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motion control during offshore lift operations

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Preface

This master thesis is about motion control during offshore lift operations. The work carried out in this master thesis is an indirect continuation of the project thesis from fall 2016. The task for this master thesis was constructed by my supervisors, Svein Sævik and Peter Sandvik.

I want to thank my main supervisor Svein Sævik, professor at NTNU and Co-supervisor Peter Sandvik, senior research scientist at Marintek for the good support and academic assistance during the thesis work. I also want to thank student assistant Yuna Zhao for technical help concerning the SIMO software.

Trondheim, 2017-06-11

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THESIS WORK SPRING 2017

for

Stud. tech. Sten Martin Grønlund Andersen

Motion control during offshore lift operations

Kontroll av bevegelser ved løfteoperasjoner til havs

The background for this project is related to offshore lift operations with focus on controlling the motions of lifted objects. This has many applications such as avoiding excessive object pendulum motions and in operations that requires precise positioning of the lifted object, e.g. where the object is to be connected to an existing fixed installation (already installed objects). The purpose of the work is to investigate measures of reducing such motions by means of active control methods. The thesis works represents a continuation of the project work conducted in Fall 2016 and includes:

1. Literature study, including relevant standards for lift operations, classification and characterisation of passive heave compensators, theoretical basis for computational tools like Sima (Simo/Riflex) and familiarization with the Sima tool.

2. Establish a model that can be used to evaluate the lift operation responses and as basis for future case studies. This requires input data in terms of environmental and vessel motion characteristics, geometry details and heave compensation characteristics. The basis will be established in close cooperation with co-advisor Peter Sandvik, Marintek.

3. Perform sensitivity analyses with respect to means of controlling the motion of the lifted object during the lift-off phase. This may include winch wires in two planes where the winch

characteristic may allow hysteresis, however having sufficient response time to avoid snapping. The winch characteristic is a key point to focus on with due consideration of the breaking capacity of such wires (15-20mm) and also the torsion inertia of the winch drum. For a given lift scenario, what is the optimum characteristic of such winches?

4. Conclusions and recommendations for further work.

All necessary input data is assumed to be provided by Marintek.

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

In the thesis the candidate shall present his personal contribution to the resolution of problems within the scope of the thesis work

Theories and conclusions should be based on mathematical derivations and/or logic reasoning identifying the various steps in the deduction.

The candidate should utilise the existing possibilities for obtaining relevant literature.

Thesis format

The thesis should be organised in a rational manner to give a clear exposition of results, assessments, and conclusions. The text should be brief and to the point, with a clear language. Telegraphic language should be avoided.

The thesis shall contain the following elements: A text defining the scope, preface, list of contents, summary, main body of thesis, conclusions with recommendations for further work, list of symbols and acronyms, references and (optional) appendices. All figures, tables and equations shall be numerated.

The supervisors may require that the candidate, in an early stage of the work, presents a written plan for the completion of the work.

The original contribution of the candidate and material taken from other sources shall be clearly defined. Work from other sources shall be properly referenced using an acknowledged referencing system.

The report shall be submitted in two copies:

- Signed by the candidate
- The text defining the scope included
- In bound volume(s)
- Drawings and/or computer prints which cannot be bound should be organised in a separate folder.

Ownership

NTNU has according to the present rules the ownership of the thesis. Any use of the thesis has to be approved by NTNU (or external partner when this applies). The department has the right to use the thesis as if the work was carried out by a NTNU employee, if nothing else has been agreed in advance.

Thesis supervisors:

Prof. Svein Sævik, NTNU

Peter Sandvik, Marintek

Deadline: June 11, 2017

Trondheim, January, 2017

Svein Sævik

Candidate – date and signature:

11.06.2017 Martin Andersen

Summary

Offshore lifting is present in many offshore operations. Offshore lifting operations is very sensitive to environmental loads which reduces the weather window for the entire operation. The weather criteria for offshore heavy lifting according to DNV recommended practice is set to 2.5 m significant wave height. To increase the weather window of the offshore lifting operations, it is necessary to control the motion of the lifted object and understand the basis of behavior. The most common way of controlling the motion of the lifted object is by use of tugger lines.

In this project, a SIMO model of a general heavy lifting operation was provided by Marintek and modified according to this project. Several simulations are carried out for three different phases representing different initial positions of the lifted object or module. The use of tugger lines proved to reduce the module displacement relative to the ship drastically according to the simulations. And a deeper understanding of how tugger lines affect the behavior of the system was retrieved.

The relevant theory for the SIMO software is provided in the report. The simulations are not verified, but seems to give fundamentally correct physical behavior with the exception of the relative module displacement at low peak periods which should be studied further.

Further work can roughly be summarized in the following points:

- Verify the time domain analysis carried out in this project and improve the quality of the simulations.
- Simulate the offshore heavy lifting operation with a continuous crane module position from where it is lifted off deck to where it is hoisted down in the water.
- Study the system behavior of reaching the maximum velocity of the tugger winch.
- Study different damping models of the tugger lines.

Contents

List of Figures

List of Tables

List of Graphs

List of Equations

1 Introduction

1.1 Background

In the offshore industry, the need for lifting are very present. Every offshore operation prefers as huge weather window as possible, but the weather operation of an operation is just as big as the smallest weather operation. Offshore heavy lifting operations are very sensitive to environmental loads and waves. this means that heavy lifting operations often has a small weather window compared to other parts of the operation. By increasing the critical boundaries of the lifting operations, the cost and time spent can be reduced. To pursuit this, a deeper understanding of how the crane configurations and weather parameters affect the operation are wanted.

A lifting operation involves planning, equipment and manpower and therefor there are a lot of parameters to consider in order to improve lifting operations. One important design aspects are the tugger lines. Tugger lines is used to control the motions of the crane module by providing sufficient damping and tension. A tugger line design can be quite complex to design, but design and simulation software like SIMO are very useful tools.

1.2 Objectives

The objectives of this report are to model a lifting operation involving tugger lines and determine the characteristics of the tugger lines and the crane module based on different environmental input and tugger line configurations. The fictional lifting operation will be a general operation where a crane module is lifted off deck to where it is going to be hoisted down in the water. The operation will take place above water since the damping from the water are sufficient enough for the need of tugger lines. The focus of the report are the horizontal motions of the load and the forces, elongation/compression velocity and acceleration of the tugger lines as these are the dimensioning parameters of an offshore heavy lifting operation. The model will be simulated in SIMO which is a software that simulates the equation of motion of complex structures in marine environments.

1.3 Structure of the Report

The report first presents the problem and give a detailed description of the computer model and the failure modes or boundaries of the operation. The failure modes are what classifies the dimensioning parameters of the operation. Then the theory of the report is presented to give an understanding of how the SIMO program works. The theory only present what's relevant to the project. Following the theory, the procedure and input data is presented. The procedure and input data first introduces the tugger line configurations and input data and how the simulations are done. Then a description of the different phases of the simulations with a detailed description of how and why the tugger line configurations appears as it does and the input data for the simulations. The result and discussion are fused together for the purpose of better understanding and order. The results present different time domain results for the different phases with important observations which are then discussed below the observations. At last, the conclusion and recommendations for further work are presented.

2 Problem description

Offshore lifting operations are an important part of offshore operations, but it is very sensitive to environmental loads, especially waves. To make offshore lifting operations more suitable to operate in rougher weather, a need for controlling the motions of the crane load is necessary. This report focuses on the use of tugger lines to control the motions where only the horizontal motions of the crane load is considered.

Designing an offshore lifting operation can be quite challenging because of the many parameters and complex configurations involved. By using a software like SIMO, we can simulate a model of the operation to observe how different input data and configurations affect the system. when simulating the lifting operation, it is needed to make simplifications. In a real case, the operation is continuous from when the crane module is hoisted off deck to it is lowered down into the water. This makes it challenging to simulate since the tugger line configuration are changing along the operation and manual control are present in the operation. To encounter this, the simulation is divided in three different phases where the module is positioned in three different positions. Then the simulations are done by having the crane orientation fixed to the position it is assigned for the specific phase. By doing this simplification, the characteristic of the tugger lines and the crane module can be studied without having to deal with the problem of change in the tugger line configuration and other manual control options.

2.1 Crane model

The SIMO model is provided by Marintek with a few modifications. The modifications are the module, the couplings between the module and the hook and 4 winch points on the ship. Other than that, the model is similar to what was provided by Marintek. *Figure 1* below shows the model without tugger lines.

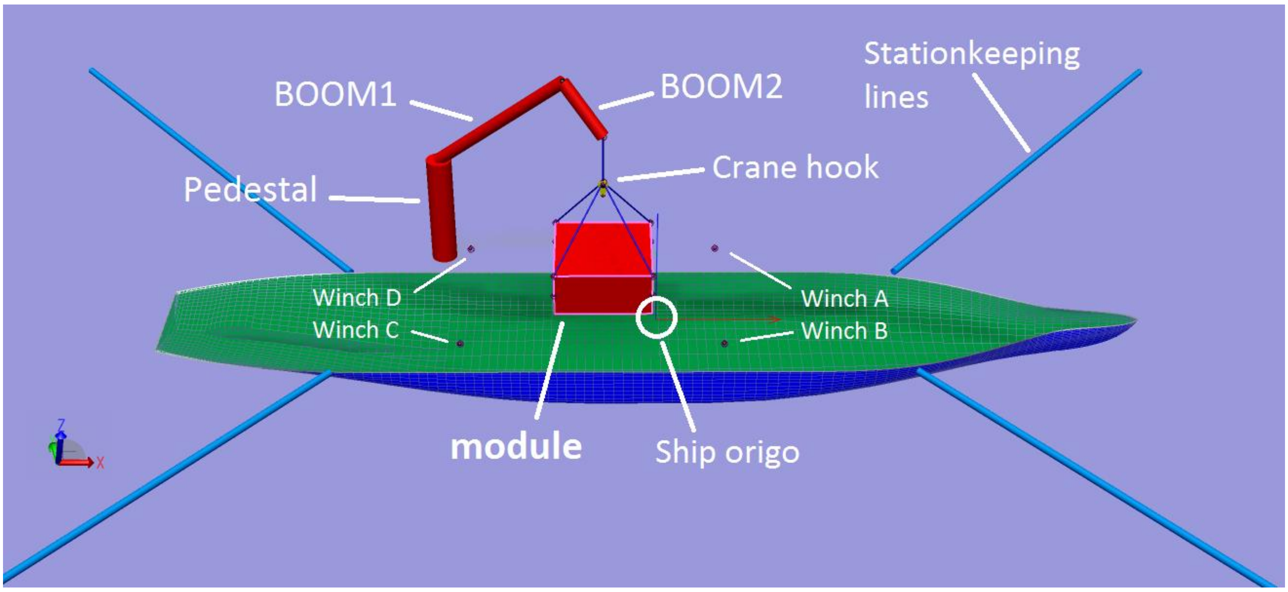


figure 2.1: SIMO model without tugger lines.

The ship is 135m long and 24m wide with a crane capable of lifting 400 ton. The ship has its origo at the same level as the water plane level where the deck is considered to be 5m above the water plane level. The distance from the crane tip to the center of gravity of the module is 23m. The crane hook weights 10 ton, but act as a point load which means it has no rotational mass. the ship has a ballast system represented as an upward pointing force at the crane tip. The magnitude of this force equals the gravity force of the module which is 1 962 000N.

The global coordinate system has the x-direction pointing along the forward direction of the ship, the y-direction is pointing in the port side direction of the ship and the z-direction is pointing upwards. The same applies to all initial local body-coordinate systems.

The crane is modelled by 3 cylindrical prescribed elements. They don't have mass and thus no inertia resistance. The pedestal has its origo in its base with a 5m vertical offset from local body-coordinate system of the ship. BOOM1 has its origo where it is connected with the pedestal and BOOM2 has its origo where it is connected with BOOM1. BOOM1 and BOOM2 follows the orientation of the pedestal. The cylinder's length and angle between the cylinder's elongation and the horizontal plane are presented in *table 2.1* below.

