

Håkon Fallmyr

Numerical modelling and dynamic analysis of a wind turbine rotor blade lifting operation from feeder barge using a jack-up vessel

A SIMA simulation

Master's thesis in Naval Architecture

Supervisor: Karl Henning Halse

Co-supervisor: Dr. Amrit Verma

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



Norwegian University of
Science and Technology

Master agreement

Background motivation

A marine lifting operation where an offshore wind turbine rotor blade is lifted from a barge to a jack-up rig is chosen to be studied in this thesis. This is a complex and difficult marine operation which requires preparation, communication and expertise. The challenges with such an operation are the geometry, size and the fragility of the object being lifted, it having small tolerances for errors during the lift either from human or technical factors.

The technical factors of interest are the environmental factor and the physical dimension of barge, jack-up and object lifted. The environmental factor can, and will, effect the operation leading to possible large motions during the crane lift. For this matter, the most interesting part of the operation is when the rotor blade is lifted from the deck of the barge until safely in the air, and the relative motion between these objects.

Objectives

The objective of this thesis is to study the first stage of a total installation operation and specifically the relative motion between a feeder barge and a lifted turbine rotor blade. Furthermore, the use of a jack-up vessel in various sea states for an operational area with different depths and a station-keeping system for the barge shall be included in the study.

The research questions to conduct this study are:

- What are the relative motions between the barge and lifting object?
- What environmental factor has the largest effect on the relative motion?
- What can be done to reduce the relative motion?
- What effect will a heave compensation system have on the relative motion?
- What are the max tension forces in the lifting wire, and will this be safe?
- What can be done to keep the barge in a safe position relative to the jack-up?

Scope of work

The general workflow of the study will be to:

- Conduct a literature study to get an understanding of the problem and what type of analysis work has previously been carried out to solve it
- Build an accurate model of the lifting operation in SIMA
- Analyse the relative motion between the barge and the lifting object with multiple environmental and physical inputs
- Conclude the study

The limitation for this thesis is to only look upon what happens in the first stages of the heavy lift operation defined earlier, meaning only when the object is lifted from deck of the barge until safely in the air above it. Furthermore, the actual environmental data will be given by an industry contact.

The scope of work may prove to be larger than initially anticipated. Subject to approval from the advisor, topics from the list above may be deleted or reduced in extent.

The thesis should be written as a research report with summary, conclusion, literature references, table of contents, etc. During preparation of the text, the candidate should make efforts to create a well arranged and well written report. To ease the evaluation of the thesis, it is important to cross-reference text, tables and figures. For evaluation of the work a thorough discussion of results is needed. Discussion of research method, validation and generalization of results is also appreciated.

The thesis shall be submitted in electronic version according to standard procedures. Instructions are found on the NTNU website (Inspira) and on Blackboard. In addition, one paper copy of the full thesis together with an electronic device carrying all relevant documents and files shall be submitted to your supervisor.

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Sammendrag

En marin løfteoperasjon der et offshore vindturbinrotorblad løftes fra en leker ved hjelp av et jack-up fartøy er en kompleks og vanskelig operasjon. Dette er en operasjon som Equinor ønsker at skal undersøkes med tanke på fremtidig operasjoner og drift. utfordringene med en slik operasjon er geometrien, størrelsen og skjørheten til gjenstanden som løftes. Andre utfordringer inkluderer liten toleranse for feil under løftet enten fra menneskelige eller tekniske faktorer. Det er imidlertid skrevet lite om de tekniske faktorene ved en slik spesifikk operasjon, og som en konsekvens, denne oppgaven fokuserer dermed på hva som vil skje når et vindturbinrotorblad løftes fra en leker ved hjelp av et jack-up fartøy i flere sjøtilstander. Oppgaven fokuserer spesielt på den relative bevegelsen mellom løftets rotorblad og leker, for tilfeller med og uten hivkompensasjon.

For å undersøke denne operasjonen ble SIMA brukt til å sette opp seks koblede RIFLEX-SIMO-modeller bestående av et jack-up fartøy, tre leker, et vindturbinrotorblad, hivkompensasjon og et enkelt fortøyningsystem som kobler lekeren til fartøyet. Denne modellen var basert på en annen modell tilgjengelig gjort av Dr. Amrit Verma, noe som gjorde det mulig å analysere operasjonen. I modellen ble jack-up fartøyet og tre forskjellige leker modellert ved bruk av SESAM GeniE. Jack-up fartøyet ble modellert etter Bold Tern, eid av Fred. Olsen Windcarrier, og de tre enkle lekerne ble modellert for å kunne bære et vindturbinrotorblad. For lekerne ble SESAM HydroD brukt til å utføre en hydrodynamisk analyse og lage RAOer, senere brukt i SIMA. Bladet som ble brukt var et *IEA 15-MW* referanseturbinrotorblad utviklet IEA Wind, og ble direkte importert til SIMA. Hivkompensasjon ble brukt for tre av modellene, noe som gjorde at endringen i hver modell var lekerne og om hivkompensasjon var inkludert eller ikke. Operasjonen ble deretter simulert for et sett med forskjellige sjøtilstander, og de mest relevante resultatene ble analysert inkludert den relative bevegelsen mellom det løftede rotorbladet og lekerne. Metocean-dataene som ble brukt ble levert av en industrikontakt hos Equinor.

For vindbølgeretningene og toppperiodene i simuleringene var verdiene som ble satt i forhold til toppperiodene og retningene til lekerens RAO i frihetsgradene hiv, rull og stamp, med størst effekt. Resultatene består av bølgehøyden og et estimat av en sannsynlig ekstrem verdi, bevegelsen til lekerne og jack-upen, rotorbladbevegelse og krefet på løftewire med og uten hivkompensasjon samt en estimering av hvilken minste diameter løftewiren kan ha. Den relative bevegelsen mellom blad og leker og til slutt kreftene på det foreslåtte fortøyningsarrangementet ble også tatt med. En casestudie av den relative bevegelsen og stampingen for lekerne viste de sikre verdiene for disse bevegelsene i forhold til de simulerte sjøtilstandene.

Fra resultatene ble det funnet at operasjonen kan være sikker under visse sjøtilstander, og at den største effekten på den relative bevegelsen var toppperioden i forhold til lekerens RAO i hiv og stamp, en økning i signifikant bølgehøyde og en bølgeretning på 045 grader i forhold til lekeren. Videre hadde størrelsen på lekeren innvirkning på resultatene ettersom den mindre lekeren induserte mer bevegelse og gjorde operasjonen mindre sikker. Den større lekeren induserte mindre bevegelse og gjorde operasjonen tryggere. Effektene av hivkompensasjon var av liten til ingen grad, annet enn å gjøre bevegelsen mer forutsigbar. Maksimal spenning i løftewiren ble vist å være innenfor verdigrensene for den virkelige løftewiren som ble sammenlignet, og den nødvendige diameteren ble gitt for denne spesifikke wiren. Fortøyningssystemet ble vist at det holdt lekeren i sikker posisjon under simuleringer.

Det anbefales at validering av modellen skjer, enten med annen programvare eller en fysisk modell og avvik korrigeres, spesielt rundt opphengsriggen. Dessuten foreslås det å lage en fysisk eller digital modell av fortøyningsystemet. En sammenligning med et DP-system kan også gjøres for å se forskjellen i operativitet og kompleksitet.

Abstract

A marine lifting operation where an offshore wind turbine rotor blade is lifted from a feeder barge using a jack-up vessel is a complex and difficult operation. This is an operation that Equinor wants researched for the purpose of future operations. The challenges with such an operation are the geometry, size and the fragility of the object being lifted. Other challenges include small tolerance for errors during the lift either from human or technical factors. However, little is written about the technical factors of such a specific operation. As a consequence, this thesis focuses on what will happen when a wind turbine rotor blade is lifted from a feeder barge with the help of a jack-up vessel in multiple sea states. The thesis focuses especially on the relative motion between the lifted rotor blade and barge, for cases with and without heave compensation.

To research this operation SIMA was used to set up six coupled RIFLEX-SIMO models consisting of a jack-up vessel, three barges, a wind turbine rotor blade, heave compensation and a simple mooring system connecting the barge to the jack-up. This model was based of another model provided by Dr. Amrit Verma, making it possible to analyse the operation. In the model, the jack-up vessel and three different barges were modelled using SESAM GeniE. The jack-up vessel was modelled after the Bold Tern, owned by Fred. Olsen Windcarrier, and the three simple barges were modelled to be able to carry a wind turbine rotor blade. For the barges SESAM HydroD was used to conduct a hydrodynamic analysis and make RAOs, used later in SIMA. The blade used was an *IEA 15-MW* reference turbine rotor blade developed the IEA Wind, and was directly imported into SIMA. Heave compensation was used for three of the models, making the change in each model the barges and if heave compensation was included or not. The operation was then simulated for a set of different sea states, and the most relevant results were analysed including the relative motion between the lifted rotor blade and the barges. The metocean data used was provided by an industry contact at Equinor.

For the wind wave directions and peak periods in the simulations, the values set were relative to the peak periods and directions of barges RAOs in heave, roll and pitch giving the greatest effect. The results consists of the wave elevation and an estimate of a probable extreme value, barge and jack-up motions, rotor blade motion and tension with and without heave compensation and an estimation what minimum diameter the lifting wire can have. The relative motion between the blade and barge and lastly the forces on the suggested mooring arrangement were included. A case study of the relative motion and the pitch angle for the barges showed the safe values of the motions relative to the simulated sea states.

From the results it was found that the operation can be safe under certain sea states, and that the largest effect on the relative motion were the peak period relative to barges RAO in heave and pitch, an increase in significant wave height and a wave direction of 045 degrees relative to the barge. Furthermore, the size of the barge had an impact on the results as the smaller barge induced more motion and made the operation less safe. The larger barge induced less motion and made the operation safer. The effects of heave compensation was little to non, other than making the motion more predictable. The max tension in the wire were shown to be within the limits of the real life wire compared and the required diameter was given for this specific wire. The mooring system was shown to keep the barge in safe position during simulations.

It is recommended that validation of the model takes place, either with another software or a physical model and discrepancies corrected, especially around the suspension rig. Moreover, making a physical or digital model of the mooring system is suggested. A comparison against a DP system could also be made, to see the difference in operability and complexity.

Preface

This thesis is the final delivery of a master's degree in naval architecture at the Norwegian University of Science and Technology, NTNU, department of Ocean Operations and Civil Engineering in Ålesund. The study is discipline oriented and the workload of the thesis is equivalent to 30 ECTS. The title upon approval of the thesis becomes Master of Science in Naval Architecture.

The topic of the thesis was chosen based on own experience in the maritime field, as my time at sea and international trade routes has had an alluring effect on my interests. In addition to this, it was chosen to challenge my own abilities and hopefully improve upon them.

The thesis is written in collaboration with Equinor over the course of the final semester of my studies, where the problem to be researched has been defined together with my supervisor and industry contact. The research task has been challenging yet rewarding, where one of the most interesting parts has been the process from initial idea, problem statement and sketching of a marine operation to producing a resulting and functioning model in a software previously not used by the author. The thesis is written in an attempt to expand the academical knowledge on relative motion between a wind turbine rotor blade lifted by a jack-up vessel and a feeder barge moored alongside the jack-up.

A big thank you has to be addressed to my supervisors Karl Henning Halse and Dr. Amrit Verma for their overall guidance and feedback during the course of the thesis work and the specifics of modelling using SIMA. In addition, thank you to Equinor for the thesis topic and corresponding data, and to Fred. Olsen Windcarrier for the use of the Bold Tern and the attached data of the vessel.

Finally, to my fellow classmates thank you for two excellent years together and the motivation to complete the masters degree. These past two years have been full of discussions, social activities, challenges, new experiences and excellent memories together. Thank you all for making it captivating to go back to studying.

Ålesund 8th June 2023

Håkon Fallmyr

Nomenclature

Abbreviations

CAD	Computer-aided Design
COG	Center of Gravity
DNV	Det Norske Veritas
DNV GL	Det Norske Veritas Germanische Lloyd
DOF	Degree of Freedom
FEM	Finite Element Method
IEA	International Energy Agency
ISO	International Organization for Standardization
MBL	Max Breaking Load
NPD	Norwegian Petroleum Directorate
RAO	Response Amplitude Operator
SF	Safety Factor
SIF	Sesam Interactive File
WLL	Working Load Limit

Other symbols

$^{\circ}$	Degree
C	Thermal Temperature
g	Gravitational constant, 9.81 (m/s^2)
kg/m^3	Density
kN	Kilonewton
m/s	Velocity
m/s^2	Acceleration
m	Meter
m^2/s	Kinematic viscosity
m^2	Area
mm	Millimeter
N	Newton
Nm^2/rad	Torsion Stiffness
Nm^2	Bending Stiffness
Pa	Pascal
s	Second
<i>Tonnes</i>	Mass

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1 Introduction

1.1 Motivation

A marine lifting operation where an offshore wind turbine rotor blade is lifted from a feeder barge using a jack-up vessel was chosen to be studied in this thesis. This is a complex and difficult marine operation which requires preparation, communication and expertise. The challenges with such an operation are the geometry, size and the fragility of the object being lifted. Other challenges include small tolerance for errors during the lift either from human or technical factors.

The technical factors of interest are the environmental factor and the physical dimension of barge, jack-up and object lifted. The environmental factor could effect the operation leading to possible large motions during the crane lift. For this matter, the most interesting part of the operation is when the rotor blade is lifted from the deck of the barge until safely in the air, and the relative motion between these objects.

Another issue with this type of operation is the motion of the barge in vicinity of the jack-up vessel and how to reduce the motion. This due to the size of the total operation and the effects a collision between both vessels can have on the safety of both the operation and personnel involved. If theses vessels are involved in a collision or accident then usually the impact on both the marine environment, structures and personnel could be significant.

1.2 The problem

The problem provided by the international energy company Equinor, is what happens when a wind turbine rotor blade is lifted from a feeder barge with the help of a jack-up vessel in multiple sea states, as this will be part of future operations. Figure 1 shows a sketch of the problem [1].

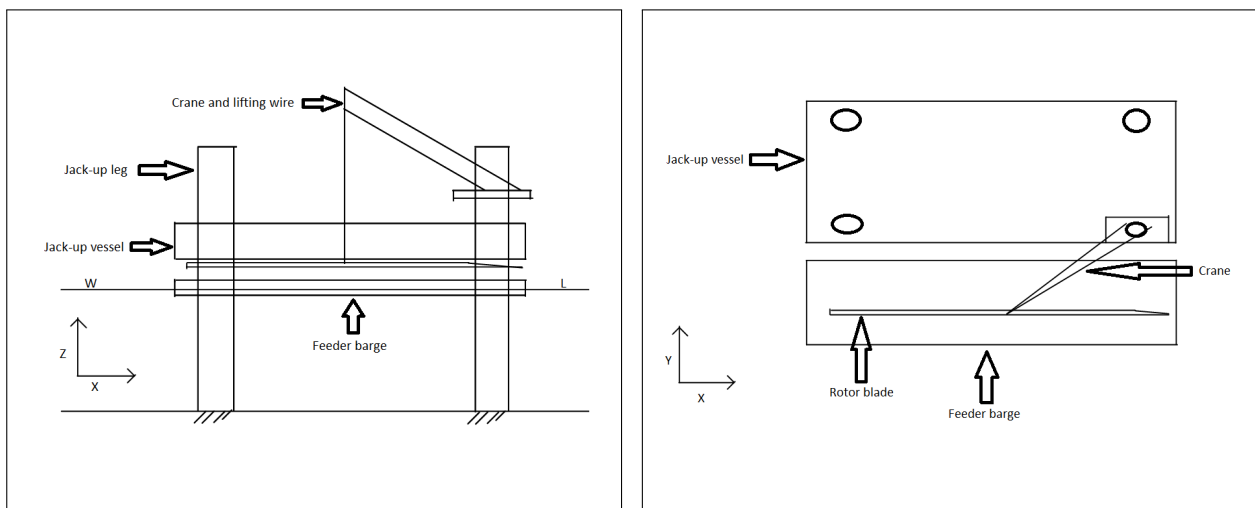


Figure 1: Sketch of the problem

1.3 Objectives

The objective of this thesis is to study the first stage of a total installation operation and specifically the relative motion between a feeder barge and a lifted turbine rotor blade. Furthermore, the use of a jack-up vessel in various sea states for an operational area with different depths and a station-keeping system for the barge shall be included in the study.

1.4 Research question

The research questions in this study are:

- What are the relative motions between the barge and lifting object?
- What environmental factor has the largest effect on the relative motion?
- What can be done to reduce the relative motion?
- What effect will a heave compensation system have on the relative motion?
- What are the max tension forces in the lifting wire, and will this be safe?
- What can be done to keep the barge in a safe position relative to the jack-up?

1.5 Scope of work

The approach to answer these questions, or scope of work, is shown as the general workflow of the study below:

- Conduct a literature study to get an understanding of the problem and what type of analysis work has previously been carried out to solve the problem
- Build a model of the lifting operation in SIMA
- Analyse the relative motion between the barge and the lifting object with multiple environmental and physical inputs

1.6 Limitations

There are multiple phases of a marine lifting operation from a feeder using a jack-up vessel, however the limitation of this thesis is to only look upon what happens in the first stages. This means only when the object is lifted from deck of the feeder barge until safely in the air above it. This study will only take the SIMA software into account when analysing the cases and providing results and a conclusion. Furthermore, the actual environmental data used in the analysis were given by an industry contact at Equinor.

2 General modelling methods

Little is written about lifting a wind turbine rotor blade from a feeder barge and the following analysis of the relative motion between the lifted rotor blade and barge. However, there have been conducted studies on a lifting operation using a jack-up vessel to lift a wind turbine rotor blade. From these studies, the process of analysing a lift from the jack-up point of view can be understood, and transfer parts of the analysis done to this study. For the barge aspect of this thesis, relevant studies and practices were researched to get a view that could be implemented into this thesis.

A reoccurring theme for the analysis process in previous relevant studies has been to analyse the response of the jack-up and the rotor blade [2], [3], [4].

2.1 Current installation method of a wind turbine

The main method currently used for these types of lifting operations is to lift each single blade using a jack-up rig. The jack-up rig is used due to it being able to sit on the seabed and provide a stable working platform for the lift, while a single blade lift is used due to small deck space requirement and flexible blade orientations during the lift. An overview of the operation is shown in Figure 2.

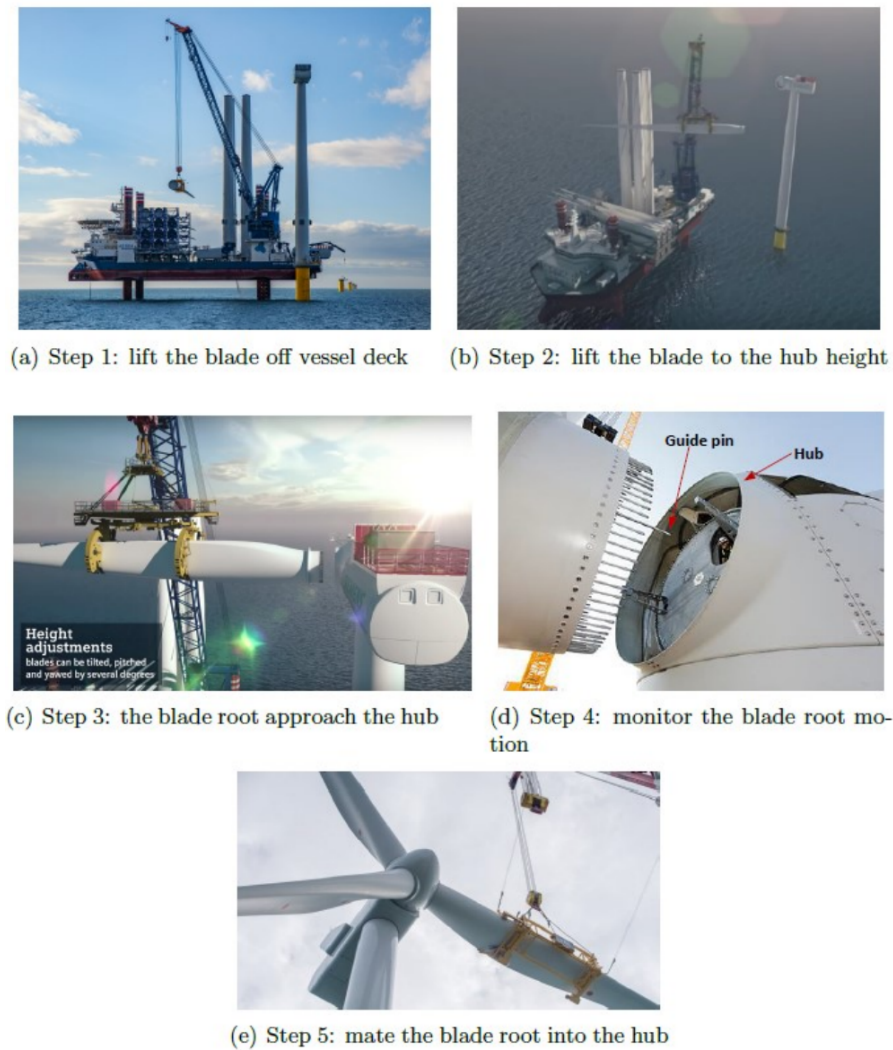


Figure 2: Current installation procedure [4]

2.2 Concept installation method from feeder barge

As per the objectives of this study the rotor blades shall be lifted from a feeder barge. This is based on a concept made by DEME Offshore where the blades are being transported out to location via a feeder barge and installed from the barge with lifting operation. This is a relatively new concept and can be seen in Figure 3 [5].

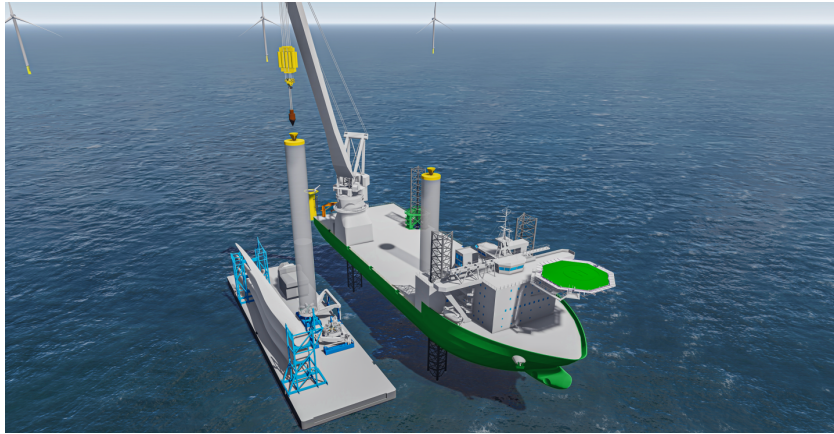
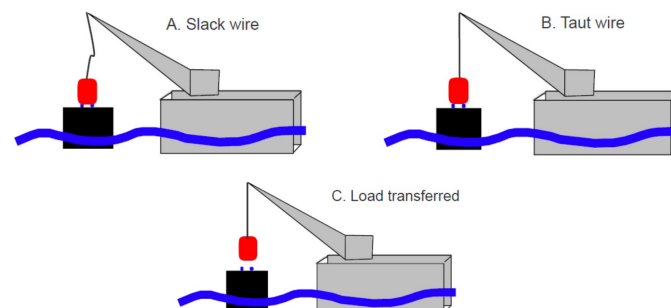


Figure 3: DEME concept [6]

2.3 Lift-off from a feeder barge

At the first stages of a total installation operation of wind turbine rotor blades from a feeder barge, three different dynamic systems can be defined. These dynamic systems can be seen in Figure 4, and show the basic principle for any lifting operation from a feeder barge or any similar vessel.

LIFT-OFF: Could define three different dynamic systems



NTNU Norwegian University of Science and Technology

Figure 4: Feeder barge lift procedure [7]

The hazards of these systems are for each step of the lift-off:

- a) Unacceptable loads in tension wire, or snap loads
- b) Re-hit of object by the barge after lift-off
- c) Unacceptable transient horizontal motion of the object after lift-off

2.3.1 Unacceptable loads in tension wire, calculation method

Unacceptable loads in tension wire, or snap loads, are a spikes in tension typically over a short time span. This can occur in the first phase of a lift or if there is any sort of re-impact. A simple estimation method for the snap loads is shown in Equation 1 with the complementary Figure 5 showing the force vectors on such a system [7]:

$$F_{snap} = V_{snap} \cdot \sqrt{K \cdot M}$$

Where:

$$V_{snap} = V_c + V_{crt} \text{ where:}$$

V_c = hoisting velocity

$$V_{crt} = V_t - V_b$$

= The characteristic value of the relative velocity between the crane tip and the barge

K = Axial stiffness of the lifting wire

M = Mass of the lifting wire

The load in the hoisting wire must also include the objects weight in air:

$$F_{tot} = Mg + F_{snap}$$

(1)

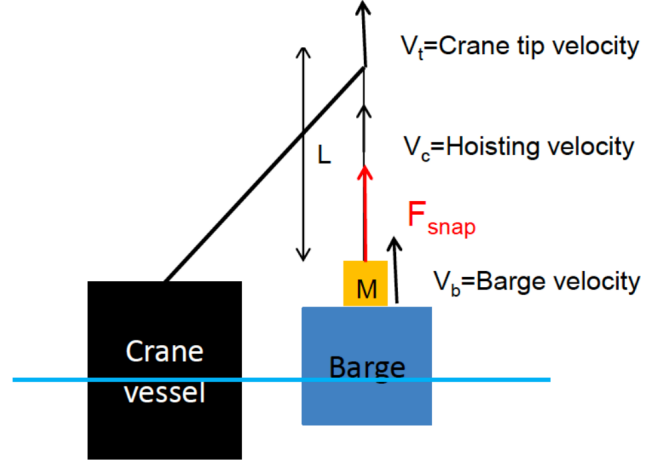


Figure 5: Force vectors on lifting system [7]

2.3.2 Probability of re-hit of object by the barge after lift-off

For a lifting operation to be safe the probability of re-hit must be sufficiently low. For this purpose the following conservative and simplifying assumptions are made, as per the DNV standard *DNV-RP-H103*:

- The hoisting velocity, V_c , is constant during the lift
- The lifted object is leaving the barge as the relative vertical motion between the barge and the crane hook has a maximum
- Only the first possible hit is considered
- The probability that the lifted object will be hit by the barge more than once is practically zero

The probability, P, that the lifted object will be hit by the barge at the next maximum value of the relative motion can be approximated by the method in Equation 2. The equations, method and resulting graph are all taken from the Det Norske Veritas (DNV) standard [8].

$$P(\tau) = \frac{1}{2} \exp\left(-\frac{\tau^2}{2}\right) \left[1 - \frac{\tau\sqrt{\pi}}{2} \exp\left(\frac{\tau^4}{2}\right) \operatorname{erfc}\left(\frac{\tau}{2}\right)\right]$$

Where:

$$\tau = \frac{V_c \cdot T_z}{\sigma}$$

where:

$$T_z = \text{zero up-crossing period for relative motion} \quad (2)$$

$$\sigma = \text{Standard deviation of relative motion}$$

and:

$$\operatorname{erfc}(x) = \frac{2}{\sqrt{\pi}} \int_x^\infty e^{-t^2} dt$$

Being the complementary error function

As per the standard, the resulting graph when plotting the probability as a function of the non-dimensional number τ can be seen in Figure 6. The guidance notes for this graph states that:

During a series of 10 lifting operations one may require that the total acceptable probability is 0.01. Hence the required probability P for each lift should be less than 0.001. ...this requires $UT_z/\sigma > 2.9$

From this it is possible to estimate the max value of the standard deviation of the relative motion between the barge and the lifting object.

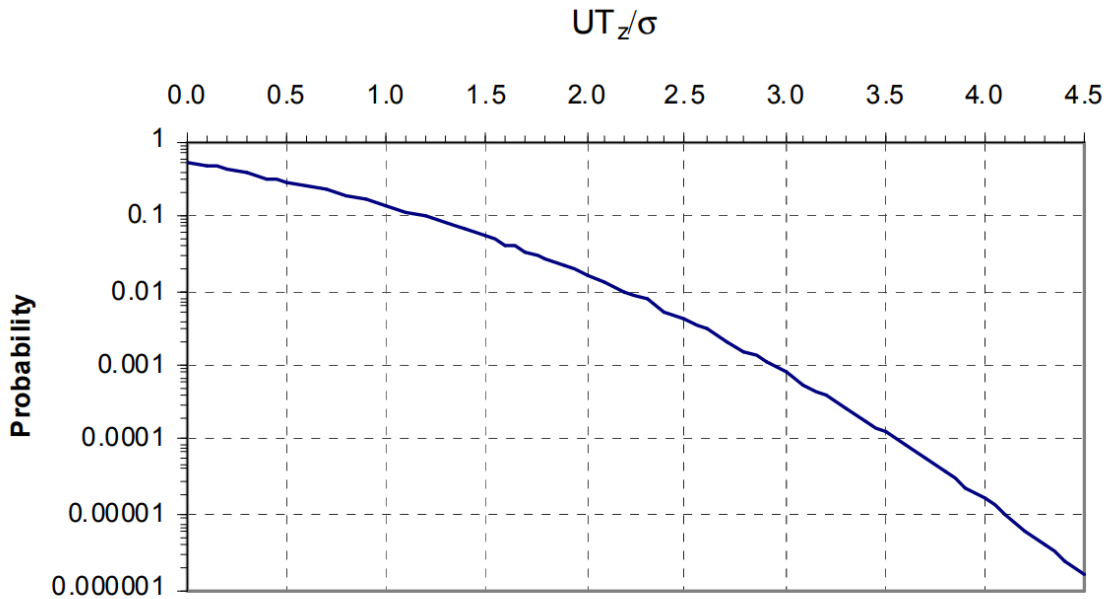


Figure 6: Probability of re-impact on the next maxima made by DNV[8]

2.4 Hydrodynamic loads and vessel RAO

2.4.1 Hydrodynamic loads on jack-up

When a jack-up vessel has its hull elevated above the sea the hydrodynamic loads acts on the legs. This is shown in Figure 7. The hydrodynamic loads on the legs can be estimated from by the use of the Morison equation if the ratio of the wavelength to the diameter of the leg is greater than 5 (or less than 0.2 for the ratio of the diameter of the leg to the wavelength). The ratio can be seen in Figure 8. Note that the descriptions are in Norwegian, however the area where the Morison equation (MORISON LIGNING) can be used can clearly be seen. In this area the mass forces are the dominating forces (Massekrefter dominerende). The wave potential, velocity, acceleration for deep water, Morison equation and method for finding the total force on a cylinder can be seen in Equation 3. The use of the equation is by simplifying the legs to a cylinder submerged vertically in water as seen in Figure 9 [9][10].

