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Effect of anchor line tension on an AHTS vessel at sea

Cand.no.1203/Kjell Lennart Nygård

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Description of Master Thesis Work in spring 2016.

Effect of anchor line tension on an AHTS vessel at sea.

Stud. Kjell Lennart Nygård

Background:

After the capsizing of Bourbon Dolphin April 2007 many questions has been raised and investigated in order to find the reason for this tragic accident. The High school in Aalesund has established a mathematical model for studying the effect from waves and various load cases on a ship at sea, and this model is the basis for this thesis.

Focus and problems:

The focus for this thesis will be to study how different parameters as load, self-weight and ocean current acting on a submerged anchor line will affect the ship motions, and check the ship stability acc. to the current criteria's.

The size and direction of the force from the anchor line should be a result from a model of the line itself.

The main computer programs used for this thesis will be 20-sim, Matlab, Maxsurf and ShipX.

Research plan:

1. Adding a simple force to the existing ship model in order to know how the model works. Find how to balance this force with force from propellers and thrusters so that the model is stable during different line directions and in waves.

2. Find stability curve (GZ) without force and with the simple force and check against the stability criteria's.

3. Make a model of a submerged anchor line from the surface attached to an anchor in the other end. The model for resulting force in the line should be based on its weight and the current in the ocean.

4. Replace the simple force on the ship model with the load case from the anchor line model.

5. Establish a case study.
   Actual cases to study is how changing of different parameters will affect the motion and dynamic of the ship (RAO), roll angle, stability according to stability criteria's, and shape of the anchor line.
   The concrete content of the case study will be settled during the project and after that the models for the ship and the cable is established and found reliable.

Karl Henning Halse
Program Coordinator

Jiafeng Xu
Research Assistant

Kjell Lennart Nygård: Kjell Lennart Nygård
Canditate

Delivery: 3rd June 2016

Preface

I would like to thank all the staff and fellow students for all support, and a pleasant time together in these years.

In addition, I want to thanks friends, family and my earlier colleges in Aker Solutions for their kindness and support during my study.

Especially I want to thank Associate Professor Karl Henning Halse and Research Assistant/ PhD candidate Jiafeng Xu for outstanding guidance with my thesis.
Their support on the road has been very inspiring and they have helped me further when the problems seemed to be invincible.

Aalesund 3rd June 2016

Kjell Lennart Nygård

Kjell Lennart Nygård

Abstract

In this thesis, the aim was to simulate a typical anchor-handling situation in order to study the influence from an anchor line.
With today's computer power and simulation programs simulations be performed at reasonable cost, and many different scenarios may be studied without any safety issues.
The roll response due to waves in the simulator was on forehand compared with RAO from ShipX and found to comply well for different wave periods.
The simulation results is compared with stability calculations and the roll motion in the simulations was found to comply well with this calculations.

Main problems

Due to limited time, it was agreed not to include forces from drag, inertia or line stiffness in the anchor line model.
Especially in deep water, operations the drag caused by strong ocean currents is assumed to have considerable influence on the results. Tuning of the propulsion forces to keep the vessel at position has influence on the results, and it was needed to find reasonable values for the controller gain without overcompensating.

Main results

In the critical anchor handling situation the weight of anchor line possible to handle had to be reduced with more than 50% compared with results from the stability calculations. From the simulations, it was concluded that the anchor line is increasing the response amplitude operator for roll, because the propulsion is creating moments while keeping the vessel in position and stable heading. It was also found that moving the line sideways on the vessel stern has significant influence on the roll amplitudes in addition to increased heel angle.

Main conclusion

The main conclusion is that the load from the anchor line is affecting the limits for safe operation by influencing on the heel and the roll amplitudes. The heel from 20-sim simulations was found to comply well with the stability calculations performed in MaxSurf.
In this thesis, the results must be read as simplifications, but still it may point out some critical moments.

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Nomentaclure

Abbreviasjons

Abbreviation	Description
a.bl.	Above baseline of the Ship
AHTS	Anchor handling tug supply
AP	Aft perpendicular
B2B	Body to body element
CB	Center of buoyancy
CG	Center of gravity
DP	Dynamic positioning
FP	Fore perpendicular
G2B	Global to body element
Mse	Measured source of effort
MV	Measured value
NMD	Norwegian Marine Directorate
RAO	Response amplitude operator
Se	Source of effort element
Sf	Source of flow element
TF	Transformer element
VCG	Vertical center of gravity
TM	Transformation matrix

Parameters and variables

Symbol	Unit	Description
a, b and c	-	Roots in the quadratic formula in est. of Q
B	m	Vessel Breadth
B	-	Damping tensor
C	-	Restoring force tensor
CB	-	Center of bouyancy
C1,C2	-	Integration constants
C_{RB}	N	Coriolis and centripetal forces of the rigid body
CBR	m	Horisontal movement of CB
C_A	N	Coriolis and centripetal forces of the added mass
Cp	-	Relative body fixed coordinates for point C
E1, E2 and E3	rad	Euler angles
E	-	Constant (k*p)
g	m/s^2	Gravity constant
GM	m	Distance cog. to metacenter
GZ	m	Righting arm
h	m	Vertical distance between ends of the line
H	m	Wave hight
k	m	Horisontal distance between ends of the line
k	-	Spring stiffness
K	m	A point at baseline in the ship centerline
L	m	Total length of the anchor line
M	m	Metasenter
MRB	-	Inertia matrix of rigid body
MA	-	Inertia matrix of added mass
p	m	Natural length of a spring segment
P	-	Variable
J_{hb}	-	Transformation matrix
T_b^h	-	Rotation matrix for angular velocity
R_b^h	-	Rotation matrix for linear velocity
Q	-	Constant
s	m	Length of spring
t	s	Time
T	N	Tension in anchor line
Ty	N	Horizontal component of tension in y dir.
Tz	N	Vertical component of tension
Tx	N	Horizontal component of tension in x dir
xA, xB, xC, zC	m	Coordinates for point A,B and C
Vx, Vy and Vz	m	Ship coordinates in the world fixed coordinate syst.

w	Kg/m	Weight in water for the anchor line
w	rad/s	Wave frequency

α	-	Integration constant
α1 and α2	-	Parameters to be estimated
β	-	Integration constant
β	-	Varible for estimation of Q
φ	degr.	Heel angle
Φ	degr.	Angle of anchorline from vertical in yz plane
$\eta 3$	rad	Roll motion
$\eta 3a$	rad/m	Response amplitude operator for roll
$\theta 3$	rad	Phase angle for roll
Δ	Ton	Ship weight displacement
ω	rad/s	Angular velocity
η	m	Transational displacement
$\overrightarrow{F_h}$	*N*	*Hydrodynamic force*
$\overrightarrow{Q_h}$	*Nm*	*Hydrodynamic torque*
τ_{exe}	*N*	*Excitation forces*
μ	Kg/m	Mass per unit length of the line
γ	-	Varible for estimation of Q

1. Introduction

1.1. Scope of work

In reality, a ship is exposed to irregular waves from any direction depending on the weather and ship heading. In this thesis the waves is assumed regular and modelled coming in perpendicular to the shipside.

In the simulation plots, motion for all 6 degrees of freedom is shown. However, in this thesis the roll motion is in focus as this is critical due to vessel stability.

1.2. Problem formulation

Ideally, a submerged anchor line should follow the ship centerline during operation, but forces from waves, wind and current may force the vessel away from this position. Then the horizontal force component from the anchor line, and the counterforce from the thruster will cause a transverse moment on the vessel. If the force is acting out of center of the vessel, the vertical component of the force will cause additional transverse moment. The main subject for this project is to study how the load from the anchor line is affecting the dynamic motion of the vessel in such cases. Particular interesting is to study how the load is affecting the ship response amplitude operator (RAO).

1.3. Objectives

- Make necessary modifications to the existing 20-sim vessel model in order to adapt the model into this project. Transferring hydrodynamic coefficients for the vessel from ShipX to the 20-sim model as preparation for the research.
- Perform a study of ship stability according to general stability criteria’s, and the NMD criteria’s for anchor handling.
- Develop a mathematical model for the anchor line and connect it to the ship model in order to study dynamic motions and interaction.
- Perform a case study

1.4. Methodology

To study the dynamic behavior of the vessel, a model of anchor line and a sub model for keeping the ship in position has been made. The dynamic vessel model developed in earlier Aalesund University College (Xu, 2014), has a central place in the work.

A model for the anchor line and a model for keeping the vessel in position has been made in 20-sim and connected to the vessel model.

In order to study the ship stability, the results from a simplified load case from the anchor line, in accordance with stability criteria's, has been obtained before the anchor line model was connected to the ship model. This was done in order to make some reliable results as a foundation for the further research.

1.5. Thesis content

Chapter 1, Introduction

This chapter contains scope of work and limitations.

Chapter 2, Background

In this chapter is a short summary of state of art literature, which has been selected as relevant for this thesis.

Chapter 3, General methodology

Here it is described the computer programs used, how the ship hull was modelled and the hydrodynamic coefficients was transferred for use in the 20-sim vessel model. In addition, the loading conditions for general intact stability and anchor handling is described here.

Chapter 4, Model development methodology

This chapter contains description for how the equations for the anchor line is derived by using catenary theory, and how the 20-sim sub models for the anchor line and the position controller is designed.

Chapter 5, Methodology for the case study simulations

In this chapter, it is described how the case study simulations is performed.

Chapter 6, Results for the stability calculations

The layout for this chapter is the same as for the methodology and contains results for the stability testing.

Chapter 7, Results for the case study simulations

In this chapter the results for the case study simulations is presented. Figures and tables illustrate the most important findings.

Chapter 8, Discussion of the stability calculation results

The results for the stability calculations are discussed. Problems and assumptions are discussed and commented.

Chapter 9, Discussion of case study simulation results

In similar way as for the stability, this chapter contain discussion of the case study results.

Chapter 10, Conclusion for the stability calculations

This chapter is a summary of the major findings and some reflection about the results found in the stability calculation results.

Chapter 11, Conclusion for the case study simulations

Similar to chapter 10 this chapter is a summary of the major findings for the case study simulations.

Chapter 12, Recommendations for further work

Based on the analysis and conclusion, this chapter contains recommendations for further work and improvements.

Chapter 13, References

In this chapter, all the sources, which are referred to in the report, listed.

2. Background

2.1. Anchor handling

The understanding of how the force from a submerged anchor line is affecting the stability and the dynamic motions of a ship is important when designing new ships, and to improve safety during operations at the sea.

Especially for anchor handling at deep water this is important as the tension from the line can be very high, and combined with other factors lead to tragically accidents.

Search of resources takes place in ever greater water depths and, for example, depth where it is possible to drill for oil increased from a few hundred meters to over a 2300m in the years 1960 to 1988 (Patel, 1989).

An AHTS (Anchor handling tug supply) vessel can perform many different operations at sea. In fig.2.1 below is shown a typical vessel for anchor handling. This picture of MS Far Saphire was taken 1.May 2016.

Typical this vessel type has big engine power to keep position during operation and deck equipment as thrusters, winch, stern roller, crane, towing pins and locking device in order to guide the anchor line, and lock it at the ship centerline at the stern.

Figure 2.1: Typical anchor handling tug supply vessel

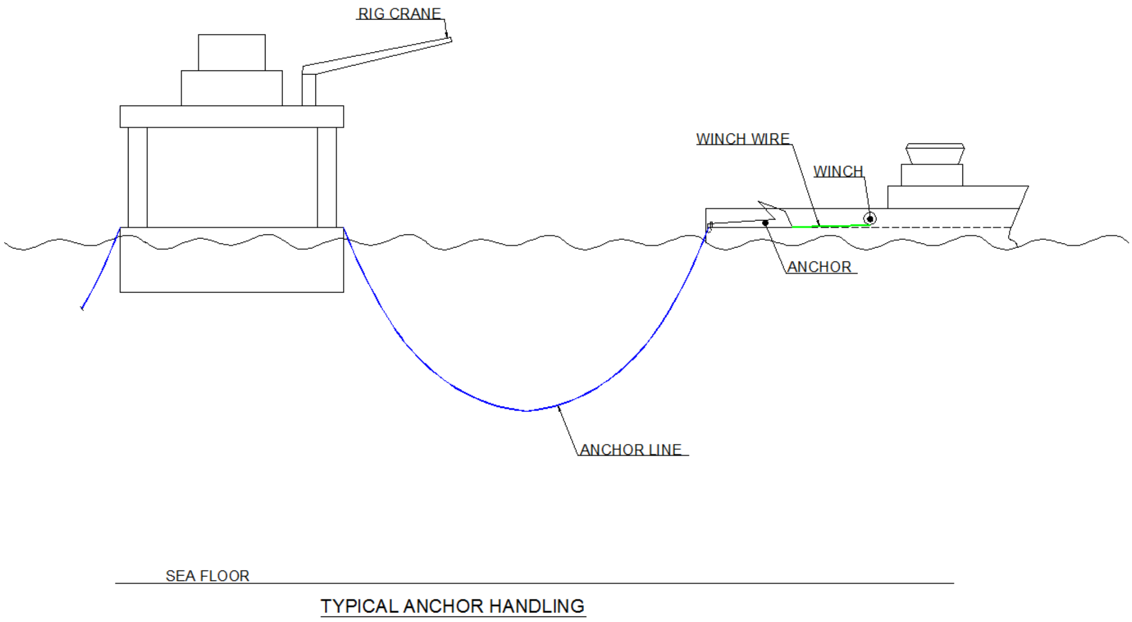


Figure 2.2: Typical anchor handling situation

A typical situation for anchor handling is shown in fig.2.2 above. In a case, this can be thought as described below in some main steps.