Table 2.1: Crane Dimensions.

Body parts	**Length [m]**	**Angle between vertical axis and horizontal plane [deg]**
pedestal	18	90
Boom1	28	30
Boom2	10	-50

If the tugger lines are neglected, the couplings in the model serves two purposes. One for lifting the crane load and the other ones for station keeping. The four couplings used for station keeping are modelled as fixed-force elongation couplings and the five couplings used in the lifting configuration is modelled as simple wire couplings. The most important design and properties of the mentioned couplings are shown in *table 2.2* below.

Table 2.2: Coupling data.

Couplings	**Length [m]**	**Flexibility [m/N]**	**Damping [Ns/m]**
Main lifting wire	7.84	1.3e-08	1.0e+07
4xSmall lifting wires	16.02	1.3e-08	1.0e+07
4xStation keeping lines	-	1.67e-05	9.99e+05

The module is modelled as a rigid box element that are not affected by wind or waves. The mass distribution is uniform with the center of gravity and its origo in the geometrical center of the module. The points where the tugger lines are supposed to attach to the module are situated on each corner of the module in the vertical center. Dimensions and structural mass for the module is shown in *table 2.3* below.

Table 2.3: Module data.

Width [m]	15
Length [m]	15
Height [m]	7
Mass [kg]	2e+05
Mass moment of inertia, I_{xx} [kgm^2]	6.85e+07
Mass moment of inertia, I_{yy} [kgm^2]	6.85e+07
Mass moment of inertia, I_{zz} [kgm^2]	5.25e+07

The winch points are where the tugger lines are going to attach. These are not modeled as a winch, but just stationary body points or attachment points connected on the ship body. The reason for that is because the winch points in SIMO doesn't have the necessary properties for a constant tension tugger winch, but the tugger line applied in the model consist the necessary properties needed to represent a winch. The position of each winch point is shown in *table 2.4* below.

Table 2.4: Winch point distance from the ship's origo.

Winch ID	**Distance from ship origo in x-direction [m]**	**Distance from ship origo in y-direction [m]**	**Distance from ship origo in z-direction [m]**
A	30	13	5
B	30	-13	5
C	-30	-13	5
D	-30	13	5

2.2 Tugger line configuration

The tugger lines in the SIMO model is modelled with two fixed-force elongation lines which act as a compression rod. One of the lines provides the force depending on the current length and velocity of the line where the constant tension is modeled as a constant force for all lengths. While the other line act as a measuring line.

The damping in the tugger line is defined by specifying the damping coefficient dependent on the length of the line and the damping exponent or order. In this case, the damping exponent is set to be zero which means that the damping force act as a friction force. The friction force will be activated when the elongation/compression velocity of the tugger line reach a certain velocity where. SIMO applies a first order damping before the friction force is activated. The purpose of this first order damping force is to avoid numerical instability and simulate a more real case scenario.

The fixed-force elongation coupling does not have an option to measure the elongation/compression velocity so a tugger line need to consist of two couplings, one to provide constant tension and damping and one for measuring the elongation/ompression velocity. The velocity is measured by applying a close to zero constant tension and a linear first order damping force with damping coefficient set to be one. That way, the damping force that the measuring line coupling provides equals the velocity of the elongation/compression. The constant tension of the measuring line is set to 0.001N.

2.3 Failure modes of the lifting operation

There are many ways an offshore lifting operation can experience failure, but only a few are considered in this report and those are:

- too large module displacement
- too high pay in/out velocity of tugger winch
- too high pay in/out acceleration of tugger winch

when lifting offshore, it is important that the module displacement don’t exceed critical displacement. This it to maintain the safety for the crew and equipment. Maximum allowed displacement of the crane load varies depending on the operation, but typical value for horizontal displacement is 1.5m *(Det Norske Veritas, 2014).*

a winch has a maximum pay in/out velocity. If this velocity gets exceeded, the winch and/or tugger line may be damaged. If the module is heading towards the tugger winch with a velocity greater than the winch is able to pay in wire, the line can experience a slack in the line. This slack will be straightened out when the module turn in the opposite direction. This can create a high frequency snap force which can damage the winch or break the wire. If the module is heading away from the tugger winch with a velocity greater than the winch are able to pay out wire, the force in the tugger line can damage the winch or break the wire due to the high tension. Every winch has a maximum pay in/out acceleration for which exceeding can either cause a slack or to high tension. This will result in the same failure as mentioned when maximum velocity is exceeded, but this type of failure is not as common as exceeding the maximum velocity.

3 SIMO time domain method

SIMO is a software developed by Marintek that simulate the equation of motion of complex structures in marine environments. The information in the following sections are gathered from SIMO Theory manual *(SIMO project team, 2009).*

3.1 Coordinate systems, Bodies and couplings

SIMO applies four types of right hand coordinate systems where the z-axis is pointing upwards, x-axis is pointing along the ship direction and the y-axis are pointing into the plane seen from the ships starboard side. Global (earth-fixed) coordinate system are the reference for the body-related coordinate system. the environmental parameters are applied with respect to the global coordinate system. the bodies in this report are modelled as rigid elements with 6 degree of inertia resistance and the couplings act as compression rods where different types of stiffness and damping are applied.

3.2 Environment

Linear potential theory is used in the program. The incoming undisturbed wave field is determined by the wave potential. Unidirectional wave spectra are thought of as a sum of a large number of regular waves at different frequencies. Short-crested waves are constructed by introducing a directional distribution in addition to the frequency distribution. The program can apply several different wave spectra as well as user specified spectra. In this report, JONSWAP is used.

3.3 Force models

The forces the act on the bodies are arranged in several different force models and combined in the equation of motion. The force models that are relevant in this report is structural and added mass forces, linear damping forces, structural and hydrostatic stiffness forces and external forces such as first order wave excitation forces, wave drift forces and station keeping forces. All hydrodynamic forces are acting on the ship since no other body are supposed to have any interaction with the water.

The mass forces are described by the product of a six-degree acceleration vector and the structural and added mass in infinite frequency mass matrix. The linear damping force is the product of a six-degree velocity vector and a damping matrix which simulates the damping due to wave radiation. Since the bodies are modelled as rigid bodies, only couplings have structural stiffness where the stiffness data differs from what type of coupling applied and the stiffness profile set by the user. The hydrostatic stiffness is a product of six-degree displacement vector and a hydrostatic stiffness matrix.

Both the first order wave forces and the wave drift forces are described by six-degree frequency dependent transfer functions. And for every first order wave force transfer function there are a phase angle function. These functions are divided into what degree the force act on and the angle of attack of the incoming waves.

The station keeping forces in this model is modeled by force-elongation coupling with hysteresis. The stiffness and damping are modelled as defined by the user.

3.4 Generation of time series

The time series are generated by discretizing the variance spectrum into finite number of finite-valued harmonic components, and by sampling phases from a uniform distribution over $[0,2\pi]$. Time series generated in this way will repeat themselves with the smallest delta period. Normally, the addition of harmonic components to obtain time series is done by the Fast Fourier transform (FFT). A Cooley-Tukey Fourier transform algorithm is used to compute FFT in SIMO.

3.5 Equation of motion

The time domain results are generated by deriving the equation of motion and the use numerical integration to solve for each time step in the analysis. The numerical integration is done by using the third order Runge Kutta method.

4 Procedure and input data

The simulations are done in three phases that represent three different module positions. This is because, instead of running a continuous simulation that consists of a moving crane and change in tugger line configuration, the simulation is divided up in three phases where stationary simulations are done for simplicity. the three phases are lift off, horizontal transition and out of deck. In all phases, the types of winches and wires are assumed to be the same for every simulation. The winches used in the simulations is an electrically driven constant tension winch from Palfinger with a 0.022 m marine grade steel wire. The properties for the winch and wire are described in *table 4.1* below.

Table 4.1: Winch and tugger wire properties.

Maximum winch pull [t]	**maximum brake holding force [t]**	**Recommended constant tension/ friction force [-]**	**Activation velocity for friction force [m/s]**	**Wire breaking strength [N]**
10-13.8	16.8-23.2	0.4	0.02	286 000

The maximum pull, brake and velocity of the winch will vary depending on how much wire that is on the spool. More wire on the spool will result in a lower maximum pull and brake force while a higher pay in/out velocity. This is because, more wire on the spool will increase the distance from where the wire attaches to the spool to the center of the spool. To be conservative, the lowest maximum value is considered. The relationship between the constant tension is set to be 0.4 which is recommended by the supervisors. the activation force for the friction force is set to 0.02 m/s which is the default option in SIMO.

The simulations are done by first running a static simulation with a 0.05s time step in order to find the equilibrium. The dynamic simulation is then run for 500s with a 0.001s time step. The environmental input parameters are only from waves where JONSWAP is the wave spectrum used in the simulations. The JONSWAP wave spectrum applies waves of 3 different parameters, wave direction, significant wave height and peak period.

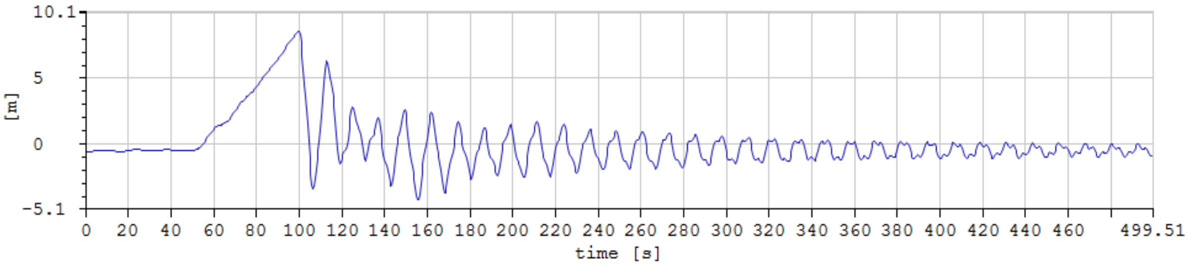
The environmental input date consists of a wave direction of 155° angle relative to the global x-axis. which is constant for all simulations. This is because it gives shielding from the waves when the front of the ship blocks the module from the incoming waves and it is also necessary to face the waves head on as much as possible to reduce the roll motions of the ship.

The significant wave height is set to 2.5m and 3.5m. 2.5m is the recommended significant wave height *(Det Norske Veritas, 2014).* 3.5m are simulated to challenge the recommended wave height where this value seems to be the limit where the behavior of the system operates within its criteria.

Further on, the peak period for the simulations is set to 6s, 9.7s, 12.8s, 15s and 20s. The basis for these values are based on analytical and numerical calculation of the eigen periods of the module as well as reasonable guessing of appropriate values. The analytical undamped eigen period of a simplified pendulum motion in this case is 9.7s and is calculated from the *equation 4.1* below.

$$T_0 = 2\pi\sqrt{\frac{L}{g}} \qquad 4.1$$

Where L is the length from the crane tip to the center of gravity of the module and g is the gravitational constant set to 9.81 m/s^2. The simplified equation doesn't take account for the mass of the lifting wires and hook load since the mass of the module are much larger in comparison. The simulated eigen period of the load motion is 12.8s. which is found by doing a drop test of the module at phase 2 – horizontal transition where no tugger lines were attached. The drop test was done by applying a ramp force working on the module in positive y-direction with a magnitude 200 000N. At 100s the force shut down and the module could swing freely so that the computational eigen period could be calculated. In the *graph 4.1* below the drop test shows the module displacement in the y-direction relative to the ship on the vertical axis where the simulated eigen period can be observed directly from the graph.



Graph 4.1: Drop test at phase 2 with no tugger lines attached.

The other three peak periods are based on reasonable guessing where the reason for their values are meant to cover the stiffness dominated response and the inertia dominated response. A peak period of 6s is much smaller than the eigen period and 15s and 20s are much larger than the eigen period.

Before the results are evaluated, it is important to know the eigen period of the roll and pitch motion of the ship. Based on the motion transfer function provided in the SIMO file, the eigen periods are 14s for the roll motion and 10.7s for the pitch motion at a wave direction of 150°.