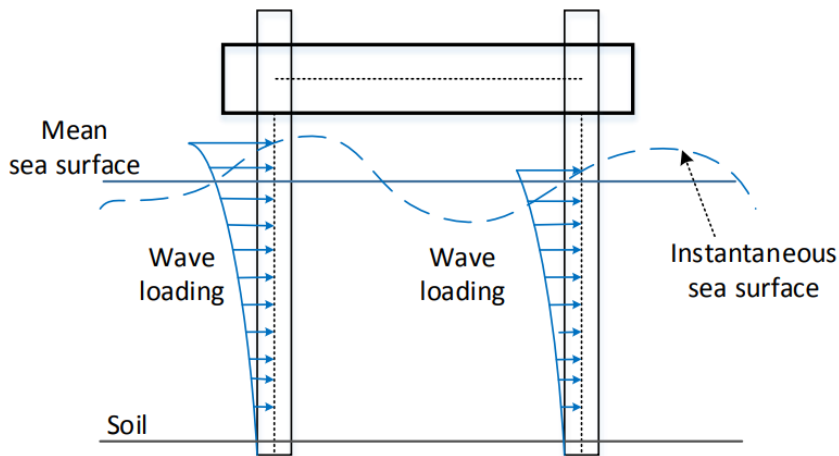


Figure 7: Hydrodynamic loads on the jack-up [11]

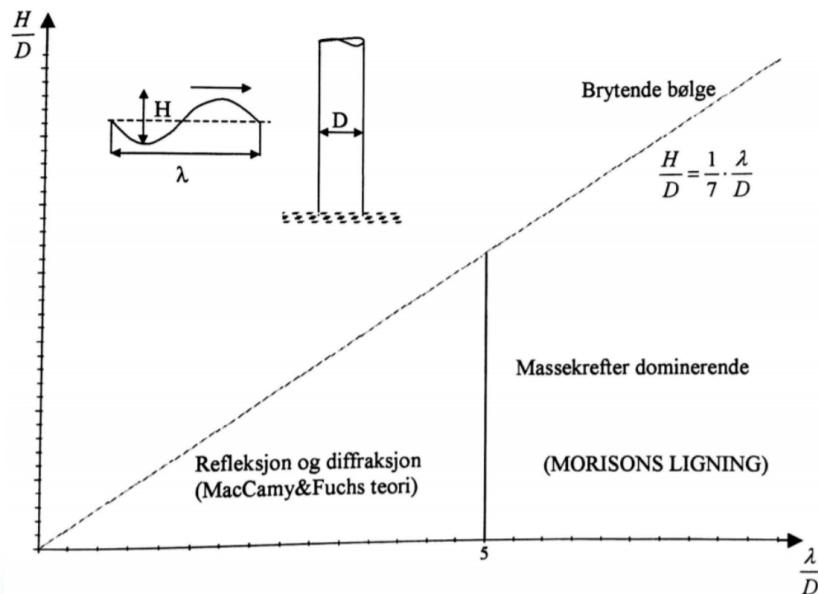


Figure 8: Area defining use of Morison equation, here H = wave height (MORISON LIGNING = Morison equation, Massekrefter dominerende = Mass forces dominating, Refleksjon og diffraksjon = Reflection and diffraction, Brytende bølge = Breaking wave) [12]

Deep water when:

$$\frac{H_{height}}{\lambda} > \frac{1}{2}$$

Wave velocity potential:

$$\phi(x, z, t) = \frac{g\zeta_a}{\omega} \cdot e^{kz} \sin(kx - \omega t)$$

x-component of wave velocity:

$$u = \frac{\partial \phi}{\partial x} = \frac{kg\zeta_a}{\omega} \cdot e^{kz} \cos(kx - \omega t)$$

x-component of wave acceleration:

$$\dot{u} = \frac{\partial \phi}{\partial t} = kg\zeta_a e^{kz} \sin(kx - \omega t)$$

Morison equation:

$$dF = \rho \frac{\pi D^2}{4} C_M a_x dz + \frac{1}{2} \rho C_D Du |u| dz$$

And to find the total force on the cylinder integration along the the cylinder length below sea must occur

$$F_{tot} = \int_{-H}^0 dF$$

(3)

Where:

H_{height} = Wave height

λ = Wave length

$\phi(x, z, t)$ = Wave potential

u = Wave velocity

$\dot{u} = a_x = \ddot{\phi}$ = Wave acceleration

g = Gravitational constant

ζ_a = Wave amplitude

ω = Angular frequency

k = Wave number

z = Water depth

x = Horizontal position

t = Time

ρ = Water density

D = Diamter of cylinder

C_M = Inertia coefficient

C_D = Drag coefficient

H = Water depth

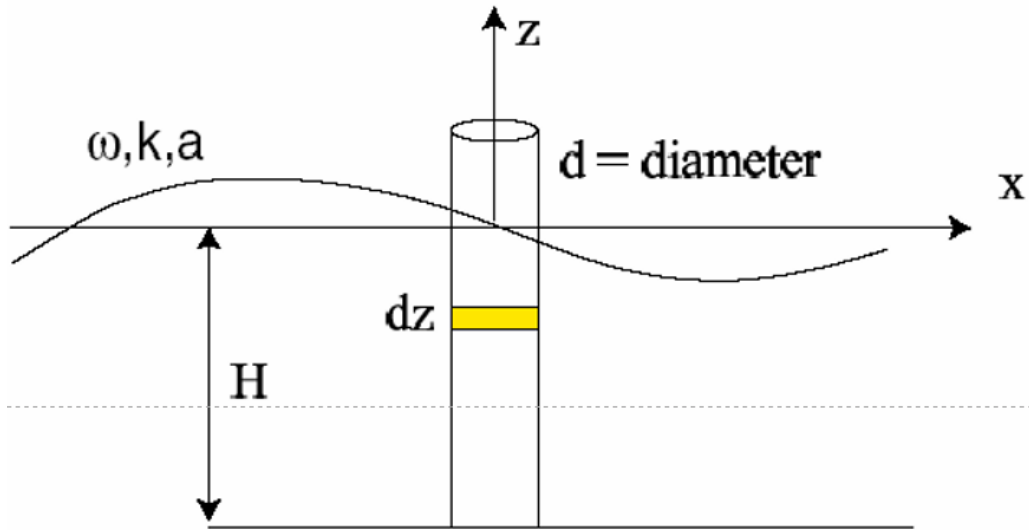


Figure 9: Visual representation of a cylinder vertically submerged in water, here $H =$ water depth [10]

2.4.2 Hydrodynamic loads on feeder barge and vessel RAO

For floating vessels the hydrodynamic loads are calculated based on potential flow theory. In a linear model the resulting wave motion may be considered as a superposition of the forces on a restrained body in waves and the forces acting on a body moving harmonically in still water. The total load, based on Newton's 2nd law then becomes a combination of the hydrodynamic forces, constraining forces and control forces. The hydrodynamic forces consists in turn of the excitation and the radiation loads. This is shown in Figure 10. A simple equation of the total load is shown in Equation 4. Note that if one were to include a mooring system this would be calculated as *constraining forces*.

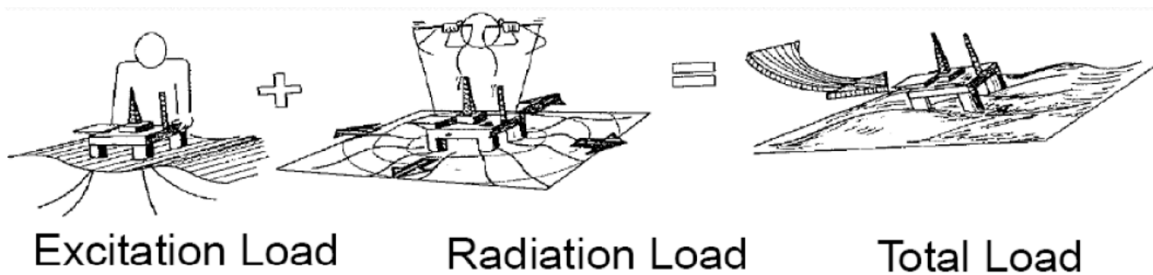


Figure 10: Total hydrodynamic loads with a force superposition assumption

$$M \cdot \ddot{\eta}_3(t) = \sum F(t)$$

Where:

M = Mass

$\ddot{\eta}_3(t)$ = Acceleration in heave vertical heave direction

Total forces:

$$\sum F = F_{Hyd} + F_{const} + F_{ctrl}$$

Where:

F_{Hyd} = Hydrodynamic loads

F_{const} = Constraining forces(mooring systems)

F_{ctrl} = Control forces(generated by acutators)

(4)

$$F_{Hyd} = F_{FK} + F_{Diff} + F_{Rad} + F_{Visc} + F_{Rest}$$

Where:

Excitation load:

F_{FK} = Froude-Krylov forces

F_{Diff} = Diffraction forces

Radiation load:

F_{Rad} = Radiation forces

F_{Visc} = Viscous forces

F_{Rest} = Restoring forces

The likely behaviour of a vessel is determined by its Response Amplitude Operator (RAO). An RAO is the response amplitude of a vessels motion in a set DOF relative to a wave amplitude causing that motion. RAOs are usually calculated for multiple wave headings and all Degree of Freedom (DOF). Figure 11 shows a simple description of a vessels DOF. Another type of RAOs of importance are the force RAOs. Instead of motion these RAOs represent the load on the vessel. This is useful if the vessel is constrained [14] [15].

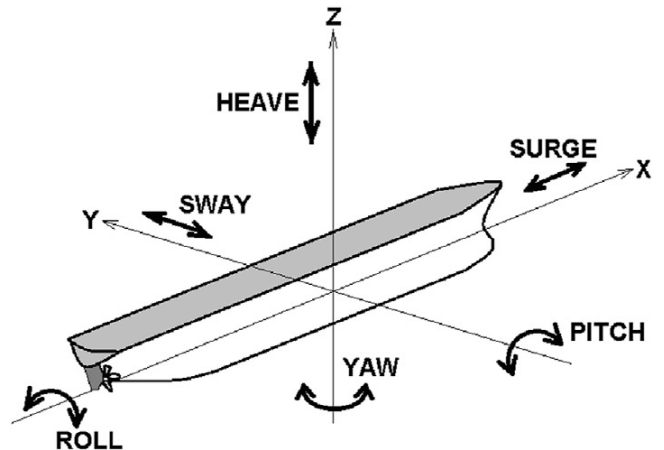


Figure 11: A vessels DOF [13]

2.5 Analysis of irregular waves

An irregular sea state, or the wave situation in the open sea, can be represented by a sum of harmonic wave components with different amplitudes, frequency and direction. A combined wave elevation time series can be seen in Figure 12.

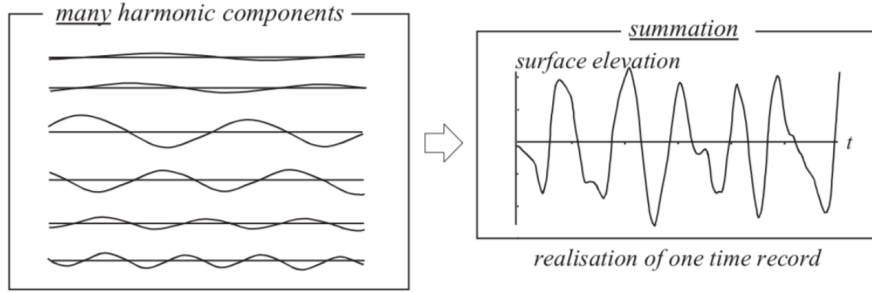


Figure 12: Many harmonic components, summed

A simple statistical analysis of the time series can be done by:

- Measuring all the wave heights and classify them in groups according to their height
- Defining the frequency quotient of a wave group by use of the number of waves within the group and subsequently establish a discrete distribution function
- Establish the cumulative frequency quotient or the cumulative distribution function

From the grouping it is possible to calculate the mean wave height, \bar{H} , and the significant wave height, H_s . By extent, it is also possible to calculate the standard deviation, σ , of the time series. These are shown in Equation 5 [16].

$$\bar{H} = \frac{\sum_{n=1}^N (\bar{H}_I \cdot N)}{N_{tot}}$$

$$H_s = H_{1/3} = \frac{1}{\frac{1}{3}N} \sum_{n=1}^{\frac{1}{3}N} H_m$$

$$\sigma = \sqrt{\frac{1}{N-1} \sum_{n=1}^N \zeta_n^2}$$

(5)

Where:

\bar{H}_I = Wave height average relative to an interval

N = Number of waves

N_{tot} = Total number of waves

H_s = Significant wave height

H_m = The individual wave heights

σ = Standard deviation

ζ_n = Amplitude of individual, n, wave

Moreover, Equation 6 - 9 shows further methods of analysing an irregular sea state. Notice the second method of calculating the significant wave height based on the zeroth spectral moment, H_{m0} .

$$m_k = \int_{f=0}^{\infty} f^k S(f) df$$

Where:

m_k = The kth spectral moment

f = Frequency of wave

$S(f)$ = Spectrum as a function of frequency

(6)

$$H_M = 2\sqrt{2m_0 \ln N}$$

Where:

H_M = The most probable extreme wave height

m_0 = The zeroth moment of the wave spectrum(σ^2)

$$N = \frac{T_L}{T_s}$$

T_L = Long period waves

T_s = Short period waves

(7)

$$H_{m0} = 4\sqrt{m_0}$$

Where:

H_{m0} = Significant wave height

m_0 = The zeroth moment of the wave spectrum(σ^2)

(8)

$$T_z = T_{m02} = \sqrt{\frac{\int_{f=0}^{\infty} S(f) df}{\int_{f=0}^{\infty} f^2 S(f) df}}$$

(9)

Where:

T_z = Mean wave period

In addition to this two important wave spectrum can be seen in Figure 12. These are the Pierson-Moskowitz, denoted as $S_{PM}(f)$ and JONSWAP, denoted as $S(f)$, wave spectrum. Equation 10 shows the formulation of both, while Figure 13 shows the plot of both. From the equations it is seen that the JONSWAP spectrum is a Pierson-Moskowitz spectrum multiplied by a peak enhancement factor [17].

$$S_{PM}(f) = \frac{A \exp \frac{-B}{f^4}}{f^5}$$

Where:

$$A = \frac{5}{16} H_{m0}^2 f_p^4$$

$$B = 5 \frac{f_p^4}{4}$$

Where:

f_p = Peak frequency

(10)

$$S_J(f) = S_{PM}(f) \gamma^{\exp \left(\frac{-(f-f_0)^2}{2\sigma^2 f_0^2} \right)}$$

Where:

$$\gamma^{\exp \left(\frac{-(f-f_0)^2}{2\sigma^2 f_0^2} \right)} = \text{Peak enhancement factor}$$

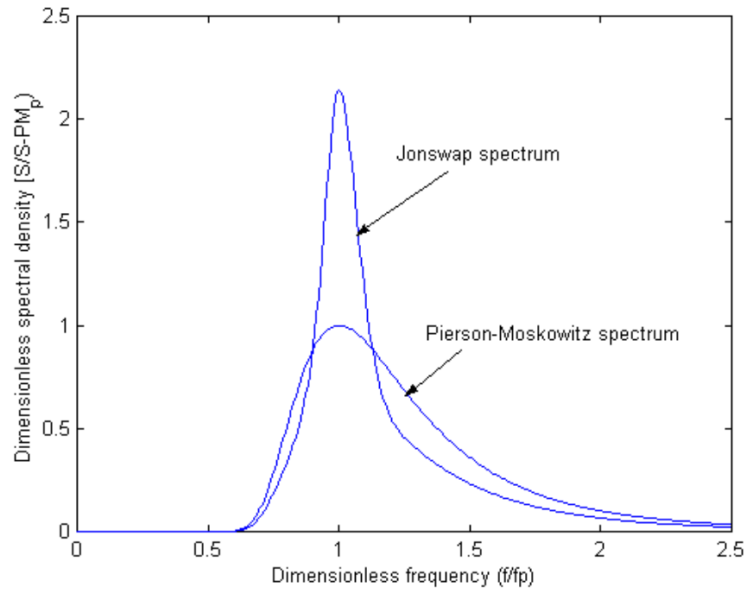


Figure 13: Plot of Pierson-Moskowitz and JONSWAP wave spectrum [18]

2.6 Jack-up soil-structure interaction

A general method of modelling the jack-up soil-structure interaction is by the use of linear springs and dampers. Its real life counterparts are that of spudcans on the jack-up legs. These can be seen on the bottom of the legs in Figure 14. The soil reaction force as a function of displacement for a spudcan can be expressed as shown in Equation 11. Figure 15 shows a linear springs and dampers model of the soil-structure interaction using spudcans.

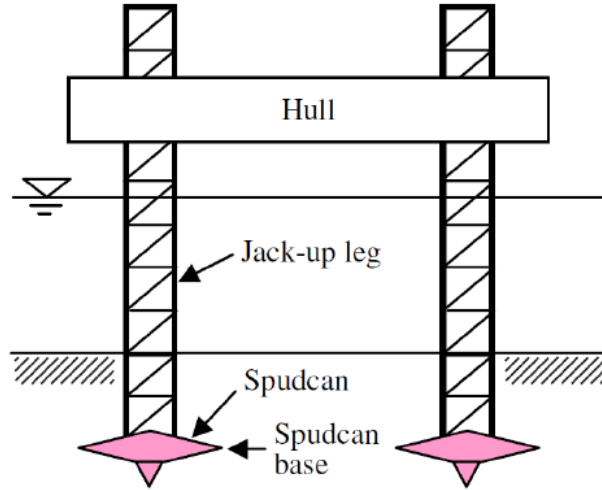


Figure 14: Jack-up including spudcans [19]

$$F_s = \mathbf{K}X + \mathbf{C}\dot{X}$$

Where:

F_s = Soil reaction force

\mathbf{K} = Soil stiffness vector

X = Spudcan displacement

\mathbf{C} = Damping vector of soil

(11)

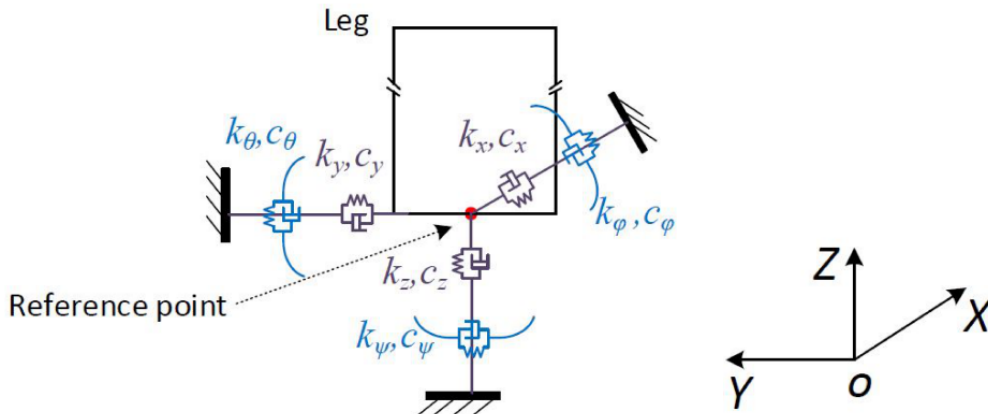


Figure 15: Soil-structure interaction [20]

2.7 Aerodynamic loads on the turbine rotor blade

Aerodynamic loads on a turbine rotor blade exist due to a relative inflow velocity on the blade and its angle of attack. To calculate the aerodynamic loads the steady-state lift and drag coefficients are used. In addition, a moment coefficient is used to calculate the pitching moment about the z-axis. Figure 16 shows an illustration of the co-ordinate system and aerodynamic load components on an airfoil, while Equation 12 shows the equations for the lift and drag force and the pitching moment about the z-axis.

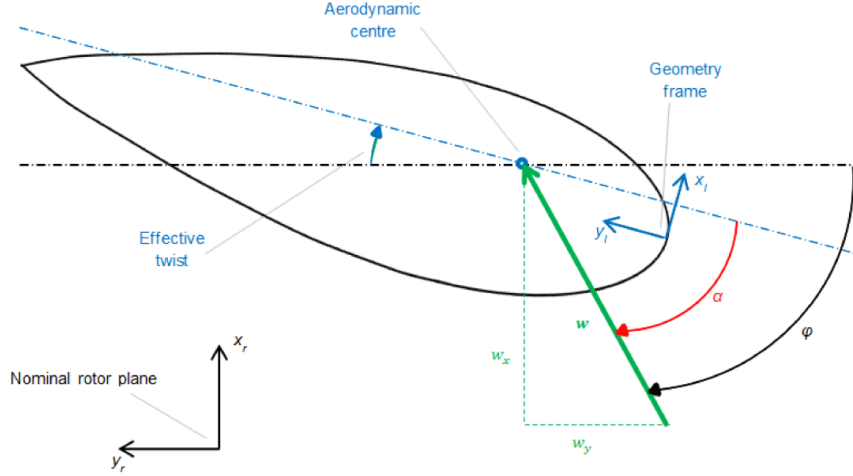


Figure 16: Co-ordinate system and aerodynamic load components on an airfoil section [21]

The lift force is given by:

$$f_L = \frac{1}{2} \rho A C_L(\alpha) |\omega|^2$$

The drag force is given by:

$$f_D = \frac{1}{2} \rho A C_D(\alpha) |\omega|^2$$

The pitching moment about the z-axis is given by:

$$m_z = \frac{1}{2} \rho A c C_M(\alpha) |\omega|^2$$

(12)

Where:

ρ = Air density

α = Angle of attack

ω = Relative inflow velocity

A = Element area

c = Chord length

C_L = Lift coefficient

C_D = Drag coefficient

C_M = Moment coefficient

2.8 Current heave compensation systems

There are three groups of heave compensation systems. These are *passive*, *active* or a mix of both. Passive systems are in principle a pure spring-damper system which do not require any input of energy during operation. A spring-damper showcasing this can be seen in Figure 17. On the other hand, an example of an active system could be actively controlled winches and actively controlled hydraulic pistons. To control the active system a reference signal must be available. This can be [23]:

- Wire tension
- Crane top motion
- Winch or hydraulic piston motion
- Object position
- Reference point or relative motion
- Vessel motion
- Waves and current

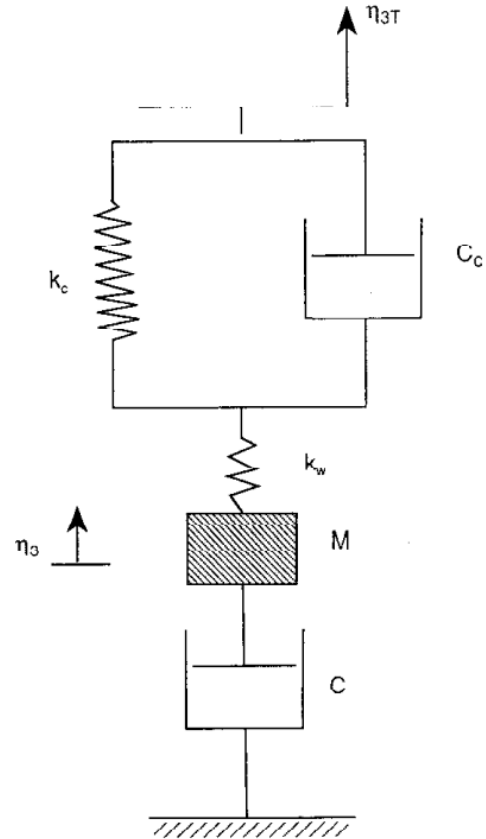


Figure 17: Spring-damper system for passive heave compensation [22]

2.9 SIMA modelling

SIMA is a marine operations and mooring analysis software used for efficient analysis of complex multi-body systems. The software is a complete tool for simulation of marine operations from modelling to results [24].

2.9.1 SIMO

SIMO is a computer program for simulation of motions and station-keeping behaviour of complex systems of floating vessels and suspended loads. It uses the three separate modules titled STAMOD, DYNMOD and S2XMOD to calculate initial condition and static equilibrium, for dynamic response calculations and to export time series to various file formats. SIMO is also important for equations of motion in kinetics for rigid bodies moving in water. Other qualities of SIMO include calculations of environmental factors and different formulations of these factors such as wind, wave and current formulations [25] [26] [27].

A useful wind formulations in SIMO is the ISO 19901-1 wind spectrum (International Organization for Standardization (ISO)), previously referred to as the NPD spectrum (Norwegian Petroleum Directorate (NPD)). For strong wind conditions the design wind speed, $u(z, t)$ (m/s) at height z (m) above sea

level and corresponding to an averaging time period $t \leq t_0 = 3600(s)$ is given by Equation 13:

$$u(z, t) = U(z)[1 - 0.41 \cdot I_u(z) \cdot \ln\left(\frac{t}{t_0}\right)]$$

Where the 1 hour mean wind speed $U(z)$ is given by

$$U(z) = U_0[1 + C \cdot \ln\left(\frac{z}{10}\right)]$$

$$C = 5.73 \cdot 10^{-2}(1 + 0.15 \cdot U_0)^{0.5} \quad (13)$$

and where the turbulence intensity factor $I_u(z)$ is given by

$$I_u(z) = 0.061 + 0.043 \cdot U_0\left(\frac{z}{10}\right)^{-0.22}$$

Where $U_0 (m/s)$ is the 1 hour mean wind speed at 10 m

An important wave spectrum formulation is that of the JONSWAP spectrum. In SIMA this is formulated as shown in Equation 14:

$$S_{\zeta}^+(\omega) = \frac{\alpha g^2}{\omega^5} \exp\left(-\beta\left(\frac{\omega_p}{\omega}\right)^4\right) \gamma^{\exp\left(\frac{(\frac{\omega}{\omega_p}-1)^2}{2\sigma^2}\right)}$$

Where:

α = Spectral parameter

ω_p = Peak frequency

γ = Peak dense parameter(or peak enhancement factor)

β = Form parameter

σ = Spectral parameter with default values:

$\sigma_a = 0.07$ for $\omega < \omega_p$

$\sigma_b = 0.09$ for $\omega > \omega_p$

(14)

The current in SIMO is formulated as a profile with specified directions and speeds at different levels. It is used linear interpolation to determine the current velocity between points defined in the profile, and if the profile does not cover the complete water column, the current is assumed to be constant outside the tabulated range [28].

2.9.2 RIFLEX

RIFLEX is a computer program for analysis of slender structures, such as mooring lines. RIFLEX uses a catenary analyses, Static Catenary Analysis, and a fully nonlinear Finite Element Method (FEM) analysis, Static Finite Element Analysis, as a static analysis method and a linear and nonlinear time domain analysis, Dynamic Time Domain Analysis and Eigenvalue Analysis, as a dynamic analysis method. In addition to this, RIFLEX uses beam elements and different load models and forced motion excitation for hydrodynamic and aerodynamic loads, and contact force models such as a seafloor contact formulation to describe contacts between objects. The seafloor contact formulation includes contact normal to the seafloor modelled by springs and in-plane contact modelled by a combination of springs and frictional forces[29] [30] [31].

3 Modelling the operation

3.1 Modelling steps

The modelling of the operation was done by collecting physical data including metocean data for the model, designing and modelling the rigid bodies in Sesam GeniE, then conducting a hydrodynamic analysis for the floating barges in Sesam HydroD to obtain their RAOs. The last steps were to set up the operation with a coupled RIFLEX-SIMO model in SIMA, then run the specific simulations with the metocean data. A flowchart of the modelling steps can be seen in Figure 18.

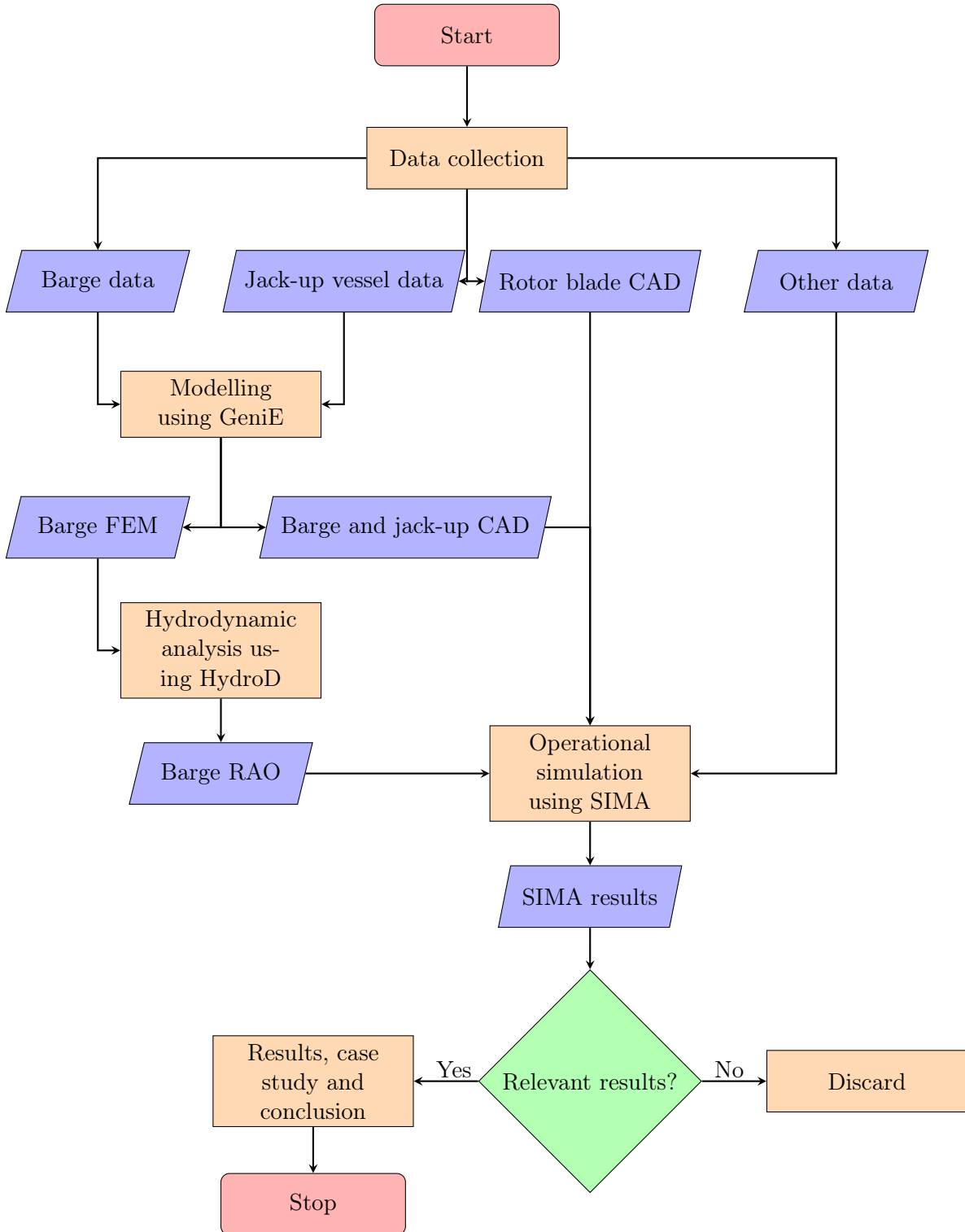


Figure 18: Modelling steps flowchart

3.2 Physical data

The physical data collected for this model were that of the jack-up vessel used, 2D dimensions of one of the barges, the rotor blade and the metocean data.