- The vessel is maneuvering close to the rig and receives the anchor line from the rig crane.
- The vessel starts to move away from tre rig at the cource to the point the anchor shall be dropped. The rig is feeding out line gradually as the distance increasing.
- The vessel reaches the drop position and dropping the anchor. Then the anchor is hanging in the winch wire and lowered to the seabed by using the winch on the vessel.

If bad weather conditions forces the vessel out of course and wanted position under way to the drop position, it may struggle to reach the drop position. The vessel then need to change its heading and then the load from the anchor line also will have a component in the vessel transverse direction. Simplified this was the case when Bourbon Dolphin capsized April 2007.

2.2. Ship intact stability

The explanation below is found in (Johansen, 1975) and describe the ship stability for large heeling angles. GZ is is the righting arm which for small angles of heel can be written as shown in eq.2.1 below. Please also see fig.2.3 below for illustration.

$$GZ = GM * \sin(\varphi)$$

Equation 2.1

It can be shown that GZ can be written as in eq.2.2 below, known as Atwood's formula.

$$GZ = CBR - CBCG * \sin(\varphi)$$

Equation 2.2: Atwood's formula

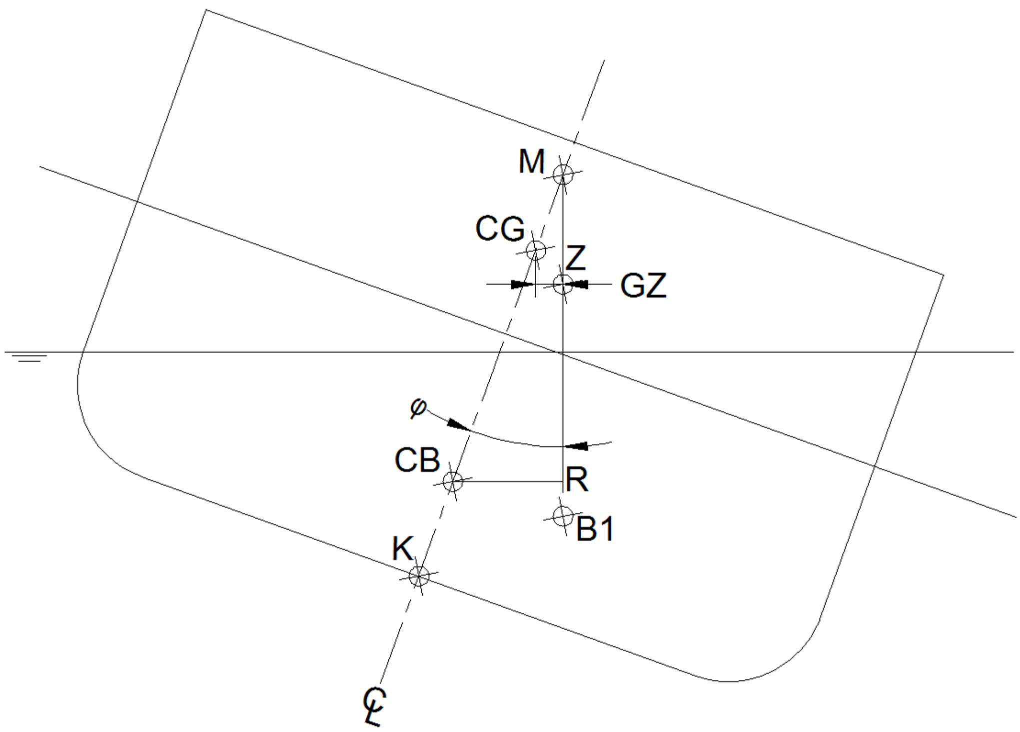


Figure 2.3: Illustration for ship intact stability

From Atwood's formula, a GZ curve can be plotted, but the problem is to find a waterline for the ship so that the displacement is the same when the ship is heeling.
This may be overcome by calculate the GZ and displacement for a set of waterlines for each heel angle. From this so-called cross curves can be made can be made showing the GZ for any displacement and heel angle. Please see fig.2.4 below.
From the cross curves the GZ curve can be plotted. A typical GZ curve is shown in fig.2.5 below. Fig.2.6 shows a more unusual curve with double top.

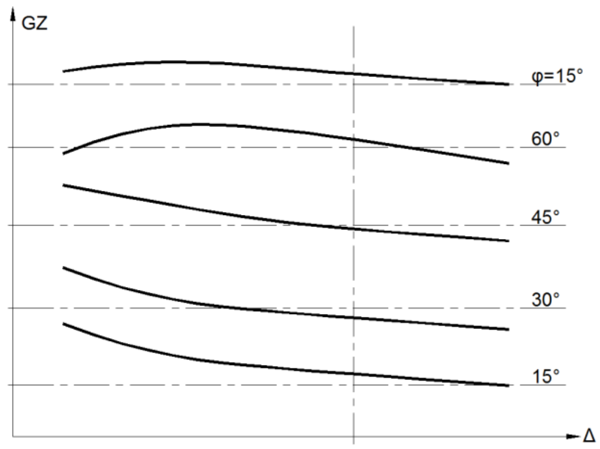


Figure 2.4: Cross curves for plotting of GZ

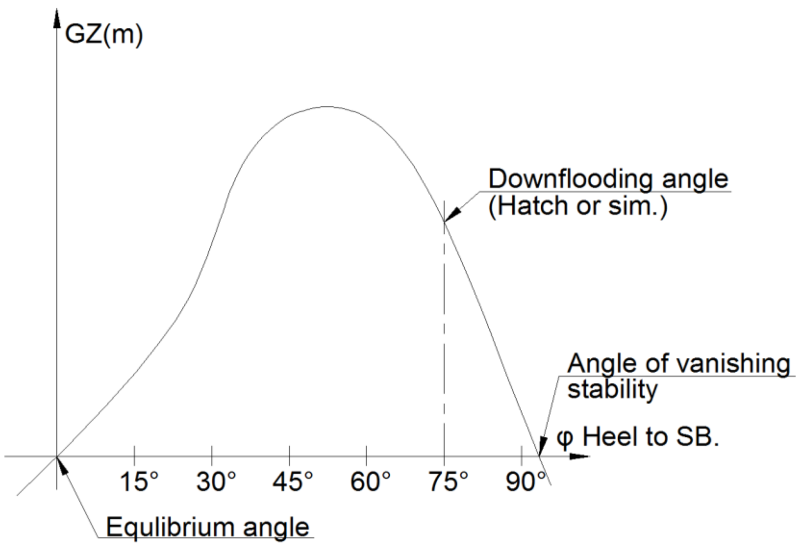


Figure 2.5: Typical GZ curve

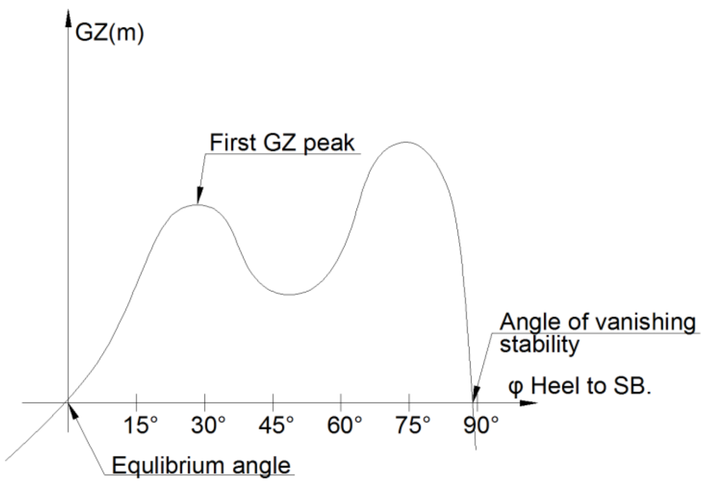


Figure 2.6: GZ curve with double top

2.3. Stability criteria’s according to IMO A.749 4,5

These criteria’s is one of the sets of criteria’s that is built into MaxSuf Stability, and is used directly in this thesis. The criteria’s is valid for offshore supply vessels, and according to ship rules for offshore service vessels this rules also is valid for anchor handling vessels (DNV GL AS, 2016).

Fig.2.7 and fig.2.8 below is requirements for the area between specified heel angles, and the lesser of the marked angles.

		4.5 Offshore supply vessel 4.5.6.2.1: GZ area between 0 and angle of maximum GZ	Value	Units
1	☐	*from the greater of*		
2	☑	spec. heel angle	0.0	deg
3	☐	angle of equilibrium		deg
4	☐	*to the lesser of*		
5	☐	spec. heel angle	30.0	deg
6	☐	spec. angle above equilibrium	0.0	deg
7	☑	angle of first GZ peak		deg
8	☑	angle of max. GZ		deg
9	☐	first downflooding angle		deg
10	☐	angle of vanishing stability		deg
11	☐	lower heel angle	15.0	deg
12	☐	required GZ area at lower heel angle	4.0107	m.deg
13	☐	higher heel angle	30.0	deg
14	☐	required GZ area at higher heel angle	3.1513	m.deg
15	☐	**shall not be less than (>=)**	**3.1513**	**m.deg**

Figure 2.7: IMO stability criteria 4.5.6.2.1

		4.5 Offshore supply vessel 4.5.6.2.2: Area 30 to 40	Value	Units
1	☐	*from the greater of*		
2	☑	spec. heel angle	30.0	deg
3	☐	angle of equilibrium		deg
4	☐	*to the lesser of*		
5	☑	spec. heel angle	40.0	deg
6	☐	spec. angle above equilibrium	0.0	deg
7	☐	angle of first GZ peak		deg
8	☐	angle of max. GZ		deg
9	☑	first downflooding angle		deg
10	☐	immersion angle of	DeckE	deg
11	☑	angle of vanishing stability		deg
12	☐	**shall not be less than (>=)**	**1.7189**	**m.deg**

Figure 2.8: IMO stability criteria 4.5.6.2.2

Figure 2.9 below shows the requirement for minimum GZ between 30 degr. heel and to 90 degr. heel, or angle of max GZ if that angle occurs first.

		4.5 Offshore supply vessel 4.5.6.2.3: Maximum GZ at 30 or greater	**Value**	**Units**
1	☐	*in the range from the greater of*		
2	☑	spec. heel angle	30.0	deg
3	☐	angle of equilibrium		deg
4	☐	*to the lesser of*		
5	☑	spec. heel angle	90.0	deg
6	☐	spec. angle above equilibrium	0.0	deg
7	☐	angle of first GZ peak		deg
8	☑	angle of max. GZ		deg
9	☐	first downflooding angle		deg
10	☐	**shall not be less than (>=)**	**0.200**	**m**

Figure 2.9: IMO stability criteria 4.5.6.2.3

Fig.2.10 below shows required angle where the first GZ peak occurs.

		4.5 Offshore supply vessel 4.5.6.2.4: Angle of maximum GZ	**Value**	**Units**
1	☑	limited by first GZ peak angle		deg
2	☐	limited by first downflooding angle		deg
3	☐	**shall not be less than (>=)**	**15.0**	**deg**

Figure 2.10: IMO stability criteria 4.5.6.2.4

In fig.2.11 below it is shown the minimum requirement for GMt at zero degr. heel.

		4.5 Offshore supply vessel 4.5.6.2.5: Initial GMt	**Value**	**Units**
1	☑	spec. heel angle	0.0	deg
2	☐	angle of equilibrium		deg
3	☐	Select calculation from list		
4	☐	**shall be greater than (>)**	**0.150**	**m**

Figure 2.11: IMO stability criteria 4.5.6.2.5

2.4. NMD Criteria's for anchor handling

The criteria's is found in guidelines paper from (NMD, 2007).