4.1 Phase 1 - Lift off

The lift off phase of an offshore lifting operation can be the most challenging phase with respect to horizontal displacement tolerances. This is because the module and the tugger lines are close to surrounding equipment and personnel. It is therefore important to design the lift off phase such that the surroundings are not in danger of collision. The *figure 4.1* below shows the tugger line configuration at phase 1 with a -23° angle between the crane orientation and the x-axis of the ship.

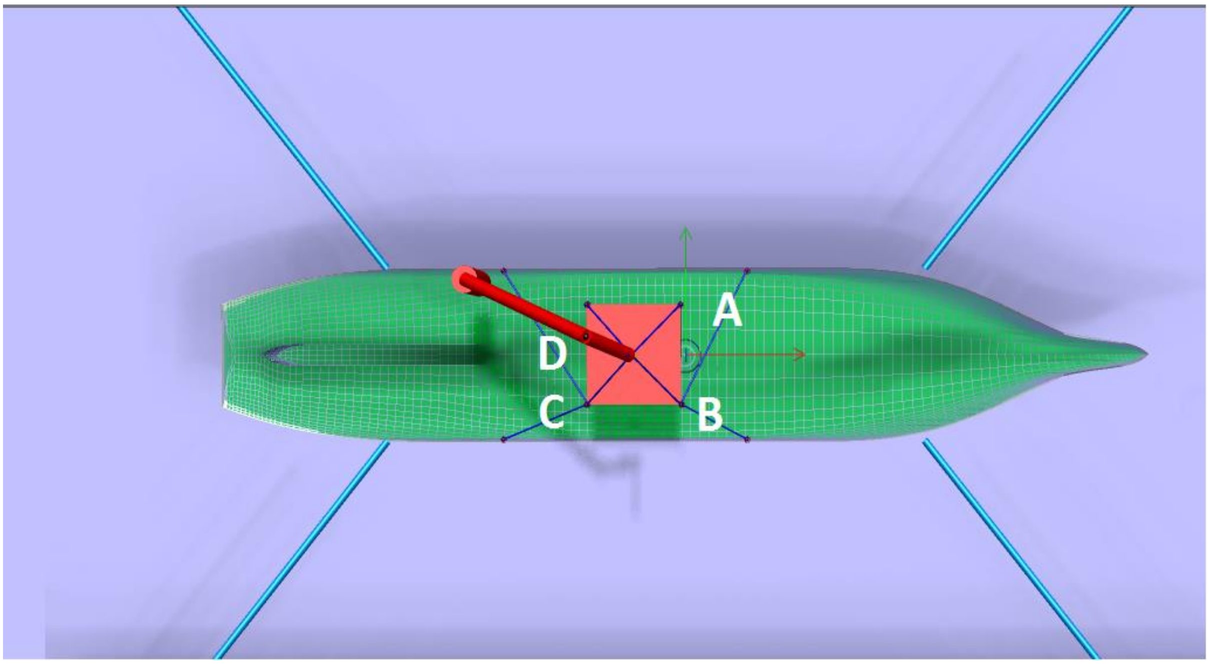


figure 4.1: Tugger line configuration at phase 1.

The basis for this configuration is because it gives damping in both x- and y-direction as well as rotational damping and restoring around the z-axis. The rotation around the z-axis is likely to have a low magnitude due to the low torsion stiffness in the lifting wire. A problem with this configuration is that a rotation of the module can cause the tugger lines to collide with the module itself. To minimize that happening, the constant tension in tugger line B and C should be so large compared to tugger line A and D so that the tugger lines is slightly pulling the module towards the starboard side of the ship. This will cause an inclination in the lifting wire which is recommended to be of 15° *(Det Norske Veritas, 2014).* In this case, it is not possible to have an inclination of 15° because the damping in the y-direction will be become too small with the current layout of the tugger lines. This means that the inclination is approximately 4°. The constant tension is also symmetrical to keep the load rotation as close to the initial rotation right before it is lifted off the deck. The constant tension and damping for each tugger line is showcased in *table 4.3* below.

Table 4.2: Constant tension and friction force at phase 1.

Tugger line ID	Constant tension [N]	Friction force [N]
A	50000	20000
B	100000	40000
C	100000	40000
D	50000	20000

The input data for the 20 simulations at phase 1 are shown in *table 4.3* below.

Table 4.3: Input data for the simulations at phase 1.

Significant wave height [m]	Tugger lines attached	Peak period [s]	Simulation ID
2.5	yes	6	1
		9.7	2
		12.8	3
		15	4
		20	5
	no	6	6
		9.7	7
		12.8	8
		15	9
		20	10
3.5	yes	6	11
		9.7	12
		12.8	13
		15	14
		20	15
	no	6	16
		9.7	17
		12.8	18
		15	19
		20	20

4.2 Phase 2 - Horizontal translation

The horizontal transition is the phase where the module is moved from the lift off phase to the where it is out of deck. In this phase, tugger line B and C will detach from the module as soon as the module is out of deck and the two remaining tugger lines are fit to handle the module by themselves. The *figure 4.2* below shows the tugger line configuration at phase 2 with a 5° angle between the crane orientation and the x-axis of the ship.

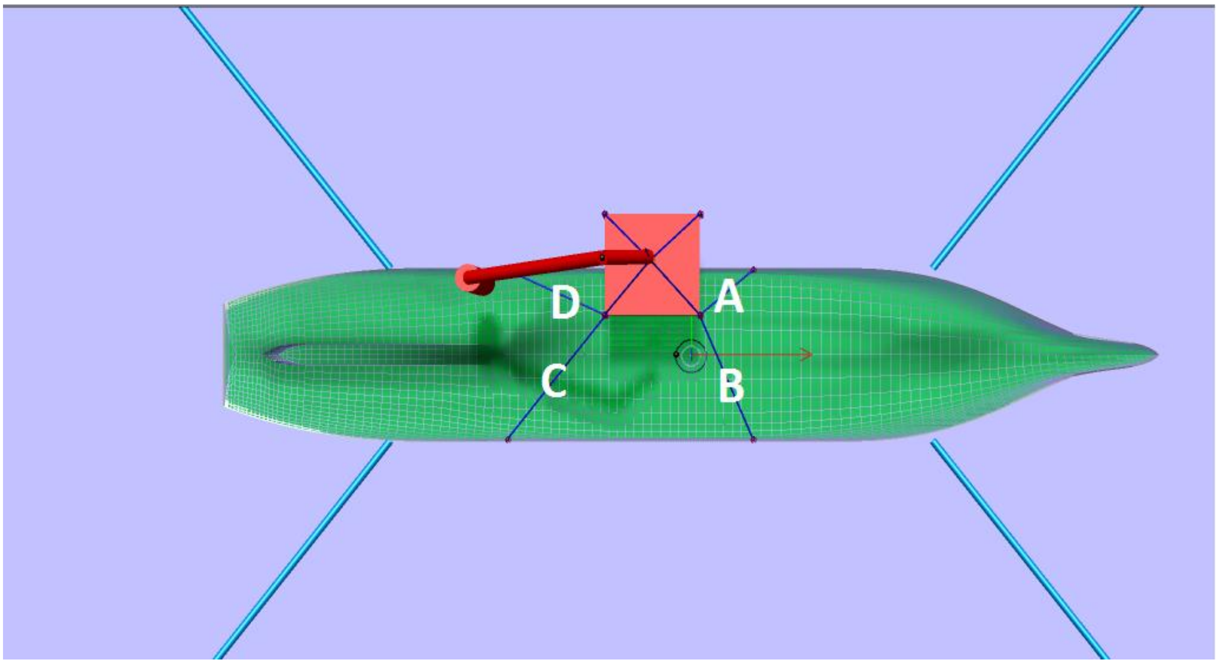


figure 4.2: Tugger line configuration at phase 2.

The configuration will provide damping in x- and y-direction. It will also provide damping in the rotation around the z-axis. The constant tension is chosen such that the lifting wire have an inclination of 15° which give rotational restoring around the z-axis and minimize the risk of slack in the tugger lines. The inclination is done the same way as in phase 1, by having the tugger lines pulling the module towards the starboard side of the ship. The constant tension and damping for each tugger line is showcased in *table 4.4* below.

Table 4.4: Constant tension and friction force in phase 2.

Tugger line ID	**Constant tension [N]**	**Friction force [N]**
A	20000	8000
B	100000	40000
C	100000	40000
D	20000	8000

The input data for the 20 simulations at phase 1 are shown in *table 4.5* below.

Table 4.5: Input data for the simulations at phase 2.

Significant wave height [m]	Tugger lines attached	Peak period [s]	Simulation ID
2.5	yes	6	21
		9.7	22
		12.8	23
		15	24
		20	25
	no	6	26
		9.7	27
		12.8	28
		15	29
		20	30
3.5	yes	6	31
		9.7	32
		12.8	33
		15	34
		20	35
	no	6	36
		9.7	37
		12.8	38
		15	39
		20	40

4.3 Phase 3 - Out of deck

When the crane load is out of deck the module are ready for lowering into the water. In this phase, the eigen period of the crane load will change depending on how much of the lifting wire that are payed out, but the risk of experiencing resonance as the lifting wire are payed is considered to be fairly low due to the short time it takes to reach the water. The length of the lifting wire is kept the same for simplicity. The *figure 4.2* below shows the tugger line configuration at phase 3 with a 60° angle between the crane orientation and the x-axis of the ship.

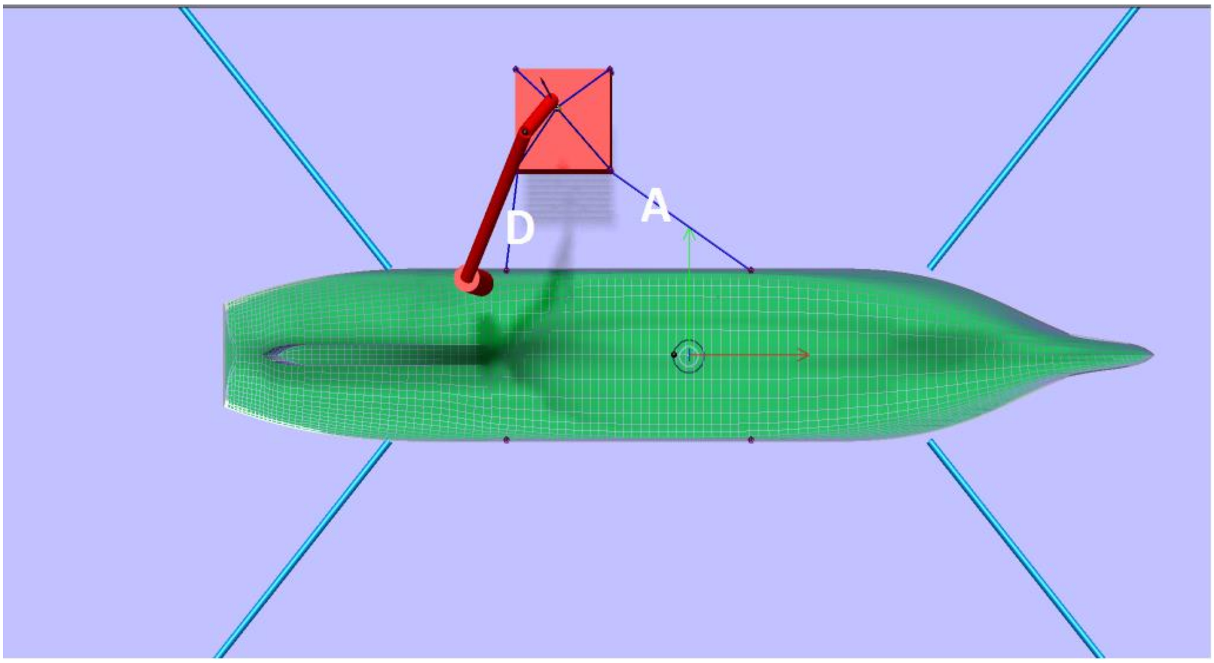


figure 4.3: Tugger line configuration at phase 3.

