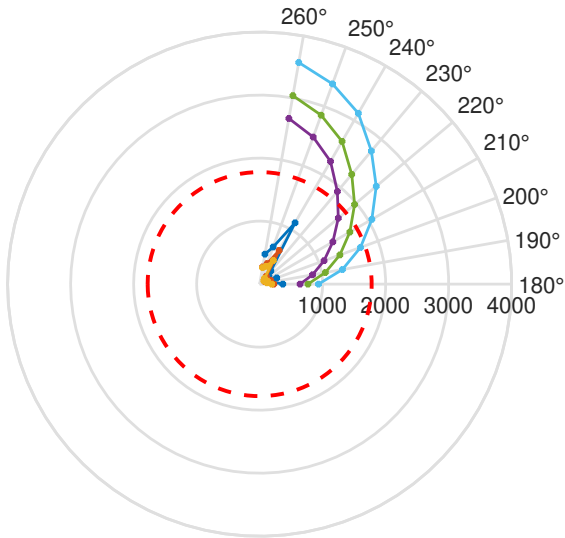
(a) In x direction

MPM yz crane wire angle [deg] for $H_s = 1.5$ m

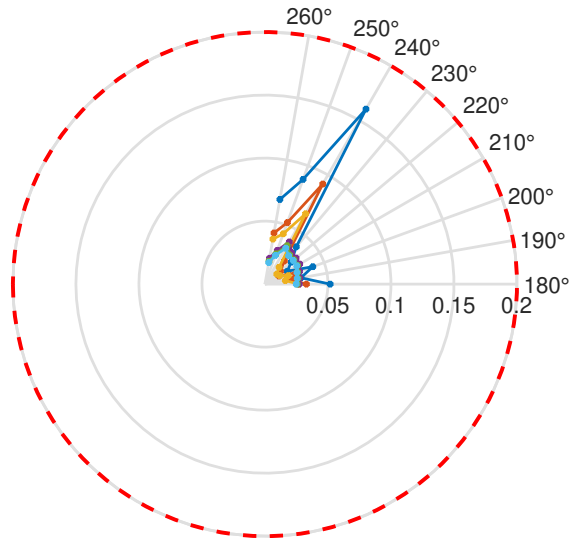
(b) In y direction

Figure A.6: MPM crane wire angle for $H_s = 1.5$ m and $k = 8887$ kN/m **$H_s = 1$ m**Polar plots for $H_s = 1$ m and different peak periods and $k = 8887$ kN/m

Resultant spring force MPM in kN



Relative x MPM in m



—●— $T_p = 4$ s
 —●— $T_p = 5$ s
 —●— $T_p = 6$ s
 —●— $T_p = 13$ s
 —●— $T_p = 14$ s
 —●— $T_p = 15$ s