3.2.1 Jack-up

The jack-up vessel chosen for this model was that of the Fred. Olsen Windcarrier owned "Bold Tern". The reason for choosing this particular jack-up vessel was mainly the shape of its legs being cylindrical and therefore easier to model than other vessels. The Bold Tern can be seen in Figure 19 while the principal dimensions, weights and natural sway periods can be seen in Table 1. The data was collected from the Det Norske Veritas Germanische Lloyd (DNV GL), now DNV, report *Hull Sway Accelerations Study to ISO 19905-1* provided by Fred. Olsen Windcarrier. It is seen that natural sway periods in wave direction of 000 ($^{\circ}$), 045 ($^{\circ}$) and 090 ($^{\circ}$) at a leg length below the hull of 47.5(m) for the jack-up are short. Subsequently, the assumption that the vessel stiffness when stationary above sea resting on the legs was made to be high [32].

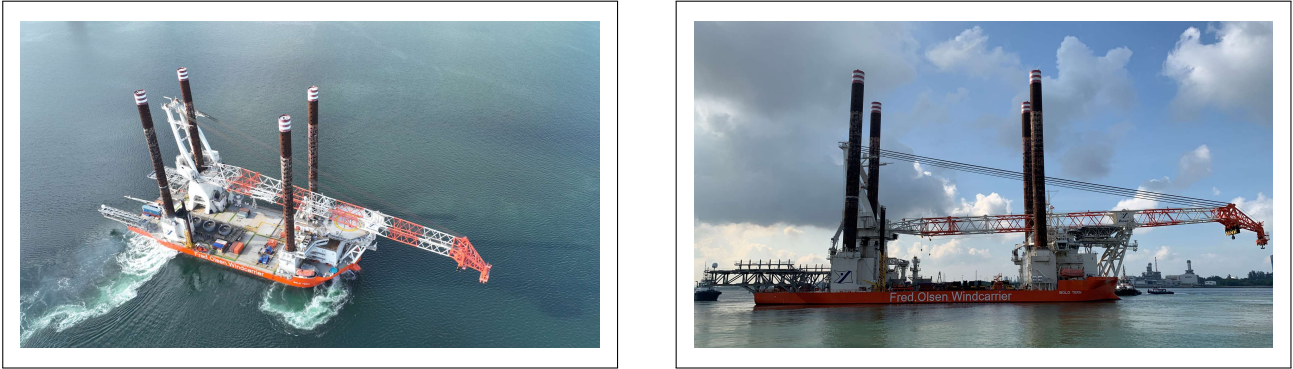


Figure 19: Bold Tern [33] [34]

Table 1: Bold Tern Principal Dimensions

Bold Tern Principal Dimensions, Weights and Natural Sway Period *

Length of Hull	(m)	132.0
Breadth of Hull	(m)	39.0
Depth of Hull	(m)	9.0
Leg Length	(m)	92.4
Longitudal Leg Spacing	(m)	68.3
Transverse Leg Spacing	(m)	30.6
Leg Outer Diameter	(m)	4.5
Operational Airgap	(m)	7.5
Hull Lightship Weight	(tonnes)	11,876
Mass of Single Leg, Including Spudcan	(tonnes)	1,056
Natural Sway Periods, Wave Direction 000 ($^{\circ}$), Leg Length 47.5(m)	(s)	2.9 - 3.7
Natural Sway Periods, Wave Direction 045 ($^{\circ}$), Leg Length 47.5(m)	(s)	2.9 - 3.7
Natural Sway Periods, Wave Direction 090 ($^{\circ}$), Leg Length 47.5(m)	(s)	2.9 - 3.7

* Data provided by Fred. Olsen Windcarrier.

3.2.2 Wind turbine rotor blade

For the modelling of the rotor blade a 15-MW reference turbine rotor blade, *IEA 15-MW*, developed by International Energy Agency (IEA) Wind was used. The model and the tabular for the physical data was downloaded and the Center of Gravity (COG) was verified. Figure 20 shows the geometry of the blade and Table 2 shows it's weight and COG. Note the axis cross in the origin of the geometry, as the COG is relative to this [35] [36].

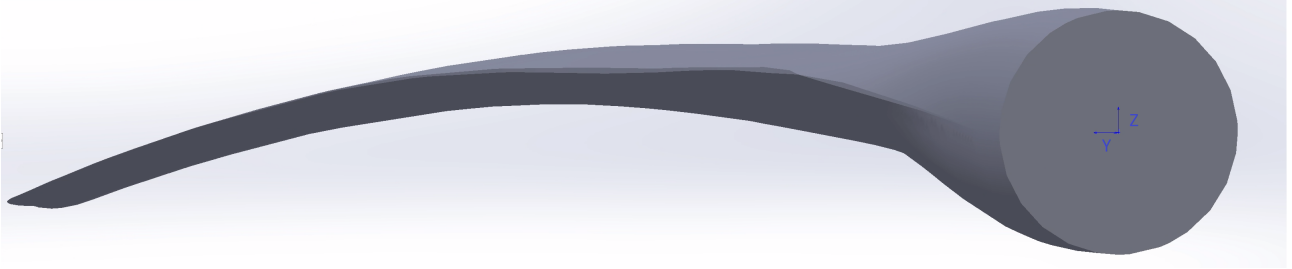


Figure 20: IEA 15-MW reference turbine rotor blade

Table 2: IEA 15-MW Wind Turbine Rotor Blade data

IEA 15-MW Physical Data		
Model Designation		IEA-15-240-RWT
Weight	(tonnes)	68.415
COG X-direction	(m)	30
COG Y-direction	(m)	0
COG Z-direction	(m)	0

3.2.3 Barges

Three barges were designed, all with different lengths while had the same depth. These were designed with the intent to see what happens when the length was alternated. The barges were designed to have enough displacement to carry the turbine rotor blade. The main dimensions of the three can be seen in Table 3, while Figure 21 shows a sketch of the first barge, Barge 1, were the change to the second and third were the dimensions only.

Table 3: Main dimensions of the barges

Barges Main Dimensions

Barge 1	(m)	(feet)
Length	122.0	400.0
Breadth	32.0	105.0
Depth	6.5	21.3
Barge 2		
Length	92.0	302.0
Breadth	32.0	105.0
Depth	6.5	21.3
Barge 3		
Length	152.0	499.0
Breadth	32.0	105.0
Depth	7.0	23.0

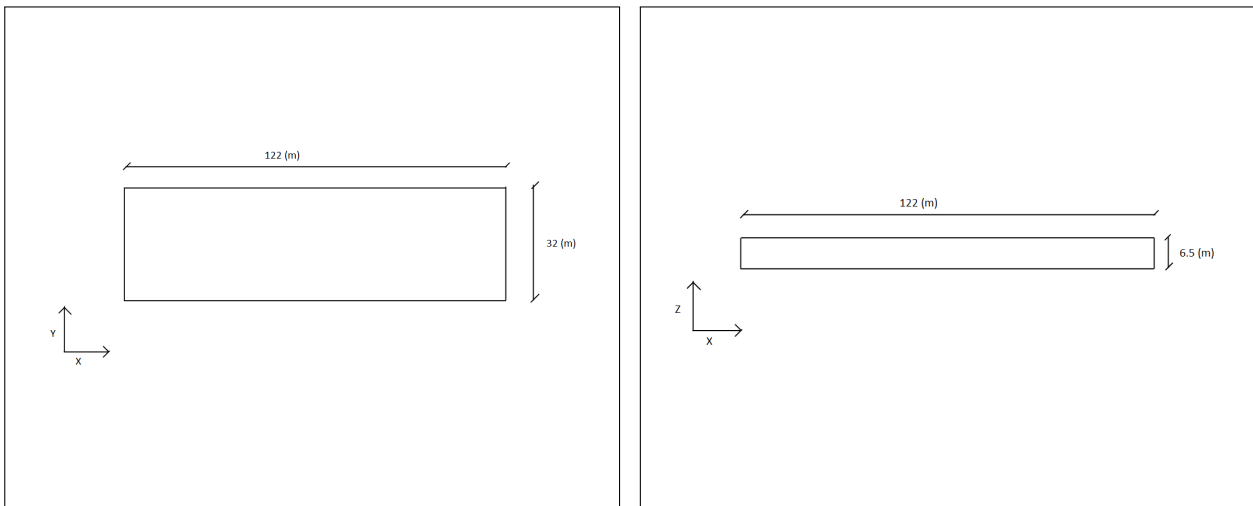


Figure 21: Sketch of Barge 1

3.2.4 Vessel material

For the design of the rigid bodies the material Aluminium Alloy 5083 was used. This was based on the assumption that the material is commonly used for shipbuilding . The properties of this material is shown in Table 4 [37].

Table 4: Aluminium properties

Aluminium Alloy 5083		
Yield	(Pa)	228000000
Density	(kg/m^3)	2650
Young's Modulus	(Pa)	7.2e+10
Poisson	(-)	0.3

3.2.5 Station-keeping system

To keep the barges at the side of the jack-up a station-keeping system was designed. This consists of traditional mooring using polypropylene mooring ropes and three vertical beams on the side of the jack-up vessel. The reasons for using polypropylene mooring ropes were that traditional mooring would most likely be less complex to use and that polypropylene mooring lines would maintain elasticity of the system and provide a safety factor in case the system should fail. The parameters used for the mooring lines are shown in Table 5 while a sketch of the mooring arrangement can be seen in Figure 22. Note that the mooring lines are shown in red and the vertical beams are shown in green.

Table 5: Mooring lines parameters

Mooring Lines		
Type		Polypropylene
Mass Coefficient	(kg/m)	2.0636
External Area	(m^2)	0.21362
Internal Area	(m^2)	0.0
Gyration Radius	(m)	0.01
Thermal Temperature	(C)	20.0
Axial Stiffness	(N)	1.06e+06
Bending Stiffness	(Nm^2)	4.2e+07
Torsion Stiffness	(Nm^2/rad)	1.4e+09

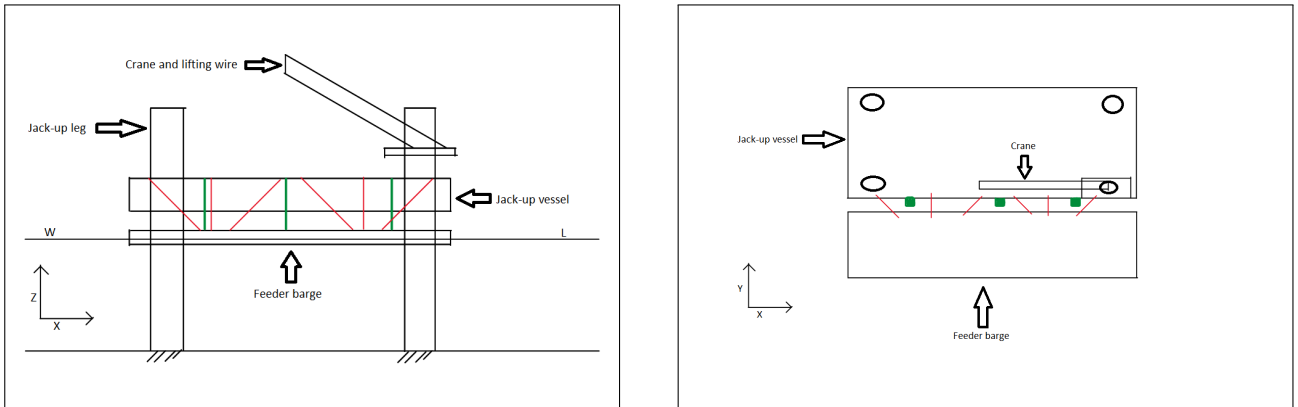


Figure 22: Sketch of Barge 1

3.2.6 Metocean data

The metocean data used for this model was given by the industry contact in Equinor. These can be seen in Table 6.

Table 6: Metocean data provided by Equinor

Metocean Data *		
Wave Direction	(°)	000, 045
Water Depth	(m)	20.0 - 65.0
Irregular Waves		
Significant Wave Height, H_s	(m)	1.0 - 2.5
Peak Period	(s)	5.0, 7.0, 9.0, 11.0
Wave Spectrum	(-)	JONSWAP
Peak Enhancement Factor, γ	(-)	$max[1.0; 42.2(\frac{2\pi H_s}{gT_p^2})^{\frac{6}{7}}]$
Spreading function	(-)	2.0
NPD Wind Spectrum		
Wind Velocity	(m/s)	6.0, 8.0, 10.0
Reference Height	(m)	10
Current		
Regular Constant Surface Current	(m/s)	0.6

* Data provided by Equinor.

3.3 Modelling using GeniE

The GeniE Computer-aided Design (CAD) modeller is a powerful FEM modelling and analysis tool for conceptual modelling of offshore and maritime structures used in offshore structural engineering. Here the use of the software was to design the jack-up vessel and the three barges. In addition to these, three FEM meshes for the barges were generated as per DNV recommended practices *DNV-RP-H103* stating that the "*diagonal length of panel mesh should be less than 1/6 of smallest wave length analysed*". The wave length was calculated relative to the shortest wave period from metocean data provided, and the calculation method and mesh value can be seen in Equation 15 [38] [39].

$$\begin{aligned}
 c &= \frac{T \cdot g}{2\pi} \\
 \lambda &= c \cdot T \\
 \lambda &\approx 39.0 (m) \\
 \text{Diagonal mesh} &< \lambda \cdot \frac{1}{6} \\
 \text{Diagonal mesh} &< 6.5 (m)
 \end{aligned} \tag{15}$$

3.3.1 Modelling of the jack-up vessel

The Bold Tern was reverse engineered and modelled using the model parameters, and the thickness of the hull was defined to be 0.15 meters. This means assumptions were made for the modelling. The design parameters, mass and COG of the jack-up can be seen in Table 7. The model of the jack-up vessel can be seen in Figure 23.

Table 7: Design parameters, weight and COG of Jack-up

Jack-up Design Parameters		
Material	(-)	Aluminium Alloy 5083
Thickness of Hull	(m)	0.15
Weight and COG *		
Mass	(tonnes)	11,876
COG X-direction	(m)	2.5
COG Y-direction	(m)	-0.3
COG Z-direction	(m)	-0.2

* COG in relation to center of jack-up.

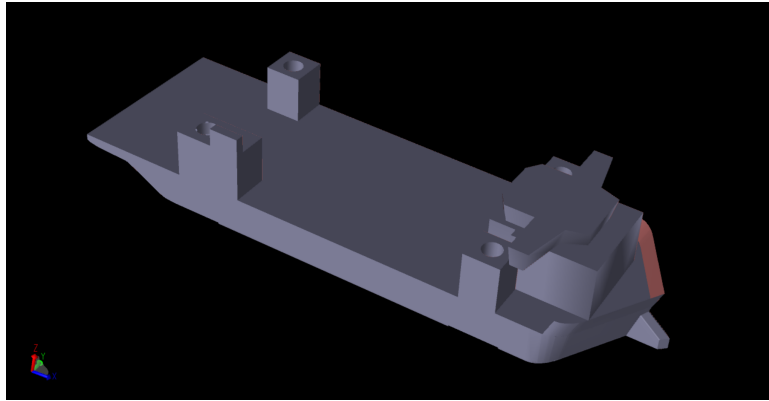


Figure 23: CAD of the Bold Tern

3.3.2 Modelling of the barges

The GeniE software was used to model the barges. The design parameters including the material, thickness and mesh size can be seen in Table 8, while the dimensions of the barges including the mass and COG can be seen in Table 9. The CAD and FEM model can be seen in Figure 24-26.

Table 8: Material, hull thickness and mesh size for the Barges

Design parameters of the Barges		
Material	(-)	Aluminium Alloy 5083
Thickness of Hull	(m)	0.15
Mesh Barge 1	(m)	1
Mesh Barge 2	(m)	1
Mesh Barge 3	(m)	1

Table 9: Extended dimensions

Barges Main Dimensions(with mass)

COG in relation to center of barge		
Barge 1	(m)	(feet)
Length	122.0	400.0
Breadth	32.0	105.0
Depth	6.5	21.3
Mass	(tonnes)	3955.3
COG X-direction	(m)	8.8e-10
COG Y-direction	(m)	1.4e-10
COG Z-direction	(m)	-3.14
Barge 2		
Length	92.0	302.0
Breadth	32.0	105.0
Depth	6.5	21.3
Mass	(tonnes)	3058.7
COG X-direction	(m)	4.4e-05
COG Y-direction	(m)	-1.0e-05
COG Z-direction	(m)	-3.14
Barge 3		
Length	152.0	499.0
Breadth	32.0	105.0
Depth	7.0	23.0
Mass	(tonnes)	5007.7
COG X-direction	(m)	-1.12e-07
COG Y-direction	(m)	2.15e-07
COG Z-direction	(m)	-3.4

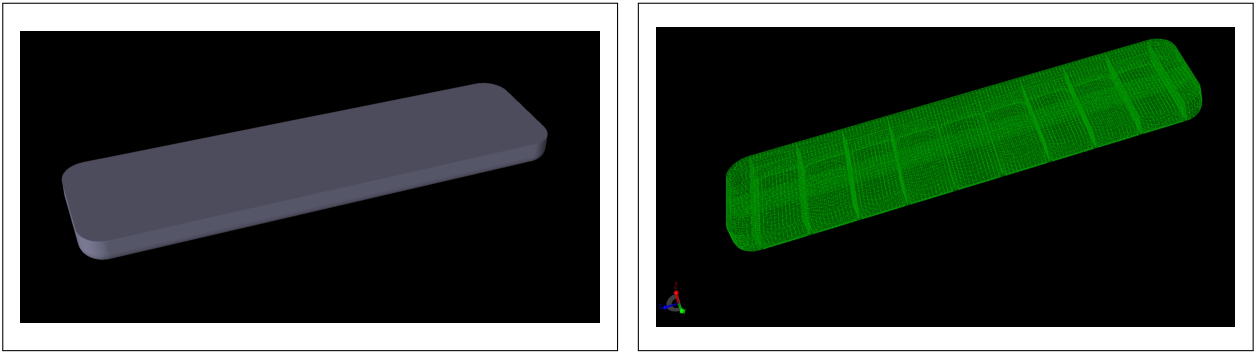


Figure 24: CAD and FEM model of the Barge 1

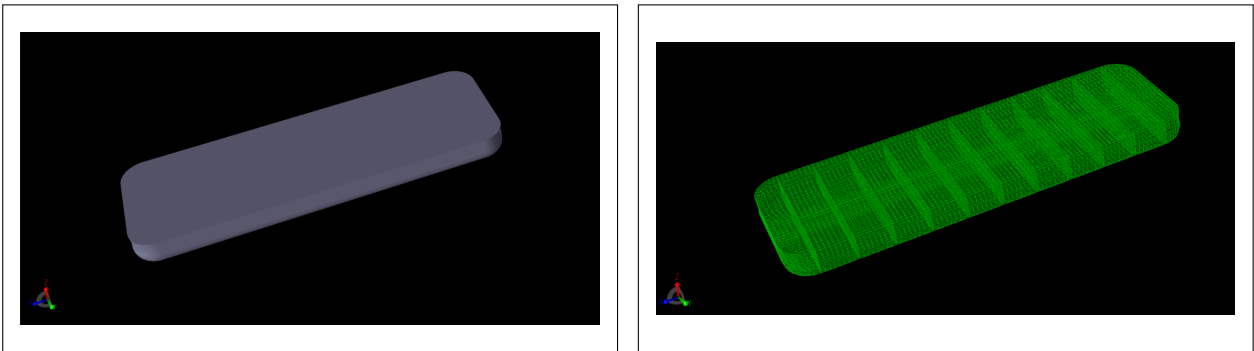


Figure 25: CAD and FEM model of the Barge 2

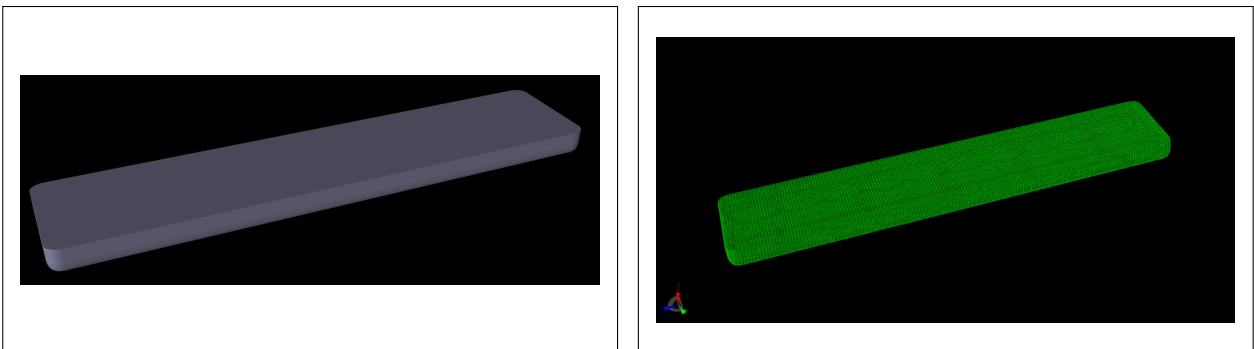


Figure 26: CAD and FEM model of the Barge 3

3.4 Hydrodynamic analysis using HydroD

HydroD is a software package for robust hydrodynamic and stability analysis including fully automated load transfer to finite element analysis developed by DNV, and was used to conduct a hydrodynamic analysis for all floating barges using the FEM files generated from GeniE, to obtain the structures motion and force RAOs. The specific analysis used was a WADAM analysis. The analysis gave a Sesam Interactive File (SIF) for extraction of the data. The set up parameters used for the analysis can be seen in Table 10. Here the peak periods from 7 to 12 seconds were given extra attention to make as accurate RAOs as possible. The resulting RAOs can be seen in chapter 4.2 RAO [40].

Table 10: Parameters of HydroD set up

HydroD set up parameters for all barges

Direction Set		
From	To	Step
0 (°)	360 (°)	45 (°)

Frequency set		
From	To	Step
5 (s)	7 (s)	1 (s)
7 (s)	12 (s)	0.5 (s)
12 (s)	30 (s)	1 (s)

Location		
Gravity	(m/s^2)	9.80665
Water Depth	(m)	65

Water		
Density	(kg/m^3)	1025
Kinematic Viscosity	(m^2/s)	1.19e-06

Air		
Density	(kg/m^3)	1.222
Kinematic Viscosity	(m^2/s)	1.462e-05

Heel Angles		
From	To	Step
-70 (°)	70 (°)	5 (°)

Loading Condition	Balanced

HydroD set up parameters for Barge 1

Roll Damping Model		
From	To	Step
-55 (m)	55 (m)	10 (m)

HydroD set up parameters for Barge 2

Roll Damping Model		
From	To	Step
-40 (m)	40 (m)	10 (m)

HydroD set up parameters for Barge 3

Roll Damping Model		
From	To	Step
-66 (m)	66 (m)	10 (m)

3.5 Numerical modelling using SIMA

SIMA was used to model the operation. The model was made with two parts:

- The SIMO model
- The RIFLEX model

Here the SIMA computations are based on the well-known and highly efficient solvers, SIMO and RIFLEX. As mentioned in chapter 2.7.1, SIMO calculates the equations of motion for rigid bodies in water and environmental factors such as wind, wave and currents. RIFLEX on the other hand, uses beam elements and a fully nonlinear FEM analysis for the static analysis and a linear and nonlinear time domain analysis for its calculations.

Both parts of the model were joined into a coupled RIFLEX-SIMO model under a RIFLEX task consisting of the jack-up vessel, wind turbine rotor blade and a mix between the 3 barges with and without heave compensation. The model was based on another model provided by Dr. Amrit Verma.

3.5.1 SIMO model and numerical implementation including heave compensation

The SIMO model of the operation consists of:

- The rigid bodies
- The kinetics of each body including RAOs of the barges imported from the *.SIF file
- A slender system connection to couple the RIFLEX and SIMO model for each rigid body
- Simple wire couplings
- Bumpers used as fenders in the suggested mooring system

For the models with heave compensation the following parts were included as well:

- Lifting line coupling
- Heave Compensator
- Winch used with the Heave Compensator

Figure 27 show two of the rigid bodies used in the model.

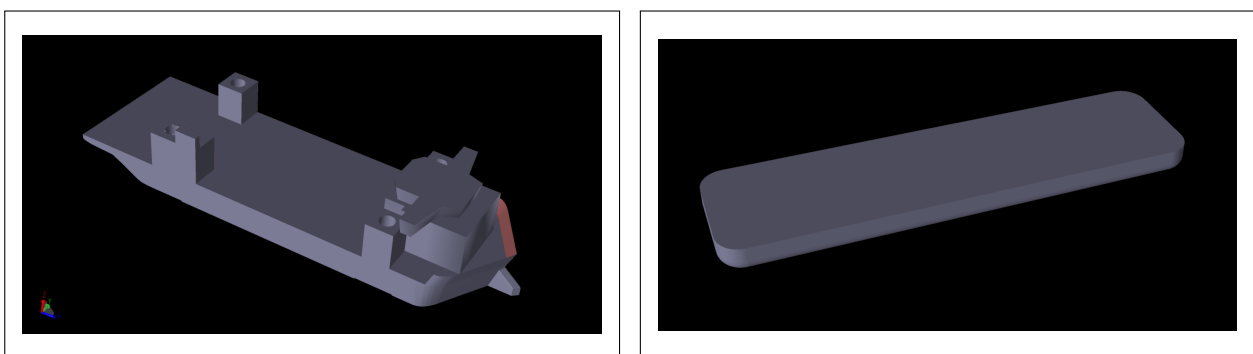


Figure 27: Model of jack-up and Barge 1

The SIMO setup can be seen in Figure 28. The setup was defined under the sub folder "Bodies" and "Couplings". This setup is the same for all models where the only difference is which barge was used and if heave compensation was included. There was in total mad 6 different combinations of the model.

The barges and the jack-up vessel was included under the subfolder bodies, where the RAOs and all other kinematics were imported using a SESAM interactive file, *.SIF file. This makes it easy to model and set up a marine operation in SIMA, and other DNV softwares. The CAD files for the rigid bodies were then imported to have a better view of the bodies in operation.

The rotor blade was imported as a rigid body and was connect to the jack-up model by using two simple wire couplings. These were aimed out from the rotor blade in opposite transverse direction between the body points of the rotor blade and the jack-up).

The heave compensation system was modelled using the winch and the heave compensate functions, "Winch1" and "HeaveCompensator2", and the SIMO lifting wire, "LiftLineCoupling". Figure 29 shows the implementation in SIMA. The winch and the Heave Compensator functions in this model were connected to the jack-up body point; "Jack-upBodyPointTop". This point was located on the top of the lifting line coupling shown in Figure 30.

The SIMO part of the mooring system were that of three bumpers acting as fenders on the outside of the RIFLEX beams. The second connection point of these bumpers are directly across on the side of the barge. This can be seen in Figure 31 on the following page.

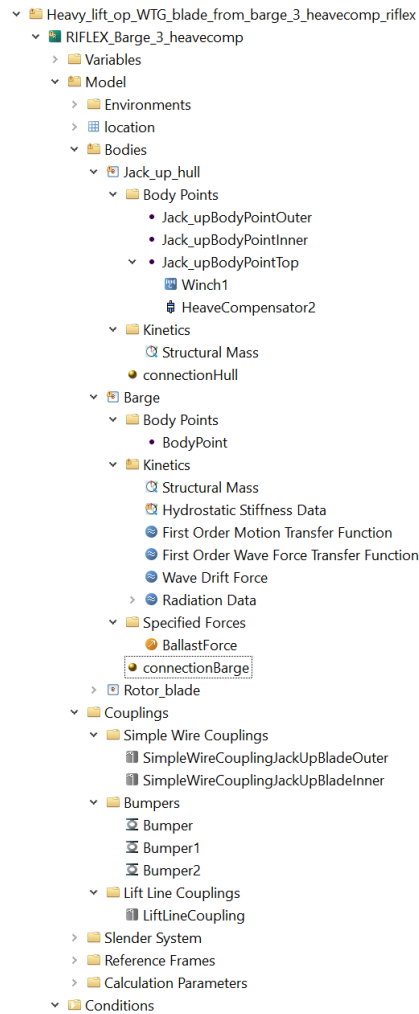


Figure 28: SIMO setup

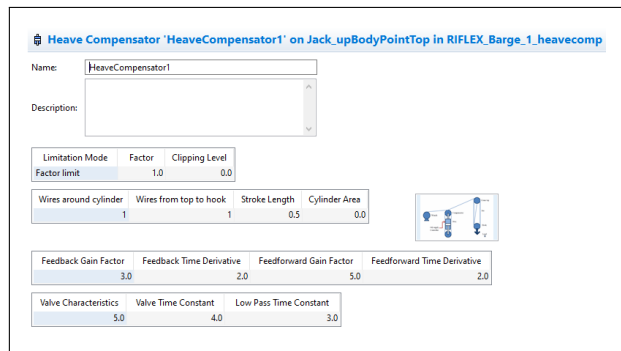
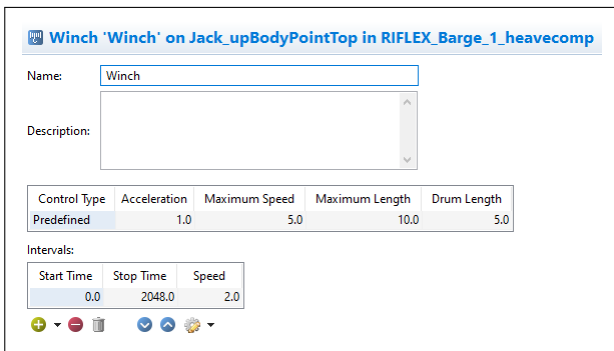


Figure 29: Heave compensation implementation in SIMA

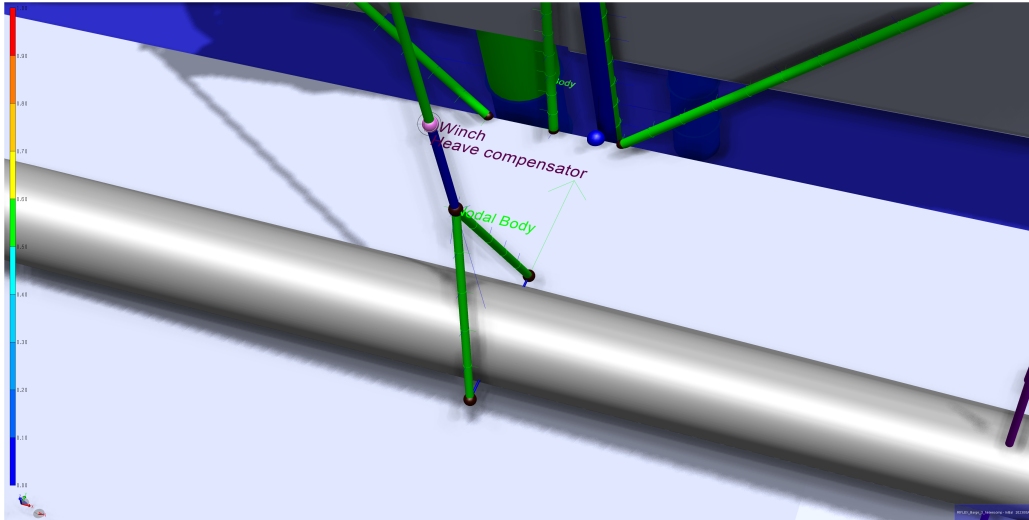


Figure 30: Position of winch and heave compensator

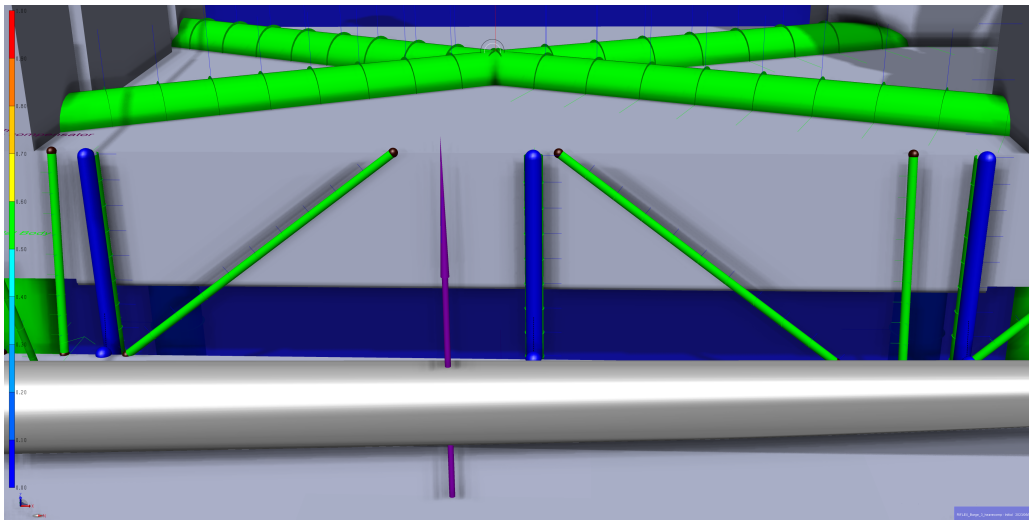


Figure 31: Bumpers used as fenders in the mooring system

3.5.2 RIFLEX model and numerical implementation

A RIFLEX model uses beam elements instead of rigid bodies as a method of modelling. This was used for the modelling of the legs, crane, lifting wire and a suggested mooring system, and became an easier method of modelling than using rigid bodies. With a RIFLEX model SIMA was able to calculate the hydrodynamic loads on the jack-up legs. A full overview of the RIFLEX model used can be seen in Figure 32.