Again, the tugger line configuration will provide damping in both x- and y-direction and rotational restoring around the z-axis due to the 15° inclination of the lifting wire. it is expected that the tugger line D is handling most of the damping in the y-direction and the tugger line A to handle most of the damping in the x-direction. In this case, the module will experience a large static rotation around the z-axis, but this is acceptable since it is supposed to be lowered down in the water. This would not be the case for a lifting operation involving transport from one marine vessel to another as the orientation is crucial to the safety of the operation. The constant tension and damping for each tugger line is showcased in *table 4.5* below.

Table 4.6: Constant tension and friction force in phase 3.

Tugger line ID	Constant tension [N]	Friction force [N]
A	100000	40000
D	100000	40000

The input data for the 20 simulations at phase 3 are shown in *table 4.7* below.

Table 4.7: Input data for the simulations at phase 3.

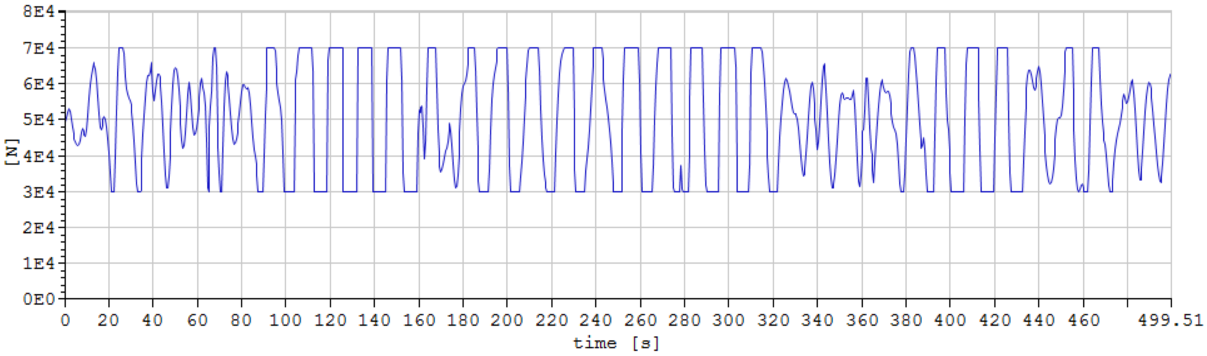
Significant wave height [m]	Tugger lines attached	Peak period [s]	Simulation ID
2.5	yes	6	41
		9.7	42
		12.8	43
		15	44
		20	45
	no	6	46
		9.7	47
		12.8	48
		15	49
		20	50
3.5	yes	6	51
		9.7	52
		12.8	53
		15	54
		20	55
	no	6	56
		9.7	57
		12.8	58
		15	59
		20	60

5 Result and Discussion

As the title implies, the result and discussion are not presented separately, but instead presented together. That's because the quantity of the results is high which make it easier to comprehend if fused together. the result is divided in four sections. The first section present the general results which applies for all simulations. The three other sections are divided up in the three phases for which the simulations are arranged in, lift off, horizontal transition and out of deck. each section present the results in a combined total of 13 graphs and tables. Each result will have an introductory description for why the result are relevant and what the result represents. Then the important observations are listed followed by a discussion of why the observation occurred. At last, the reliability of the results is discussed.

5.1 SIMO time domain analysis

The forces in the tugger lines are only determined by the constant tension and the friction force. The forces for each tugger line follows approximately the same pattern. The total force for the tugger line A for phase 1 at the significant wave height (Hs) equals 3.5m and the peak period (Tp) equals 12.8s are shown in *graph 5.1* below where the vertical axis represents the total force in the tugger line.



Graph 5.1: Total force in tugger line A for phase 1 at Hs=3.5m and Tp=12.8s.

Observations from *graph 5.1:*

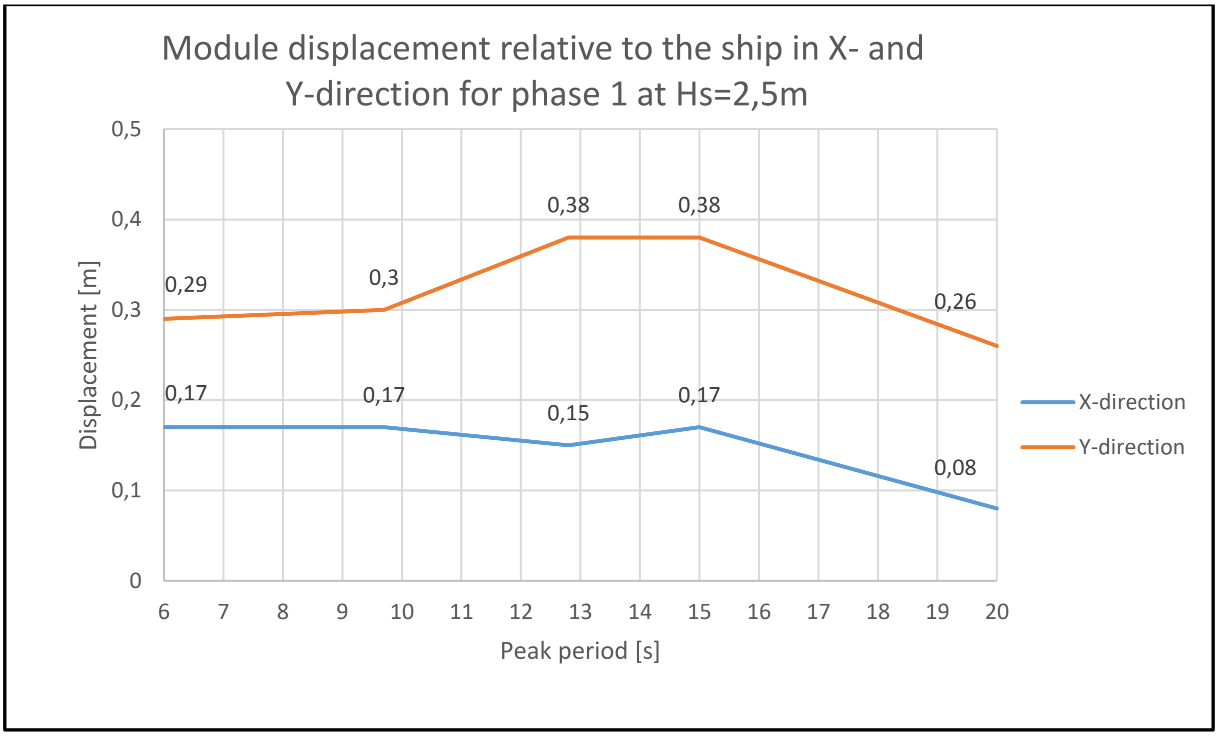
- The constant tension appears to be perfectly constant at 50 000N.
- The varying force have first order linear damping before it reaches the friction force.

When studying the forces in the tugger line A for phase 1 at a significant wave heights of 3.5m and a peak period of 12.8s shown in *graph 5.1*, it can be observed that the constant tension appears to be perfectly constant at 50000N. It is a good property for a tugger winch to have a perfectly constant tension, but this will not occur in a real case scenario. In a real case scenario, a tugger winch will have a certain upper and lower limit of the tension. The problem with SIMO is that the software doesn't have any option for introducing these limits which means that the tugger winch or fixed-force elongation line in the software has an immediately response. In other words, the tugger line doesn't experience any spring effect in the line.

The friction force in the tugger line seems to have a first order damping before it reaches the damping limit or friction force. In a real case scenario, the damping caused by the tugger winch will not act as a perfect friction force and there will always be some gradually inclining force to reach the friction force, but it doesn't have to be a first order force. The purpose of introducing first order damping force in the software in not only to simulate how it will act in a real case scenario, but to avoid numerical instability. When excluding the first order linear damping force, the damping force would have a chaotic force "jumping" up and down before reaching the friction force limit.

5.1.1 Phase 1 – Lift off

How the tugger lines affect the motion of the module can best be shown by comparing the module displacement relative to the ship in x- and y-direction. The module displacement in x- and y-direction will not be compared to the ones without tugger lines attached because it will dwarf the ones with tugger lines attached simply because of its higher displacement values. The comparison between the module displacement relative to the ship in both x- and y-direction with tugger lines attached is shown in *graph 5.2* below where each value represents the absolute maximum of the time series generated for the specific simulations.



Graph 5.2: Module displacement relative to the ship in X- and Y-direction for phase 1 at Hs=2.5m.

Observations from *graph 5.2*:

- The relative module displacement in the x-direction is lower than in the y-direction.
- The relative module displacement in the x-direction seems to be critically damped
- The relative module displacement in the y-direction peaks at the peak periods of 12,8s and 15s.
- The values at low peak periods is higher than the values at the big peak periods.

As seen in *graph 5.2,* the displacement in x-direction is lower than in the y-direction. There are several factors affecting the motion of the module so the forces acting on the module must be highlighted in order to explain this observation. The forces are transferred to the module via the inclination in the lifting wire which again depends on the crane tip displacement. The forces are also transferred to the module via the tugger lines. All those forces come from the motion of the ship which again come from the waves affecting the ship. The pitch and roll of the ship doesn't have much effect on the forces transferred via the tugger lines to the module since the module are situated close to the center of gravity of the ship. This means that most of the forces transferred to the module goes via the crane tip displacement or lifting wire inclination to the module. The crane tip displacement is most affected by the pitch and roll of the ship because of the longer distance to the center of gravity. The roll of the ship is greater than the pitch which contribute to the explanation why the module displacement in the y-direction is greater than in the x-direction.

It is expected that the peak periods of 9.7s and 12.8s, which is the analytical and simulated eigen periods of the module, should have higher values than the surrounding peak periods. This is not the case for the module displacement in the x-direction. This is a strong indication that the module displacement in x-direction is critically damped. In the y-direction, it appears not to be critically damped, but strongly damped.

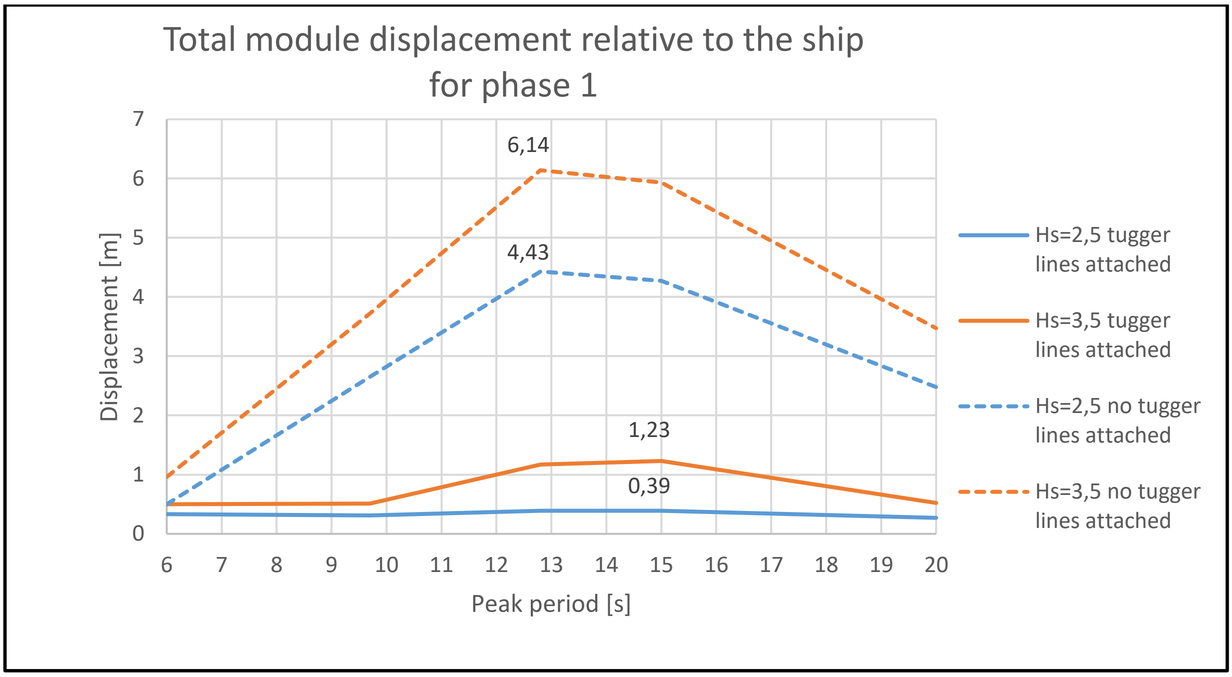
At the peak period of 15s it appears to act as if the effective eigen period has increased by attaching tugger lines. This shows that the tugger line change the effective eigen period of the module. There are two ways how the tugger line change the eigen period. the eigen period of a system is a function of mass, damping and the restoring coefficient. For an ordinary 2nd order differential equation, the formula for the eigen period are defined as the *equation 5.1* below.