Figure A.7: Surge polar plot for $H_s = 1$ m and $k = 8887$ kN/m

Polar plots for $H_s = 1$ m and different peak periods and $k = 8887$ kN/m

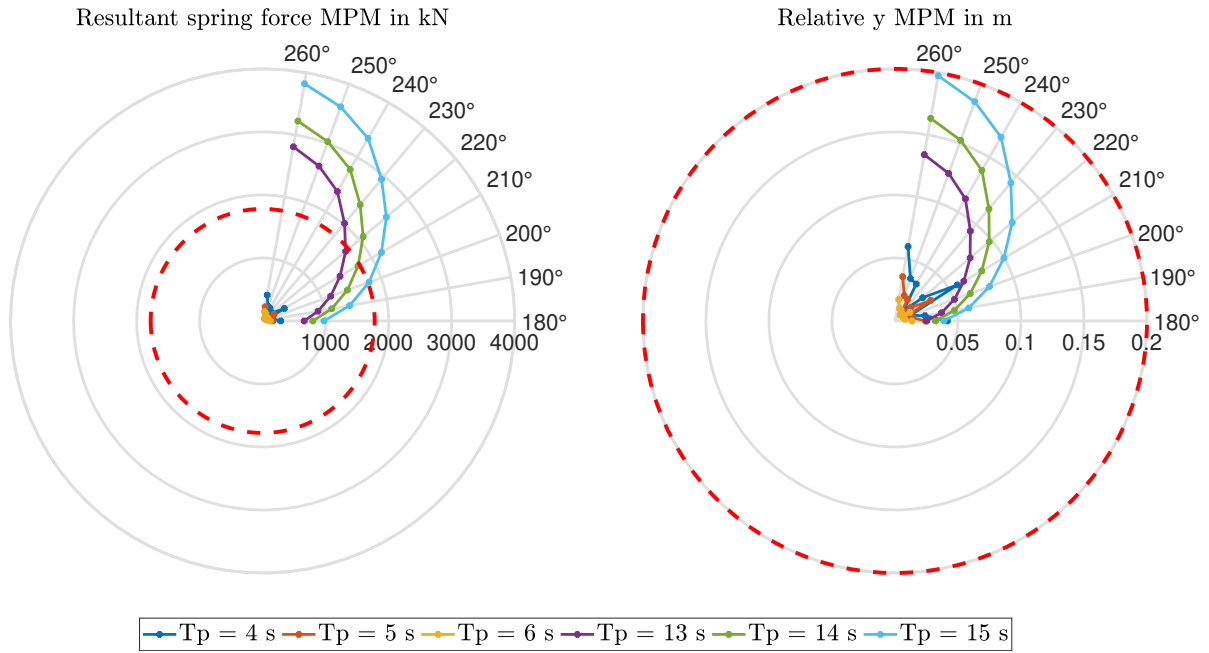


Figure A.8: Sway polar plot for $H_s = 1$ m and $k = 8887$ kN/m

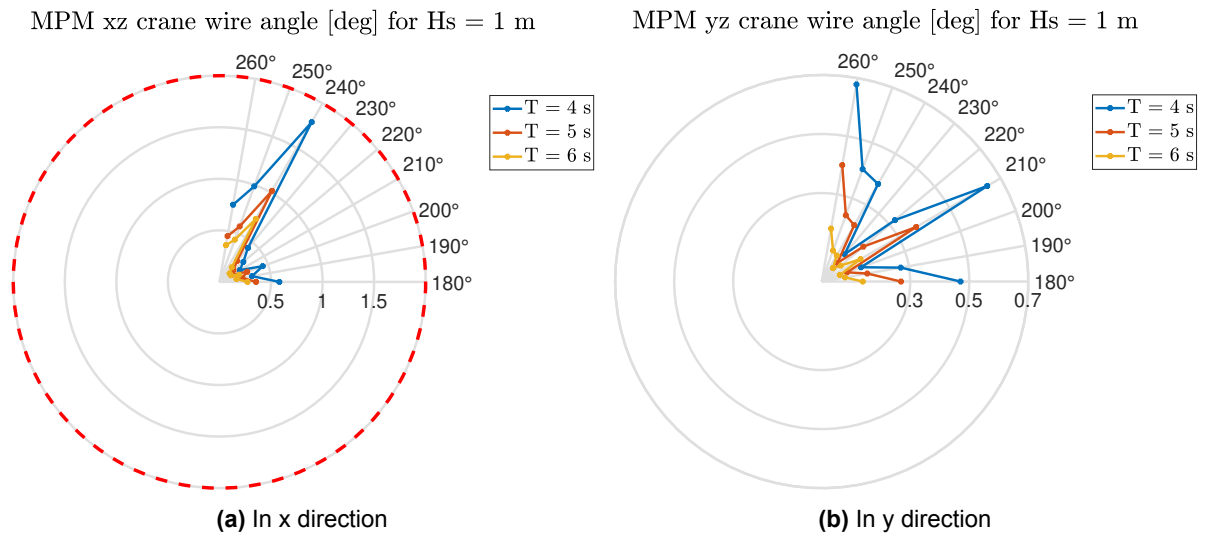


Figure A.9: MPM crane wire angle for $H_s = 1$ m and $k = 8887$ kN/m (for visibility, only the small wave periods are shown, which gives the largest angles)

Maximum forces and corresponding sea states

Table A.1: The maximum forces for different H_s and a T_p range of 6 to 11 s and wave heading where these maxima occur

	$H_s = 2.5$ m	$H_s = 2$ m	$H_s = 1.5$ m	$H_s = 1$ m
$F_{res,x}$ max [kN]	3788	3201	2587	1925
T_p - heading	11 - 260	11-260	11-260	11-260
$F_{res,y}$ max [kN]	3877	3267	2638	1961
T_p [s] - heading [deg]	11 - 260	11-260	11-260	11-260
F_x max [kN]	1823	1477	925	797
T_p [s] - heading [deg]	9 - 240	8-240	9-240	8-240
F_y max [kN]	1655	1363	1078	789
T_p [s] - heading [deg]	11 - 260	11-240	11-260	11-260