Calculations must be made for the maximum acceptable tension in wire/chain, including the maximum acceptable transverse force/tension that can be accepted in order for the vessel's maximum heeling to be limited to one of the following angles, whichever occurs first:

- Heeling angle equivalent to a GZ-value equal to 50 % of GZ-max.
- The angle of flooding, which results in water aft on working deck when the deck is calculated as flat.
- 15 degrees.

The heeling moment must be calculated as the total effect of the horizontal and vertical transverse components of force/tension in the wire or the chain. The torque arm of the horizontal components shall be calculated as the distance from the height of the work deck at the guide pins to the center of main propulsion propeller or to center of stern side propeller if this projects deeper. The torque arm of the vertical components shall be calculated from the center of the outer edge of the stern roller and with a vertical straining point on the upper edge of the stern roller.

The other loading conditions for the vessel shall be as stated for anchor handling in approved stability calculations and in accordance with prevailing practice with regards to loads on deck and winch reels. The vertical force from the tension shall be included in the loading conditions, upon which calculations of trim and curve for righting arm (GZ-curve) are based.

2.5. The vessel model

The vessel model (Xu, 2014) is a 6 degree of freedom bond graph model designed in 20-sim and Matlab. The vessel data used in this model is generated with ShipX. The description below is found in (Xu, 2014), and only the main equations used in the vessel model is superficial explained here.

A floating ship is a dynamic system, where the hydro mechanical forces are the total reaction forces from the fluid on the oscillating ship in still water. The mass of the ship and accelerated water multiplied with the acceleration represents the inertia force. The damping coefficient multiplied with velocity represents the damping force, and the restoring coefficient multiplied with the displacement represents the restoring force. Please see eq.2.3 below.

$$(M_{RB} + M_A(\omega)) * \ddot{\eta}(t) + (C_{RB} + C_A(\omega)) * \dot{\eta}(t) + J^{-1}{}_b^h * B(\omega) * J_b^h * \dot{\eta}(t) + J^{-1}{}_b^h * C * \int J_b^h * \eta(t) = J^{-1}{}_b^h * \tau_{exc} + \tau$$

Equation 2.3

Here M_{RB} and M_A is the inertia matrix of the rigid body and the added mass respectively. C_{RB} is coriolis and centripetal forces of rigid body, and C_A is coriolis and centripetal forces of added mass.

ω is the angular velocity. η is the transational displacement. *B* is the damping tensor, and *C* is the restoring force tensor.

$\tau=[\underset{F_h}{\rightarrow},\underset{Q_h}{\rightarrow}]^T$, Where $\underset{F_h}{\rightarrow}$ and $\underset{Q_h}{\rightarrow}$ is the hydrodynamic force and torque acting on the body.

τ_{exe} is the excitation forces from wind and waves.

J_h^b is the transformation matrix used to transform the hydrodynamic forces from a hydrodynamic reference frame to a body fixed coordinate system. Please see eq.2.4 below.

$$J_h^b = \begin{bmatrix} R_b^h & 0_{3x3} \\ 0 & T_b^h \end{bmatrix}$$

Equation 2.4

Where R_b^h is the rotation matrix for linear velocity and T_b^h is the rotation matrix for angular velocity.

Fig.2.12 below shows how the different 20-sim sub models are connected with multi-bonds. The I-element represent the inertia from the rigid body and the added mass, which is the first term in eq.2.3 above, and is a function off the acceleration. In addition, Coriolis and centripetal forces is calculated in this element.
The R-element represents the velocity dependent damping. This can be found in the second and third term of eq.2.3.
The C-element represent the restoring force found in the fourth term of eq.2.3.
The EULER_ZYX element is performing the coordinate transformation, and output a rotation matrix used to transform the external forces from the global coordinate system into the body fixed coordinate system.
A word fixed force, as the gravity force, is acting in the word fixed coordinate system while a body fixed force is acting in the body fixed coordinate system. A propeller is a body fixed force as it is fixed to the hull and following the hull motions.

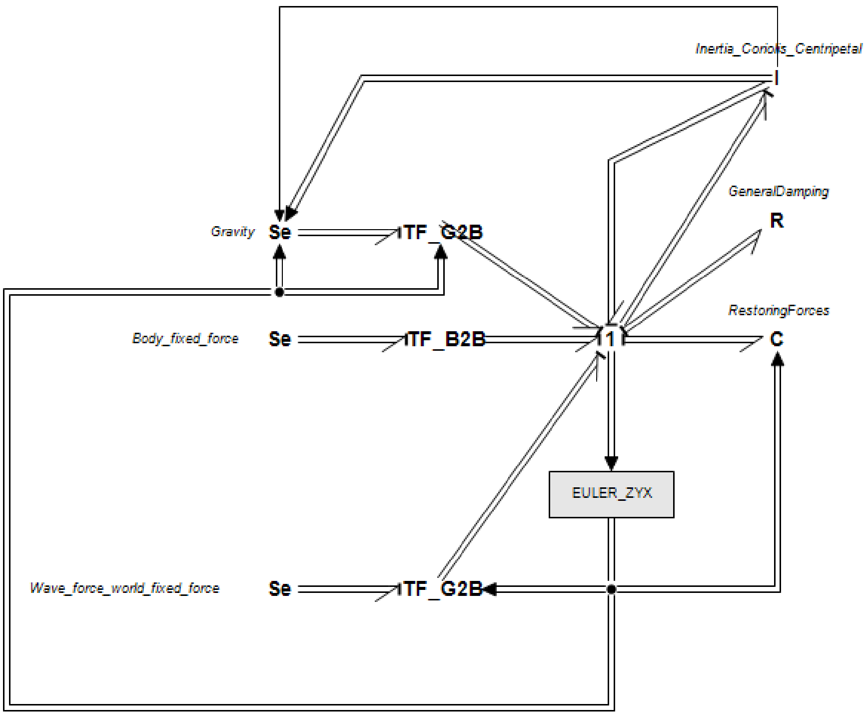


Figure 2.12: The existing 20-sim vessel model

2.6. Ship response amplitude operator (RAO)

In fig.2.13 below is shown in principle a ROA curve for roll motion.

The equation for roll motion is defined as shown in eq.2.5 below.

$$\eta_3 = \eta_{3a} * \cos(w * t + \theta_3)$$

Equation 2.5

Here η_{3a} is the response amplitude per unit wave amplitude and is often referred to as the response amplitude operator (RAO). w is the wave frequency, and θ_3 is the phase angle. From this, if the wave height is 2m, the amplitude is 1m, and the roll motion response will be the same as the RAO.

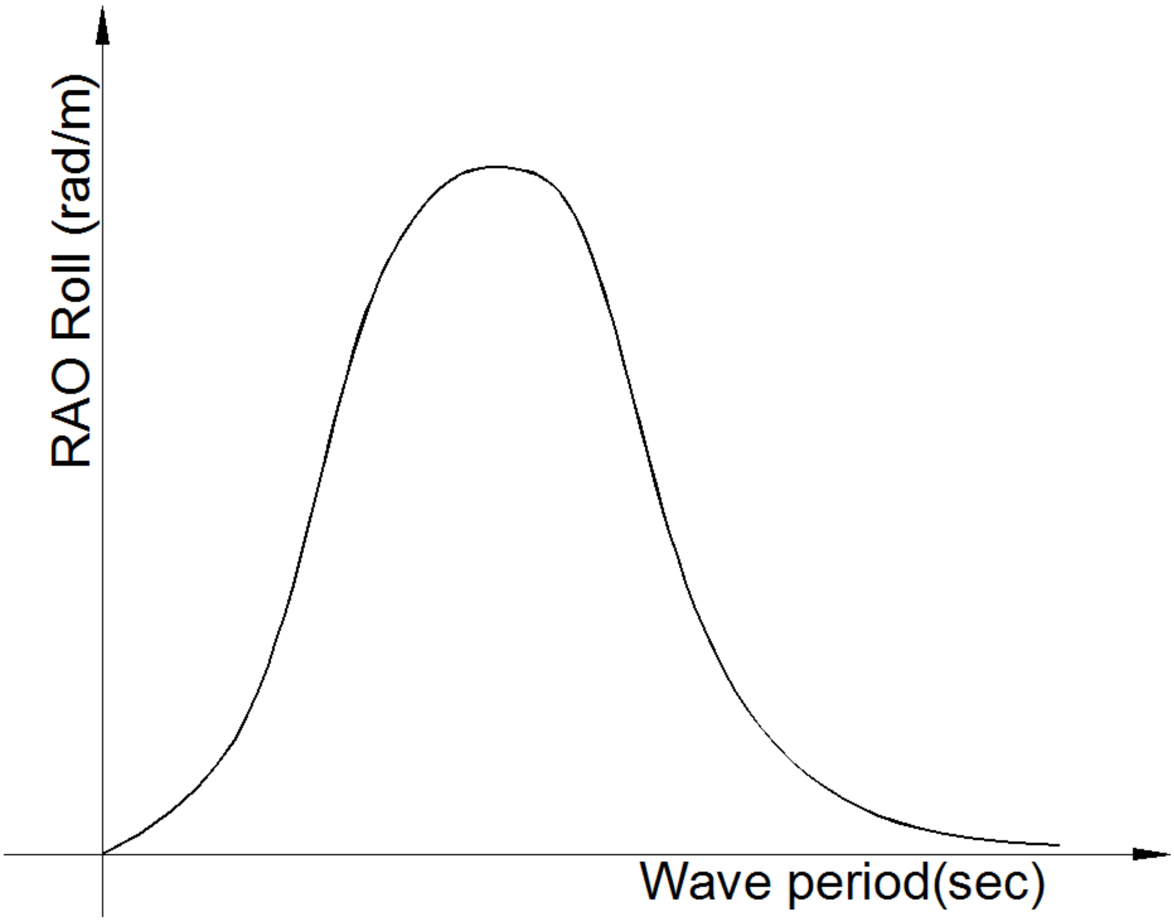


Figure 2.13: Response amplitude operator (RAO)

2.7. Anchor line modelling

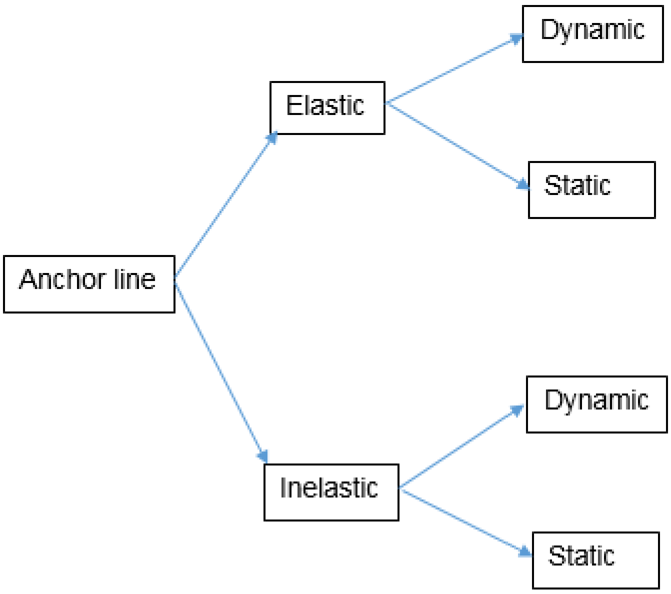


Figure 2.14: Anchor line modelling approaches

In fig.2.14 above is shown different approaches for modelling an anchor line, which all are based on the Catenary theory. In an elastic line, the uniform mass per unit length will change with tension, while for an inelastic line this will be constant. (Bhattacharya, 2010). In the static model, the model is time independent, while the dynamic model is time dependent.
In equation 2.6, 2.7 and 2.8 below is shown the set of equations governing the motion of a time dependent, or dynamic catenary. The variables in the equations is explained by figure 2.15. The three unknowns, x, y and T may be found by using appropriate boundary conditions.

$$\frac{\partial^2}{\partial t^2} = \frac{1}{\mu}(T\frac{\partial^2 x}{\partial s^2} + \frac{\partial T \partial x}{\partial s \partial s}$$

Equation 2.6

$$\frac{\partial^2 y}{\partial t^2} = \frac{1}{\mu}\left(T\frac{\partial^2 x}{\partial s^2} + \frac{\partial T \partial y}{\partial s \partial s}\right) - g$$

Equation 2.7

$$(\frac{\partial x}{\partial s})^2 + (\frac{\partial y}{\partial s})^2 = 1$$

Equation 2.8

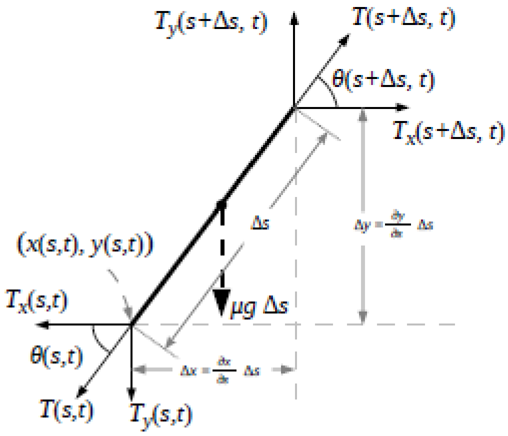


Figure 2.15: Anchor line segment

When x, y and T are independent of time the equations above will be reduced to ordinary differential equations describing the static catenary problem.