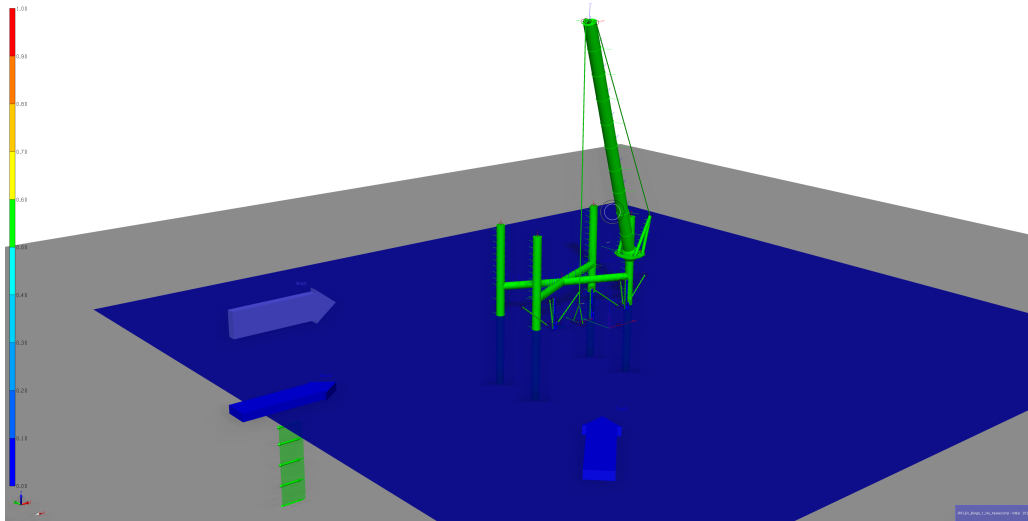


Figure 32: RIFLEX model

In the model a slender system was made consisting of:

- Supernodes
- Lines
- Line Types
- Cross Sections
- Flex Joints
- Nodal Bodies
- Seafloor Contacts and by extent Seafloor Contact Specification
- Global Springs

3.5.3 RIFLEX model - Crane

The crane was modelled to have same length of the crane arm from the base of the crane to the main hook as the Bold Tern. This was found to be ≈ 145.0 meters. Along with the crane arm, the two stay wires, at the aft of the crane, and the connection points were modelled as accurate as possible to mimic the crane of the jack-up vessel. The lifting wire of the crane was modelled from the tip of the crane down to the suspension arrangement holding the rotor blade, and the stiffness of the wire was calculated with the code *Stiffness calculation.py* shown in Appendix A. As a final step, two platforms of different diameter overlapping each other were modelled at the crane base, and a flex joint was included to mimic the crane joint. Figure 33 shows the crane.

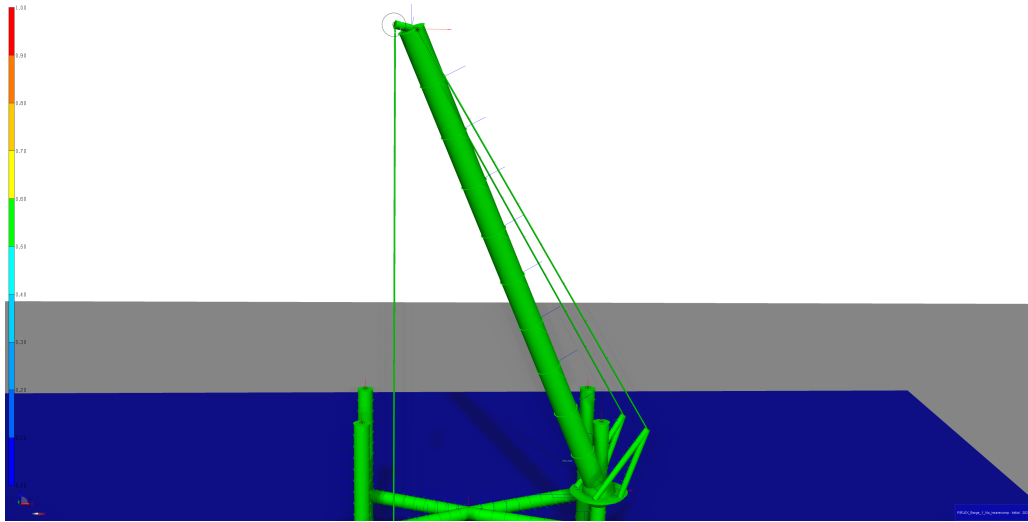


Figure 33: RIFLEX crane model

3.5.4 RIFLEX model - Jack-up legs

The jack-up legs, including the spudcans, were modelled using SIMA RIFLEX. The legs were modelled as beam elements and the spudcans were modelled as 6 global springs set for each DOF of each leg piercing the seafloor. The design parameters for each leg are shown in Table 11, while the initial sketch of the spudcan can be seen in Figure 34. The four legs under water and the four global springs acting as spudcans can be seen in Figure 35. Note that the free floating "object" in the center of all four legs is there as a modelling technique in order to have a fixed supernode as part of the full RIFLEX model. This due to RIFLEX needing at least one fixed supernode in order for the simulation of the model to be able to run.

Table 11: Main parameters for the legs of the Bold Tern

Design Parameters of the Jack-up Legs

Outer Diameter	(m)	4.5
Mass(Including Spudcan)	(tonnes)	1,056
COG X-direction	(m)	0
COG Y-direction	(m)	0
COG Z-direction	(m)	13.0

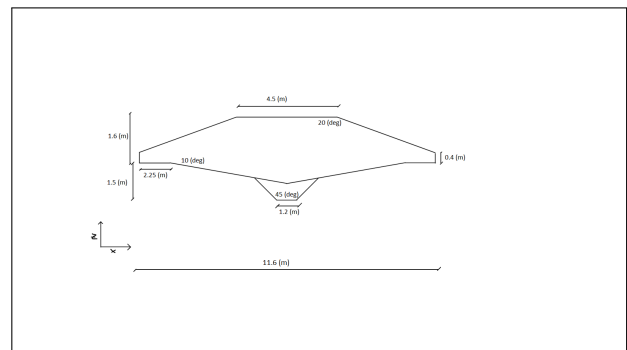
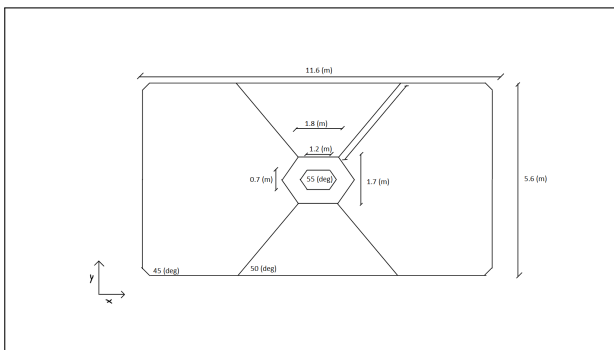


Figure 34: Sketch of spudcan

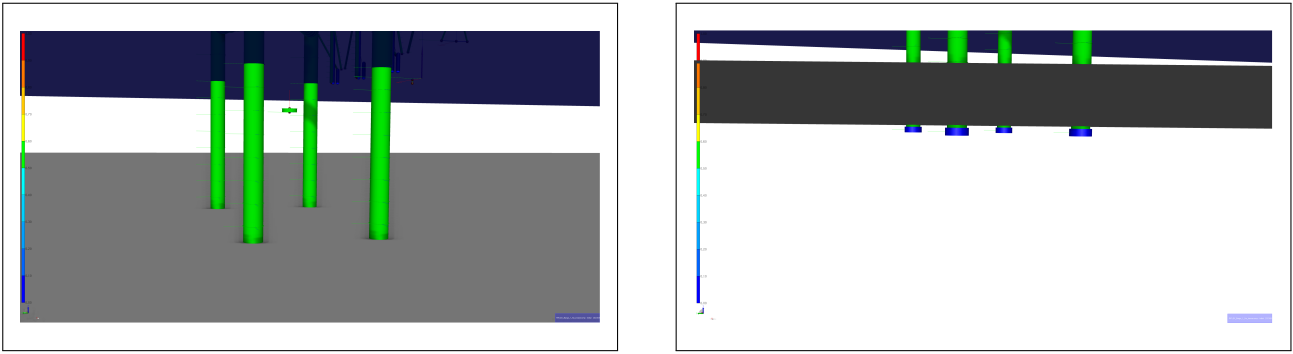


Figure 35: RIFLEX model legs and global springs

3.5.5 RIFLEX model - Mooring system and suspension rig

The mooring system suggested consists, in the RIFLEX model, of three "mooring beams" situated on the port side of the jack-up reaching vertically down to the sea surface from vessels deck, and six mooring lines connecting the jack-up to the barge. The mooring lines are modelled after traditional mooring with one head- and stern line, two brest lines and two spring lines. The material of the lines are that of polypropylene. The suggested mooring arrangement can be seen in Figure 36. Furthermore, in the figure the suspension arrangement for the lifting load can be seen. Here the suspension arrangement is simplified to only include two lines coming down from the supernode connected to the lifting wire. The center of the lifting arrangement and the lifting wire were positioned such as to be right over the COG of the lifting load.

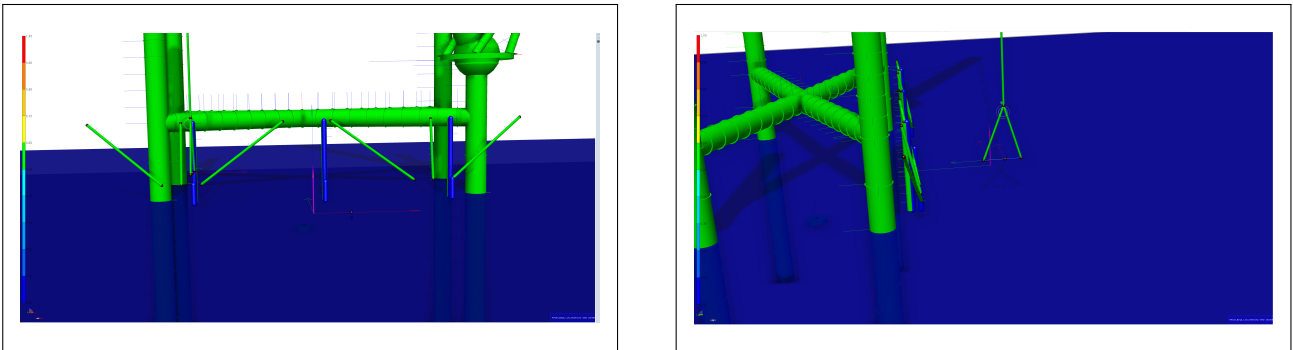


Figure 36: RIFLEX model mooring system and suspension arrangement

3.5.6 Coupled RIFLEX-SIMO and full model

To set up the total model the separated RIFLEX and SIMO parts were connected. This was done by making two supernodes and connecting them with a RIFLEX line, which in turn was specified as the connection line for the SIMO bodies "*slender system connection*". The supernodes and the connecting line can be seen in Figure 37, while the full model can be seen in Figure 38. Figure 39 and 40 shows the full model with Barge 2 and Barge 3 included. Notice the length difference between the rotor blade and the barges, giving three different systems.

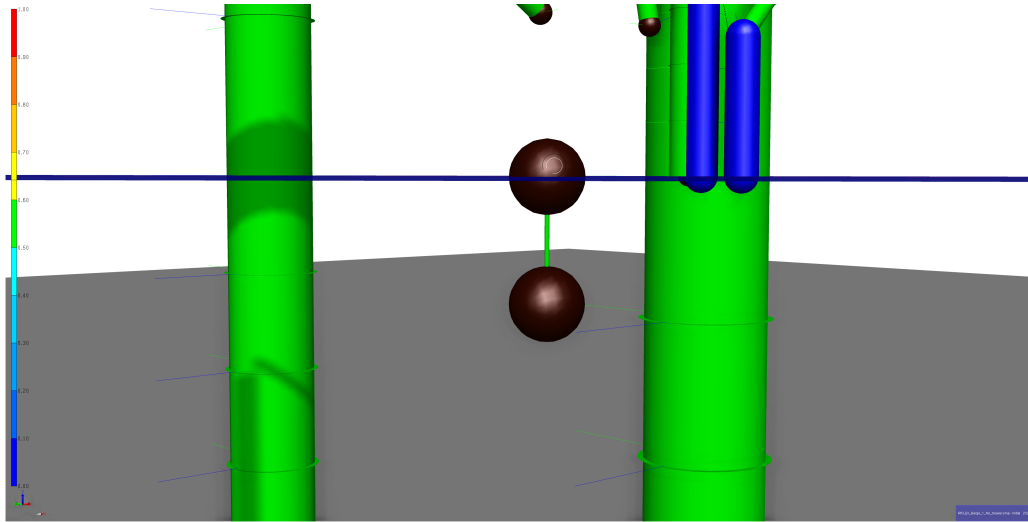


Figure 37: Method for coupling the SIMO model to the RIFLEX model

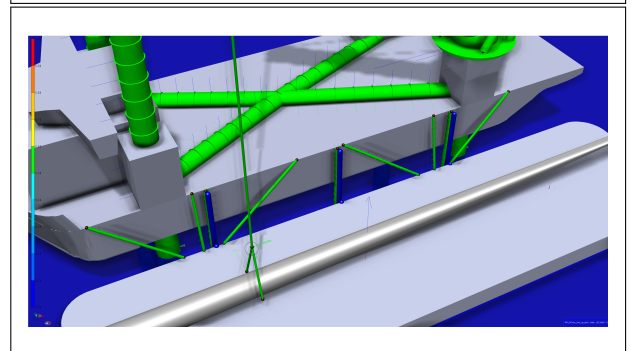
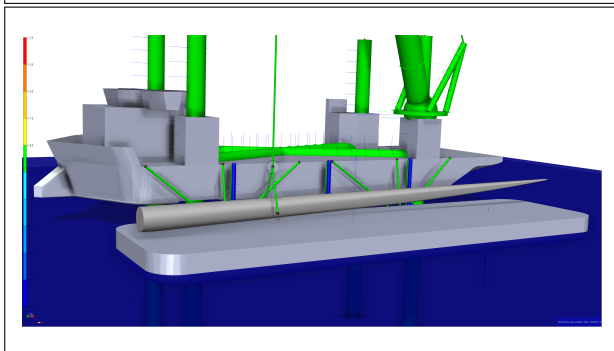
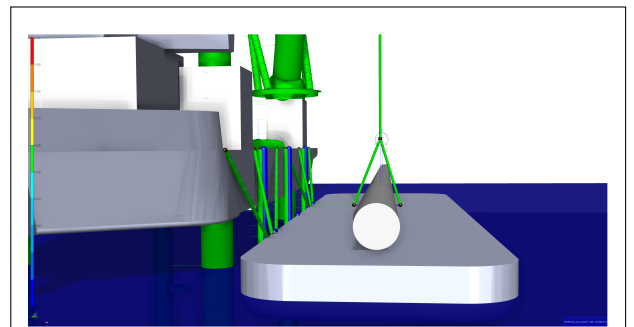
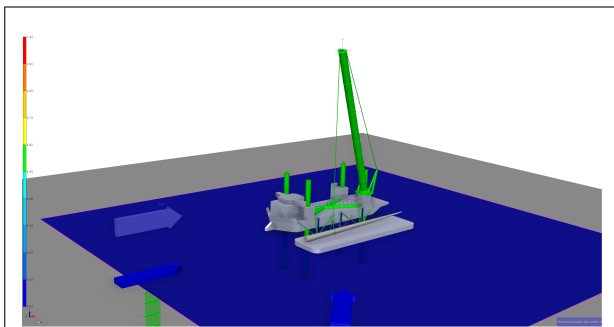


Figure 38: Full model with Barge 1

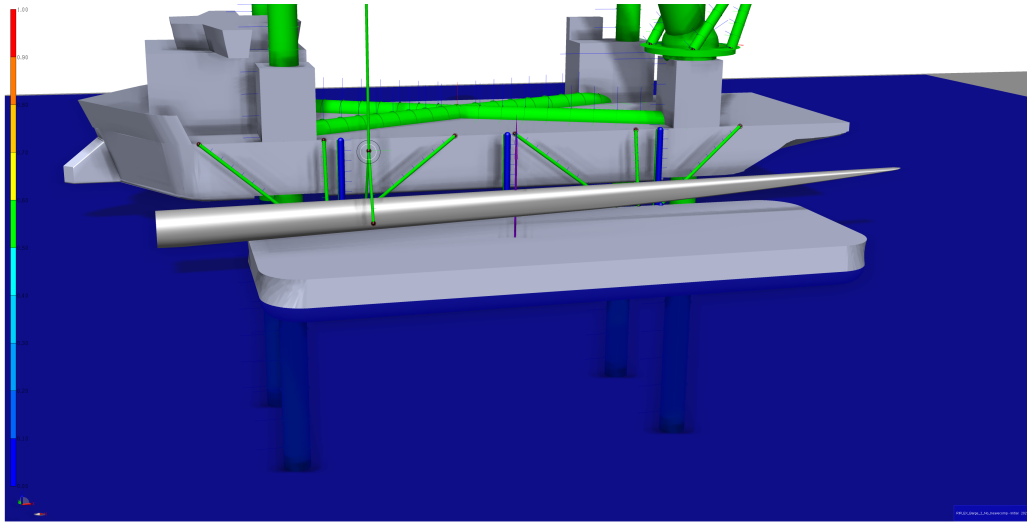


Figure 39: Full model with Barge 2

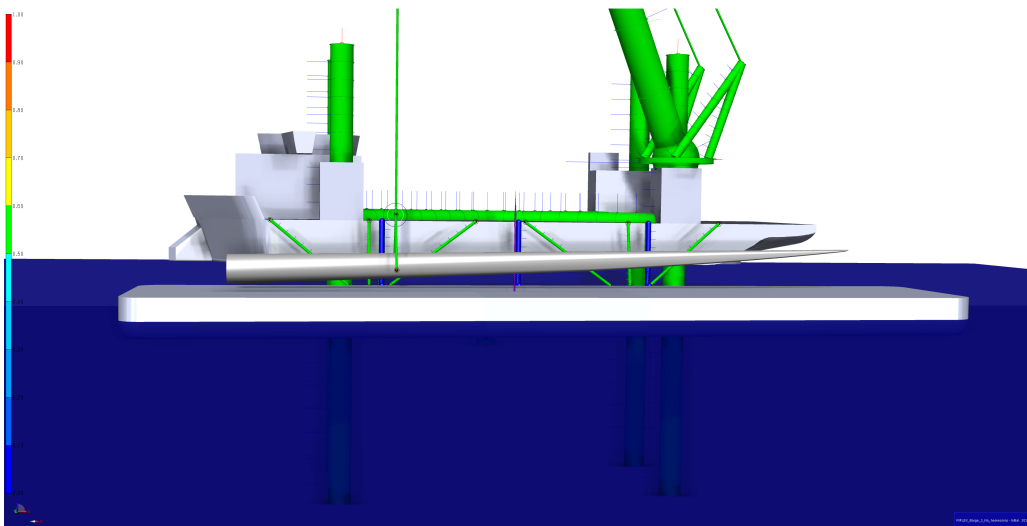


Figure 40: Full model with Barge 3

3.6 Simulation setup

The simulation was split into 6 different main cases with 72 sub cases. The analysis of the model was set up as a "*condition set*" in the time domain. It was first run a static then a dynamic simulation. However, due to limits in computational hardware and time only parts of the metocean data provided were used. The parameters chosen were done so with the intent of gaining an as accurate result as possible for the worst case scenarios. All simulations were put through a post processor.

3.6.1 Variables

In order for the condition set to work the model was parameterized. This was done with the *Double Variables* function. Here, the values were automatically changed according to the sub case run.

The values for the direction of the current, depth of the hull, height from the sea surface to the keel of the hull, and the height of leg houses from the deck, were kept fixed. These parameters were used, along with the depth, to set the length and vertical position of jack-up legs.

3.6.2 Environmental factors

The environmental factors of this model included:

- Water depth
- Wind waves
- Swell waves
- Current
- Wind field

The water depth was set to 40 meters, for simplification of the simulation. For the wind and swell waves the JONSWAP spectrum was used with a peak enhancement factor, gamma, based on Equinor guidelines. The significant wave height, and peak period varied as the metocean data used. The current was defined with a constant velocity in the water column, and the wind field was modelled as a NPD wind field at a reference height of 10 meters above sea level.

3.6.3 Static and dynamic calculation setup

The static and dynamic calculation were set up to give as accurate simulation results as possible. In the static calculation the load types calculated were:

- Volume Forces
- Active global springs
- Specified Displacements
- Body Forces
- Boundary Change

In the dynamic calculation the highlighted setup topics were:

- Displacement
- Force response (of interesting lines)
- Curvature response
- Wave kinematics
- Body results
- 3D visualization

3.6.4 Post processor

To analyse the result from the model a post processor was set up. This was done as a workflow task. The task can be seen in Figure 41.

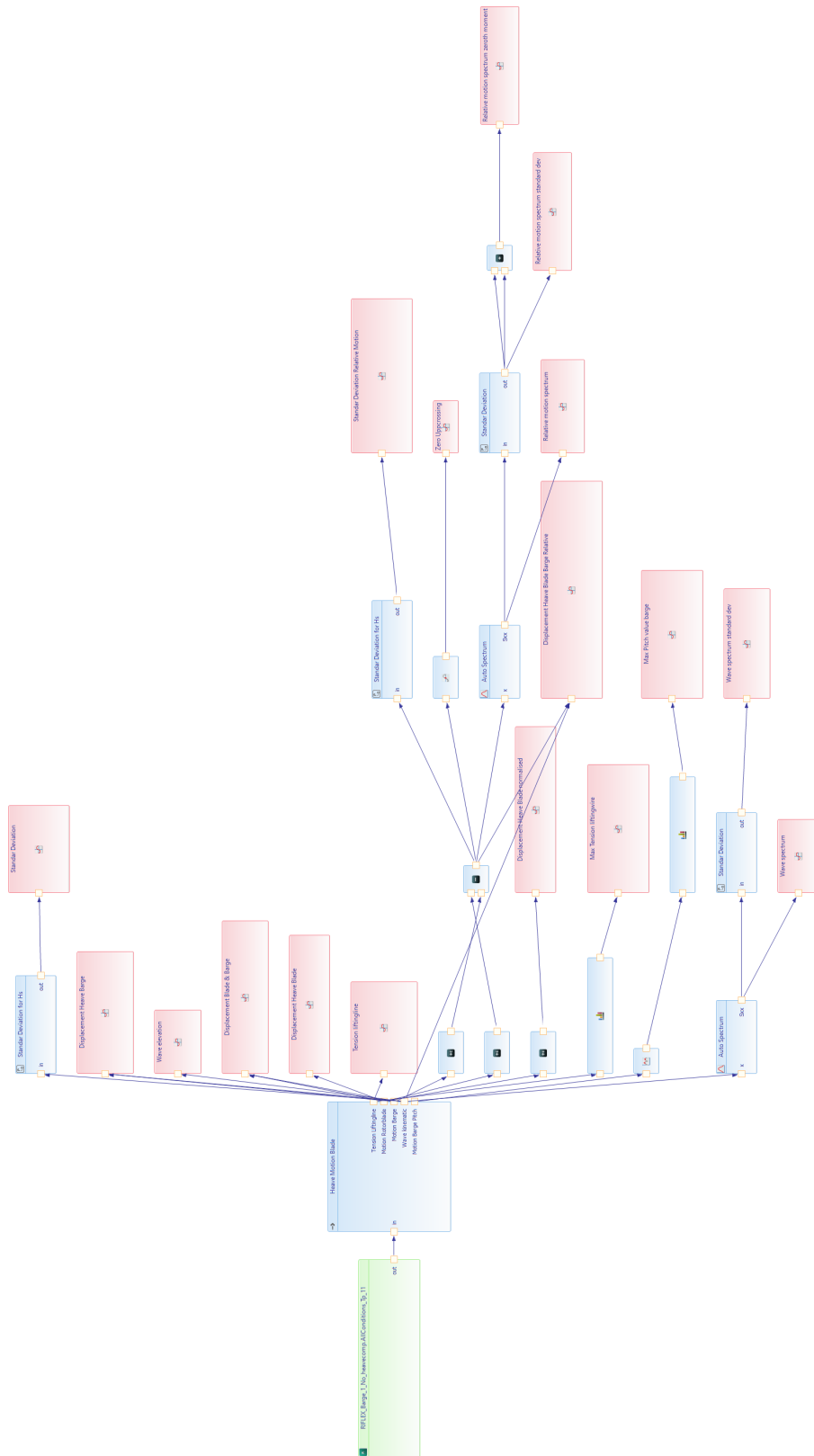


Figure 41: Post processor and workflow tasks set up

4 Simulation results and motion analysis

4.1 Sea state

The results shown are those of the RAOs for the first barge and the simulation results for sub case number 18 with a peak period of 11 seconds. Table 12 shows the metocean data for the particular sub case presented in this chapter. Note that the simulation results are in the time domain and that the period of simulation is 1800 seconds, or 30 minutes, as this can be defined as a short operation.

Table 12: Metocean Data for one subcase

Metocean Data, sub case 18, Tp11 *		
Wind Wave Direction	(°)	000
Swell Wave Direction	(°)	045
Water Depth	(m)	40.0
Irregular Waves		
Significant Wave Height, Hs	(m)	2.5
Significant Wave Height Swell, HsSwell	(m)	1.0
Peak Period, Tp	(s)	11.0
Peak Period Swell, Tps	(s)	20.0
Wave Spectrum	(-)	JONSWAP
Peak Enhancement Factor, γ	(-)	$max[1.0; 42.2(\frac{2\pi H_s}{gT_p^2})^{\frac{6}{7}}]$
Spreading function	(-)	2.0
NPD Wind Spectrum		
Wind Velocity	(m/s)	10.0
Reference Height	(m)	10
Current		
Regular Constant Surface Current	(m/s)	0.6

* Data provided by Equinor.

4.2 RAO

Figure 42 - 44 shows 3D plots of the RAOs of Barge 1 in the time domain. The RAOs for Barge 2 and 3 can be seen in Figure 69 - 74 in Appendix B. Table 13 shows the peak periods and wave directions of interest. These values are representative for all three barges and are reasons for using the specific direction and period in the analysis. Notice the natural period of the jack-up vessel in the same table. The value is representative for wave directions and a leg length below the keel as stated in chapter 3.2.1, and corresponds with water depth and the wave directions of interest. The period shows that the Bold Tern is stiffer than the barges, and the assumption that the jack-up motion is smaller than that of the barges were made.