$$T_0 = \frac{4\pi}{\sqrt{4\frac{k}{m} - \frac{d^2}{m^2}}} \tag{5.1}$$

Where T_0 is the eigen period, k is the restoring coefficient and d is the linear damping coefficient. Even tho the damping on the module are dominated by a zero order damping force or friction force, the first order expression can help explaining how the damping affect the eigen period. if the damping coefficient are increased, then the eigen period also increase. Usually this eigen period are neglected because the damping is usually very small, but when the damping becomes so large that the system is heavily or critically damped, the damping should be considered in the calculation of the eigen period. As seen in *equation 5.1,* the eigen period will increase when the damping coefficient increase as to the point it becomes infinitely large which is when the system is considered critically damped. The constant tension in the tugger lines may also contribute to a change in the eigen period, but in the opposite direction. when the module moves, the tugger lines attached to the module will change their angle compared to the direction of the direction the module moves in. This will cause a non-constant force acting in the specific direction. This non-constant force due to change in tugger line angle will introduce a new restoring coefficient to the system. This coefficient will be a varying value, but will increase the overall restoring of the system. This contribute by lowering the eigen period of the system. By comparing the contribution of the damping and the constant tension in the tugger lines, the damping is what increases the eigen period of the system.

The module displacement in each direction seems to get smaller on the right side of the resonance period compared to the left side of the resonance period. This is an unexpected observation since the dynamic amplification factor are supposed to converge towards one when the peak period goes to infinity and converge towards zero when the peak period goes towards zero which it doesn't seem to do in this case. The reason for this may be due to the tugger lines not reaching the friction. At this simulation, the forces that affect this module is smaller and therefor the velocity of the module are small compared to higher peak periods. This results in the tugger lines to not reach the activation velocity for the friction force which means it operates with linear damping. This may be the reason for the unexpected behavior at low peak periods.

when studying the effect of tugger lines, it is important to compare those results with a module without tugger lines attached. When there is no tugger lines attaches, the module is simply a freely hanging pendulum with no damping other than the interaction with the ship via the crane tip. The total module displacement relative to the ship is the dimensioning displacement since it represents the distance from the current position to the equilibrium position of the module. *Graph 5.3* below shows the total module displacement relative to the ship with tugger lines attached and no tugger lines attached at phase 1 for the significant wave heights of 2.5m and 3.5m where each value represents the absolute maximum of the time series generated for the specific simulations.



Graph 5.3: Total module displacement relative to the ship for phase 1.

Observations from *graph 5.3:*

- The total relative module displacement with tugger lines attached is much lower than the total displacement without tugger lines attached.
- The total relative module displacement without tugger lines attached shows similar pattern as a general dynamic amplification pattern.
- The total relative module displacement without tugger lines peaks at the peak period of 12.8s.
- The total relative module displacement with tugger lines attached have higher eigen periods than the total relative module displacement without tugger lines attached.

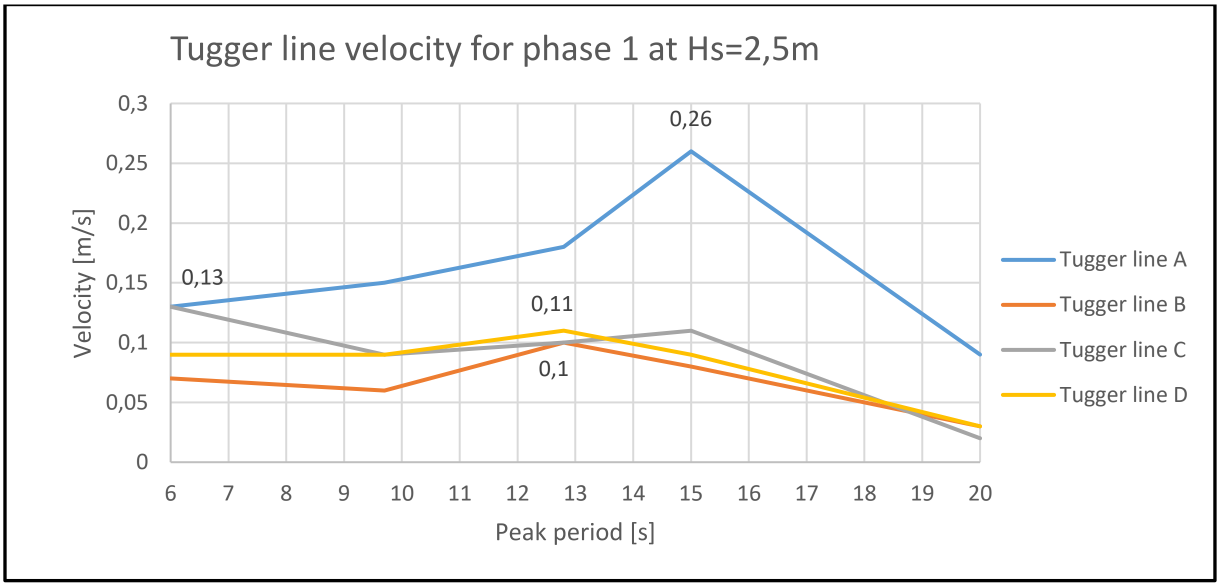
The Result shows that there is a huge reduction of the module displacement relative to the ship by attaching the tugger lines. This can clearly be seen in *graph 5.3* where the displacement without tugger lines at a significant wave height of 2.5m is as much as 11 times higher than the corresponding relative displacement with tugger lines attached. According to the DNV recommended practice, the maximum module displacement relative to the ship should not exceed 1.5m and the recommended limit for significant wave height is 2.5m. The result shows that the module displacement satisfy the DNV criteria with a total relative displacement of 0.39m at a significant wave height of 2.5m. The total displacement of the module at a significant wave height of 3.5m, which is the significant wave height meant to challenge the DNV recommended practice, do not exceed the maximum displacement limit. The reason for this reduction is simply because of the damping provided by the tugger lines.

The total module displacement without the tugger lines attached have an expected shape. It shows that the displacement looks like it converges towards zero when the peak period goes towards zero on the left side of the resonance period. On the right side of the resonance period, the total displacement looks like it converges towards a specific value. The significant wave height seems to affect the result as a scaling factor where the shape of each significant wave height stays equal to each other. This observation shows the same traits as a dynamic amplification factor where the factor converges towards zero when the input period goes towards zero and converges towards one when the input period goes to infinity and an increased value around the resonance period.

The tugger less total displacement is peaking around 12.8s which is expected as it shows the same eigen period as the drop test.

As stated from *graph 5.2*, increased damping will increase the eigen period. This becomes clearly visible in *graph 5.3* where the eigen period are shifting towards a higher value when the tugger lines are attached. And the damping will also reduce the magnitude of the total displacement.

To evaluate the effect of the tugger line configuration, it is important to look at each individual tugger line and make clear of their contribution and behavior. In this case, the elongation/compression velocity is the most critical factor of a tugger winch and thus relevant to study. The elongation/compression velocity of each individual tugger line for phase 1 at a significant wave height of 2.5m is shown in *graph 5.4* below.



Graph 5.4: Tugger line velocity for phase 1 at Hs=2,5m

Observations from *graph 5.4*:

- The tugger line A has the highest elongation/compression velocity.
- The tugger lines B and C tends to have increased elongation/compression velocity at the peak period of 6s.

The Tugger line A has the highest velocity. The tugger line A is perpendicular to the incoming wave directions which makes it unexpected that the tugger line A should have the largest velocities. It is expected that the tugger line D should have the highest velocities because the angle is more aligned with the incoming waves. Both tugger line A and D are more aligned with the y-direction than tugger line B and C and by looking at *graph 5.4*, it shows that the module displacement relative to the ship is higher in the y-direction. The reason why the velocities in the tugger line D is not larger than it appears is not fully understood, but it may be due to module displacement moves in an elliptical shape where it moves in a positive x- and y-direction at the same time. This results in that the tugger line A aligns with the elliptical shape and the tugger line D is perpendicular to the wide side of the elliptical shape.

The velocity in tugger line B and C seems to increase when the peak period is small. The reason for this may be that the tugger lines does not reach the friction force due to small velocities of the tugger lines and therefor operated with linear damping. As mentioned under *graph 5.2,* the exact behavior under these circumstances is unclear, but may be the reason for the sudden increase in the velocity.

The dimensioning values that set the criteria for the design of the lifting operation are shown in *table 5.1* below where each value represents the maximum out of all peak periods. Only the maximum value out of all tugger lines are shown because types of winches and tugger lines that should be in use should be equal to each other. The maximum acceleration of a winch is also something that can challenge the design, but the velocity is usually the challenging parameter when it comes to designing a tugger winch.

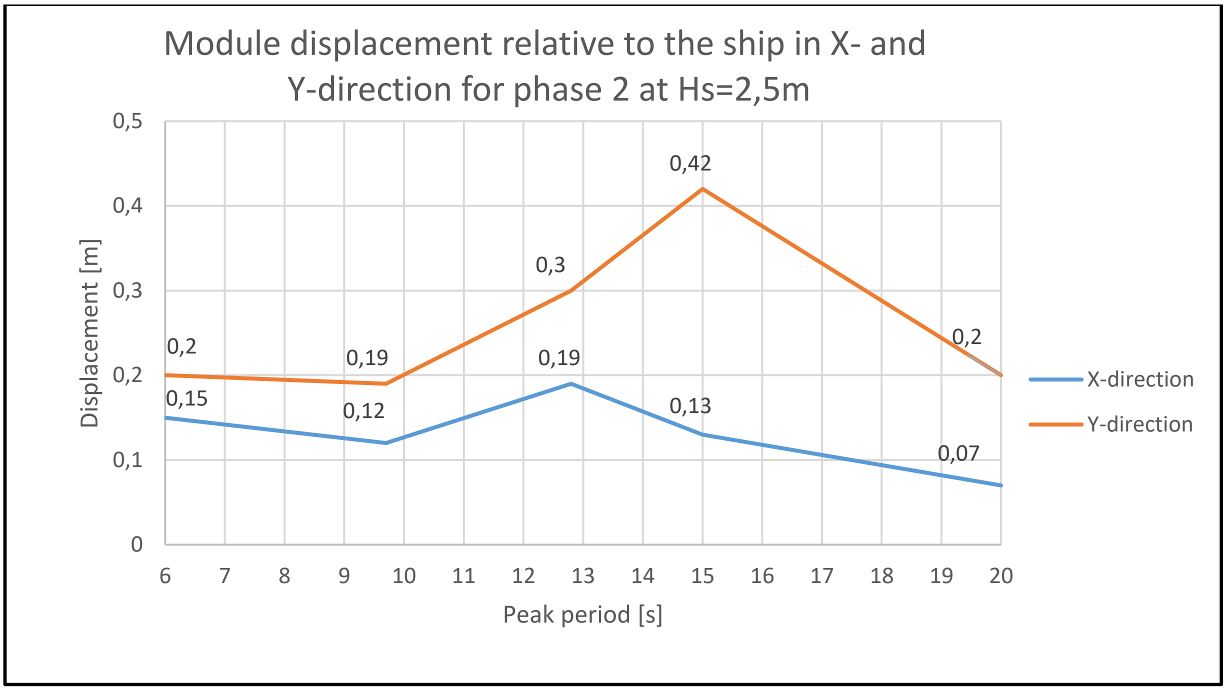
Table 5.1: Dimensioning values of the simulations at phase 1

Significant wave height [m]	**Max total module displacement/tugger lines attached [m]**	**Max tugger line velocity [m/s]**	**Max tugger line acceleration [m/s^2]**
2.5	0.39	0.26	0.26
3.5	1.23	0.65	0.35

According to DNV recommended practice, the horizontal module displacement relative to the ship should not exceed 1.5m. With a recommended significant wave height limit of 2.5m, the criteria are satisfied with a safety factor of 3.8. The total displacement of the module is also able to satisfy the criteria at a significant wave height of 3.5m.