In an elastic catenary problem, the line is replaced by a spring, which is assumed to stretch in response to tension according to Hooke's law. (Wikipedia, 2016).
The derivation for x and y can be done from the relation shown in eq.2.9 below.

$$s = \left(1 + \frac{T}{E}\right) * p$$

Equation 2.9

Here T is the line tension, E is equal to k*p, where k is the spring stiffness. p is the natural length of a section of the spring and s is the length of the spring. The final equations for x and y is shown in eq.2.10 and eq.2.11 below. a is a constant (To/λg), named Q in Ch.4. α and β is integration constants which can be set to zero by shifting the coordinate system.

$$x = a * \operatorname{arcsinh}\left(\frac{p}{a}\right) + \frac{T_o}{E} * p + \alpha$$

Equation 2.10

$$y = \sqrt{a^2 + p^2} + \frac{T_0}{2Ea} * p^2 + \beta$$

Equation 2.11

When E is large, the shape of the curve will be reduced to the inelastic line.

3. General methodology

3.1. Computer programs

Several engineering computer programs has been used in this thesis. Below is given a brief description of the main programs.

ShipX

ShipX is Marintek's common platform for ship design analyses. This program has several plugins that make it possible to calculate vessel responses, characteristics for maneuvering and station keeping.

MaxSurf

Maxsurf is a suite of software for ship design from Bentley Engineering. It has tools for hull modelling, stability, hull resistance and more. In this thesis the tools for modelling and stability has been used.

20-sim

20-sim is a modelling and simulation program from Controllab B.V. The program makes it possible to use the Bond graph method to model and simulate the behavior of dynamic systems.

Matlab

Matlab is developed by MathWorks Inc, and is a high-level language for numeric computation, visualization, programming and application development. Beside of transferring hydrodynamic data from ShipX, the program was used to differentiate the equation used in Newton's method in the anchor line model.

AutoCAD

This is a software application for 2D and 3D computer-aided design and drafting from Autodesk Inc. In this thesis, the program was used to make figures for illustration.

3.2. The ship hull

The hull studied in this thesis is typical for an anchor-handling vessel. Please see fig.3.1 below. The hull model is made in MaxSurf by importing the data points from an existing hull definition file in ShipX (mgf file format).

Tab.3.1 below shows the data for section no.1 in the mgf file. The number 39.099 is the distance from the mid-frame which is a vertical section in middle between aft and fore perpendicular of the ship.

The next number means that it is 21 points in the section. The first and second column is the offset from the ship centerline and high above the baseline respectively.

1	
39.09999847	
21	
0.00000000	8.30207157
2.70000005	8.30200005
8.19250011	8.30200005
8.19250011	6.90140009
8.10000038	6.83860016
7.75000000	6.61049986
7.71479988	6.58890009
7.50000000	6.46169996
7.40390015	6.41079998
7.00000000	6.22119999
6.91629982	6.18620014
6.50000000	6.02939987
6.00000000	5.84999990
5.50000000	5.68540001
5.00000000	5.52239990
4.50000000	5.36250019
4.00000000	5.19960022
3.50000000	5.02659988
3.37030005	4.97800016
2.70000005	4.97800016
0.00000000	4.97792816

Table 3.1: Ship hull data points from ShipX

Preparation of the data was done in Ms Excel before pasting them into the marker table in MaxSurf modeller as shown in tab.3.2 below.

	Station Inde	Long. Pos. m	Offset m	Height m	Surface	Kind	Name	Error m
1	1	-39.100	0.000	4.978	None			--
2	1	-39.100	2.700	4.978	None			--
3	1	-39.100	3.370	4.978	None			--
4	1	-39.100	3.500	5.027	None			--
5	1	-39.100	4.000	5.200	None			--
6	1	-39.100	4.500	5.363	None			--
7	1	-39.100	5.000	5.522	None			--
8	1	-39.100	5.500	5.685	None			--
9	1	-39.100	6.000	5.850	None			--
10	1	-39.100	6.500	6.029	None			--
11	1	-39.100	6.916	6.186	None			--
12	1	-39.100	7.000	6.221	None			--
13	1	-39.100	7.404	6.411	None			--
14	1	-39.100	7.500	6.462	None			--
15	1	-39.100	7.715	6.589	None			--
16	1	-39.100	7.750	6.610	None			--
17	1	-39.100	8.100	6.839	None			--
18	1	-39.100	8.193	6.901	None			--
19	1	-39.100	8.193	8.300	None			--
20	2	-38.100	0.000	4.160	None			--
21	2	-38.100	1.609	4.160	None			--
22	2	-38.100	2.000	4.364	None			--

Table 3.2: Ship hull marker table in MaxSurf

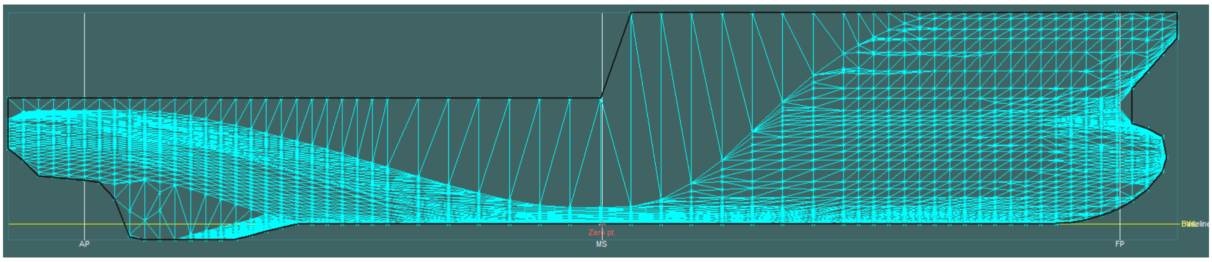


Figure 3.1: AHTS vessel hull

Main characteristics for the hull:

Length over all: 77,0m

Length between perpendiculars: 68,2m

Breadth: 17,2m

Depth to main deck: 8,3m

3.3. Transferring hydrodynamic coefficients from ShipX to 20-sim

The hydrodynamic coefficients for the hull was transferred from ShipX to the 20-sim model. This was done by adding the actual loading condition into ShipX, and running a vessel response calculation. Some main input for this calculation is shown in fig.3.2 below. For condition information, zero velocity, wave periods from 2 to 60 sec. and wave headings in several steps from zero to 180 degrees was given in.

Radius of gyration, R44 was calculated as 0.4*B acc. to the Veres manual (MARINTEK AS, 2015) . The result files from the calculation was then used in Fossen's MSS Hydro, which is a toolbox for Matlab. By running this in Matlab the data from the result files is read and saved in *.mat format file. The steps in this process is explained in detail in the guideline paper (Fossen, 2008).

The hydrodynamic coefficients then was transferred to the 20-sim model by using a Matlab script made by Jiafeng Xu. Some modifications was done in the script to adapt it to the 20-sim model in this thesis, and the final script can be found in appendix B.1.

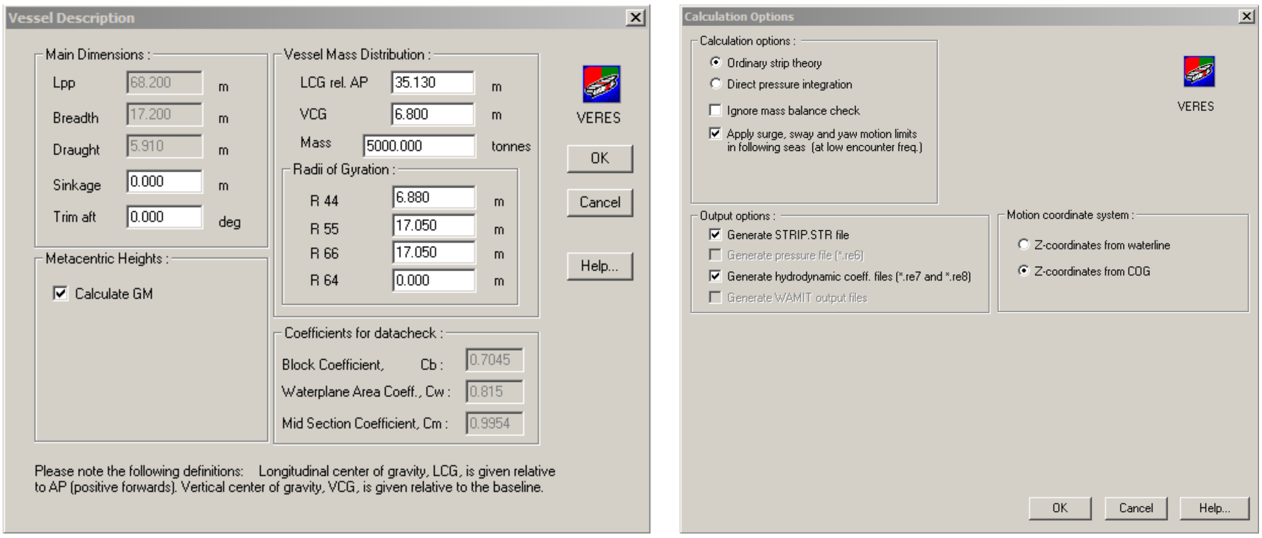


Figure 3.2: Input for ShipX

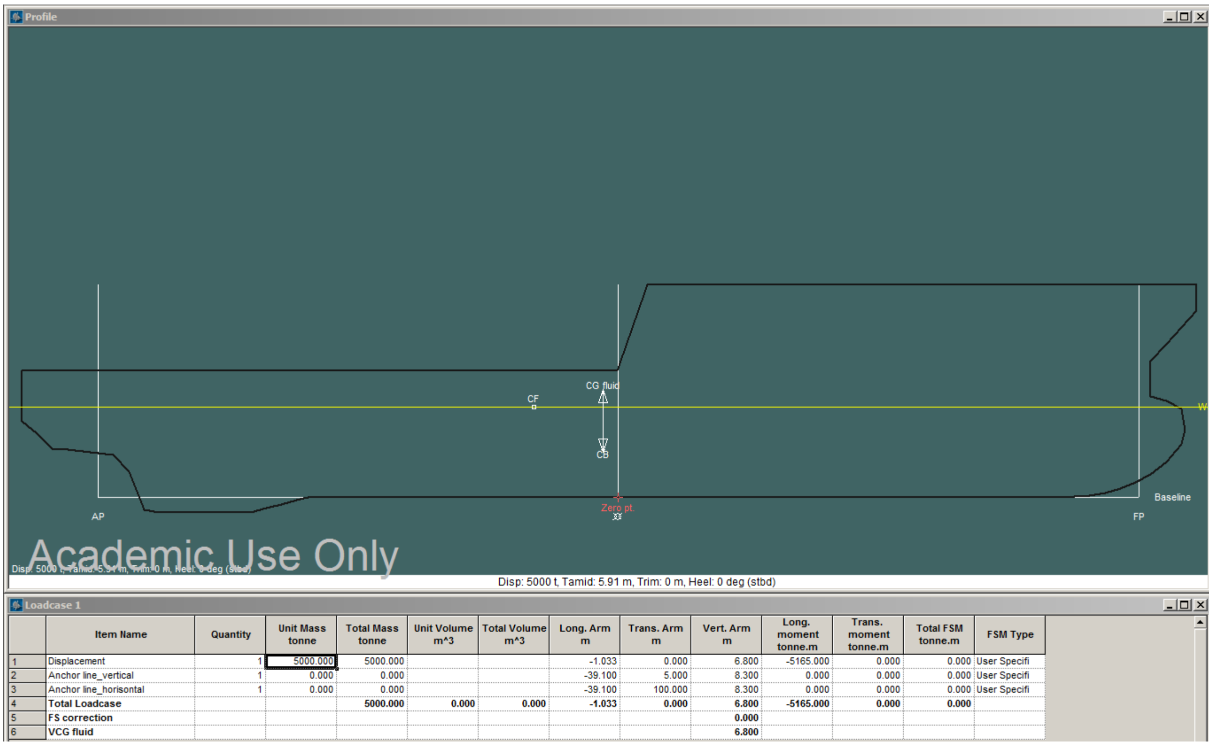
3.4. Hydrostatics and intact stability

By using MaxSurf stability computer program, the intact stability for the ship hull was checked against the stability criteria's described in Ch.2.3. The stability calculations was performed to ensure that the ship hull has sufficient stability when the hydrodynamic coefficients is transferred to ShipX. Hydrostatic data for the hull was calculated for different waterlines and the result may be found in Appendix A.1.