Table 13: Peak period and wave direction of interest, and natural period of the Bold Tern

Heave		
Wave Direction	(°)	000, 045, 090
Peak Period, T_p	(s)	6.0, 9.0, 11.0
Roll		
Wave Direction	(°)	090
Peak Period, T_p	(s)	6.0
Pitch		
Wave Direction	(°)	000, 045
Peak Period, T_p	(s)	9.0, 11.0
Natural Sway Period of the Bold Tern		
Natural Sway Period, Leg Length 47.5 (m)	(s)	2.9 - 3.7

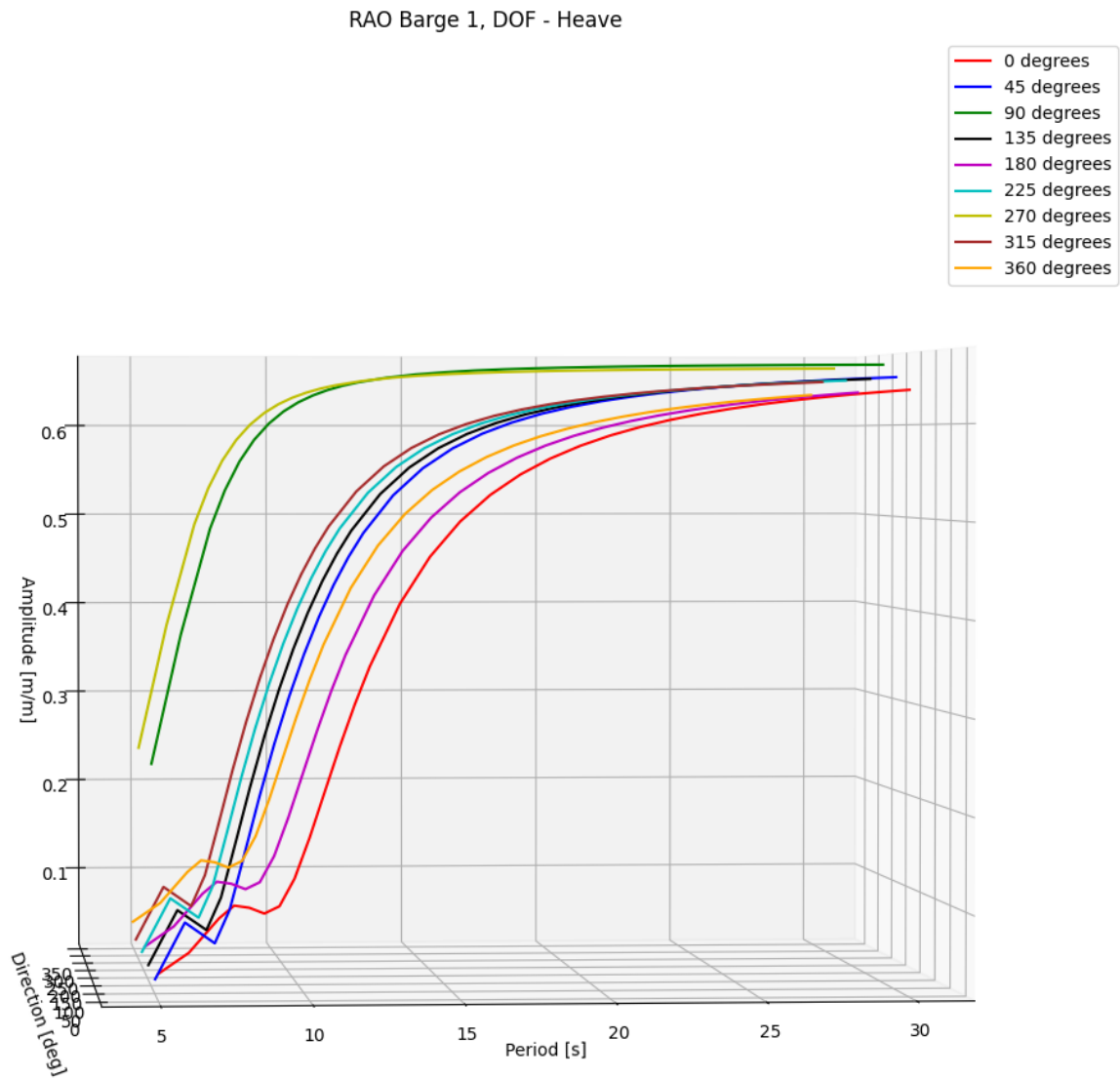


Figure 42: RAO, DOF: heave, Barge 1 in the time domain

RAO Barge 1, DOF - Roll

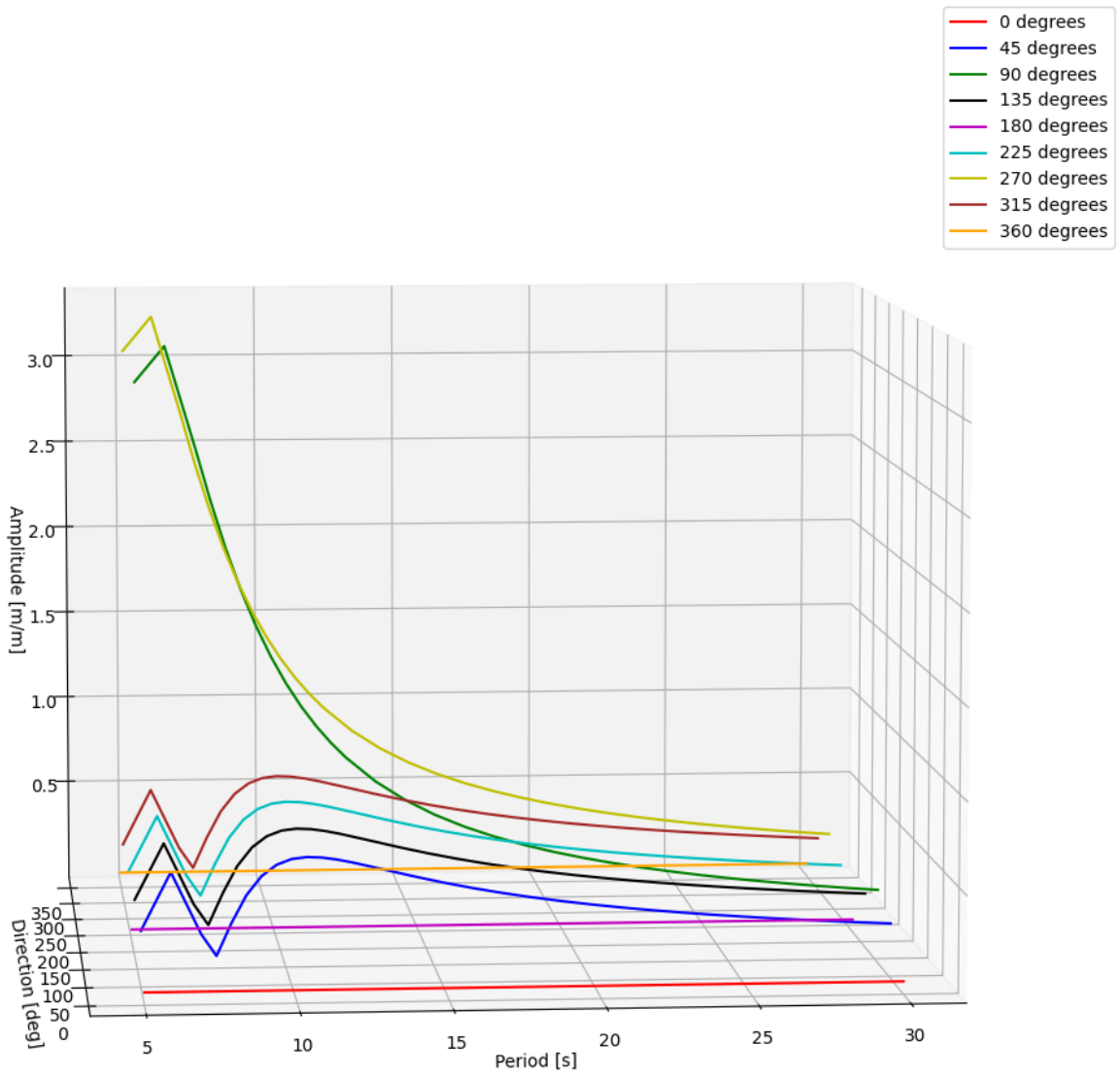


Figure 43: RAO, DOF: roll, Barge 1 in the time domain

RAO Barge 1, DOF - Pitch

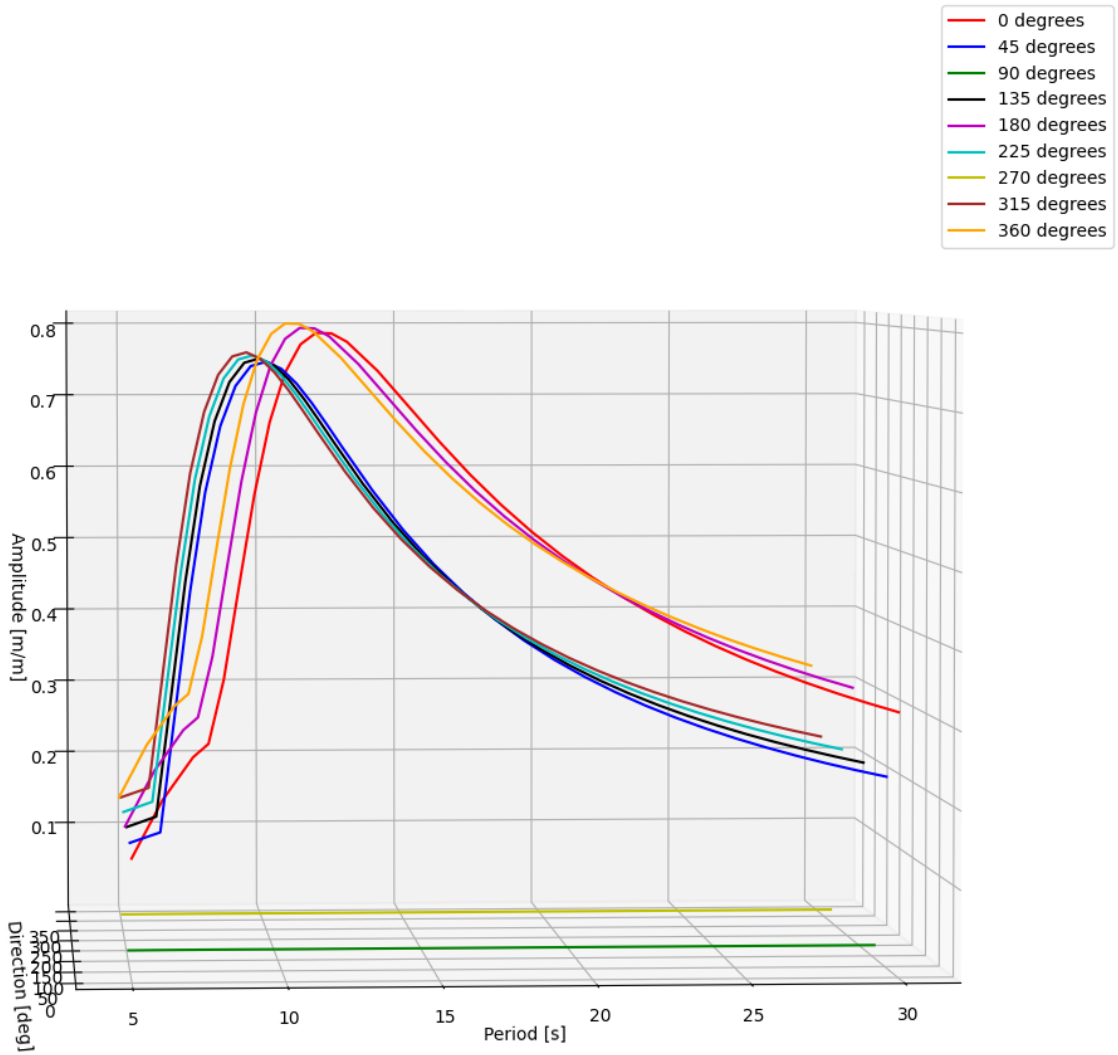


Figure 44: RAO, DOF: pitch, Barge 1 in the time domain

4.3 Simulation results - Wave elevation

The wave elevation seen by Barge 1, in this case, is shown in Figure 45. In addition to this, the wave spectrum was plotted for the simulation case with the resulting plot being shown in Figure 46. The standard deviation of the wave spectrum was found to be $\sigma = 1.1864 (m^2s)$. Based on this the most probable extreme wave was estimated to be 12 meters. Here, a long period of waves of 20 years and a short period of waves of 30 minutes were used. The calculation is shown in Equation 16.

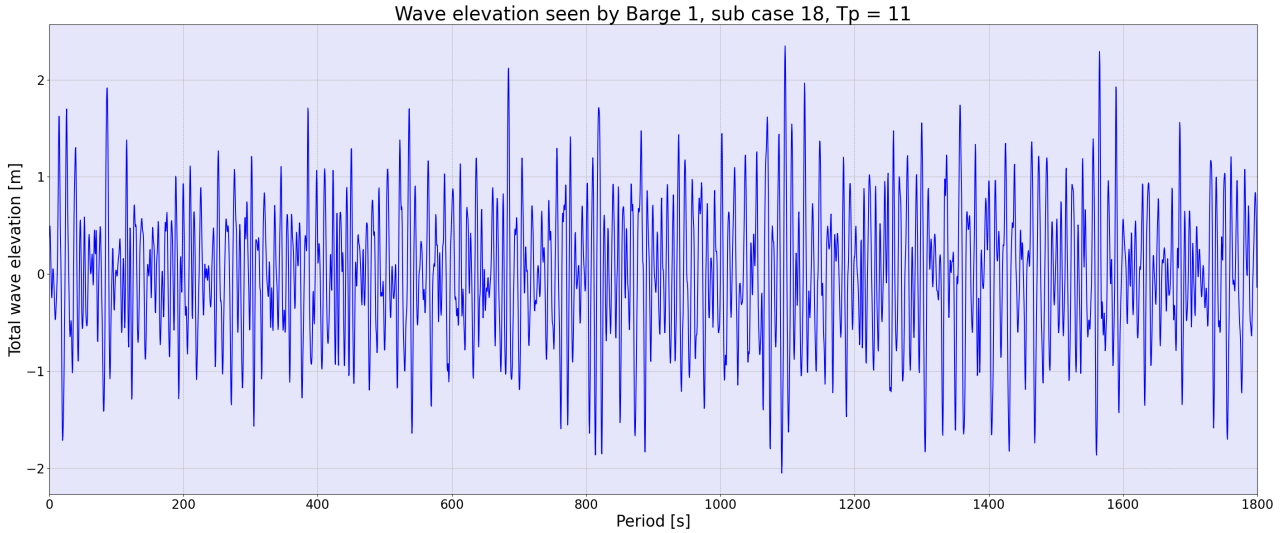


Figure 45: Wave elevation seen by Barge 1 (Sub case 18, $T_p = 11$ (s))

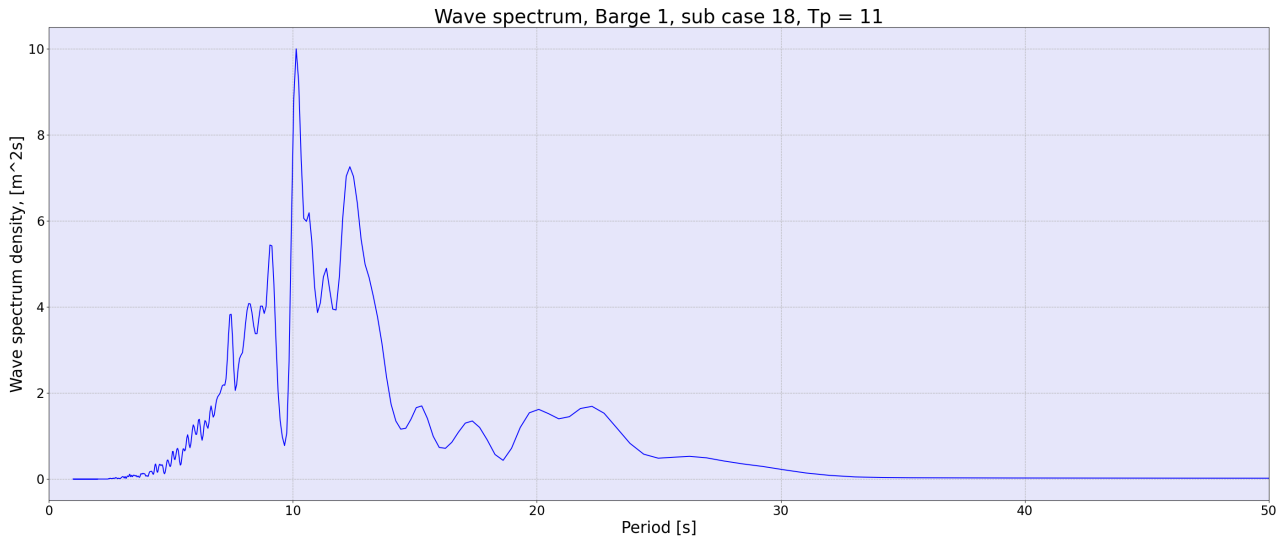


Figure 46: Wave spectrum of wave elevation seen by Barge 1 (Sub case 18, $T_p = 11$ (s))

$$\begin{aligned}
 H_M &= 2\sqrt{2m_0 \ln N} \\
 H_M &= 2\sqrt{2 \cdot 1.40754 \cdot \ln 350632.5} \\
 H_M &\approx 12.0 (m)
 \end{aligned}
 \tag{16}$$

4.4 Simulation results - Barge and jack-up motion

Figure 47 - 50 shows the motion of Barge 1 in DOF: heave, roll and pitch respectively. If one compares the heave motion of the barge to the wave elevation it can be seen that the graph follows the wave elevation. However, the two graphs are not identical. The pitch motion can be seen to be of such value that it can have an impact on the operation. The roll motion is shown to be small, and due to the direction of the rotor blade hanging cannot be of danger to the operation. This DOF is not elaborated any further. Figure 48 on the following page shows a graph of Barge 1 following the wave. This is a combination plot of the graphs for the wave elevation and the responding heave motion of Barge 1. The yellow coloured graph shows the wave elevation while the red coloured graph shows the heave response of the barge.

A simple comparison of the sway motion for the jack-up vessel and Barge 1 can be seen in Figure 51. The blue graph is the displacement of the barge sway motion over time, while the red graph shows the same for the jack-up. Here it is seen that the assumption of the jack-up vessel being stiffer than the barge to be true. The reason as the graph shows, is that the sway motion of the jack-up is so small that any difference in value can hardly be seen, while the graph of the barge fluctuates irregularly, and with greater effect.

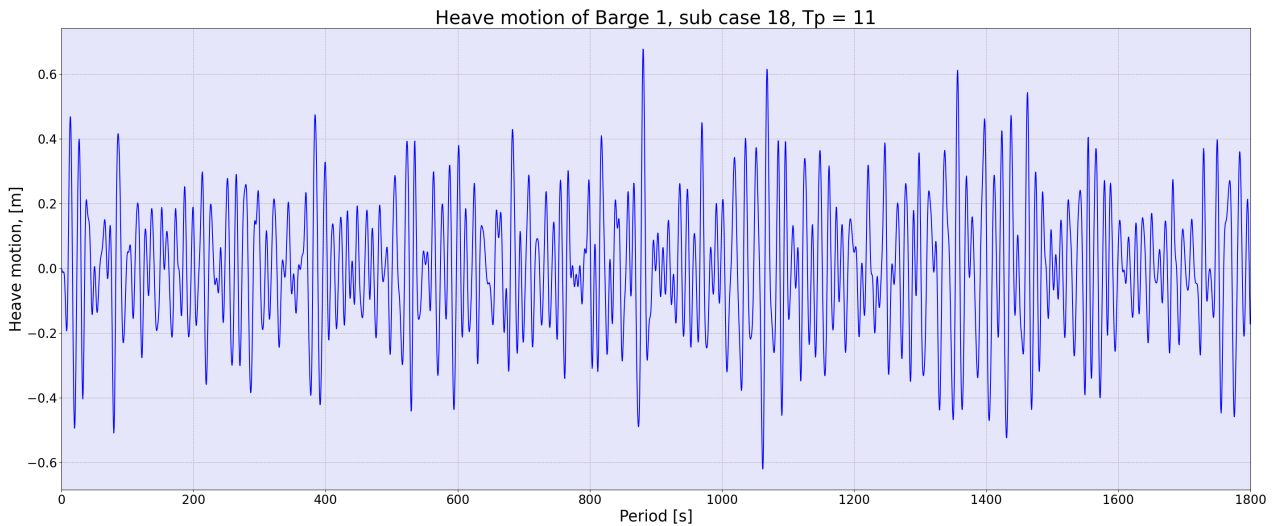


Figure 47: Heave motion of Barge 1 (Sub case 18, $T_p = 11$ (s))

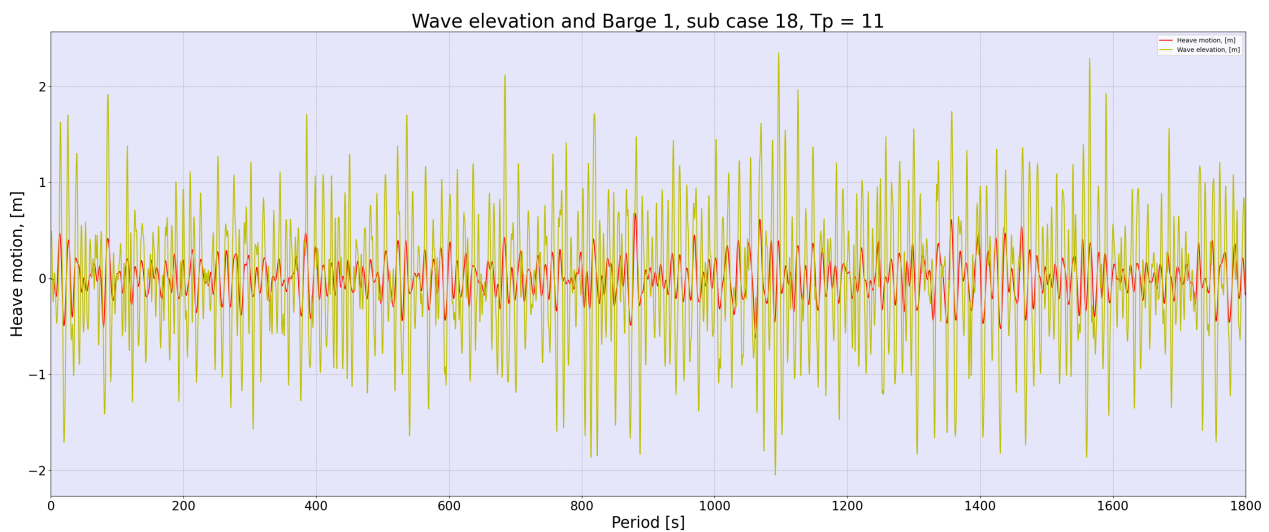


Figure 48: Wave and Barge 1 heave motion (Sub case 18, $T_p = 11$ (s))

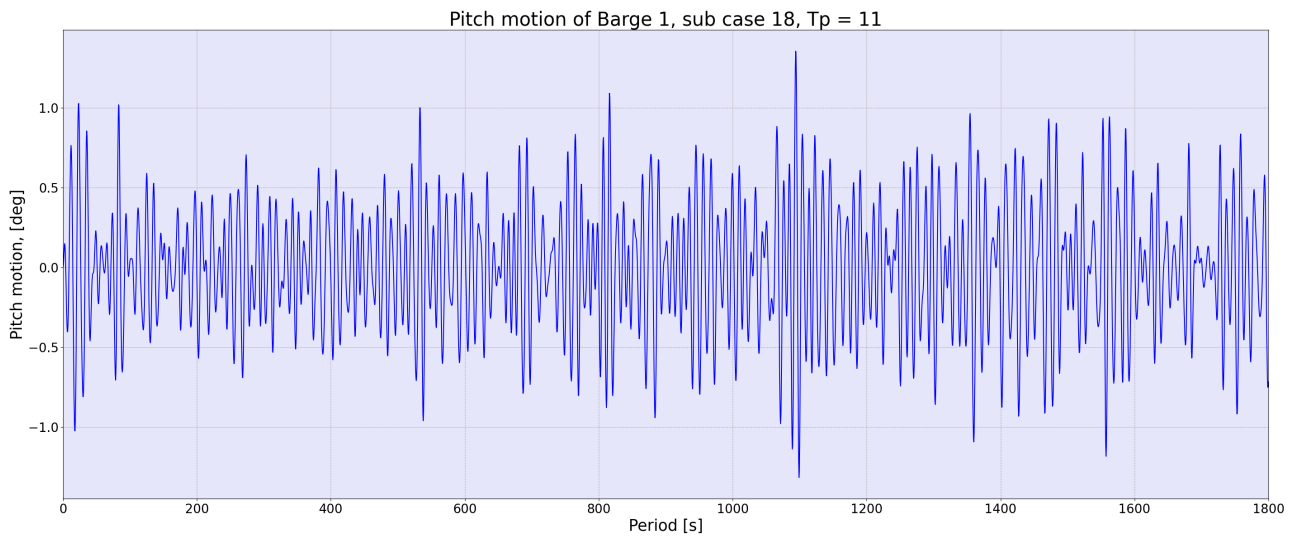


Figure 49: Pitch motion of Barge 1 (Sub case 18, $T_p = 11$ (s))

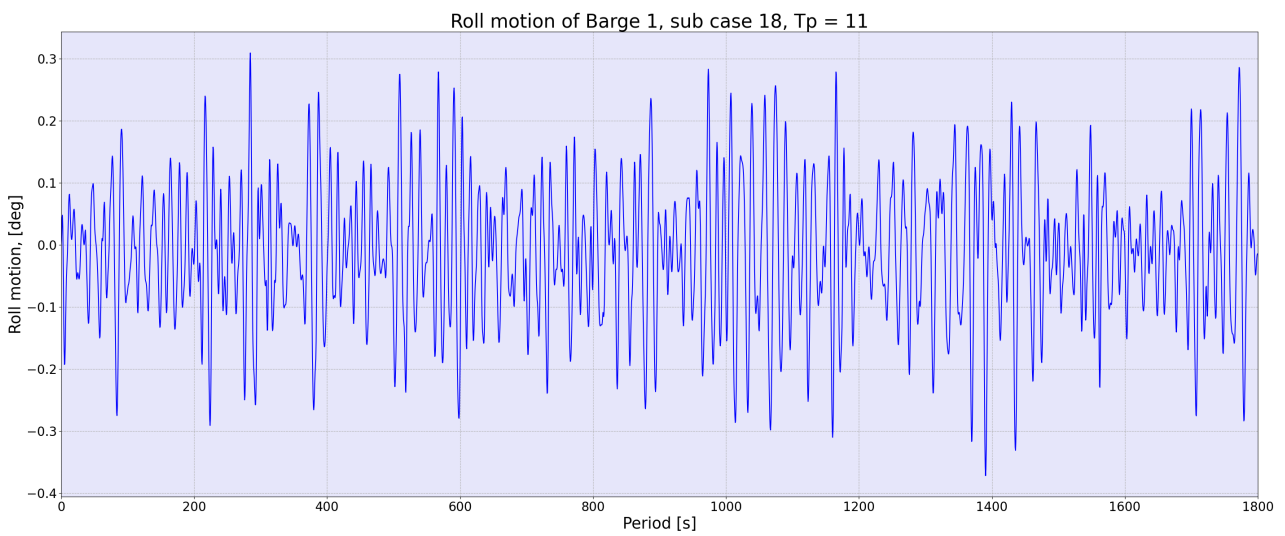


Figure 50: Roll motion of Barge 1 (Sub case 18, $T_p = 11$ (s))

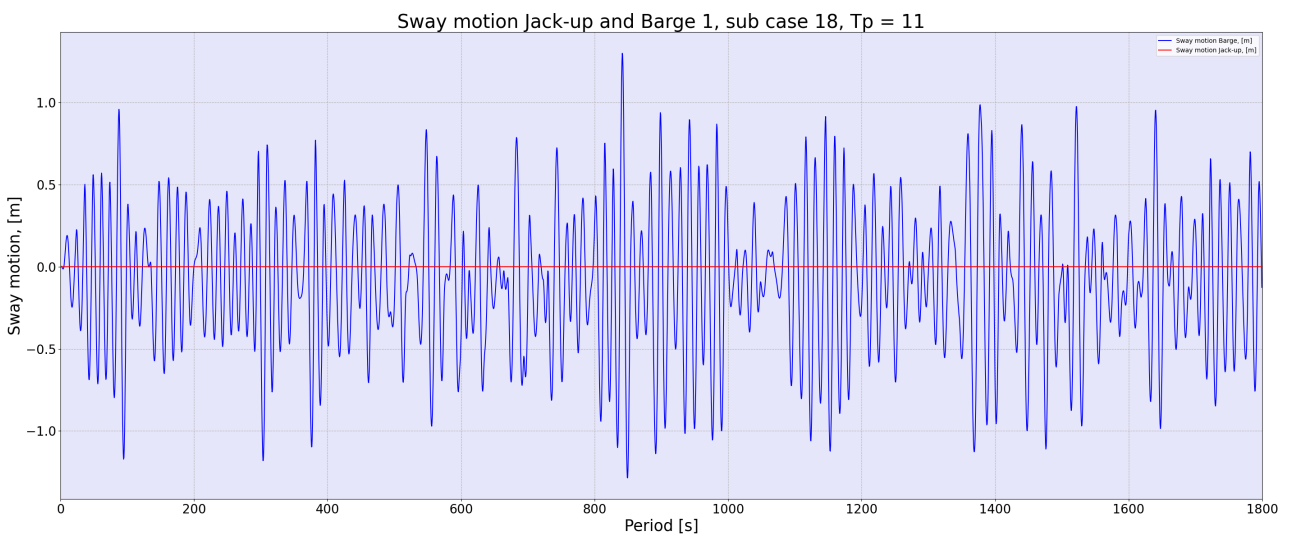


Figure 51: Sway motion of Jack-up vessel and Barge 1 compared (Sub case 18, $T_p = 11$ (s))

4.5 Simulation results - Rotor blade motion

Figure 52 and 53 shows the graphs for the heave motion of the rotor blade in the cases with and without a heave compensation system. A heave compensation system such as that of the *Cranemaster* system could be a solution to reducing the motion of the rotor blade. This system is mainly an active system, however it combines passive heave compensation for balancing the load and active heave compensation for tension regulation. On the rotor blade the aerodynamic loads, or wind, has to be the main contributor to its motion, due to the jack-up vessel hardly moving.

The graphs looks to fluctuate around 7.9 meters , which is the distance above water level. For the case with heave compensation the graph looks to have a damping effect. However, for both cases the values of the graphs are small. Figure 54 and 55 shows a time series of the sway motion of the rotor blade. Heave compensation should not have a big impact on the sway motion, and in terms values on the graph it dose not. Practically, the blade is kept stationary in the air in sway direction. The only effect seen is without heave compensation the value of the sway motion is slightly more elevated. A possible reason could be the extra weight of the heave compensation system [41].