5.1.2 Phase 2 – Horizontal transition

The comparison between the module displacement relative to the ship in both x- and y-direction with tugger lines attached is shown in *graph 5.5* below where each value represents the absolute maximum of the time series generated for the specific simulations.



Graph 5.5: Module displacement relative to the ship in X- and Y-direction for phase 2 at Hs=2.5m.

Observations from *graph 5.5*:

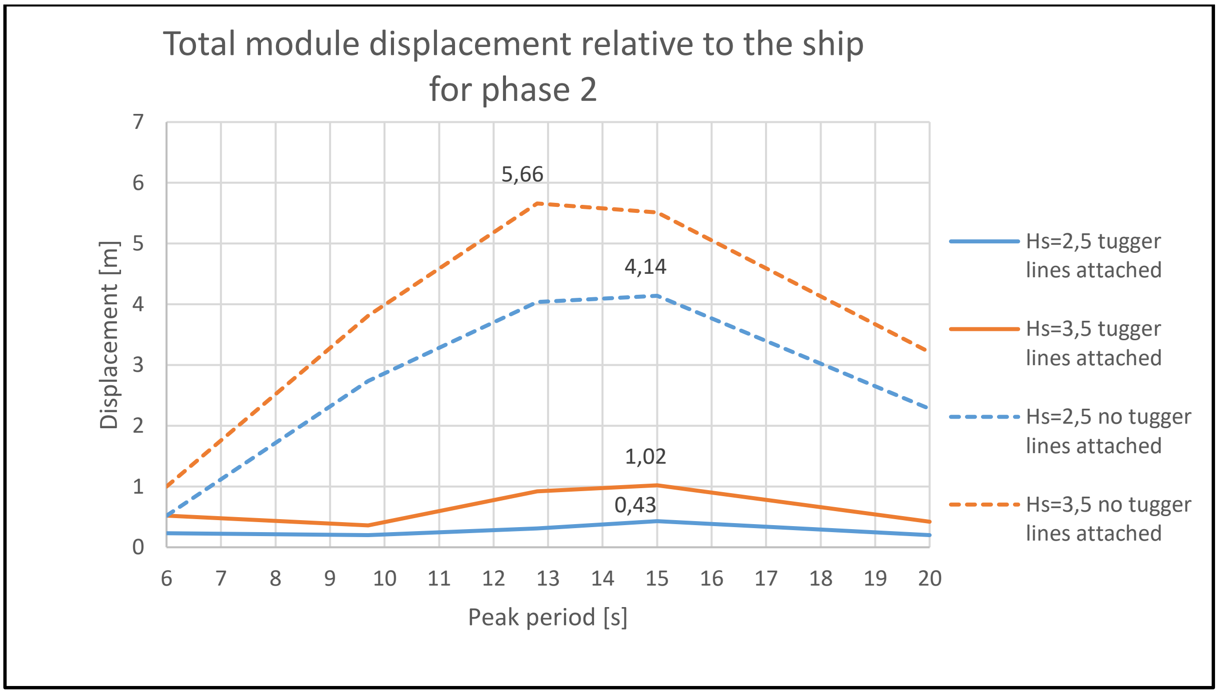
- The relative displacement in the x-direction is lower than the y-direction.
- The relative displacement in both directions peaks at different peak periods.
- The values at low peak periods is higher than the values at the big peak periods.

The relative displacement at phase 2 shows similar patterns as in phase 1 with a few differences. The relative displacement in the x-direction is almost critically damped which means that the tugger lines contributes with sufficient damping in the x-direction. The damping in the y-direction also has good damping, but it has a resonance displacement of about twice the surrounding values. The reason why the damping is less at phase 2 compared to phase 1 is mostly because the tugger lines A and D have lower friction force. The module is also closer to the deck which means that tugger line B and C have a larger angle between the x-direction and the direction of the tugger line which again leads to less contribution of damping in the x-direction, but contribute more in the y-direction.

The relative displacement in x- and y-direction experience resonance at the peak period of 12.8s and 15s. The eigen period of the pitch motion of the ship is 10.7s and 14s for the roll motion of the ship. Resonance in the motion of the ship will affect the motion of the module such that the motion will increase. Considering that the damping in both direction doesn’t have a huge different to each other, the eigen periods of the pitch and roll motion of the ship are the cause of this resonance difference between the relative displacement directions.

The values at lower peak periods of the resonance period is higher than the values at the big peak periods of the resonance periods. This is not supposed to happen when the peak period moves towards smaller periods from the resonance period. The reason for this may be as explained under *graph 5.2* for phase 1. The tugger lines operates with small velocities which cause the tugger line to operate with first order damping.

Graph 5.6 below shows the total module displacement relative to the ship with tugger lines attached and no tugger lines attached at phase 2 for the significant wave heights of 2.5m and 3.5m where each value represents the absolute maximum of the time series generated for the specific simulations.



Graph 5.6: Total module displacement relative to the ship for phase 2.

Observations from *graph 5.6*:

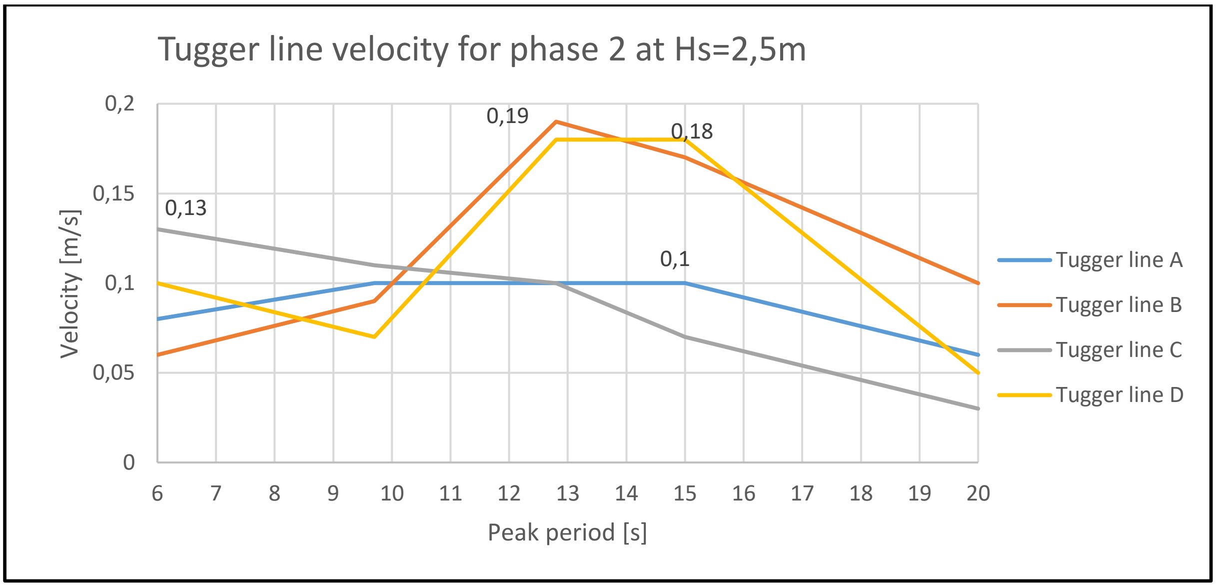
- The total relative displacement with tugger lines attached is much lower than the total relative displacement without tugger lines attached.
- The total relative displacement without tugger lines attached shows similar patterns as a general dynamic amplification factor, but the effect of significant wave height doesn't seem to function as a scalar.
- The total relative displacement with tugger lines attached have higher eigen periods than the total relative displacement without tugger lines attached.

The criteria of maximum module displacement of 1.5m is satisfied for both the DNV recommended significant wave height of 2.5m and the challenged significant wave height of 3.5m. With the highest displacement of 0.43m at the significant wave height of 2.5m, the criteria were satisfied with a safety factor of 3.5. The reason for the difference in the total relative displacement is the same as in phase 1, the tugger lines provide the module with damping.

The total relative displacement without tugger shows similar patterns as a general dynamic amplification factor, but the effect of significant wave height doesn't seem to function as a scalar. In phase 1, the total relative displacement between the significant wave heights of 2.5m and 3.5m has the same shape thus different scalar. For phase two the total relative displacement peaks at different peak periods. The reason for this is that the coupled system has some chaotic behavior because of all the interactions between the bodies, but this can simply be coincidences which may show expected behavior when using longer simulation time, use different wave seeds or just changing the general input data a little bit.

Just as previously explained, the damping causes the eigen period to shift towards higher periods. This is described in detail under *graph 5.2* in phase 1.

The elongation/compression velocity of each individual tugger line for phase 2 at a significant wave height of 2.5m is shown in *graph 5.7* below where each value represents the absolute maximum of the time series generated for the specific simulations.



Graph 5.7: Tugger line velocity for phase 2 at Hs=2,5m.

Observations from *graph 5.7:*

- The tugger lines B and D have much higher elongation/compression velocities than tugger line A and C.
- The tugger lines C and D tends to have increased elongation/compression velocity at the peak period of 6s.

The tugger lines B and D tends to have the highest velocities. This is expected since the tugger lines are more aligned with the direction of the incoming waves. As for the tugger lines A and C, the direction of the tugger lines is perpendicular to the incoming wave direction which results in lower velocities as expected.

The tugger line C and D tends to get larger at lower peak period. As assumed in phase 1, it may be due to the tugger lines operating in lower velocities which cause the damping to operate at first order damping.

The dimensioning values from the simulations that set the basis for the design of the operation are stated in *table 5.2* below where each value represents the maximum out of all peak periods. The maximum values representing the tugger lines account for the largest values from all the tugger lines.

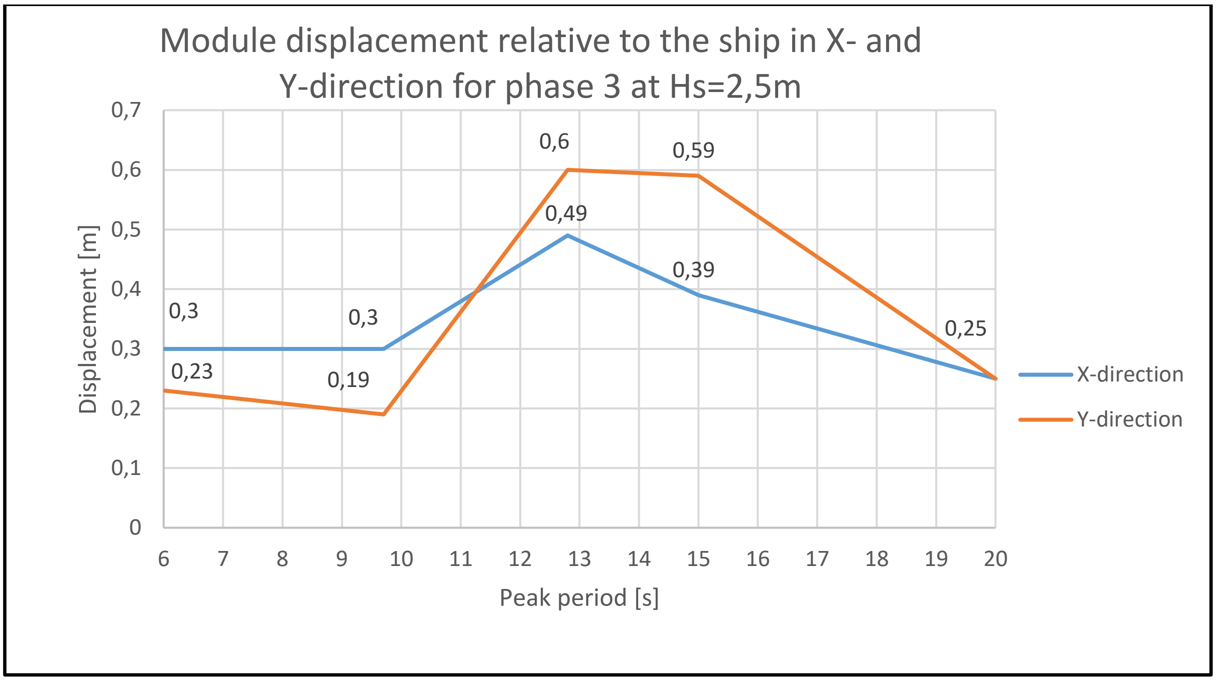
Table 5.2: Dimensioning values of the simulations at phase 2.