3.5. General loading condition

The ship hull made in Maxsurf modeller was taken into Maxsurf stability and a loading condition was established as shown in fig.3.3 below. In order to make the ship float at a credible waterline the weight displacement was set to 5000 Ton. The longitudinal center of gravity was chosen 1,033m aft of the zero point so that the trim is zero degree.

VCG was set to 6,8m above baseline, as this was assumed realistic for this type of vessels. This loading condition is also basic for the input to ShipX in order to calculate the hydrodynamic coefficients for the hull.



	Item Name	Quantity	Unit Mass tonne	Total Mass tonne	Unit Volume m^3	Total Volume m^3	Long. Arm m	Trans. Arm m	Vert. Arm m	Long. moment tonne.m	Trans. moment tonne.m	Total FSM tonne.m	FSM Type
1	Displacement	1	5000.000	5000.000			-1.033	0.000	6.800	-5165.000	0.000	0.000	User Specifi
2	Anchor line_vertical	1	0.000	0.000			-39.100	5.000	8.300	0.000	0.000	0.000	User Specifi
3	Anchor line_horisontal	1	0.000	0.000			-39.100	100.000	8.300	0.000	0.000	0.000	User Specifi
4	**Total Loadcase**			**5000.000**	**0.000**	**0.000**	**-1.033**	**0.000**	**6.800**	**-5165.000**	**0.000**	**0.000**	
5	**FS correction**								**0.000**				
6	**VCG fluid**								**6.800**				

Figure 3.3: General loading condition

3.6. Stability calculation for the general loading condition

The stability for the hull was checked by applying the stability criteria's described in Ch.2.3, and a large angle stability calculation was performed in Maxsurf Stability.

The program is defining a set of heel angles between -30 to 180 degrees, and the hydrostatic data and righting lever is calculated for each of these angles by balancing the load case displacement against the hull buoyancy. In addition, the center of buoyancy is balanced against the center of gravity such that the longitudinal trimming moment is zero.

The main value for each heel angle is the GZ (righting lever) which is used to plot the GZ curve, but also other values as upright GM and area under the GZ curve can be plotted from the values. Fig.3.4 below illustrates the waterline, center of buoyancy and center of gravity when the heel angle is 30 degree. GZ is the horizontal distance between center of gravity (CG) and center of buoyancy (CB), and is positive as long as the line for CB is to the right for the line for CG.

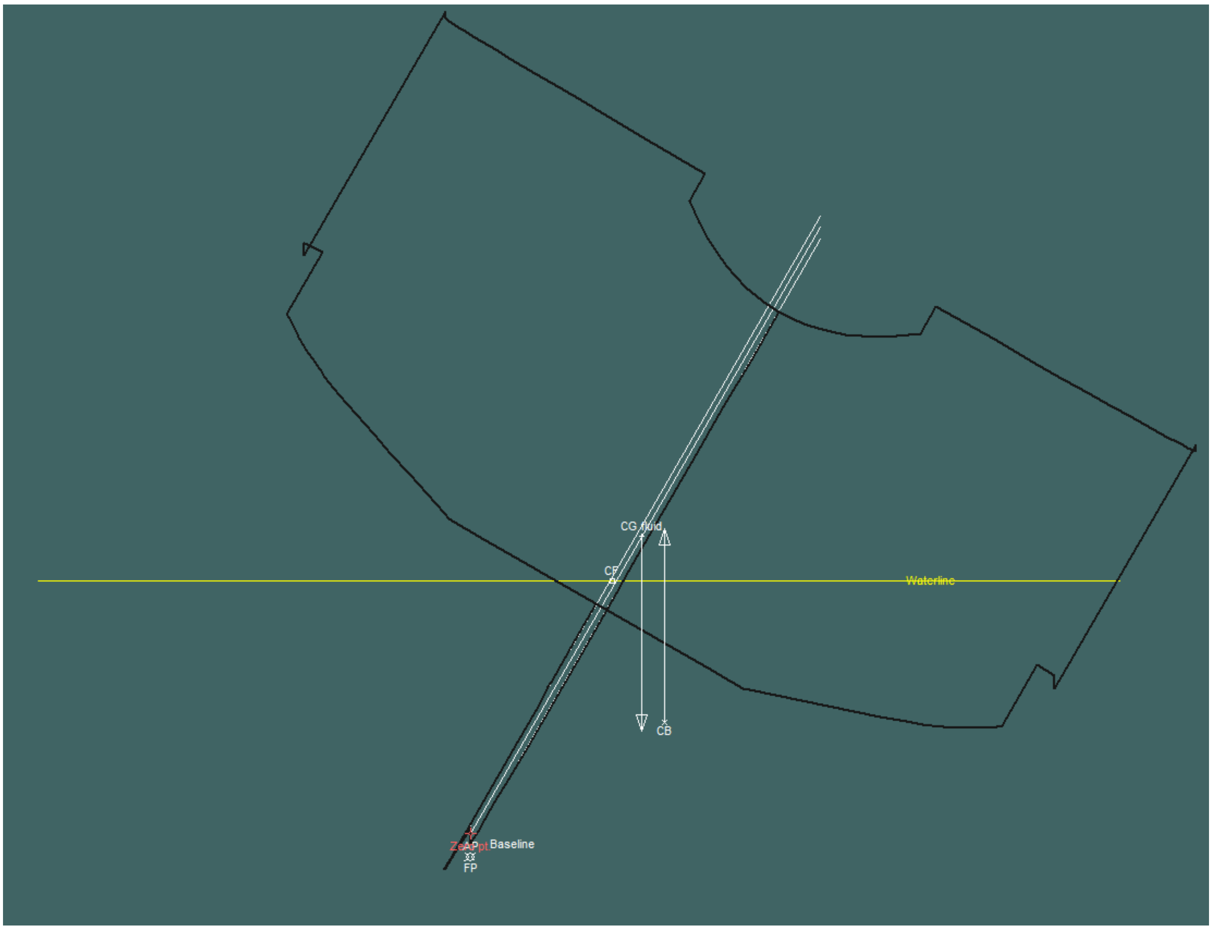


Figure 3.4: Illustration from stability calculation for the general loading condition

3.7. Loading condition during anchor handling

The stability requirements for anchor handling is described in Ch.2.4

According to these requirements calculations showing the maximum acceptable vertical and horizontal line tension to which the vessel can be exposed in the most unfavorable conditions was performed.

In Maxsurf Stability a tension (T) was added acc. to the criteria's for anchor handling (NMD, 2007), in addition to the general loading condition as described in Ch.3.5.

For the horizontal force arm of 8,3m, it has been assumed that the center of the propeller and the side thrusters is on the same height as the ship baseline.

The stern roller was assumed 10m wide as shown in fig.3.5 below.

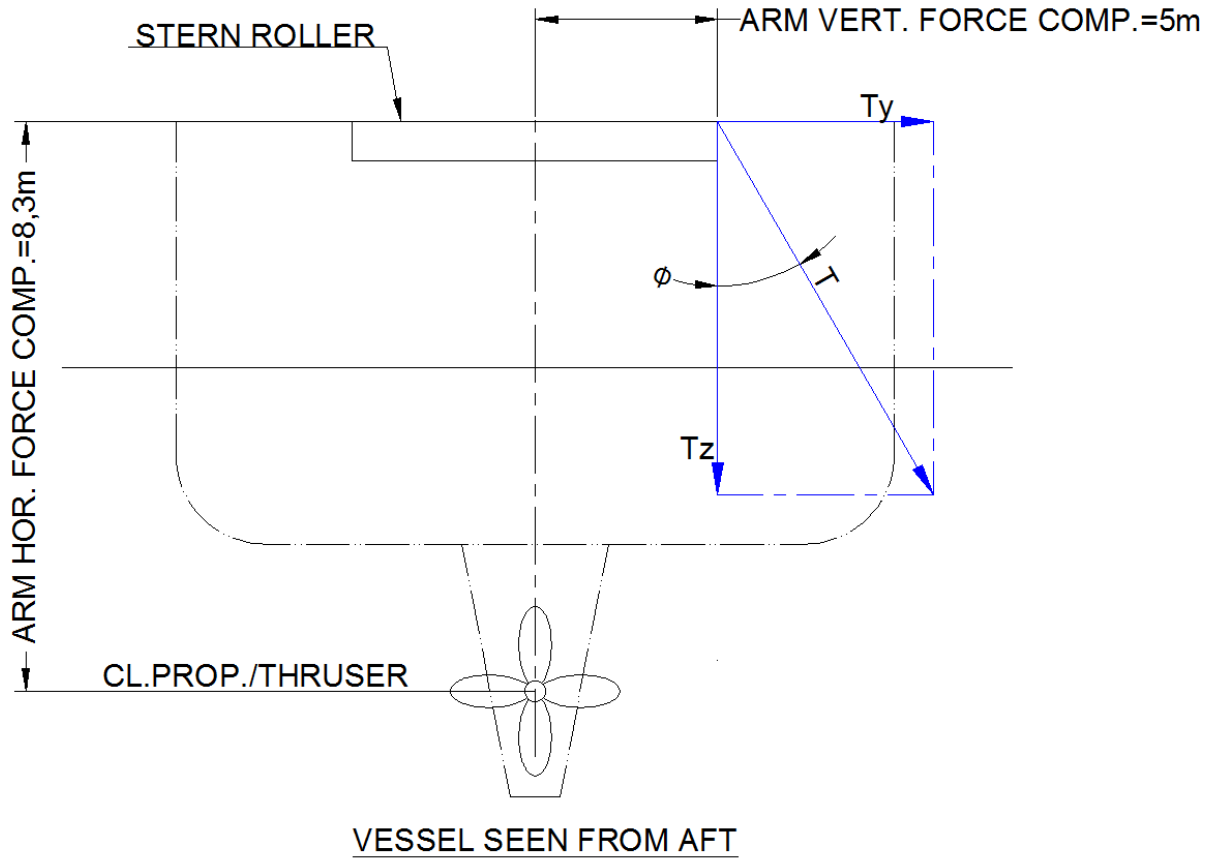


Figure 3.5: Sketch for anchor handling loading condition

3.8. Stability calculation for the anchor handling condition

This calculation was done by varying the tension (T) until the maximum tension without failing on any of the stability criteria is described in Ch.2. This was done for each angle ϕ in steps between 0 and 90 degrees.

In Maxsurf stability, it is possible to define down flooding points by adding them in the key points table. This feature was not used as the program calculates freeboard for the deck edge automatically.

Therefore, the NMD criteria regarding water aft on working deck was checked in the report made by the program, in additional to observing the freeboard visual in the graphical window during the equilibrium calculation.

As given in the NMD criteria's (NMD, 2007), the moment arm for the horizontal force component in this case is 8,3m. In Maxsurf it was not found possibilities to add horizontal forces. Therefore, the transversal moment from the horizontal component was created by giving a vertical force 100m from the vessel centerline. Please see fig.3.6 below for one example load case in MaxSurf.

Loadcase 1

	Item Name	Quantity	Unit Mass tonne	Total Mass tonne	Unit Volume m^3	Total Volume m^3	Long. Arm m	Trans. Arm m	Vert. Arm m	Long. moment tonne.m	Trans. moment tonne.m	Total FSM tonne.m	FSM Type
1	Displacement	1	5000.000	5000.000			-1.033	0.000	6.800	-5165.000	0.000	0.000	User Specifi
2	Anchor line_vertical	1	102.700	102.700			-39.100	5.000	8.300	-4015.570	513.500	0.000	User Specifi
3	Anchor line_horisontal	1	3.530	3.530			-39.100	100.000	8.300	-138.023	353.000	0.000	User Specifi
4	**Total Loadcase**			**5106.230**	**0.000**	**0.000**	**-1.825**	**0.170**	**6.831**	**-9318.593**	**866.500**	**0.000**	
5	**FS correction**								**0.000**				
6	**VCG fluid**								**6.831**				

Figure 3.6: Example load case for anchor handling condition

4. Model development methodology

4.1. The submerged anchor line

In general, the anchor line can be modelled either static or dynamic. In addition, the line may be assumed inelastic or elastic. In Ch.2 is described different approaches to model the anchor line. Due to limited time, it was agreed to study the static inelastic line. The equations below is based on a publication about the Catenary problem. (Bhattacharya, 2010).

4.2. Static inelastic Catenary line

In the static model, the variables will not change through time. This means that the line can move during one time step to the next, but the line will not change its shape between each time step. The inertia effect when moving the line is neglected.