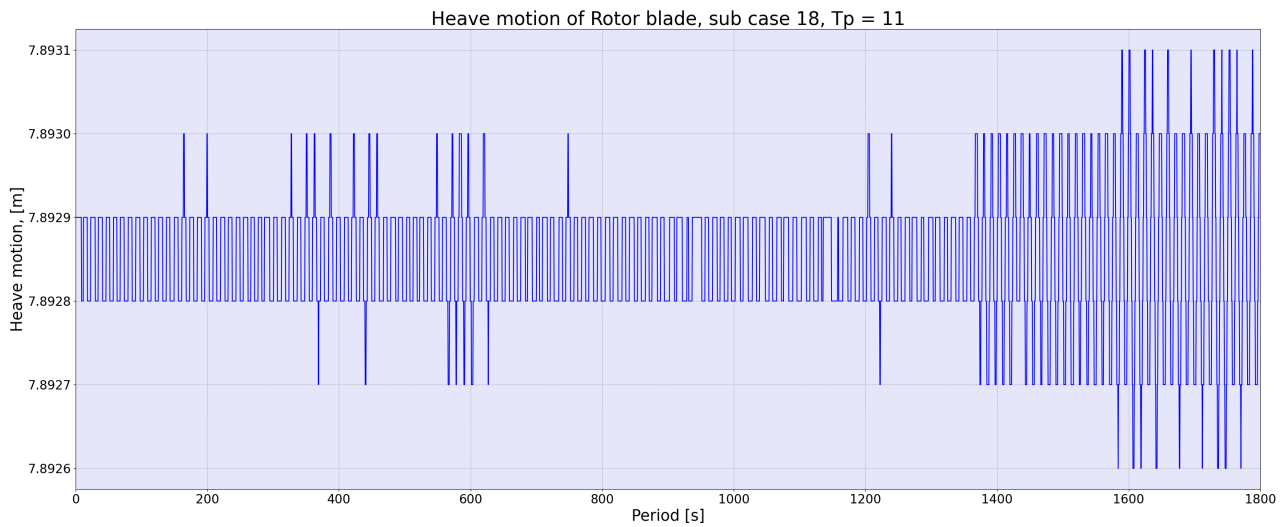


Figure 52: Heave motion of rotor blade from case without heave compensation (Sub case 18, $T_p = 11$ (s))

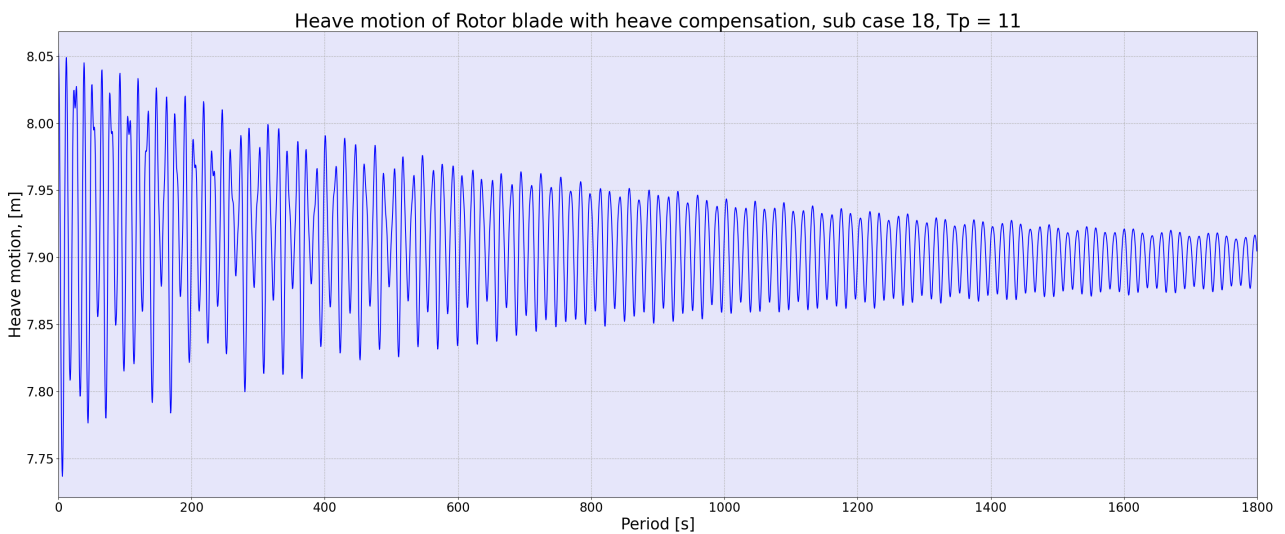


Figure 53: Heave motion of rotor blade from case with heave compensation (Sub case 18, $T_p = 11$ (s))

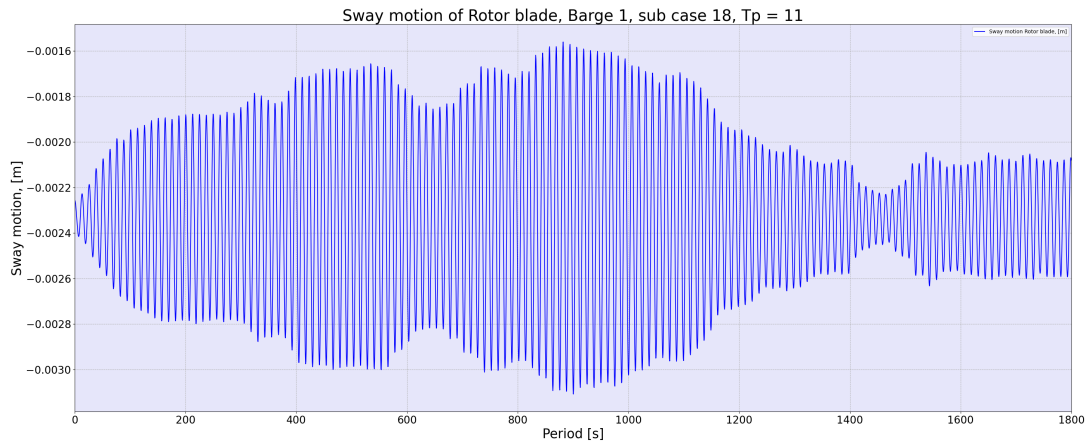


Figure 54: Sway motion of rotor blade from case without heave compensation (Sub case 18, $T_p = 11$ (s))

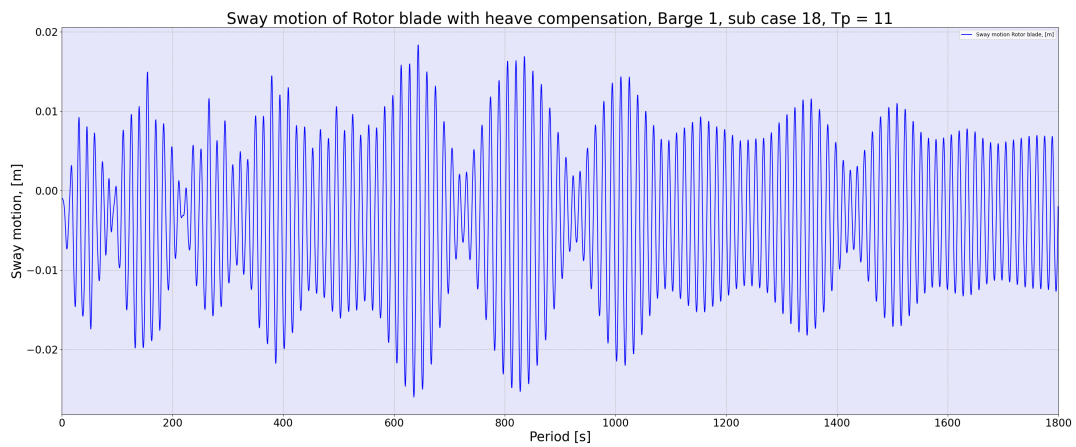


Figure 55: Sway motion of rotor blade from case with heave compensation (Sub case 18, $T_p = 11$ (s))

4.6 Simulation results - Tension in lifting wire

Figure 56 and 57 shows the tension in the lifting wire during the simulation. Here it can be seen that the case without a heave compensation system the graph is more irregular than that of the case including a heave compensation system where the graph has a damping effect over time. Notice the force value for both cases, and especially the initial and final force values. As per the graphs, the values look to fluctuate around 196.8 (kN) without heave compensation, and 200 (kN) with heave compensation.

The max tension of the lifting wire without heave compensation is read to be about 197.3 (kN) , or $\approx 200 \text{ (kN)}$, and about 340 (kN) with heave compensation. An explanation for the forces being much larger with heave compensation could be the added weight from the heave compensation system. Note that the graphs only contains the time series from 400 to 1800 seconds. This due to the assumption that there might be transient forces involved.

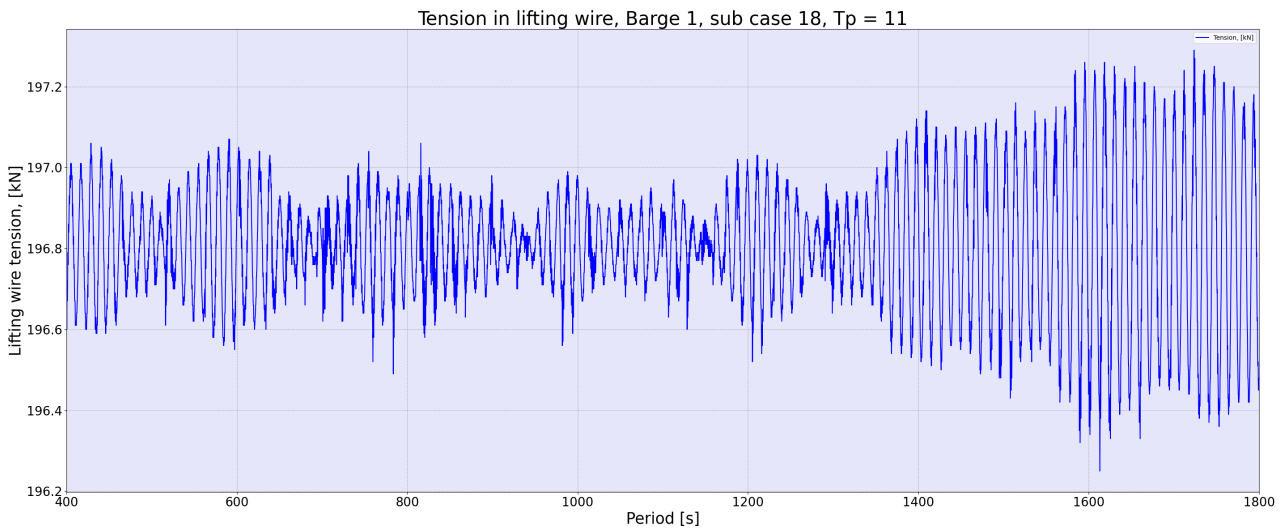


Figure 56: Tension in lifting wire from case without heave compensation (Sub case 18, $T_p = 11 \text{ (s)}$)

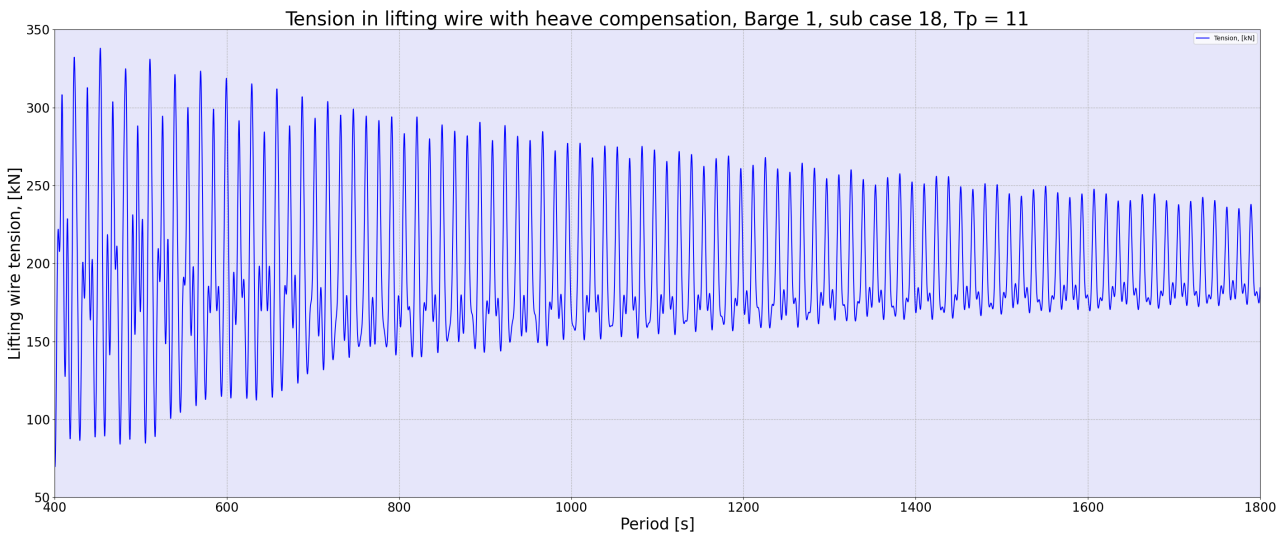


Figure 57: Tension in lifting wire from case with heave compensation (Sub case 18, $T_p = 11 \text{ (s)}$)

Knowing the max tension in the lifting wire with and without heave compensation during the operation, the required Max Breaking Load (MBL) for a lifting wire can be estimated. The method of estimation is as shown in Equation 17, where the Safety Factor (SF) is calculated from the known Working Load Limit (WLL) and the MBL is calculated as a continuation MBL. From the plots of the lifting wire a tension a value for WLL of 700 (kN) was used to give the estimation extra safety. The estimated SF was used to find a lifting wire resembling this value. The wire was compared to that of the 8x61+FC produced by Nantong Guangming Steel Wire Products Co.Ltd, and the required MBL and diameter were estimated. The 8x61+FC uses a MBL factor equivalent to 1/SF, where the value is 0.251 [42] [43] [44].

The MBL calculated was used to find the closest safe value of the diameter from Figure 75 in Appendix B. Table 14 shows the values for max tension of both cases, the safety factor, or rather MBL factor, the MBL and the closest safe diameter to the value of the MBL. If the wire was to be underdimensioned the "right" load could cause it to break, leading to the rotor blade falling onto the deck of the barge.

$$SF = \frac{10^4}{0.885 \cdot WLL + 1910}$$

$$WLL = \frac{MBL}{SF}$$

$$MBL = WLL \cdot SF$$

Where:

WLL = Work Load Limit

MBL = Minimum Breaking Load

SF = Safety Factor

Estimated SF:

$$SF_{est} = 3.953$$

$$Estimated\ MBL\ factor = 0.253$$

MBL of lifting wire:

$$MBL_{est} = 2967\ (kN)$$

MBL factor from manufacturer:

$$MBL\ factor = 0.253$$

$$SF_{supp} = \frac{1}{0.251} = 3.984$$

MBL of lifting wire:

$$MBL_{supp} \approx 2975\ (kN)$$

(17)

Table 14: Max tension in lifting wire compared to MBL

Sub case 18, Tp = 11 (s)		
No heave compensation		
Tension	(kN)	200
Heave compensation		
Tension	(kN)	340
MBL, SF and Diameter *		
SF	(kN)	0.251
MBL	(kN)	2975
Closest safe diameter	(mm)	88

* Simple assumption of MBL based on the *8x61+FC* steel wire produced by Nantong Guangming Steel Wire Products Co.Ltd and a tension of 700 (kN), taking into account discrepancies in SF differences.

4.7 Simulation results - Relative motion between barge and rotor blade

Part of the main results of the simulations are the relative motion between the barge and the rotor blade. These are shown in Figure 58 - 63, where the graphs show the relative motion between different combinations of barges with and without heave compensation. The graphs can be seen revolving around a value of 1.3 meters. This is the initial distance between the lowest point of the rotor blade and the deck of the barge. It is also seen a similarity between the cases with the same barge were the difference being inclusion of heave compensation or not. However, the standard deviation for each time series show a little to no difference in the cases with or without heave compensation. This is due to small motions from the jack-up. The order of the graphs is:

- Barge 1 without heave compensation
- Barge 1 with heave compensation
- Barge 2 without heave compensation
- Barge 2 with heave compensation
- Barge 3 without heave compensation
- Barge 3 with heave compensation

The results are elaborated further in the following chapter.

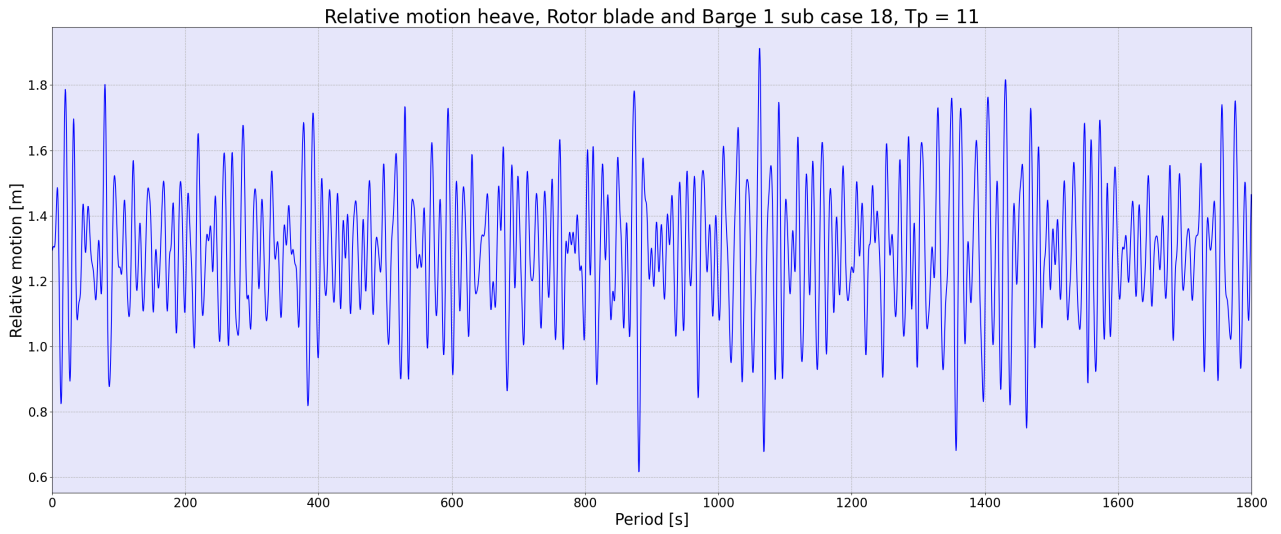


Figure 58: Relative motion between rotor blade and Barge 1 from case without heave compensation (Sub case 18, $T_p = 11$ (s), $\sigma = 0.19(m)$)

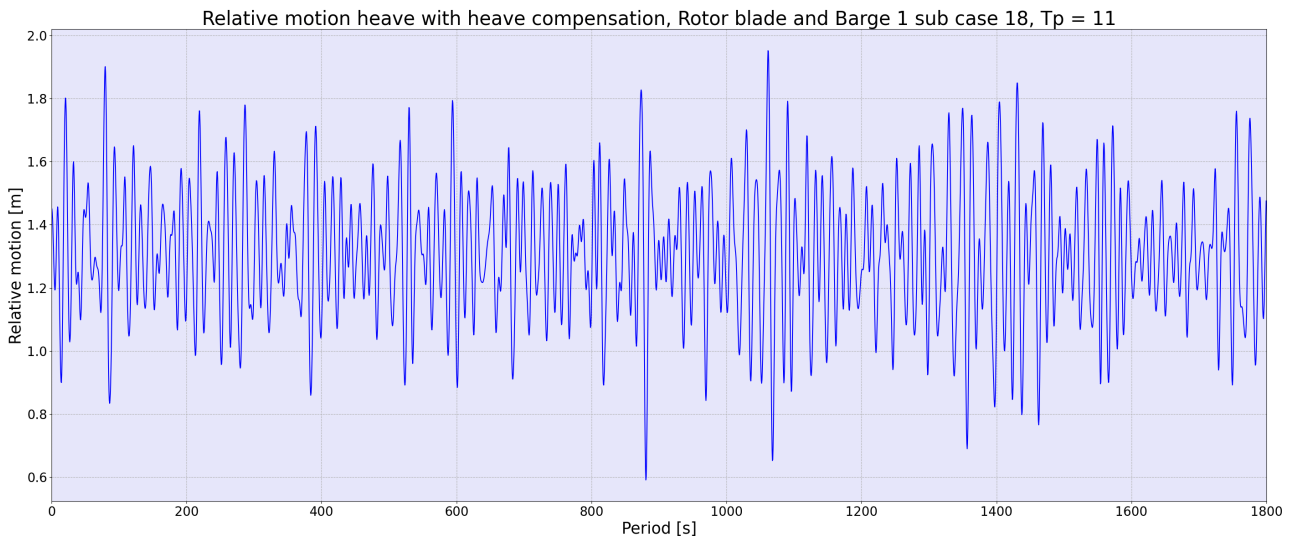


Figure 59: Relative motion between rotor blade and Barge 1 from case with heave compensation (Sub case 18, $T_p = 11$ (s), $\sigma = 0.20(m)$)

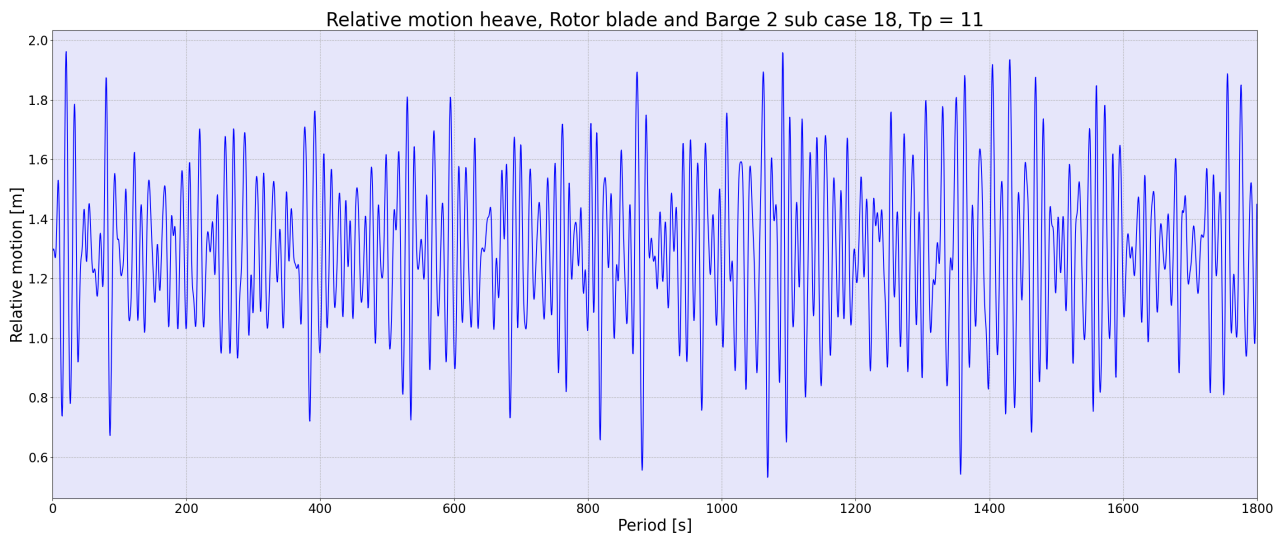


Figure 60: Relative motion between rotor blade and Barge 2 from case without heave compensation (Sub case 18, $T_p = 11$ (s), $\sigma = 0.24(m)$)

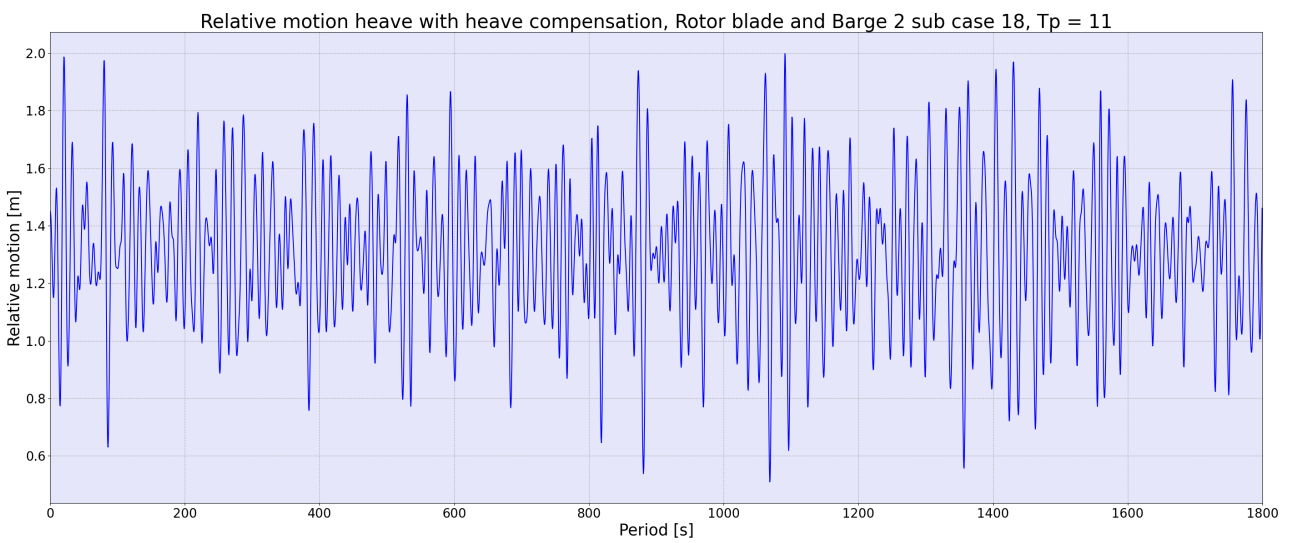


Figure 61: Relative motion between rotor blade and Barge 2 from case with heave compensation (Sub case 18, $T_p = 11$ (s), $\sigma = 0.24(m)$)

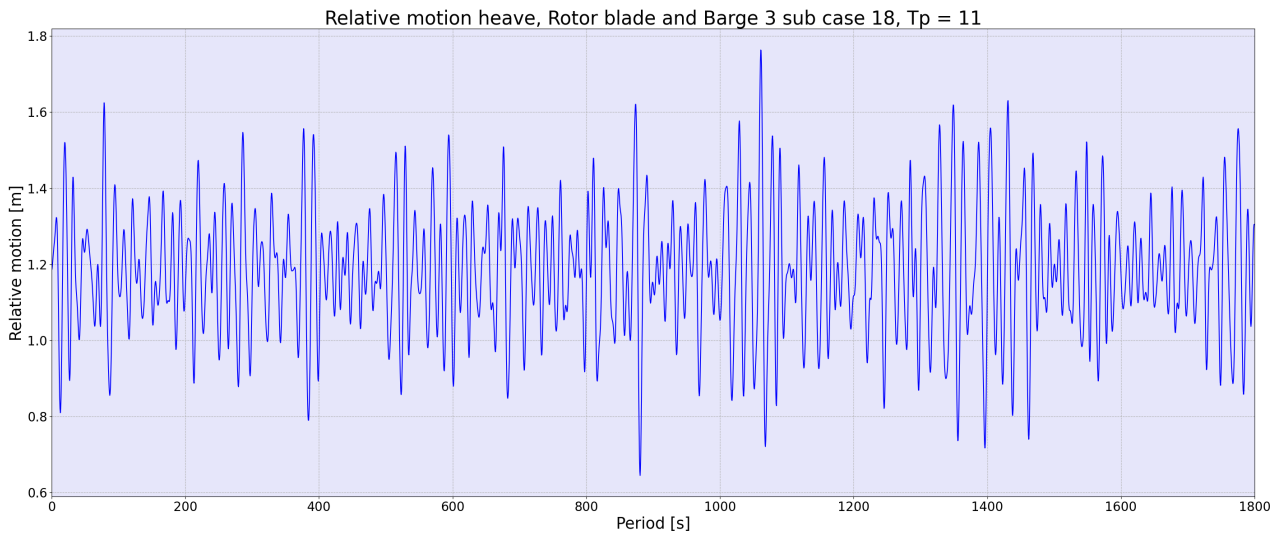


Figure 62: Relative motion between rotor blade and Barge 3 from case without heave compensation (Sub case 18, $T_p = 11$ (s), $\sigma = 0.16(m)$)

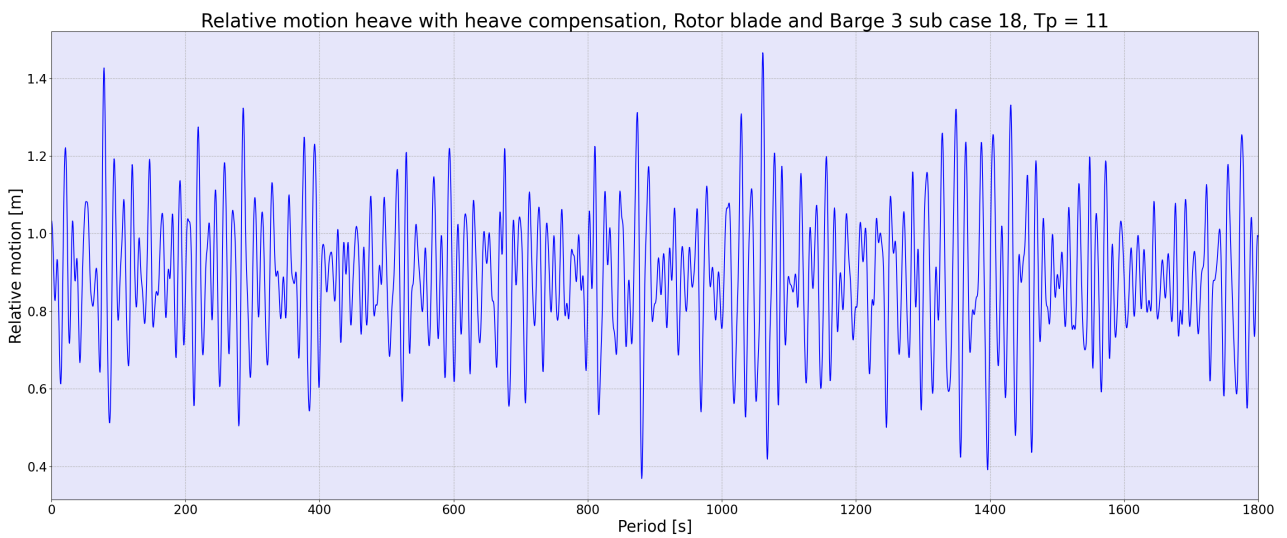


Figure 63: Relative motion between rotor blade and Barge 3 from case with heave compensation (Sub case 18, $T_p = 11$ (s), $\sigma = 0.16(m)$)

4.8 Simulation results - Mooring arrangement

The resulting max axial and shear and forces upon the three different mooring arrangements are shown in Table 15 - 17. Here a negative value for the shear force in the mooring beam represents negative y-direction, or away from the jack-up on its port side towards the barge.

Table 15: Mooring system, Barge 1

Max shear and axial force in mooring system, Barge 1		
Mooring line, axial force		
Head line	(kN)	89.9
Forward Brest line	(kN)	78.8
Forward Spring line	(kN)	33.2
Aft Spring line	(kN)	86.1
Aft Brest line	(kN)	53.7
Stern line	(kN)	88.8
Mooring beams, axial force		
Forward Beam	(kN)	66300
Mid Beam	(kN)	64200
Aft Beam	(kN)	62200
Mooring beams, shear force		
Forward Beam	(kN)	-1190
Mid Beam	(kN)	-718
Aft Beam	(kN)	-872

Table 16: Mooring system, Barge 2

Max shear and axial force in mooring system, Barge 2		
Mooring line, axial force		
Head line	(kN)	87.5
Forward Brest line	(kN)	115
Forward Spring line	(kN)	68.5
Aft Spring line	(kN)	60.0
Aft Brest line	(kN)	67.0
Stern line	(kN)	95.0
Mooring beams, axial force		
Forward Beam	(kN)	66300
Mid Beam	(kN)	64200
Aft Beam	(kN)	62200
Mooring beams, shear force		
Forward Beam	(kN)	-810
Mid Beam	(kN)	-436
Aft Beam	(kN)	-107

Table 17: Mooring system, Barge 3

Max shear and axial force in mooring system, Barge 3

Mooring line, axial force		
Head line	(kN)	84.0
Forward Brest line	(kN)	55.0
Forward Spring line	(kN)	83.5
Aft Spring line	(kN)	84.7
Aft Brest line	(kN)	41.2
Stern line	(kN)	89.0
Mooring beams, axial force		
Forward Beam	(kN)	66300
Mid Beam	(kN)	64300
Aft Beam	(kN)	62300
Mooring beams, shear force		
Forward Beam	(kN)	485
Mid Beam	(kN)	-828
Aft Beam	(kN)	-756

5 Case study

If the barge were to re-hit the rotor blade snap loads could occur. This due to the barge would lift the rotor blade up making the lifting line slack, and when dropping down again there would most likely occur some form of load on the wire. If this load would be to great the lifting line would snap and the rotor blade would fall down landing on the barge. In order to check if there was any probability of re-impact during the lift, and to understand at what sea states the pitch motion of the barges would be problematic when the rotor blade was hanging above the deck a case study was conducted.