Significant wave height [m]	**Max total module displacement/tugger lines attached [m]**	**Max tugger line velocity [m/s]**	**Max tugger line acceleration [m/s^2]**
2.5	0.43	0.19	0.14
3.5	1.02	0.57	0.38

The total relative module displacement does not exceed the DNV recommended limit of 1.5m for either of the significant wave heights. As for the maximum relative displacement at the significant wave height om 3.5m, the safety factor is 1.5 and thus not very conservative for a dynamic operation.

5.1.3 Phase 3 – Out of deck

The comparison between the module displacement relative to the ship in both x- and y-direction with tugger lines attached is shown in *graph 5.2* below where each value represents the absolute maximum of the time series generated for the specific simulations.



Graph 5.8: Module displacement relative to the ship in X- and Y-direction for phase 3 at Hs=2.5m.

Observations from *graph 5.8*:

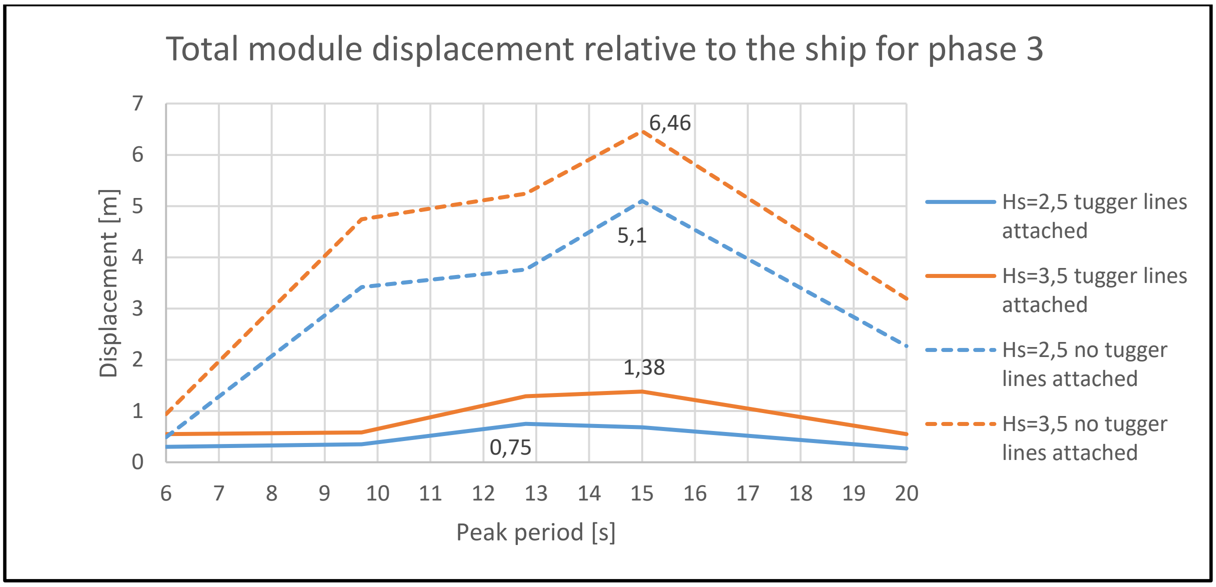
- The relative displacement in x- and y-direction are larger for phase 3 than for phase 1 and 2.
- The relative displacement in the x-direction is lower than the y-direction at resonance period.
- The relative displacement in the x-direction is larger than the y-direction for the peak period of 6 and 9.7s.

The relative displacement in x- and y-direction are larger for phase 3 than for phase 1 and 2. This is simply because the tugger line B and C are detached which means that less damping is introduced to the module.

The relative displacement in x-direction have lower displacement than for y-direction. The roll motion of the ship has larger motions than pitch and larger eigen period. This results in a larger crane tip displacement in the y-direction which again results in a larger relative displacement in the module. This occurs at the larger peak periods of around 12.8s and 15s which reflect the effect the resonance in the roll motion has on the module. the eigen period of the roll motion of the ship is 14s. It is also worth knowing that the tugger line D is aligned with the y-direction and the tugger line A is equally aligned with both direction which means that the damping provided for the module is highest in the y-direction.

The relative displacement in the x-direction is lower than for the y-direction at the peak periods of 6 and 9.7s. there are 3 different reasons for this. The first reason is that the eigen period of the pitch motion of the ship is lower than the roll motion which cause the pitch to be dominant at lower peak periods. The second reason may be as previously explained, that the low velocities of the module causes the tugger lines to operate with first order damping. This is explained in detail under *graph 5.2* in phase 1. The third reason may be due to an unpredictable chaotic behavior of the module due to the unsymmetrical configuration of the tugger lines.

Graph 5.3 below shows the total module displacement relative to the ship with tugger lines attached and no tugger lines attached at phase 2 for the significant wave heights of 2.5m and 3.5m where each value represents the absolute maximum of the time series generated for the specific simulations.



Graph 5.9: Total module displacement relative to the ship for phase 3.

Observations from *graph 5.9*:

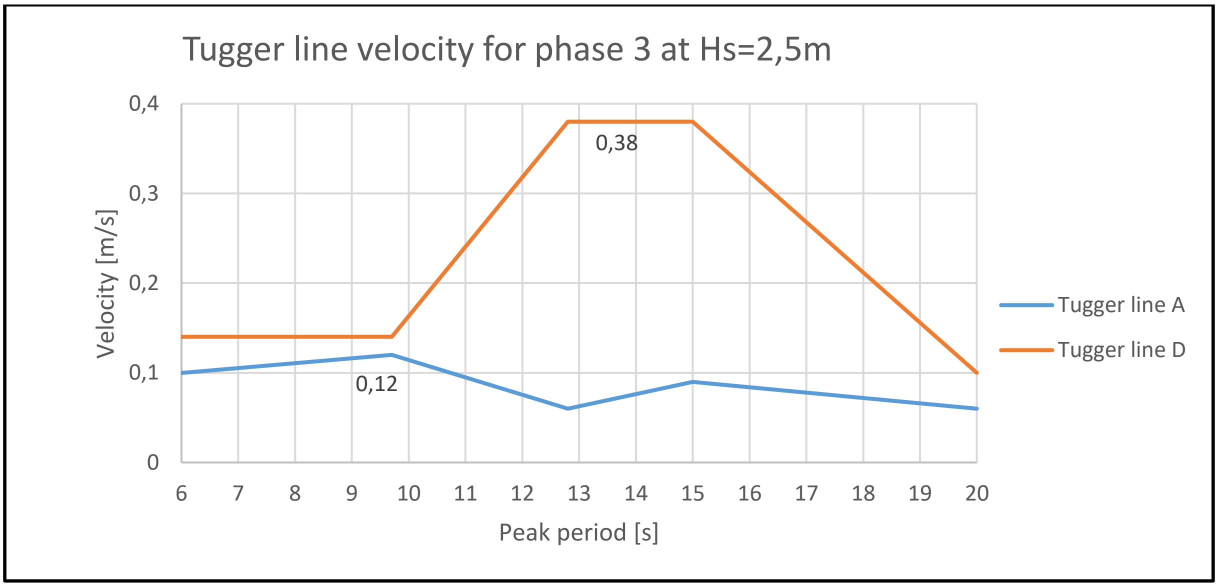
- The total relative displacement with tugger lines attached is much lower than the total displacement without tugger lines attached.
- The total relative displacement without tugger lines attached shows similar patterns as a general dynamic amplification pattern.
- The eigen period doesn't seems to shift towards higher periods when the tugger lines is attached.

The criteria of maximum total relative displacement of 1.5m are still satisfied for both the DNV recommended significant wave height of 2.5m and the challenged significant wave height of 3.5m. With the highest displacement of 0.75m at the significant wave height of 2.5m, the criteria were satisfied with a safety factor of 2. The reason for this is the damping provided from the tugger lines just as for phase 1 and 2.

The total module displacement without tugger lines seems to be perfectly identical between both significant wave heights in terms of shape similarity. The effect of the significant wave height has a scaling effect which is expected. The resonance also occurs at the peak periods of 9.7s and 15s.

Despite the damping provided by the tugger lines, the eigen period doesn't seems to shift towards greater values compared to the tugger less displacement. This is different from phase 1 and 2 where this seems to be the case. This show the sensitivity of the effect of eigen period shifting due to damping. The damping in phase 3 is lower than for phase 1 and 2 and does not introduce enough damping to make a significant shift in the eigen period og the relative module displacement.

The elongation/compression velocity of each individual tugger line for phase 3 at a significant wave height of 2.5m is shown in *graph 5.10* below where each value represents the absolute maximum of the time series generated for the specific simulations.



Graph 5.10: Tugger line velocity for phase 3 at Hs=2,5m

Observations from *graph 5.10*:

- The tugger line D have much higher elongation/compression velocities than tugger line A.
- The tugger lines C and D tends to have increased elongation/compression velocity at lower peak periods.

The tugger line D has much higher velocities than tugger line A, especially at peak periods of 12.8 and 15s. Tugger line D is almost perfectly aligned with the y-direction and the tugger line A is approximately equally aligned with the x-direction as the y-direction. This makes the tugger line D take up much of the load in the y-direction. it is also possible that the relative displacement pattern of the module moves in a specific shape that causes the tugger line A to not experiencing enough celongation/compression.

Despite the fact that the relative module displacement in both x-direction and y-direction is highest at the peak periods of 12.8s and 15s, the velocity in the tugger line A seems to get bigger as the peak periods gets lower. The shape of the module displacement which may cause the observation above, may only apply for the peak periods of 12.8s and larger. And for the lower peak periods, the shape of the relative module displacement changes in a way that makes the tugger line A take up more of the motion of the module. The assumption previously explained that the tugger line operate with first order damping due to lower velocities may also be the cause of this enlargement of the velocities at low peak periods.

The dimensioning values from the simulations that set the basis for the design of the operation are stated in *table 5.3* below where each value represents the maximum out of all peak periods. The maximum values representing the tugger lines account for the largest values from all the tugger lines.

Table 5.3: Dimensioning values of the simulations at phase 3

Significant wave height [m]	**Max total module displacement/tugger lines attached [m]**	**Max tugger line velocity [m/s]**	**Max tugger line acceleration [m/s^2]**
2.5	0.75	0.38	0.26
3.5	1.38	0.58	0.36

The total module displacement does not exceed the DNV recommended limit of 1.5m for either of the significant wave heights. the total relative module displacement are not very conservative as the safety factor are only 1.1 and thus not very conservative.

5.2 Reliability of the results

The goal of any simulation is to simulate a real-world scenario with as little error as possible. There are many factors that come into play of how good a simulation is. In order to get better results there are always some specific adjustments that can be done to make the simulation converge towards results with less error. The first adjustment is to minimize the time step as much as possible and increase the length of the simulation. This will result in a longer simulation but the result will be more accurate. Depending on the simulation, it may not be necessary to use to low time step in order to produce results within range of acceptance. To big time step will cause unstable behavior in periodic numerical integration methods. For this project the eigen periods and peak periods are much larger than the time step of 0.001s and will produce both stable and detailed results. The length of the simulations can on the other hand give unreliable values. Large simulation lengths are good when dealing with resonance and large periods. Comparing the time an offshore lifting operation would spend on one position from lift off to out of deck with the simulation length off 500s, the results should produce results within acceptance.