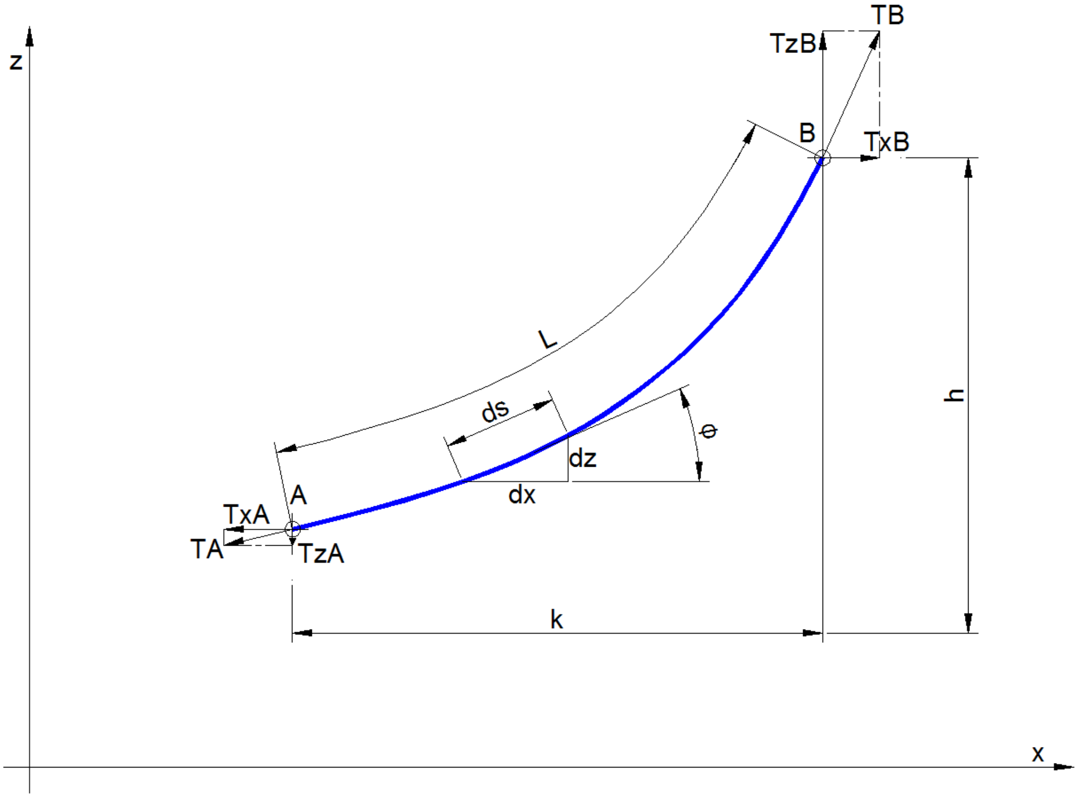


Figure 4.1: Sketch of the catenary line

In fig.4.1 above is shown a catenary line between point A and point B.

For a segment of the line to be in equilibrium, it requires the forces in x direction, $T_x A$ and $T_x B$ to be equal. Also the forces in z direction must be equal as shown in eq.4.1 below.

$$T_{Z(S)} = T_{Z(0)} + \int_0^S w\, ds$$

Equation 4.1

By using the relation in eq.4.2, this equation can be written as shown in eq.4.3 below.

$$ds = \sqrt{dx^2 + dz^2} = dx * \sqrt{1 + (\frac{dz}{dx})^2}$$

Equation 4.2

$$T_x * \frac{dz}{dx} = T_{Z(0)} + w * \int_0^x \sqrt{1 + \left(\frac{dz}{dx}\right)^2}\, dx$$

Equation 4.3

Differentiating eq.4.3 twice, gives eq.4.4 below.

$$T_x \frac{dz^2}{dx^2} = w * \sqrt{1 + (\frac{dz}{dx})^2}$$

Equation 4.4

This is a second order differential equation, and by integrating and assume that the curve has a hyperbolic shape, the resulting expression for z is shown in eq.4.5 below.

$$z = Q * \cosh\left(\frac{x}{Q} + C1\right) + C2 \,, \qquad where\ Q = \frac{T_X}{w}$$

Equation 4.5

By using the relations in eq.4.6, and eq.4.7 below, an equation for L can be written as shown in eq.4.8

$$(\frac{dz}{dx})^2 = sinh^2\left(\frac{x}{Q} + C1\right)$$

Equation 4.6

$$sinh^2\left(\frac{x}{Q} + C1\right) = cosh^2(\frac{x}{Q} + C1)$$

Equation 4.7

$$L = \int_0^k \sqrt{1 + (\frac{dz}{dx})^2}\, dx \ = \int_0^k \cosh(\frac{x}{Q} + C1)\, dx$$

Equation 4.8

After integrating from zero to k, eq.4.8 becomes:

$$L = Q * \sinh\left(\frac{k}{Q} + C1\right) - Q * \sinh(C1)$$

Equation 4.9

By inserting the points A(0,0) from fig.4.1, into eq.4.5, C2 can be written as in eq.4.10 below.

$$C2 = -Q * \cosh(C1)$$

Equation 4.10

And in the same manner by using point B(k,h) from fig.4.1, h will become as shown in eq.4.11 below.

$$h = Q * \cosh(\left(\frac{k}{Q}\right) + C1) + C2$$

Equation 4.11

For a small segment in fig.4.1 the following relation exist:

$$k^2 = L^2 - h^2$$

Equation 4.12

Then by using eq.4.12 and calculation rules for hyperbolic functions, eq.4.13 below is obtained.

$$L^2 - h^2 = 2 * Q^2 * sinh^2(\frac{k}{2Q})$$

Equation 4.13

Finding the constant Q from eq.4.13 can be found in two ways, either non iterative, or by using Newton’s method which is iterative. The non-iterative solution for Q can be written as in eq.4.14 below, similar to (Journee & Massie, 2001):

$$Q = \sqrt{\frac{k^3}{24 * ((L^2 - h^2) - k)}}$$

Equation 4.14

By inserting C2 from eq.4.10 into eq.4.11, h may be written as shown in eq.4.15 below.

$$h = Q * \left[\cosh\left(\frac{k}{Q}\right) + C1\right) - \cosh(C1)]$$

Equation 4.15

By introducing a new variable P as shown in eq.4.16, the expression for h can be simplified to as shown in eq.4.17 below. This is done by using the calculation rules for hyperbolic functions.

$$P = C1 + \frac{k}{2Q}$$

Equation 4.16

$$h = 2 * Q * \sinh\left(\frac{k}{2Q}\right)\sinh(P)$$

Equation 4.17

From eq.4.17, P may be written as shown in eq.4.18 below.

$$P = sinh^{-1}\left(\frac{h}{2Qsinh(\frac{k}{2Q})}\right)$$

Equation 4.18

Using eq.4.16 and eq.4.18, C1 may be found as shown in eq.4.19 below.

$$C1 = sinh^{-1}\left(\frac{h}{2Qsinh\left(\frac{k}{2Q}\right)}\right) - \frac{k}{2Q}$$

Equation 4.19

4.3. Catenary line with seabed interaction

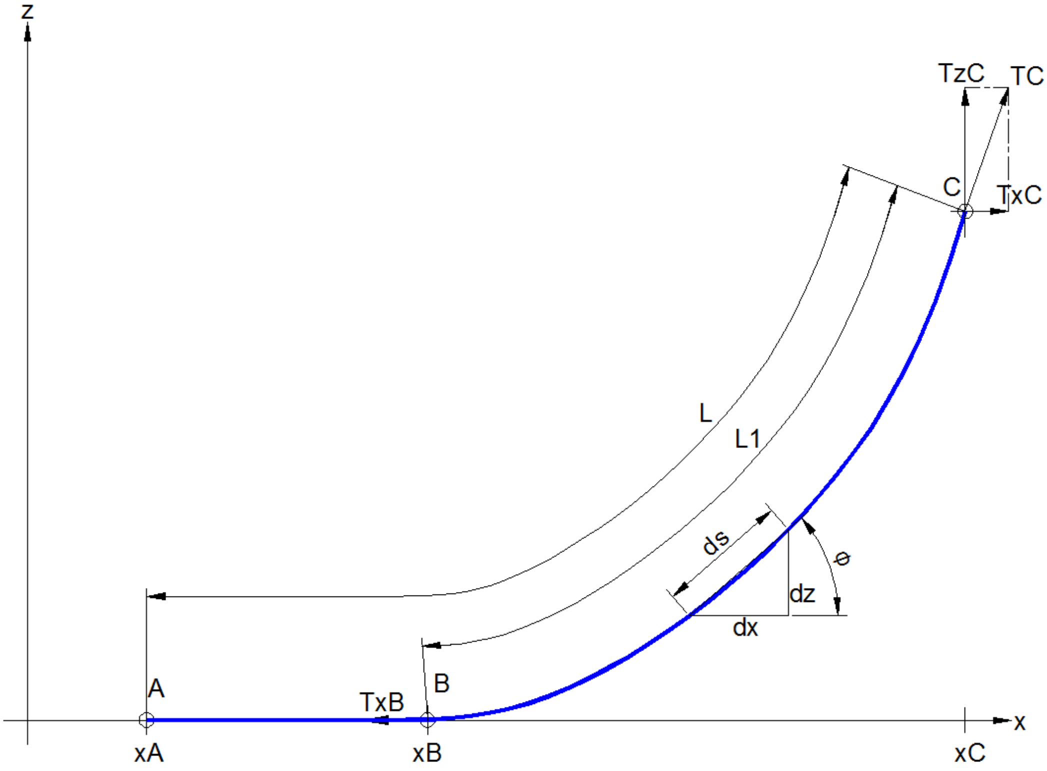


Figure 4.2: Catenary line with seabed interaction

From fig.4.2 above the following boundary conditions can be used as shown in tab.4.1 below.

	Point B	Point C
x	xB	xC
z	0	zC

Table 4.1: Boundary conditions for Catenary line with bottom interaction

When a part of the line is lying on the bottom, eq.4.5 as derived for the general catenary can be used also here. By using the boundary conditions, the following equations can be derived as shown in eq.4.20 below.

$$Q * \cosh(\left(\frac{xB}{Q}\right) + C1) + C2 = 0$$

Equation 4.20

Here cosh((xB/Q)+C1)=1 so eq.4.20 can be written as in eq.4.21 below.

$$Q + C2 = 0$$

Equation 4.21

By applying the boundary conditions for point C we get eq.4.22 below.

$$zC = Q * \cosh(\left(\frac{xC}{Q}\right) + C1) + C2$$

Equation 4.22

Inserting C2 from eq.4.21 into eq.4.22 gives eq.4.23 below.

$$zC = Q * \cosh(\left(\frac{xC}{Q}\right) + C1) - Q$$

Equation 4.23

From fig.4.8, the total length of the line can be written as shown in eq.4.24 below.

$$L1 + xB - xA = L$$

Equation 4.24

For xB, dz/dx=0 so we can write eq.4.25 below.

$$\sinh\left(\frac{xB}{Q} + C1\right) = 0$$

Equation 4.25

In addition, from this equation one can write:

$$\frac{xB}{Q} + C1 = 0$$

Equation 4.26

From eq.4.8 in the derivation for the general catenary, we have:

$$L1 = \int_{xB}^{xC} \sqrt{1 + (\frac{dZ}{dX})^2} dX$$

Equation 4.27

Solving this integral gives:

$$L1 = Q * \sinh\left(\frac{xC}{Q} + C1\right) - \sinh(\frac{xB}{Q} + C1)$$

Equation 4.28

Since the last part of this equation is zero, L1 can be written as in eq.4.29 below.

$$L1 = Q * \sinh\left(\frac{xC}{Q} + C1\right)$$

Equation 4.29

By inserting C2 from eq.4.21 into eq.4.22, eq.4.22 can be written as shown in eq.4.30 below.

$$zC + Q = Q * \cosh(\left(\frac{xC}{Q}\right) + C1)$$

Equation 4.30

Then by subtracting eq.4.30 from eq.4.29 after first squaring them, we can write:

$$(zC + Q)^2 - L1^2 = Q^2$$

Equation 4.31

From eq.4.24 and eq.4.26, we have the relation as shown in eq.4.32 below.

$$L1 = L - xB = L + C1 * Q$$

Equation 4.32

Then by solving eq.4.31 for L1 and inserting L1 into eq.4.32, this can be written as is eq.4.33 below.

$$L + C1 * Q = \sqrt{zC^2 + 2 * zC * Q}$$

Equation 4.33

Solving eq.4.33 above for C1 gives eq.4.34 below.

$$C1 = \frac{\sqrt{zC^2 + 2 * zC * Q} - L}{Q}$$

Equation 4.34

Then, by substituting C2 from eq.4.21 and C1 from eq.4.34 into eq.4.23, the final equation for zC can be written as shown in eq.4.35 below.

$$zC = Q * \cosh\left(\frac{xC}{Q} + \frac{\sqrt{zC + 2 * zC * Q} - L}{Q}\right) - Q$$

Equation 4.35

To find the variables in the equations above, the first step is to solve this equation with respect to Q. Finding Q directly from eq.4.35 is assumed to be difficult, and in this thesis this was done iterative by using Newton's method. Matlab was used for obtaining the differential, and the Matlab code for this operation can be found in appendix B.6.