The case study was done as per the DNV recommended practices *DNV-RP-H103*, stated in chapter 2, by first setting a criteria for the relative motion based on a re-impact probability that blade will be hit by the barge at the next maximum of 0.001. The criteria was then checked. What had the biggest effect and lastly if a heave compensation system had any effect on reduction of the motion were then analysed. The tension in the lifting wire and why there was a difference with and without a heave compensation system were discussed as well. The parameters used for the metocean data can be seen in Table 18, while Figure 64 shows the different combinations of the data used excluding the peak periods for wind waves.

Table 18: Metocean Data Used

Metocean Data Used in Simulation*		
Wave Direction	(°)	000, 045
Water Depth	(m)	40.0
Irregular Waves		
Significant Wave Height, Hs	(m)	1.5, 2.5
Peak Period, Tp	(s)	6.0, 9.0, 11.0
Wave Spectrum	(-)	JONSWAP
Peak Enhancement Factor, γ	(-)	$max[1.0; 42.2(\frac{2\pi H_s}{gT_p^2})^{\frac{6}{7}}]$
Spreading function	(-)	2.0
NPD Wind Spectrum		
Wind Velocity	(m/s)	6.0, 8.0, 10.0
Reference Height	(m)	10
Current		
Regular Constant Surface Current	(m/s)	0.6

* Data provided by Equinor.

	Direction wind wave [deg]	Hs [m]	Direction swell wave [deg]	Tp swell [s]	Hs swell [m]	Depth [m]	Wind velocity [m/s]	Case
Simulation conditions	0	1.5	0	20	1	40	6	1
	0	2.5	0	20	1	40	6	2
	0	1.5	0	20	1	40	8	3
	0	2.5	0	20	1	40	8	4
	0	1.5	0	20	1	40	10	5
	0	2.5	0	20	1	40	10	6
	45	1.5	45	20	1	40	6	7
	45	2.5	45	20	1	40	6	8
	45	1.5	45	20	1	40	8	9
	45	2.5	45	20	1	40	8	10
	45	1.5	45	20	1	40	10	11
	45	2.5	45	20	1	40	10	12
	0	1.5	45	20	1	40	6	13
	0	2.5	45	20	1	40	6	14
	0	1.5	45	20	1	40	8	15
	0	2.5	45	20	1	40	8	16
	0	1.5	45	20	1	40	10	17
	0	2.5	45	20	1	40	10	18
	45	1.5	0	20	1	40	6	19
	45	2.5	0	20	1	40	6	20
	45	1.5	0	20	1	40	8	21
	45	2.5	0	20	1	40	8	22
	45	1.5	0	20	1	40	10	23
	45	2.5	0	20	1	40	10	24

Figure 64: Dynamic parameters for all simulation sub case sets excluding values for peak period, Tp

5.1 Case criteria

Two criteria were set. One for the standard deviation of the relative heave motion, and the max safe pitch angle for the barge without hitting the rotor blade in stationary position. The criteria can be categorised for two points of the lifting operation: during the lift and when the load is hanging in the air.

5.1.1 Heave criteria

The criteria for the standard deviation of relative motion between the deck of the barge and the lowest point of the rotor blade was calculated using the Python script *Reimpactprob.py* shown in Appendix A. Here two methods of calculating the zeroth moment of the relative motion were carried out. With the first method the moment was based on the standard deviation of the relative motion, and with the second method a spectral analysis was carried out. The value based on the standard deviation was used. The criteria was calculated for a thought set of 10 lifts with a hoisting velocity ranging between 0.1 (m/s) and 1.0 (m/s). The reason for it only being a thought set of lifts are explained later. The smallest criteria was chosen for all velocities, and correlated all to a hoisting velocity of 0.1 (m/s). The criteria for all cases can be seen in Table 19, where the values have been shorted to two decimals. For a sub case to pass, the value of standard deviation needs to be lesser than the criteria set.

Table 19: Heave criteria

Standard deviation of relative motion criteria *

Barge 1		
No heave compensation, Tp 6	(m)	0.15
No heave compensation, Tp 9	(m)	0.18
No heave compensation, Tp 11	(m)	0.18
Heave compensation, Tp 6	(m)	0.17
Heave compensation, Tp 9	(m)	0.17
Heave compensation, Tp 11	(m)	0.20
Barge 2		
No heave compensation, Tp 6	(m)	0.22
No heave compensation, Tp 9	(m)	0.17
No heave compensation, Tp 11	(m)	0.16
Heave compensation, Tp 11	(m)	0.17
Barge 3		
No heave compensation, Tp 6	(m)	0.21
No heave compensation, Tp 9	(m)	0.19
No heave compensation, Tp 11	(m)	0.21
Heave compensation, Tp 11	(m)	0.20

* Based on *DNV-RP-H103*.

* Zeroth moment based on standard deviation i.e. $m_0 = \sigma^2$.

* Criteria taken from hoisting velocity of 0.1 (m/s).

5.1.2 Pitch criteria

The criteria for the max safe pitch angle was defined with an engineering assumption as per the graphical representation of the case and the closest safe value before collision taken from the corresponding motion graph. The value was set relative to surge and heave motion ≈ 0 . The cases with heave compensation were not included as the difference in standard deviation for the relative motion with and without heave compensation were shown to be little to none for most cases. This means there would be no significant difference in motion, and now significant effect on the results. The values set were:

- Barge 1: 0.7 degrees
- Barge 2: 1.2 degrees
- Barge 3: 0.7 degrees

5.2 Case results

The results from the case consists of the standard deviation of relative motion in heave direction between each barge and the rotor blade with or without heave compensation, and the max pitch angle for the same. The results were checked against the criteria using Microsoft Excel. Green colour identifies safe values, red identifies unsafe values and orange in between. Note case 18 and the effects on the values for different peak periods.

5.2.1 Heave

Figure 65 and 66 shows the results of the case study for the relative heave motion between each Barge 1 and the rotor blade without and with heave compensation. The rest of the results can be seen in Figure 76 - 78 in Appendix B. From the figures it is seen that the cases with a peak period, Tp, of 6 seconds are all safe, while with a peak period of 9 or 11 seconds the results are more varied. This indicates that the peak period relative to the RAOs are more unsafe for the operation. However, notice

that the results including heave compensation shows more green fields than without. This indicates that the cases including heave compensation increases the safety of operation overall, and increases the number of sea states that could be acceptable. The differences are shown to be small but impact full. Note that the values of standard deviation are taken at the point where the rotor blade is kept safe above the deck, meaning there could be some discrepancies in these results.

Case	Heave motion		
	Tp wind wave = 6	Tp wind wave = 9	Tp wind wave = 11
1	0.13	0.13	0.15
2	0.13	0.15	0.18
3	0.13	0.13	0.15
4	0.13	0.15	0.18
5	0.13	0.13	0.15
6	0.13	0.15	0.18
7	0.14	0.16	0.18
8	0.14	0.20	0.24
9	0.14	0.16	0.18
10	0.14	0.20	0.24
11	0.14	0.16	0.18
12	0.14	0.20	0.24
13	0.14	0.15	0.16
14	0.14	0.16	0.19
15	0.14	0.15	0.16
16	0.14	0.16	0.19
17	0.14	0.15	0.16
18	0.14	0.16	0.19
19	0.13	0.15	0.17
20	0.13	0.19	0.24
21	0.13	0.15	0.17
22	0.13	0.19	0.24
23	0.13	0.15	0.17
24	0.13	0.19	0.24

Figure 65: Standard deviation of relative heave motion results, for Barge 1 (Green values < Criteria)

Case	Heave motion		
	Tp wind wave = 6	Tp wind wave = 9	Tp wind wave = 11
1	0.13	0.14	0.15
2	0.14	0.15	0.19
3	0.13	0.14	0.15
4	0.14	0.15	0.19
5	0.13	0.14	0.15
6	0.14	0.15	0.19
7	0.15	0.16	0.19
8	0.15	0.20	0.25
9	0.15	0.16	0.19
10	0.15	0.20	0.25
11	0.15	0.16	0.19
12	0.15	0.20	0.25
13	0.14	0.15	0.16
14	0.15	0.16	0.20
15	0.14	0.15	0.16
16	0.15	0.16	0.20
17	0.14	0.15	0.16
18	0.15	0.16	0.20
19	0.13	0.15	0.18
20	0.14	0.19	0.24
21	0.13	0.15	0.18
22	0.14	0.19	0.24
23	0.13	0.15	0.18
24	0.14	0.19	0.24

Figure 66: Standard deviation of relative heave motion results, for Barge 1 with heave compensation (Green values < Criteria)

From the results observations show that the biggest effect on the data and the increase of the resulting values for the standard deviation are:

- An increase in peak period, T_p , and significant wave height, H_s
- Wind wave direction of 045 degrees
- Swell wave direction of 045 degrees

5.2.2 Pitch

Figure 67 shows the results of the case study for the max pitch angle of Barge 1, and if the value is safe or not. The results for Barge 2 and 3 can be seen in Figure 80 - 81 in Appendix B. For all barges the peak period of 6 seconds show the operation to be safe. However, for 9 and 11 seconds this is not the case. The results here are fluctuating more between safe and unsafe values. Note that the values for Barge 2 are greater than both Barge 1 and 2 while most are still within the criteria. This is due to the shape of the rotor blade and the barge being shorter than the other two. When the barge pitches it is then observed that the end elevates at a point closer to the center of the rotor blade and therefore away from the lowest point hanging. Notice as well that a concentration of unsafe results for this barge occurs at a peak period of 9 seconds, and wind and swell wave direction of 000 degrees. The values also rely on the significant wave height where the greatest values can be found at a significant wave height of 2.5 meters.

For Barge 3 the results show that most of the unsafe values occurs at a peak period of 9 seconds and wind wave direction of 045 degrees(case 19-24). The greatest values of these are observed to be for a significant wave height of 2.5 meters(case 20, 22 and 24). If these cases are compared to the same cases for a peak period of 11 seconds, observations show that these values are lesser, and in some cases have a value closer to acceptable levels.

Case	Pitch motion		
	Tp wind wave = 6	Tp wind wave = 9	Tp wind wave = 11
1	0.49	0.79	0.80
2	0.56	1.25	1.31
3	0.49	0.79	0.80
4	0.56	1.25	1.31
5	0.49	0.79	0.80
6	0.56	1.25	1.31
7	0.40	0.93	0.89
8	0.57	1.53	1.41
9	0.40	0.93	0.89
10	0.57	1.53	1.41
11	0.40	0.93	0.89
12	0.57	1.53	1.41
13	0.43	0.73	0.84
14	0.50	1.20	1.35
15	0.43	0.73	0.84
16	0.50	1.20	1.35
17	0.43	0.73	0.84
18	0.50	1.20	1.35
19	0.48	0.98	0.86
20	0.58	1.59	1.37
21	0.48	0.98	0.86
22	0.58	1.59	1.37
23	0.48	0.98	0.86
24	0.58	1.59	1.37

Figure 67: Max pitch angle criteria results, for Barge 1 (Green values < Criteria)

5.3 Largest effect on the relative motion

From the results it can be seen that largest effects on the relative motion are an increase in peak period relative to the barges RAOs, and an increase in significant wave height. It was also observed that waves coming from an angle of 045 degrees had the greatest impact on the heave motion. In addition, the size of the barge has an impact on the values as it is seen that a smaller barge has a greater heave motion than a bigger barge. For the pitch motion the direction of the waves, peak period and the significant wave height has the biggest impact, as it is seen that a peak period of 9 and 11 seconds gives unsafe values all over for barge 1, while for Barge 2 and 3 the direction and significant wave height needs to hit such as to excite the barges relative to the RAOs.

5.4 Effect of heave compensation

It is observed from the simulation results that the cases including heave compensation has a relatively small effect on the values of relative motion, and in some instances it is seen that the standard deviation of the relative motion between the barges and the rotor blade is slightly increased. The reason for this could be that the payload in the model is hanging at a distance above the barge deck, and could therefore give a wrong image of the total operation. However, for the motion of the rotor blade and the tension in the lifting wire the resulting graphs show that the fluctuation is more regular and reduced. This could give predictability and added safety to the operation.

6 Concluding remarks

6.1 Suggestion of mooring system and inclusion in the total operation

The suggested mooring system in the model consists of three vertical beams with bumpers acting as fenders on the port side of the jack-up. On which side the system should be is not final as it could be an idea to moor the barge, or any other vessel, to its starboard side as well. The system could then be installed on both sides to increase the versatility of the jack-up. The beam system has to be easily installed when at location, as well as removed and stowed away for steaming. A system with rails or similar could be a solution.

From the results observation show that the forces on the mooring system are at an acceptable level, be difficult to compare with other systems. From the visual representation in Figure 68 no damage to either the system or the barge can be seen. The figure shows Barge 1, the mooring system and arrangement and the stress on the mooring lines and beams. Here colours close to red indicates greater values of stress.

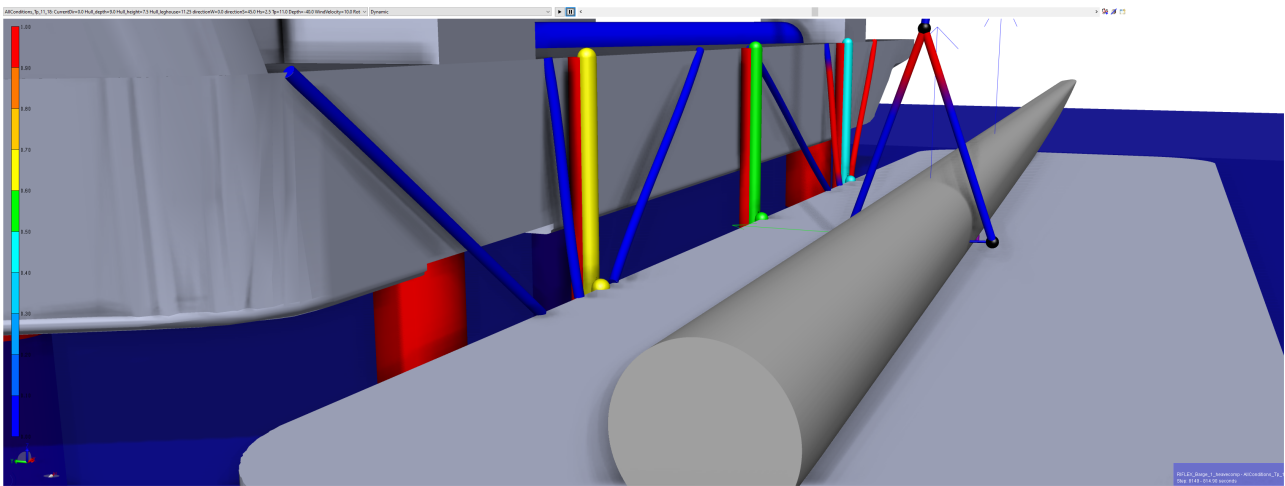


Figure 68: Mooring system with Barge 1 moored alongside

As an inclusion to the total operation, a thought overall method when at location could be to:

- Jack up as normal
- Install the beams with the deck crane
- Moor the barge
- Conduct lifting operation
- Unmoor the barge
- Remove and stow away the beams with the deck crane
- Lower the vessel as normal

6.2 Strong and weak aspects of the study and discrepancies in modelling

The strong aspects of this study is having the totality from idea, design then analysis of a model that can be used on for a marine operation. The focus on using the DNV software SESAM GeniE, SESAM HydroD and SIMA to build and analyse such a complex model has given a red thread throughout the process with multiple trusted software. The produced model of the operation can be used and analysed, especially in cases where the size of the barge needs to be changed.

The week aspects of the study is mainly its lack of validation from either another study, a secondary analysis software or a physical model. This due to not many studies have been conducted for this particular problem. There could also be a few modelling discrepancies. These discrepancies were mainly around the suspension rig of the rotor blade and the fact model did not include a winch function for hoisting the payload. The second of these was the reason for the calculation of the relative heave motion criteria being determined for 10 thought lifts with a hoisting velocity ranging between 0.1 (m/s) and 1.0 (m/s). The reason for not including the winch function and the suspension rig being simplified is that the simulation would not run with both included. Furthermore, the heave compensation in the model was most likely modelled wrong in relation to the barge, as it should compensate for the motion between the objects. To solve these discrepancies, an idea could be to change the lifting wire from a RIFLEX line to a pure SIMO lifting line and model the suspension rig as a fourth rigid body. Then the heave compensation system should be re-evaluated and improved.

Other modelling discrepancies could be the stiffness and dimensions of the RIFLEX lines and the rigid body models made for that of the Bold Tern and the three barges. The model of the Bold Tern is not a complete replica however the points where the legs are positioned and distances between each other are accurate. The model of the barges are of a simple design and not modelled after real counterparts. This has an impact on the results, and to improve the model these needs to be replaced with accurate models of real barges.

The simulation period of the analysis could also be a discrepancy, as it is only used 30 minutes and not 3 hours as a minimum. The reason for using only 30 minutes is the operation was defined to be a short operation and the amount of simulations needed for the study. To give more accurate results the simulation period should be set to a minimum of 3 hours.

6.3 Conclusion

As a conclusion based on the results and case study, it is possible and safe to do this operation with certain sea states, as it has been observed that the standard deviation of relative motion is less than the criteria set at different peak periods. However, care should be taken when the payload is hanging above the deck as with the "right" sea state can excite the pitch motion of the barges to collide with the rotor blade. Here, snap loads could occur and with an underdimensioned wire and the "right" load the wire could break, leading to the rotor blade falling onto the barge deck.

The largest effects on the relative motion was induced by an increase in peak period relative to the barges RAOs, and an increase in significant wave height. It was also observed that waves coming from an angle of 045 degrees had the greatest impact. The size of the barge has an impact on the values as it is seen that a smaller barge has a greater heave motion than a bigger barge.

To control the irregular motion of the rotor blade a heave compensation system should be included to make the motion more predictable and safe. The effects of such a system was small on the values of motion however it served to make the motion of the payload more regular and damped. This should give an added safety to the operation.

The max tension forces in the lifting wire were shown to be within the limits of the MBL and are then defined as safe for the operation.

To keep the barge stationary during the lift, a mooring system as described could be a solution. This due to it's simplicity as mooring operations are tasks seafarers are familiar with, and can therefore recognize its dangers and keep the operation safe.

6.4 Future work

Two suggestions for future work on theses or projects arises from this thesis. The first is to improve and validate the SIMA model including the modelling with either a physical model or a different analysis software. This includes the modelling of heave compensation, where it should be emphasized to make the heave compensation react to the barge heave motion. The reason the model should be improved is mainly due to the discrepancies in modelling. Furthermore, it is recommended that the model of the barges are replaced with actual models of real barges used for such operations. This could get a clearer view of the operation in question. The simulations should also be re-run with a longer simulation period to improve the results.

The second suggestion is to make a functioning model of the mooring beam system. Here it should be emphasized to make the system as simple and practical as possible for safe handling, installation and stowage. A comparison against a DP system could also be made, to see the difference in operability and complexity.

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Appendices

A Program Code in Python

Python 3D plot

Python function for 3D plot generation of RAO's: 3D_Plot.py

```
1 # Importing packages
2 import numpy as np
3 import pandas as pd
4 import matplotlib.pyplot as plt
5
6 # Importing data from *.csv
7 df = pd.read_csv(r'*.csv', sep=';', engine='python')
8
9 # Time series
10 Tp = df['Period [s]']
11
12 # Defining wave directions
13 dir = [0, 45, 90, 135, 180, 225, 270, 315, 360]
14
15 # Setting y value for each direction
16 y1 = np.ones(Tp.size)*dir[0]
17 y2 = np.ones(Tp.size)*dir[1]
18 y3 = np.ones(Tp.size)*dir[2]
19 y4 = np.ones(Tp.size)*dir[3]
20 y5 = np.ones(Tp.size)*dir[4]
21 y6 = np.ones(Tp.size)*dir[5]
22 y7 = np.ones(Tp.size)*dir[6]
23 y8 = np.ones(Tp.size)*dir[7]
24 y9 = np.ones(Tp.size)*dir[8]
25
26 # Extracting wave amplitude for wave direction
27 amp = (df['0'], df['45'], df['90'], df['135'], df['180'],
28        df['225'], df['270'], df['315'], df['360'])
29
30 # Setting z value for each direction
31 z1 = amp[0]
32 z2 = amp[1]
33 z3 = amp[2]
34 z4 = amp[3]
35 z5 = amp[4]
36 z6 = amp[5]
37 z7 = amp[6]
38 z8 = amp[7]
39 z9 = amp[8]
40
41 # Plot (3D)
42 # Defining each 3D plots
43 plt.figure()
44 ax = plt.subplot(projection='3d')
45 ax.plot(Tp, y1, z1, color='r', label='0 degrees')
46 ax.plot(Tp, y2, z2, color='b', label='45 degrees')
```

```
47 ax.plot(Tp, y3, z3, color='g', label='90 degrees')
48 ax.plot(Tp, y4, z4, color='k', label='135 degrees')
49 ax.plot(Tp, y5, z5, color='m', label='180 degrees')
50 ax.plot(Tp, y6, z6, color='c', label='225 degrees')
51 ax.plot(Tp, y7, z7, color='y', label='270 degrees')
52 ax.plot(Tp, y8, z8, color='brown', label='315 degrees')
53 ax.plot(Tp, y9, z9, color='orange', label='360 degrees')
54
55 # Defining labels and title, setting legend and executing plot
56 ax.set_xlabel('Period [s]')
57 ax.set_ylabel('Direction [deg]')
58 ax.set_zlabel('Amplitude [m/m]')
59 plt.title('RAO Barge 3, DOF - Heave')
60 plt.legend()
61
62 plt.show()
```

Python stiffness calculation

Python function for stiffness calculation used in SIMA: Stiffness calculation.py

```
1 import math
2
3 # Parameters
4
5 E = 200000000000 # E modulus [Pa]
6 G = 79300000000 # Shear modulus [Pa]
7
8 D = 0.3568248232305542 # Outer diameter of rope
9 d = 0 # Inner diameter of rope
10 r = D / 2 # Radius of rope
11
12 l = 135 # Length of rope
13
14 # Area of cross-section
15
16 A = (math.pi * D ** 2) / 4 # Area of rope
17 Aext = (math.pi * D ** 2) / 4 # Area of rope (ext area)
18 Aint = (math.pi * d ** 2) / 4 # Area of rope (int area)
19
20 x = math.sqrt((0.1 * 4)/math.pi)
21 print(f"Diameter = {x}")
22
23 # Axial stiffness
24
25 # AxialStiffness = E * A # Axial stiffness rope
26 AxialStiffness = E * (Aext - Aint) # Axial stiffness pipe
27
28 # Bending stiffness
29
30 Ix = (math.pi * D ** 4) / 64 # Moment of inertia circle
31 # Ix = (math.pi * (D**4 - d**4))/64 # Moment of inertia pipe
32
33 BendingStiffness = E * Ix
34
35 # Torsional stiffness
36
37 Ip = (math.pi * D ** 4) / 32 # Polar moment of inertia circle
38 # Ip = (math.pi * (D**4 - d**4))/32 # Polar moment of inertia pipe
39
40 Tv = E * Ip
41
42 # Rotational angle
43
44 Wp = Ip / r # Polar resistance moment
45
46 T = Tv * Wp # Rotational moment
47
48 Rotang = (T * l) / (G * Ip) # Rotational angle
49
50 # Torional stiffness with rotational angle
51
```

```
52 Tvrot = Tv / Rotang
53
54 print(f"Area: {A} [m^2] \n"
55       f"External area: {Aext} [m^2] \n"
56       f"Internal area: {Aint} [m^2] \n"
57       f"Axial stiffness: {AxialStiffness} [N] \n"
58       f"Moment of inertia: {Ix} [m^4] \n"
59       f"Polar moment of inertia: {Ip} [m^4] \n"
60       f"Bending stiffness: {BendingStiffness} [Nm^2] \n"
61       f"Torsional stiffness: {Tv} [Nm^2] \n"
62       f"Tortional stiffness with rotational angle: {Tvrot} [Nm^2/rad]")
```

Python probability of re-impact

Python script for estimation of re-impact: Reimpactprob.py

```
1 import pandas as pd
2 import numpy as np
3
4 # Importing data from *.csv
5 df = pd.read_csv(r'*.csv', sep=';', engine='python')
6
7 # Extracting data
8 T = df["T"]
9 omega = df["omega"]
10 S = df["S(f)"]
11 sigma = df["sigma"][0]
12 deltaf = omega[1] - omega[0]
13
14 # Defining estimation values
15 Tau = 2.9
16
17 # Computing Mean wave period from imported dataset
18 # to compare data from calculation of standard deviation limit
19 m0est = sigma ** 2
20 m0 = sum(S * deltaf)
21 m2 = sum((omega ** 2) * S * deltaf)
22 Tzest = (2 * np.pi) * np.sqrt(m0est / m2)
23 Tz = (2 * np.pi) * np.sqrt(m0 / m2)
24
25 # Defining lists, velocities for calculation for limit of standard deviation
26 # and calculation for the limit of standard deviation
27 sigmalist = [] # Standard deviation of relative motion from dataset. Is this less
    than calculations?
28 tzest = []
29 tau = []
30 for i in range(1, 11):
31     sig = sigma * (i / i)
32     t = Tau * (i / i)
33     tze = Tzest * (i / i)
34
35     sigmalist.append(sig)
36     tau.append(t)
37     tzest.append(tze)
38
39 Ulist = []
40 s = [] # Standard deviation of relative motion for assumption Tz and hoisting
    velocities
41 for n in range(1, 11):
42     u = 0.1 * n
43     Ulist.append(u)
44
45 for U in Ulist:
46     si = (U * Tzest) / Tau
47     s.append(si)
48
49
```

```
50 sd = [] # Standard deviation relative to dataset and hoisting velocities to compare
      with estimations
51 for U in Ulist:
52     sid = (U * Tz) / Tau
53     sd.append(sid)
54
55 column_names = ["Hoisting velocity (m/s)", "Limit method 1", "Limit method 2", "Sigma
      ", "Less than"]
56 con = np.stack((Ulist, s, sd, sigmalist, tau), axis=1)
57 res = pd.DataFrame(con, columns=column_names)
58 res.to_csv(r'*_results.csv', sep=';')
59
60 print(f"m0 = {m0} \n"
61       f"m2 = {m2} \n"
62       f"Tz estimate = {Tzest} \n"
63       f"Tz dataset = {Tz} \n"
64       f"Result: \n"
65       f"{res}")
```

Python SIMA plots

Python script for plotting of data from SIMA: SIMA_Plots.py

```
1 # Importing packages
2 import pandas as pd
3 import matplotlib.pyplot as plt
4
5 # Importing data from *.csv
6 df = pd.read_csv(r'*.csv', sep=';', engine='python')
7
8 ds = pd.read_csv(r'*.csv', sep=';', engine='python')
9
10 # Extracting time series
11 dt = df["x-axis"]
12
13 # Extracting data for timeseries
14 # surge = df["XGtranslationTotalmotion"]
15 sway = df["YGtranslationTotalmotion"]
16 swayJack = ds["YGtranslationTotalmotion.addConstant"]
17 # heave = df["ZGtranslationTotalmotion"]
18 # roll = df["XLrotationTotalmotion"]
19 # pitch = df["YLrotationTotalmotion"]
20 # yaw = df["ZGrotationTotalmotion"]
21
22 # Heave spectrum
23 # heavespec = df["ZGtranslationTotalmotion.acspec"]
24
25 # Wave
26 # wave = df["Totalwaveelevation"]
27 # wave = ds["Totalwaveelevation"]
28
29 # Wave spectrum
30 # WaveSpec = df["Wave elevation over / under the node.acspec"]
31 # WaveSpec = df["Totalwaveelevation.acspec"]
32
33 # Cranetip
34 # cranex = df["Displacement in x - direction"]
35 # craney = df["Displacement in y - direction"]
36 # cranez = df["Displacement in z - direction"]
37
38 # Wire tension
39 # tension = df["Axial force"]
40
41 # Relative motion response spectrum
42 # S = df["ZGtranslationTotalmotion.addConstant..addConstant.subtract.acspec"]
43
44 # Relative motion barge/rotor blade
45 # Rm = df["ZGtranslationTotalmotion.addConstant..addConstant.subtract"]
46
47 # Plotting data
48 # plt.style.use("Solarize_Light2")
49 # plt.style.use("ggplot")
50 fig, ax = plt.subplots(figsize=(4, 3))
51
```

```

52 # ax.plot(dt, surge, color='b', label='Surge motion barge, [m]')
53 ax.plot(dt, sway, color='b', label='Sway motion Barge, [m]')
54 # ax.plot(dt, dx, **{'color': 'blue', 'marker': 'o'}, label='Heave motion barge, [m
    ]')
55 # ax.plot(dt, heave, color='r', label='Heave motion, [m]')
56 # ax.plot(dt, roll, color='b', label='Roll motion [m]')
57 # ax.plot(dt, pitch, color='b', label='Pitch motion barge, [m]')
58 # ax.plot(dt, yaw, color='b', label='Yaw motion barge, [m]')
59
60 ax.plot(dt, swayJack, color='r', label='Sway motion Jack-up, [m]')
61
62 # ax.plot(dt, WaveSpec, color='b', label='Wave spectrum, [m^2s]')
63 # ax.plot(dt, tension, color='b', label='Tension, [N]')
64 # ax.plot(dt, Rm, color='b', label='Relative motion barge/rotor blade, [m]')
65 # ax.plot(dt, wave, color='y', label='Wave elevation, [m]')
66 # ax.plot(dt, cranez, color='b', label='Heave, [m]')
67 # ax.plot(dt, pitch, color='b', label='Pitch, [deg]')
68
69 # Defining labels and title, setting legend and executing plot
70 # ax.xaxis.tick_top()
71 ax.set_xlabel('Period [s]')
72 # ax.set_ylabel('Surge motion, [m]')
73 ax.set_ylabel('Sway motion, [m]')
74 # ax.set_ylabel('Heave motion, [m]')
75 # ax.set_ylabel('Roll motion, [deg]')
76 # ax.set_ylabel('Pitch motion, [deg]')
77 # ax.set_ylabel('Yaw motion, [deg]')
78 # ax.set_ylabel('Lifting wire tension, [N]')
79 # ax.set_ylabel('Wave spectrum density, [m^2s]')
80 # ax.set_ylabel('Heave spectrum density, [m^2s]')
81 # ax.set_ylabel('Relative motion [m]')
82 # ax.set_ylabel('Total wave elevation [m]')
83
84 ax.set_facecolor('lavender')
85 # plt.plot(dt, S, 'bo-', label='Heave motion barge, [m]')
86 # plt.xlabel('Period, [s]')
87 # plt.ylabel('Heave motion, [m]')
88 # plt.ylabel('Pitch motion, [deg]')
89 plt.grid(which="both", linestyle="dashed")
90 plt.legend()
91 plt.rc('legend', fontsize=25)
92 plt.rc('font', size=25)
93 ax.xaxis.label.set_fontsize(25)
94 ax.yaxis.label.set_fontsize(25)
95 ax.tick_params(axis='x', labelsizes=20)
96 ax.tick_params(axis='y', labelsizes=20)
97 plt.title('Sway motion Jack-up and Barge 1, sub case 18, Tp = 11')
98 plt.show()