The fixed-force elongation couplings used to simulate the tugger lines and the tugger winches in the simulations lack some realistic elements. The first problem with the tugger line configuration is that it has an immediate response time. That means that it responds by paying in and out wire immediately so that the constant tension stays perfectly constant. In a real-world scenario, it will always have an upper and lower limit of tension before it starts paying in or out wire where the wire will experience a spring effect. For the damping in the tugger lines, the first order damping that are present before it reaches the friction force is a “good enough” representation of how the friction force are activated in a real-world scenario. In a real-world scenario, the damping will always experience first of higher order damping before reaching the friction force.

The results would be a much better representation of a real-world scenario if the peak periods used in the simulation was chosen differently. The peak periods were meant to cover both sides of the estimated resonance period which it did. Within the range of peak periods, the eigen periods of the roll and pitch motion of the ship which is 14s and 10.7s was not included. This was a “mistake” which would probably produce larger values of displacements if included. Because of the unexpected results in the module displacement with tugger lines attached, it would also be necessary to include peak periods lower than 6s to see if the strange enlargement in relative module displacement was unique to the peak period of 6s. At last, it would always be useful for the understanding of the system behavior to include as much peak periods as possible to minimize the gap between each peak period. Despite some peak periods missing, the peak periods were still able to cover both sides of the resonance periods.

6 Conclusion and further work

6.1 Conclusion

The work done in this project was focused around SIMO. The results produced in the simulations show that the tugger lines reduce the module displacement relative to the ship to a level for which the criteria for an offshore lifting operation are satisfied. By comparing the relative displacement of the module with and without tugger lines attached, one can see that tugger lines are an effective method of motion control during offshore heavy lifting according to the simulations. The peak periods used in the simulations could be chosen differently to show the relative module displacement at periods corresponding to the eigen period of the pitch and roll motion of the ship. Based on experience, the elongation/compression velocities and acceleration of the tugger lines give values that are reasonable for operation. The simulations are not verified, but seems to give fundamentally correct physical behavior with the exception of the relative module displacement at low peak periods which should be studied further.

6.2 Recommendations for further work

The simulations carried out in this project seems to give fundamentally correct physical behavior with the exception of the module displacement relative to the ship at low peak periods. The results presented also lack some important peak periods that should be analyzed. It is necessary to verify the time domain analysis in the project and improve the quality of the simulations.

The simulations in this project was done for three stationary crane orientations. This may not give a good representation of the boundaries of a real-world scenario. Simulate an offshore lifting operation where the crane orientation is simulated continuously from lift off to out of deck would be necessary to see the effect om a moving crane. Simulating a moving crane will also introduce a changing tugger line configuration and possible manual control.

The risk of failure in the tugger line are important to avoid, but it is also important to know how the system behave when the boundaries are reached. To study the effect of maximum elongation/compression velocity in the tugger line is important due to its higher risk of happening compared to maximum acceleration etc. By introducing velocity limits in the tugger lines, high frequency forces cause by slack can be studied. This is already possible to study in SIMO by introducing a very high order damping set to enlarge at a specific velocity.

In the project, the module experienced some strange behavior at low peak periods. As assumed, it may be due to the damping model for which the tugger lines was operating with. Studying different damping models for tugger lines would be necessary for both explain the strange behavior of the module at low peak periods and to assign better motion control of the module.

Further work can roughly be summarized in the following points:

- Verify the time domain analysis carried out in this project and improve the quality of the simulations.
- Simulate the offshore heavy lifting operation with a continuous crane module position from where it is lifted off deck to where it is hoisted down in the water.
- Study the system behavior of reaching the maximum velocity of the tugger winch.
- Study different damping models of the tugger lines.

7 Bibliography

Det Norske Veritas (2014). DNV-OS-H205 Lifting Operations (VMO Standard - Part 2-5) [Last read 10.04.2017]

SIMO project team (2009). SIMO - Theory Manual Version 3.6 Report 516412.00.03 [Last read 03.05.2017}

8 Attachment

	max module disp.			max module vel.			max tugger vel.				max tugger acc.			
simu. ID	x	y	tot	x	y	tot	1	2	3	4	1	2	3	4
1	0,17	0,29	0,33	0,1	0,09	0,13	0,13	0,07	0,13	0,09	-0,17	0,07	0,15	0,08
2	0,17	-0,3	0,31	-0,12	0,1	0,13	0,15	0,06	-0,09	0,09	-0,13	-0,04	0,08	0,06
3	0,15	-0,38	0,39	0,08	-0,14	0,14	-0,18	0,1	0,1	0,11	0,09	-0,08	-0,07	0,08
4	0,17	-0,38	0,39	-0,06	-0,18	0,18	0,26	0,08	-0,11	0,09	0,26	0,08	-0,11	0,09
5	0,08	0,26	0,27	-0,04	-0,11	0,11	0,09	0,03	0,02	0,03	-0,05	-0,01	-0,01	-0,01
6	0,2	0,49	0,5	0,2	-0,26	0,26	-	-	-	-	-	-	-	-
7	1,52	2,3	2,65	0,77	-1,21	1,38	-	-	-	-	-	-	-	-
8	1,45	4,36	4,43	0,81	-2,04	2,07	-	-	-	-	-	-	-	-
9	-2,58	-4,18	4,27	-1,28	1,97	2,01	-	-	-	-	-	-	-	-
10	0,95	-2,48	2,48	0,46	1,12	1,14	-	-	-	-	-	-	-	-
11	0,21	0,48	0,5	0,14	0,11	0,17	-0,16	0,09	0,19	-0,07	0,2	0,08	0,18	0,07
12	0,22	-0,47	0,51	-0,17	0,13	0,2	0,13	-0,09	0,15	0,08	0,1	-0,07	-0,15	0,05
13	0,42	1,17	1,17	0,23	-0,68	0,7	-0,55	-0,45	0,19	0,65	-0,27	0,35	-0,16	0,34
14	0,35	-1,22	1,23	-0,2	0,65	0,67	0,52	0,35	0,19	-0,59	-0,24	-0,24	0,12	0,27
15	-0,16	0,52	0,52	-0,08	-0,17	0,17	0,2	0,1	0,05	-0,1	-0,12	-0,06	0,03	-0,06
16	0,33	0,95	0,96	0,27	0,43	0,43	-	-	-	-	-	-	-	-
17	2,14	3,29	3,72	1,07	-1,83	2,05	-	-	-	-	-	-	-	-
18	2,05	6,08	6,14	1,19	-2,94	2,95	-	-	-	-	-	-	-	-
19	-3,15	-5,83	5,93	-1,6	2,85	2,88	-	-	-	-	-	-	-	-
20	1,3	-3,46	3,47	0,63	1,57	1,6	-	-	-	-	-	-	-	-
21	0,15	0,2	0,23	-0,14	-0,06	0,14	0,08	-0,06	-0,13	0,1	-0,08	0,07	0,14	-0,11
22	0,12	0,19	0,2	-0,09	0,1	0,13	0,1	-0,09	0,11	0,07	0,06	0,07	-0,09	-0,06
23	0,19	0,3	0,31	0,12	-0,15	0,18	0,1	0,19	0,1	-0,18	0,06	-0,13	-0,07	0,13
24	-0,13	-0,42	0,43	-0,09	0,16	0,19	0,1	-0,17	0,07	0,18	0,06	0,13	0,06	-0,11
25	0,07	0,2	0,2	0,03	-0,11	0,11	0,06	0,1	0,03	0,05	0,04	0,05	0,02	0,03
26	-0,2	0,51	0,52	0,22	-0,26	0,27	-	-	-	-	-	-	-	-
27	1,93	2,19	2,74	0,92	-1,14	1,46	-	-	-	-	-	-	-	-
28	1,78	3,98	4,04	1	-1,85	1,89	-	-	-	-	-	-	-	-
29	3,24	-3,83	4,14	1,66	1,79	2,09	-	-	-	-	-	-	-	-
30	1,19	-2,25	2,28	-0,59	1,02	1,05	-	-	-	-	-	-	-	-
31	0,2	0,49	0,52	-0,21	-0,11	0,21	-0,12	-0,14	0,21	0,18	0,16	0,15	0,2	-0,23
32	0,2	0,35	0,36	0,17	0,15	0,22	0,1	-0,15	0,19	0,14	0,14	0,13	-0,18	-0,14
33	0,54	0,84	0,92	0,4	-0,49	0,63	0,34	-0,54	0,27	0,57	0,22	0,37	-0,2	-0,38
34	-0,48	-0,93	1,02	-0,34	0,47	0,58	0,29	0,46	0,24	-0,51	-0,19	0,28	-0,16	0,3
35	-0,16	0,38	0,42	-0,09	-0,16	0,17	0,07	0,14	0,06	0,16	-0,06	0,11	0,05	-0,11
36	-0,29	0,99	1	0,3	0,41	0,42	-	-	-	-	-	-	-	-
37	2,67	3,14	3,81	-1,28	-1,75	2,13	-	-	-	-	-	-	-	-
38	-2,39	5,57	5,66	1,45	-2,63	2,67	-	-	-	-	-	-	-	-

39	3,94	-5,36	5,51	2,1	2,59	2,84	-	-	-	-	-	-	-	-
40	1,64	-3,15	3,21	-0,82	1,43	1,48	-	-	-	-	-	-	-	-
41	-0,3	0,23	0,3	-0,14	-0,09	0,15	-0,1	-	-	0,14	0,11	-	-	0,14
42	0,3	-0,19	0,35	-0,13	-0,15	0,17	-0,12	-	-	-0,14	0,13	-	-	0,13
43	0,49	0,6	0,75	0,3	0,38	0,49	0,06	-	-	0,38	0,04	-	-	-0,26
44	-0,39	0,59	0,68	0,24	0,34	0,42	0,09	-	-	0,38	0,06	-	-	0,21
45	0,25	-0,25	0,27	-0,09	0,1	0,11	0,06	-	-	0,1	-0,01	-	-	-0,08
46	-0,3	0,41	0,49	-0,25	-0,26	0,27	-	-	-	-	-	-	-	-
47	2,63	2,73	3,42	1,2	-1,42	1,83	-	-	-	-	-	-	-	-
48	2,32	3,64	3,76	1,36	1,86	1,9	-	-	-	-	-	-	-	-
49	4,18	3,67	5,1	2,2	1,74	2,67	-	-	-	-	-	-	-	-
50	-1,61	-1,98	2,27	-0,78	0,9	1	-	-	-	-	-	-	-	-
51	-0,55	0,46	0,55	-0,2	-0,16	0,23	-0,16	-	-	0,19	0,17	-	-	0,2
52	0,43	0,47	0,58	-0,19	-0,3	0,34	-0,2	-	-	-0,25	0,2	-	-	-0,24
53	-0,77	1,12	1,29	-0,46	-0,67	0,76	0,19	-	-	-0,58	0,14	-	-	0,4
54	-0,7	1,3	1,38	-0,41	0,68	0,72	0,27	-	-	0,54	0,21	-	-	0,36
55	0,35	0,51	0,55	0,17	0,24	0,29	0,05	-	-	0,25	0,04	-	-	-0,17
56	0,39	0,81	0,94	-0,35	-0,4	0,41	-	-	-	-	-	-	-	-
57	3,41	3,98	4,74	1,8	-2,27	2,65	-	-	-	-	-	-	-	-
58	3,15	5,09	5,24	1,97	2,78	2,88	-	-	-	-	-	-	-	-
59	4,98	5,12	6,46	2,71	2,65	3,58	-	-	-	-	-	-	-	-
60	-2,26	-2,8	3,19	-1,08	1,29	1,43	-	-	-	-	-	-	-	-