4.4. Estimation of Q

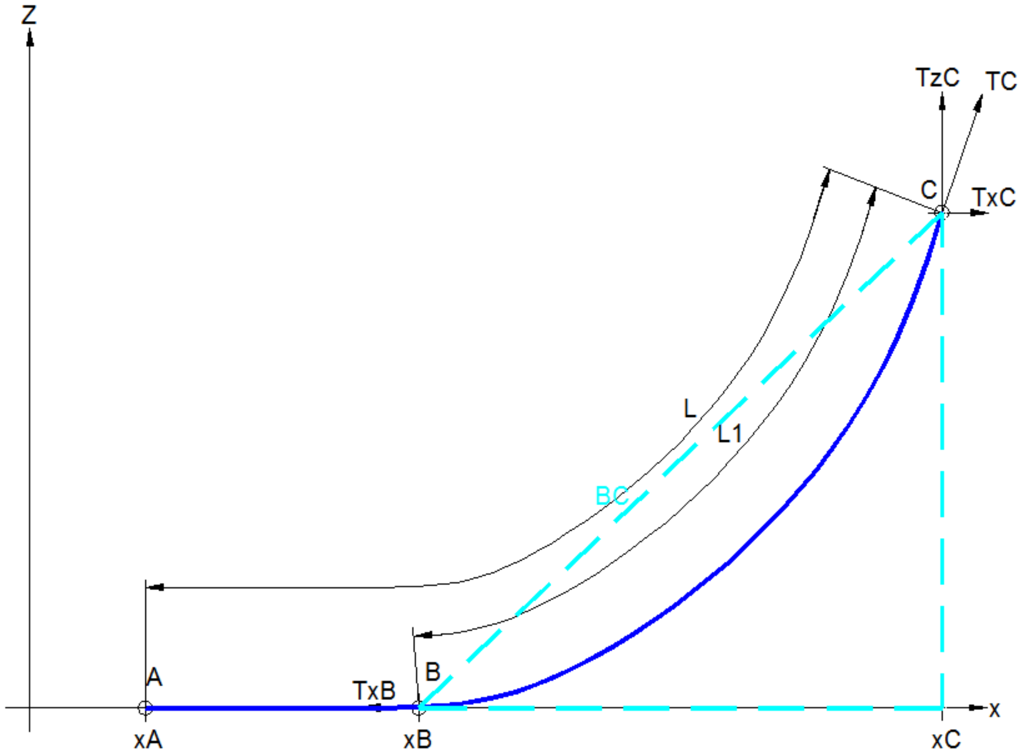


Figure 4.3: Sketch for estimation of Q

Finding Q by using Newton's method require a start value for Q. To avoid selecting an arbitrary value and thus reduce the solution time, Q was estimated by using the method as shown below. From fig.4.3 above the relations shown in eq.4.36 and eq.4.37 below is valid.

$$BC^2 = zC^2 + (xAC - AB)^2$$

Equation 4.36

$$L = AB + BC * \alpha_1$$

Equation 4.37

In eq.4.37 above, α_1 is a parameter that has to be estimated depending on the assumed slack in the line.

From eq.4.36, BC can be found as shown in eq.4.38 below.

$$BC = \sqrt{AB^2 - 2 * xAC * AB + xAC^2 + zC^2}$$

Equation 4.38

From eq.4.38, we can choose to make two new variables as shown in eq.4.39 and eq.4.40 below.

$$\beta = -2 * xAC$$

Equation 4.39

$$\gamma = xAC^2 + zC^2$$

Equation 4.40

By substituting eq.4.38 into eq.4.37, we can write L as shown in eq.4.41 below.

$$L = AB + \sqrt{AB^2 + \beta * AB + \gamma} * \alpha_1$$

Equation 4.41

Then by squaring both sides of eq.4.41 and rearranging, we can write eq.4.42 below.

$$(\alpha_1 - 1) * AB^2 + (\alpha^2 * B + 2 * L)AB + \alpha^2 * \gamma - L^2 = 0$$

Equation 4.42

Now AB can be found by using the standard quadratic formula shown in eq.4.43 for second order equations with the roots a,b and c as shown in the equations for a,b and c below.

$$\mathrm{a} = {\alpha_1}^2 - 1, \qquad \mathrm{b} = {\alpha_1}^2 * \mathrm{B} + 2 * \mathrm{L}, \qquad \mathrm{c} = {\alpha_1}^2 * \gamma - \mathrm{L}^2$$

$$AB = \frac{-b +/- \sqrt{b^2 - 4 * a * c}}{2 * \alpha_1}$$

Equation 4.43

Then L1, Tz, Tx, and finally the estimated Q can be found as shown in eq.4.44, 4.45, 4.46 and 4.47 below. In eq.4.46, α_2 is a factor used to estimate the horizontal force depending on the slack of the line. This because when the line is slack, in point C the difference in angle between the vertical for line AB, compared to the blue anchor line will be substantial. Please see fig.4.3 above.

$$L1 = L - AB$$

Equation 4.44

$$TzC = L1 * w$$

Equation 4.45

$$TxC = TxB = \alpha_2 * \frac{TzC * (xAC - AB)}{zC}$$

Equation 4.46

$$Q = \frac{TxC}{w}$$

Equation 4.47

4.5. Transforming the connection point position

Because the connection point C for the line is located away from the ship origo, its position has to be transformed into the world fixed coordinate system, shown in red color in fig.4.4 below. The vessel body fixed coordinate system is shown in blue color.

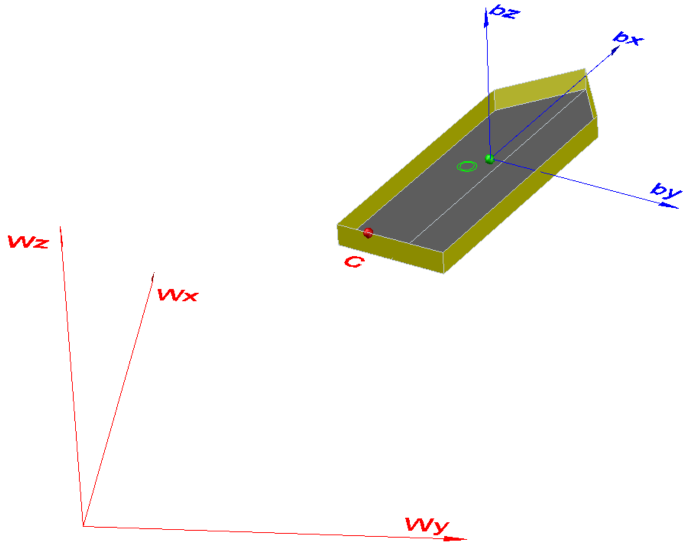


Figure 4.4: Coordinate transformation

The position of C in world x,y and z coordinates can be found by using the transformation matrix shown in eq.4.49 multiplied with the relative body fixed position for the connecting point Cp.

$$posC = TM * Cp$$

Equation 4.48

$$TM = \begin{bmatrix} \mathrm{Cos}(E3)\,\mathrm{Cos}(E2) & \mathrm{Cos}(E3)\,\mathrm{Sin}(E1)\,\mathrm{Sin}(E2) - \mathrm{C}\,os(E1)\,\mathrm{Sin}(E3) & \mathrm{Cos}(E1)\,\mathrm{Cos}(E3)\,\mathrm{Cos}(E2) & Vx \\ \mathrm{Cos}(E2)\,\mathrm{Sin}(E3) & \mathrm{Cos}(E1)\,\mathrm{C}\,os(E3) + \mathrm{Sin}(E1 * \mathrm{Sin}(E3)\,\mathrm{Sin}(E2) & \mathrm{Cos}(E1)\,\mathrm{Sin}(E3)\,\mathrm{Sin}(E2) - \mathrm{Cos}(E3)\,Sin(E1) & Vy \\ -Sin(E2) & Cos(E2)\mathrm{S}(E1) & Cos(E1)C(E2) & Vz \\ 0 & 0 & 0 & 1 \end{bmatrix}$$

Equation 4.49

Vx,Vy and Vz is the vessel coordinates in the word fixed coordinate system. The elements [1:3,1:3] inside TM is a rotation matrix for transforming rotation from a body fixed coordinate system into a world fixed coordinate system. The relative position vector for point C, Cp is given as shown in eq.4.50 below. CR is the position for point C in the vessel body frame relative to the vessel origo O, which is located amidships at the waterline (Fossen, 2008).

$$Cp = [CRx \quad CRy \quad CRz]^T$$

Equation 4.50

The Euler angles:

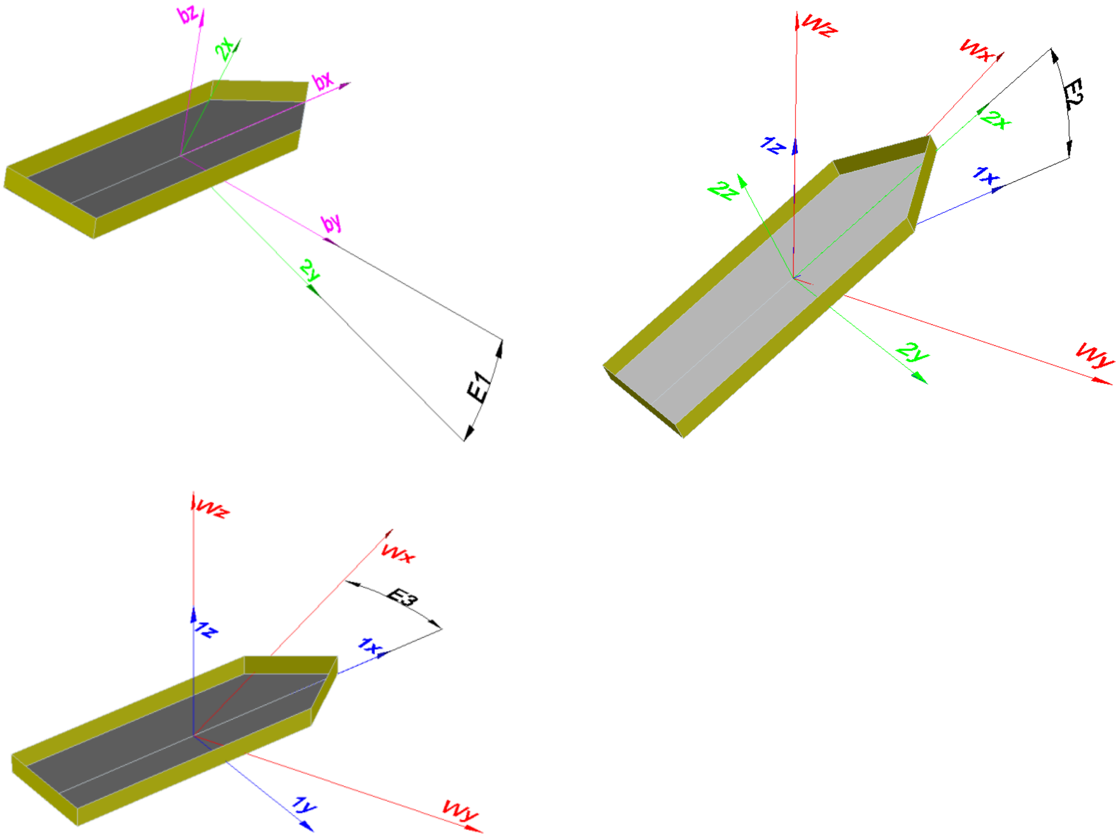


Figure 4.5: Euler angles

This explanation of the Euler angles is found in (LLC, 2016). Please note that the rotation matrix in eq.4.49, except that Yaw is named E3 and roll E1, is identical with the matrix ”R_I^B“ in the source paper (LLC, 2016).

Euler-1 (E3)-Yaw:

This is the angle for yaw, and is the angle between the word coordinate system x-axis in red, and the first coordinate system x-axis in blue. The first coordinate system is obtained by rotate the vessel around the global z-axis. Please see fig.4.5 above.

Euler-2 (E2)-Pitch:

A second coordinate system, shown as green in fig.4.5 is made by rotating the vessel around the first coordinate y-axis. E2 is then the angle between the x-axis for coordinate system one and two.

Euler 3-(E1)-Roll:

This is the angle between the second coordinate system y-axis, and the body coordinate y-axis when the vessel is rolling around the second coordinate system x-axis. The body coordinate system is here shown in magenta color in fig.4.5 above.