```


B Extra figures

B.1 Dynamic parameters

B.2 RAOs

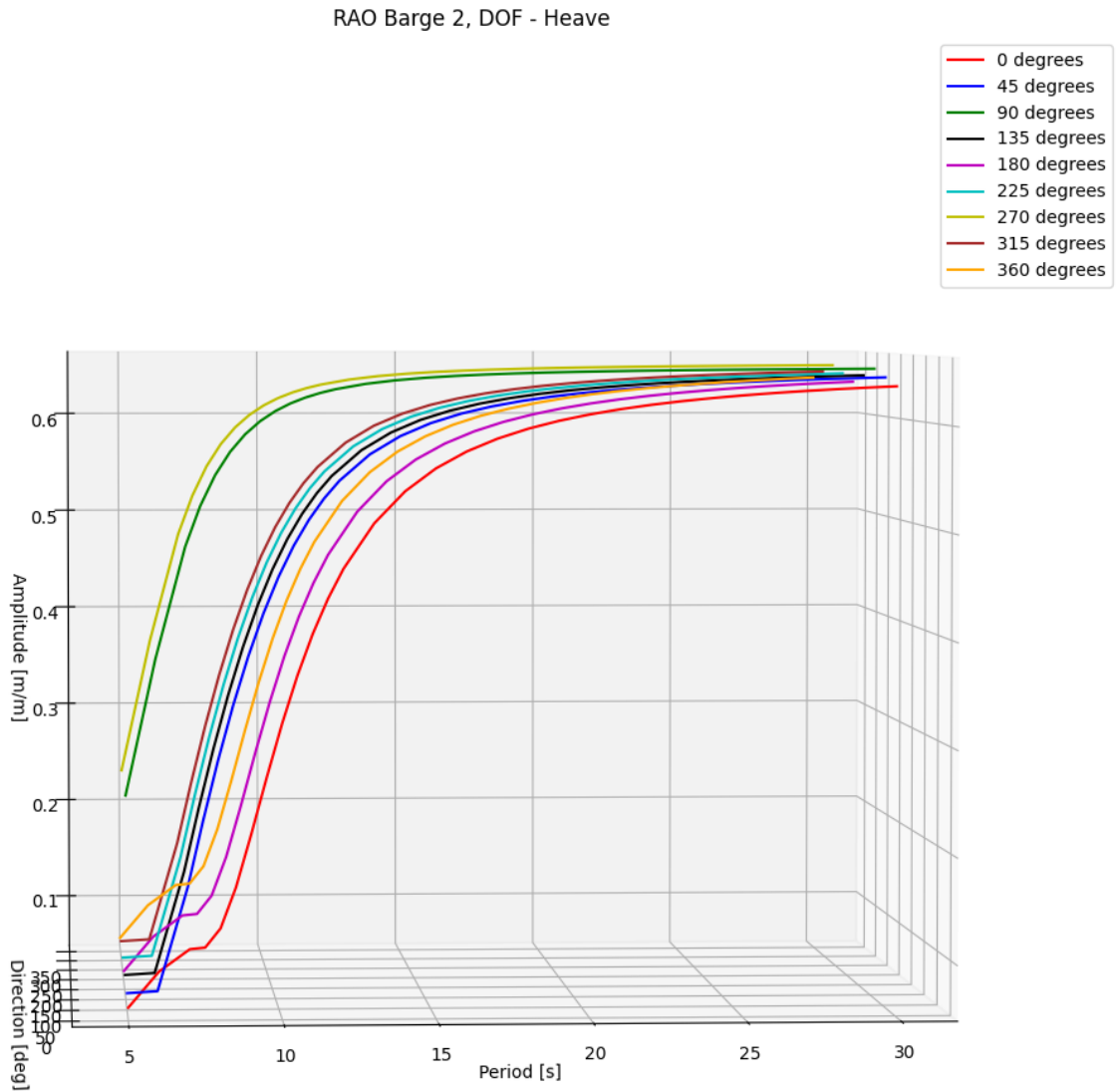


Figure 69: RAO, DOF: heave, Barge 2 in time domain

RAO Barge 2, DOF - Roll

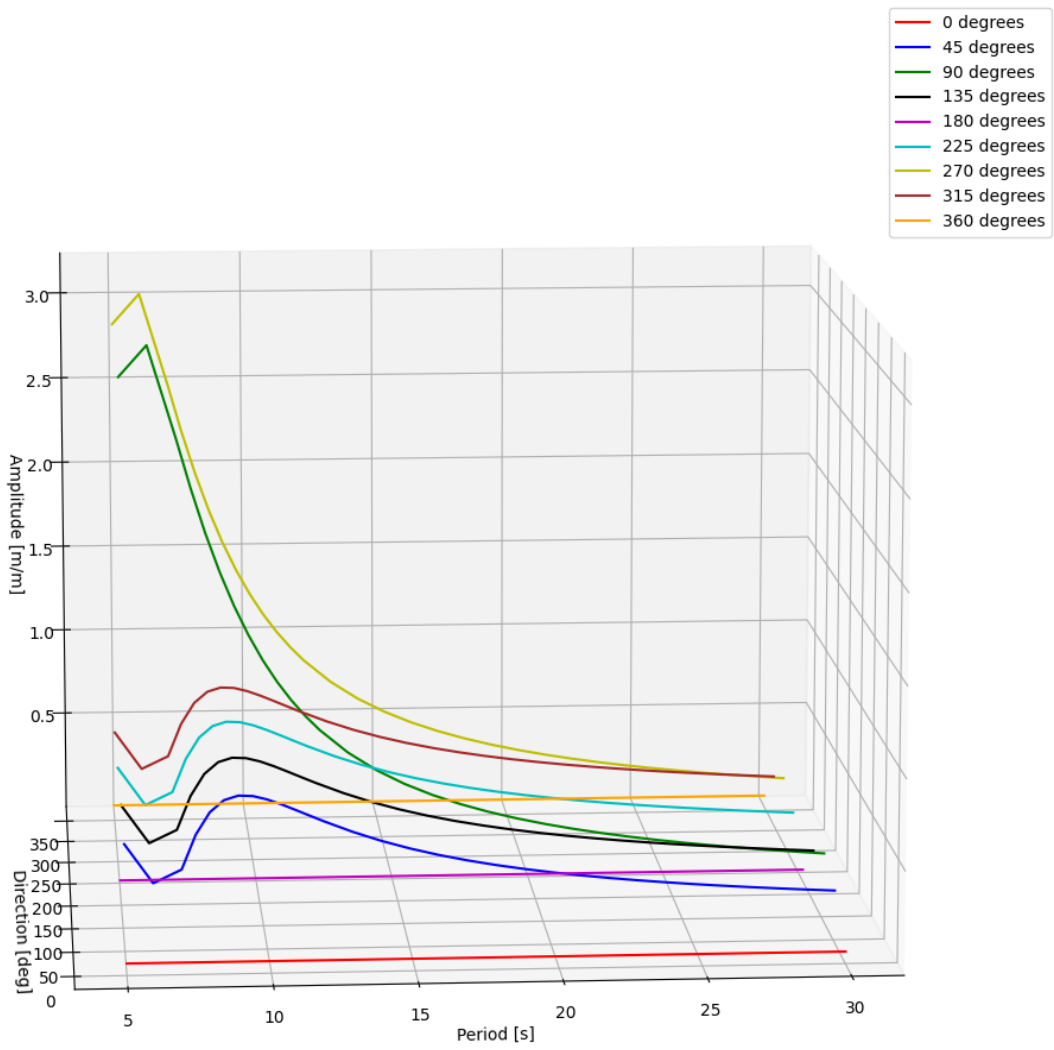


Figure 70: RAO, DOF: roll, Barge 2 in time domain

RAO Barge 2, DOF - Pitch

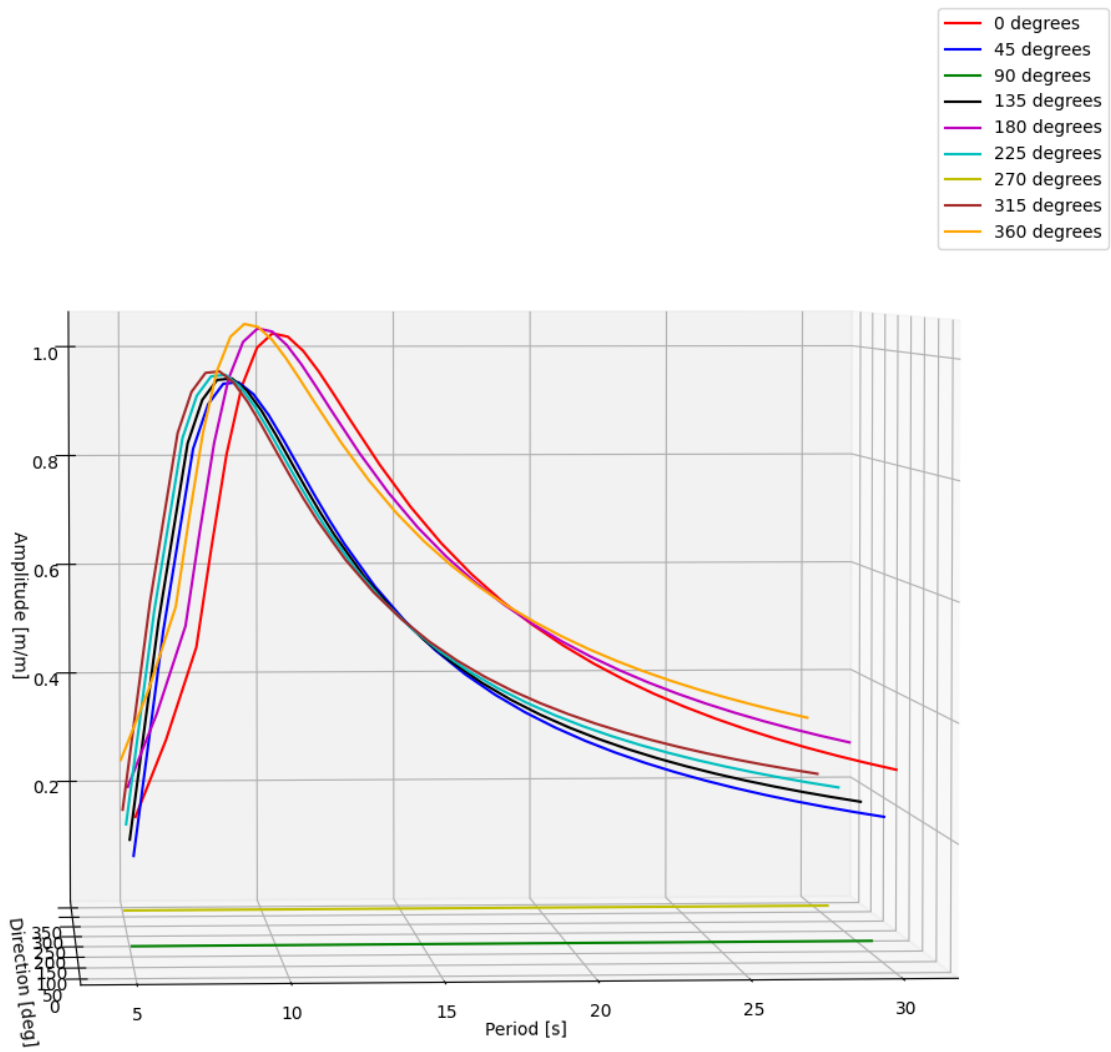


Figure 71: RAO, DOF: pitch, Barge 2 in time domain

RAO Barge 3, DOF - Heave

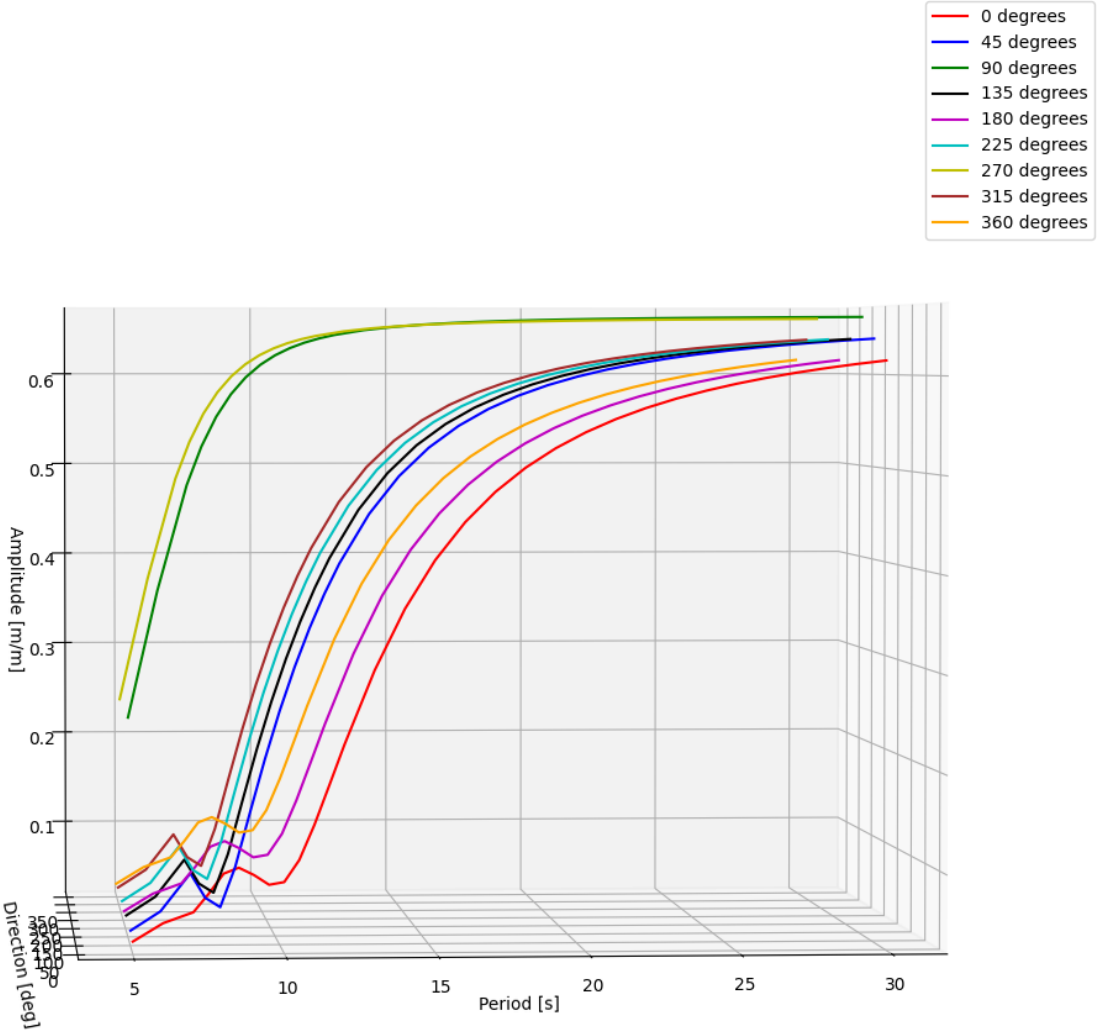


Figure 72: RAO, DOF: heave, Barge 3 in time domain

RAO Barge 3, DOF - Roll

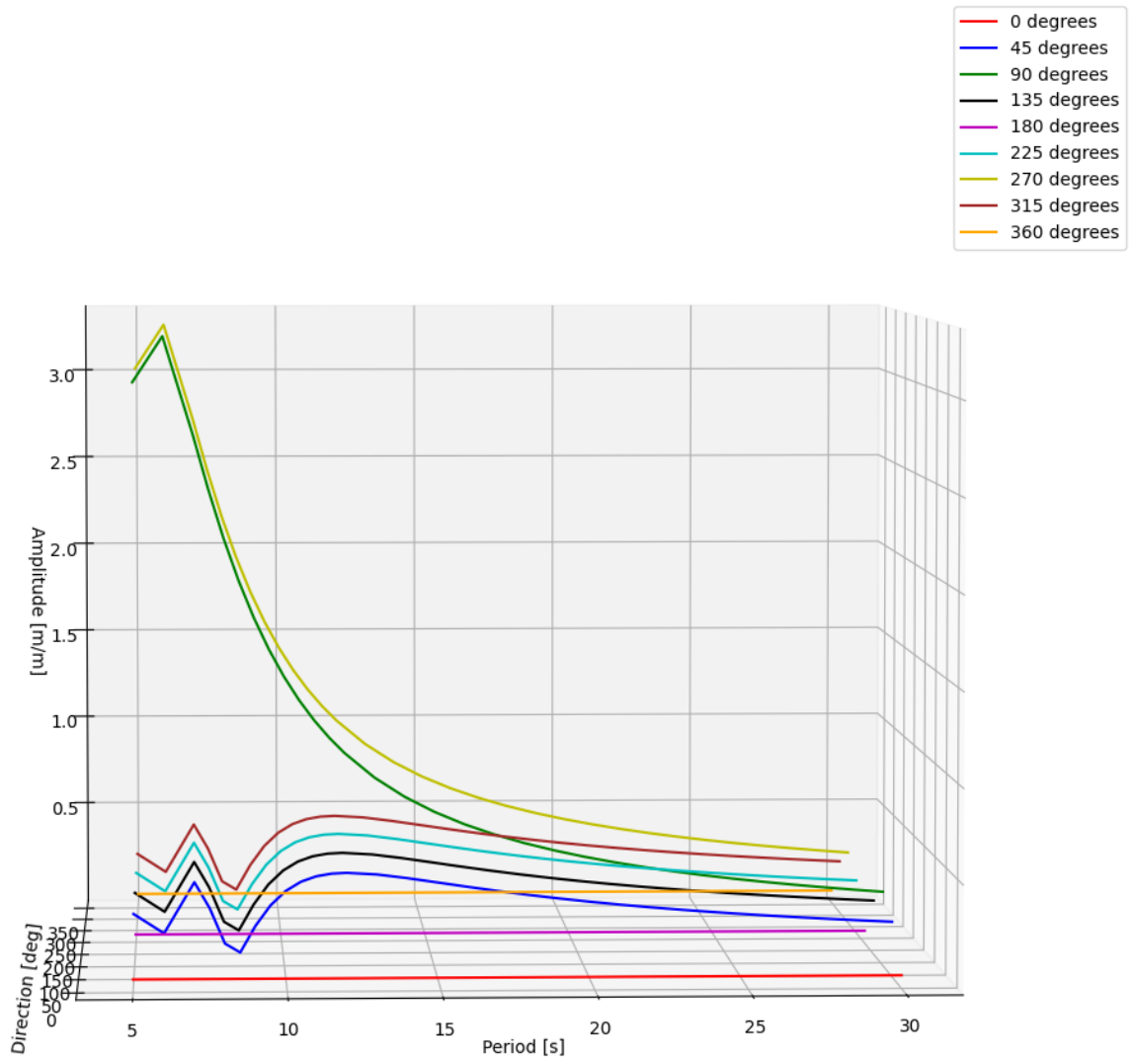


Figure 73: RAO, DOF: roll, Barge 3 in time domain

RAO Barge 3, DOF - Pitch

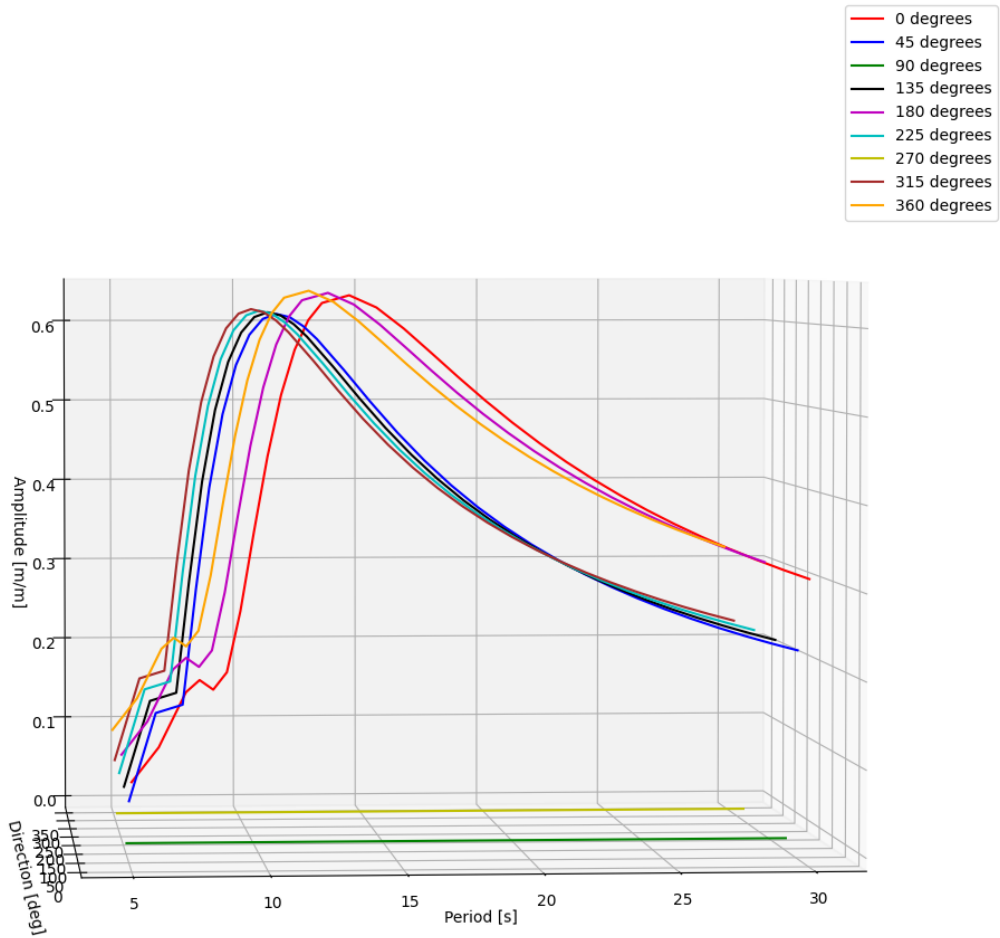


Figure 74: RAO, DOF: pitch, Barge 3 in time domain

B.3 MBL table

Diameter (mm)	Approx. Weight (kg/100m)		Tensile Strength (MPa)					
			1570		1770		1960	
	FC	WSC/WRC	Minimum Breaking Load (KN)					
			FC	WSC/WRC	FC	WSC/WRC	FC	WSC/WRC
40	570	664	630	746	710	842	787	931
42	628	732	695	822	783	928	868	1027
44	689	803	763	902	860	1018	953	1127
46	753	878	834	986	940	1113	1041	1232
48	820	956	908	1074	1023	1212	1134	1341
50	890	1038	985	1165	1110	1315	1230	1455
52	963	1122	1065	1260	1201	1422	1330	1574
56	1116	1301	1236	1461	1392	1650	1543	1825
58	1198	1396	1325	1568	1494	1769	1655	1958
60	1282	1494	1418	1678	1598	1894	1771	2095
62	1368	1595	1515	1791	1707	2022	1891	2237
64	1458	1700	1614	1909	1819	2154	2015	2384
66	1551	1808	1716	2030	1934	2291	2143	2535
68	1646	1919	1822	2155	2053	2432	2275	2691
70	1744	2034	1931	2283	2176	2577	2411	2852
72	1846	2151	2042	2416	2302	2727	2551	3017
74	1949	2273	2158	2552	2431	2880	2694	3187
76	2056	2397	2276	2692	2565	3038	2842	3362
78	2166	2525	2397	2835	2701	3200	2993	3541
80	2278	2656	2522	2982	2842	3366	3149	3725
82	2394	2790	2649	3133	2985	3537	3308	3913
84	2512	2928	2780	3288	3133	3711	3472	4107
86	2633	3069	2914	3447	3284	3890	3639	4304
88	2757	3214	3051	3609	3438	4073	3810	4507
90	2884	3362	3191	3775	3596	4261	3985	4714
92	3013	3513	3335	3944	3758	4452	4164	4926
94	3146	3667	3481	4118	3923	4648	4347	5143
96	3281	3825	3631	4295	4092	4848	4534	5364
98	3419	3986	3784	4475	4264	5052	4725	5590
100	3560	4150	3940	4660	4440	5260	4920	5820
102	3704	4318	4099	4848	4619	5473	5119	6055
104	3850	4489	4262	5040	4802	5689	5321	6295
106	4000	4663	4427	5236	4989	5910	5528	6539
108	4152	4841	4596	5435	5179	6135	5739	6788
110	4308	5022	4767	5639	5372	6365	5953	7042
112	4466	5206	4942	5846	5570	6598	6172	7301
114	4627	5393	5120	6056	5770	6836	6394	7564
116	4790	5584	5302	6270	5974	7078	6620	7831
118	4957	5778	5486	6489	6182	7324	6851	8104
120	5126	5976	5674	6710	6394	7574	7085	8381

Figure 75: Table of Minimum Breaking Load for the $8x36WS+FC$ steel wire produced by Nantong Guangming Steel Wire Products Co.Ltd [43]

B.4 Case study results - heave

Case	Heave motion		
	Tp wind wave = 6	Tp wind wave = 9	Tp wind wave = 11
1	0.14	0.16	0.17
2	0.14	0.19	0.23
3	0.14	0.16	0.17
4	0.14	0.19	0.23
5	0.14	0.16	0.17
6	0.14	0.19	0.23
7	0.15	0.18	0.20
8	0.16	0.24	0.28
9	0.15	0.18	0.20
10	0.16	0.24	0.28
11	0.15	0.18	0.20
12	0.16	0.24	0.28
13	0.14	0.16	0.18
14	0.15	0.19	0.24
15	0.14	0.16	0.18
16	0.15	0.19	0.24
17	0.14	0.16	0.18
18	0.15	0.19	0.24
19	0.14	0.18	0.20
20	0.15	0.24	0.28
21	0.14	0.18	0.20
22	0.15	0.24	0.28
23	0.14	0.18	0.20
24	0.15	0.24	0.28

Figure 76: Standard deviation of relative heave motion results, for Barge 2 (Green values < Criteria)

Case	Heave motion
	Tp wind wave = 11
1	0.18
2	0.23
3	0.18
4	0.23
5	0.18
6	0.23
7	0.21
8	0.29
9	0.21
10	0.29
11	0.21
12	0.29
13	0.18
14	0.24
15	0.18
16	0.24
17	0.18
18	0.24
19	0.20
20	0.28
21	0.20
22	0.28
23	0.20
24	0.28

Figure 77: Standard deviation of relative heave motion results, for Barge 2 with heave compensation (Green values < Criteria)

Case	Heave motion		
	Tp wind wave = 6	Tp wind wave = 9	Tp wind wave = 11
1	0.11	0.12	0.12
2	0.12	0.13	0.15
3	0.11	0.12	0.12
4	0.12	0.13	0.15
5	0.11	0.12	0.12
6	0.12	0.13	0.15
7	0.13	0.14	0.16
8	0.13	0.17	0.20
9	0.13	0.14	0.16
10	0.13	0.17	0.20
11	0.13	0.14	0.16
12	0.13	0.17	0.20
13	0.13	0.13	0.14
14	0.13	0.14	0.16
15	0.13	0.13	0.14
16	0.13	0.14	0.16
17	0.13	0.13	0.14
18	0.13	0.14	0.16
19	0.11	0.13	0.15
20	0.12	0.15	0.19
21	0.11	0.13	0.15
22	0.12	0.15	0.19
23	0.11	0.13	0.15
24	0.12	0.15	0.19

Figure 78: Standard deviation of relative heave motion results, for Barge 3 (Green values < Criteria)

Case	Heave motion
	Tp wind wave = 11
1	0.13
2	0.15
3	0.13
4	0.15
5	0.13
6	0.15
7	0.16
8	0.21
9	0.16
10	0.21
11	0.16
12	0.21
13	0.14
14	0.16
15	0.14
16	0.16
17	0.14
18	0.16
19	0.15
20	0.20
21	0.15
22	0.20
23	0.15
24	0.20

Figure 79: Standard deviation of relative heave motion results, for Barge 3 with heave compensation (Green values < Criteria)

B.5 Case study results - pitch

Case	Pitch motion		
	Tp wind wave = 6	Tp wind wave = 9	Tp wind wave = 11
1	0.56	1.22	1.18
2	0.82	2.00	1.90
3	0.56	1.22	1.18
4	0.82	2.00	1.90
5	0.56	1.22	1.18
6	0.82	2.00	1.90
7	0.68	1.08	1.05
8	1.06	1.82	1.70
9	0.68	1.08	1.05
10	1.06	1.82	1.70
11	0.68	1.08	1.05
12	1.06	1.82	1.70
13	0.53	1.15	1.18
14	0.78	1.94	1.91
15	0.53	1.15	1.18
16	0.78	1.94	1.91
17	0.53	1.15	1.18
18	0.78	1.94	1.91
19	0.71	1.14	1.06
20	1.09	1.85	1.69
21	0.71	1.14	1.06
22	1.09	1.85	1.69
23	0.71	1.14	1.06
24	1.09	1.85	1.69

Figure 80: Max pitch angle criteria results, for Barge 2

Case	Pitch motion		
	Tp wind wave = 6	Tp wind wave = 9	Tp wind wave = 11
1	0.41	0.59	0.65
2	0.44	0.75	0.88
3	0.41	0.59	0.65
4	0.44	0.75	0.88
5	0.41	0.59	0.65
6	0.44	0.75	0.88
7	0.37	0.75	0.71
8	0.43	1.21	1.12
9	0.37	0.75	0.71
10	0.43	1.21	1.12
11	0.37	0.75	0.71
12	0.43	1.21	1.12
13	0.37	0.51	0.59
14	0.40	0.71	0.91
15	0.37	0.51	0.59
16	0.40	0.71	0.91
17	0.37	0.51	0.59
18	0.40	0.71	0.91
19	0.42	0.81	0.74
20	0.47	1.26	1.10
21	0.42	0.81	0.74
22	0.47	1.26	1.10
23	0.42	0.81	0.74
24	0.47	1.26	1.10

Figure 81: Max pitch angle criteria results, for Barge 3



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