4.6. Supplementations to the existing 20-sim vessel model

In the following chapters, is explained the sub models which are added to the existing 20-sim ship model.

4.7. Overview of the model

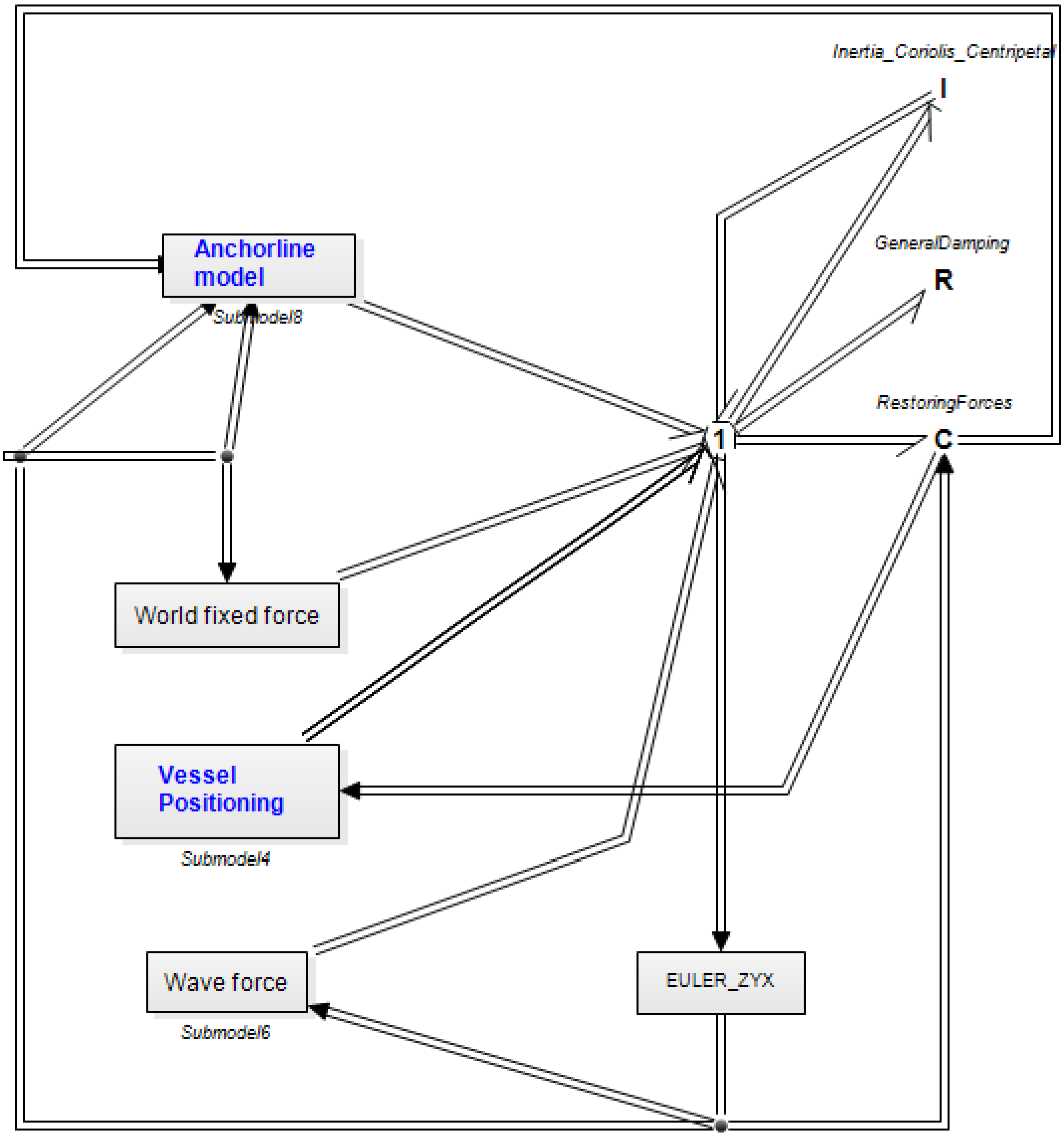


Figure 4.6: Overview of the complete 20-sim model

In this thesis, the sub models for anchor line and vessel positioning has been added to the existing 20-sim vessel model as described in Ch.2.5.
For better overview the sub models has been imploded into a bigger model as shown in fig.4.6 above. The added sub models will be explained in the following chapters.
Please note that here only the additions to the existing vessel model (Xu, 2014), is described below.

4.8. The vessel position control model

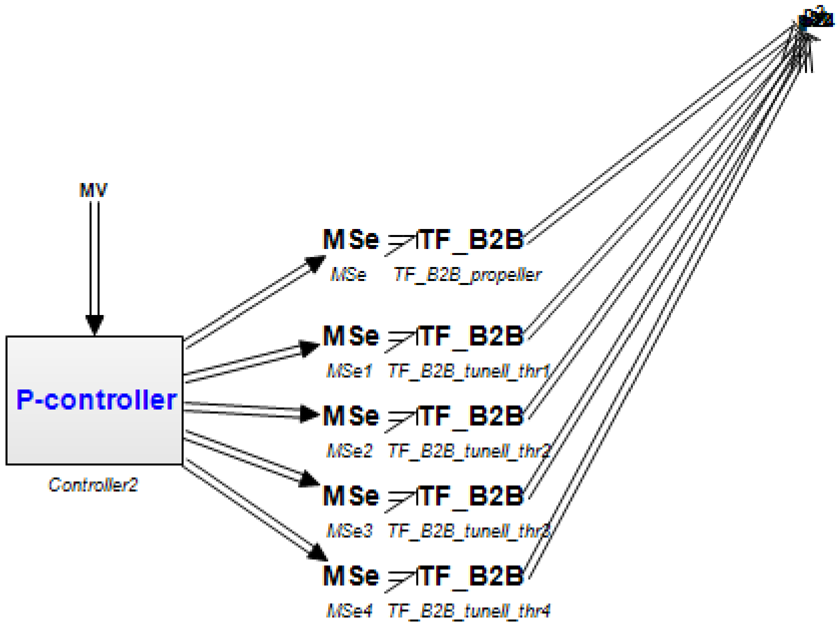


Figure 4.7: Position controller

The sub model shown in fig.4.7 above was made to keep the vessel in position when the force from the anchor line has a resultant force acting in x (longitudinal, y (transverse) direction or yaw moment around the vertical z-axis.

This model is not meant to be a dynamic positioning system, but a simple solution which purpose is to keep the vessel at a fixed position.

The P_controller sub model is from the MV signal receiving the distance that the vessel is moving away from the zero-position, and linear to the discrepancy in the surge, sway and yaw it gives signal to the Mse elements representing the propeller and thrusters.

The Mse elements is making the signal into effort, witch in the TF_B2B elements is transformed from the ship origin to the body fixed position for each thruster and the main propeller.

Thruster 2 (aft) and 3 (fore) is receiving the same effort, and as they are located at equal x-distance from the ship origo, they will not create any moment, and the force will correct the discrepancy from the zero point in the world fixed coordinate system.

Thruster 1 (aft) and 4 (fore) also receives equal effort, but here the effort is set to negative in the MSe4 element so the created moment will correct the ship yaw motion. The TF-B2B_propeller is correcting the vessel surge motion.

The B2B elements is transforming the effort from the ship origin to the location of the thrusters/propeller by using a 6x6 transformation matrix from inside the existing TF_B2B sub models. Please see appendix B.5 for the complete 20-sim code for the positioning controller sub model.

The coordinates and mission for each propeller is given in the table 4.2 below.

Propeller	**X (m)**	**Y (m)**	**Z (m)**	**Compensating**
Main propeller	-30	0	-5	Surge
Thruster 1	-25	0	-5	Yaw
Thruster 2	-20	0	-5	Sway
Thruster 3	20	0	-5	Sway
Thruster 4	25	0	5	Yaw

Table 4.2:Coordinates for propulsion

4.9. Basic model for the submerged anchor line

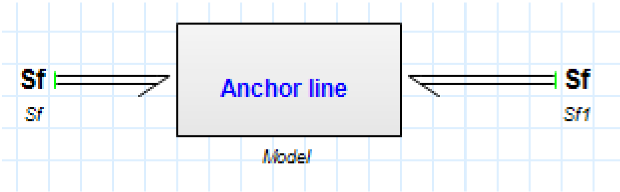


Figure 4.8: The basic anchor line model

Before explaining the connected anchor line model, it may be clearer to describe the basic model without interaction with the vessel and sea bottom.

In general, this model find the position for each end of the line by integrating the velocity as flow at each end of the line, and uses this to calculate the tension as effort. In fig.4.8 above the velocities is given by the Sf elements.

When the distances in x and z direction is calculated, Q can be calculated as shown in eq.4.14. After finding Q the rest of the variables and tension in both ends are calculated.

The complete 20-sim code for this basic model can be found in appendix B.2.

4.10. Anchor line model with seabed interaction

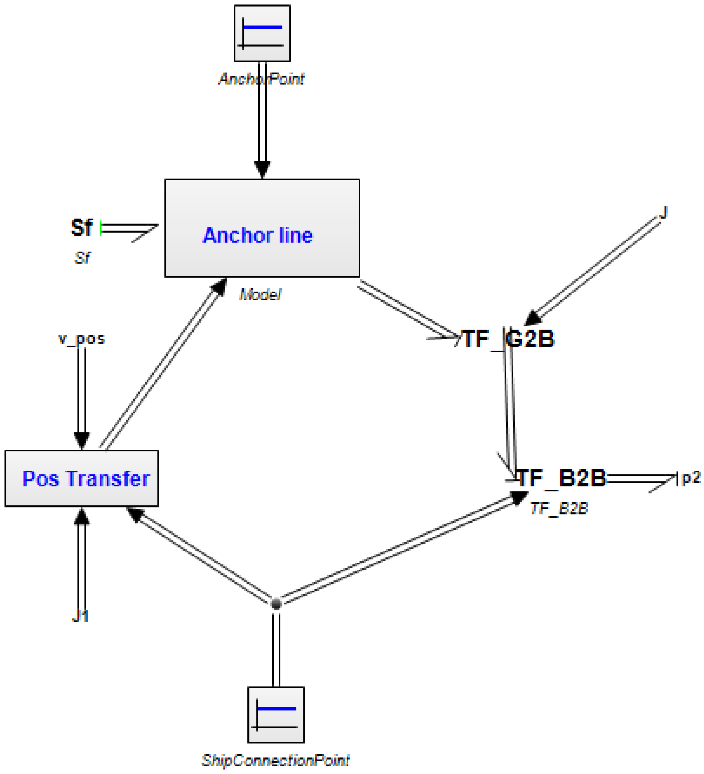


Figure 4.9: Anchor line model with seabed interaction

In fig.4.9 above is shown the sub models inside the Anchor line model in the overview in fig.4.6.

As it can be seen in Ch.4.3, the basic equations for this model is common with the basic Catenary line model in Ch.4.2 The main difference is new boundary conditions as a anchor point and lifting point (B) is introduced.

Now port 2 is connected to the vessel. The connection is done by using a transformer (TF_G2B) to transform the power from the global coordinate system to the vessel origo. Then the power is transferred from the vessel origo to the connection point for the line on the vessel, which is given from the "ShipConnectionPiont" sub model. The "Anchor Point" submodel gives in the world fixed coordinates for the anchor which is used together with the integrated velocity for point A to calculate its position.

The "Pos Transfer" sub model is transferring the connection point for the line from the vessel origo to point C as explained in ch.4.5. The "v_pos" signal is the vessel position in world coordinates given as signal from the vessel C-element, and J1 is the rotation matrix inside the transformation matrix TM. (Ref.eq.4.49).

"Sf" represents the anchor velocity, which is integrated and added to the given anchor, point in the Anchor line model to find the position for point A.

5. Methodology for the case study simulations

5.1. Simulation in the general loading condition

In this simulation, the 20-sim model was set up so that the hull is only exposed to force from the waves. When the data was transferred from ShipX to 20-sim by using Fossen's toolbox (Fossen, 2008) in Matlab, the wave direction was chosen 90 degree, so that the waves is coming from the shipside. The wave period of 10 sec. was chosen and wave high was set to H=2m.

5.2. Simulation with a vertical force at stern

A mass of 50 Ton was located at stern in outer edge of the stern roller (x=-39.1m, y=5m, z=2.39m).

z=2.39m represents the level of main deck because the zero-point, ref. (Fossen, 2008), in the 20-sim model is at the waterline of the vessel, 5.91m above baseline. The wave direction and period was chosen the same as for the simulation with the ordinary load case, respectively 90 degree, and 10 sec.

5.3. Situation 1-Vessel close to the rig

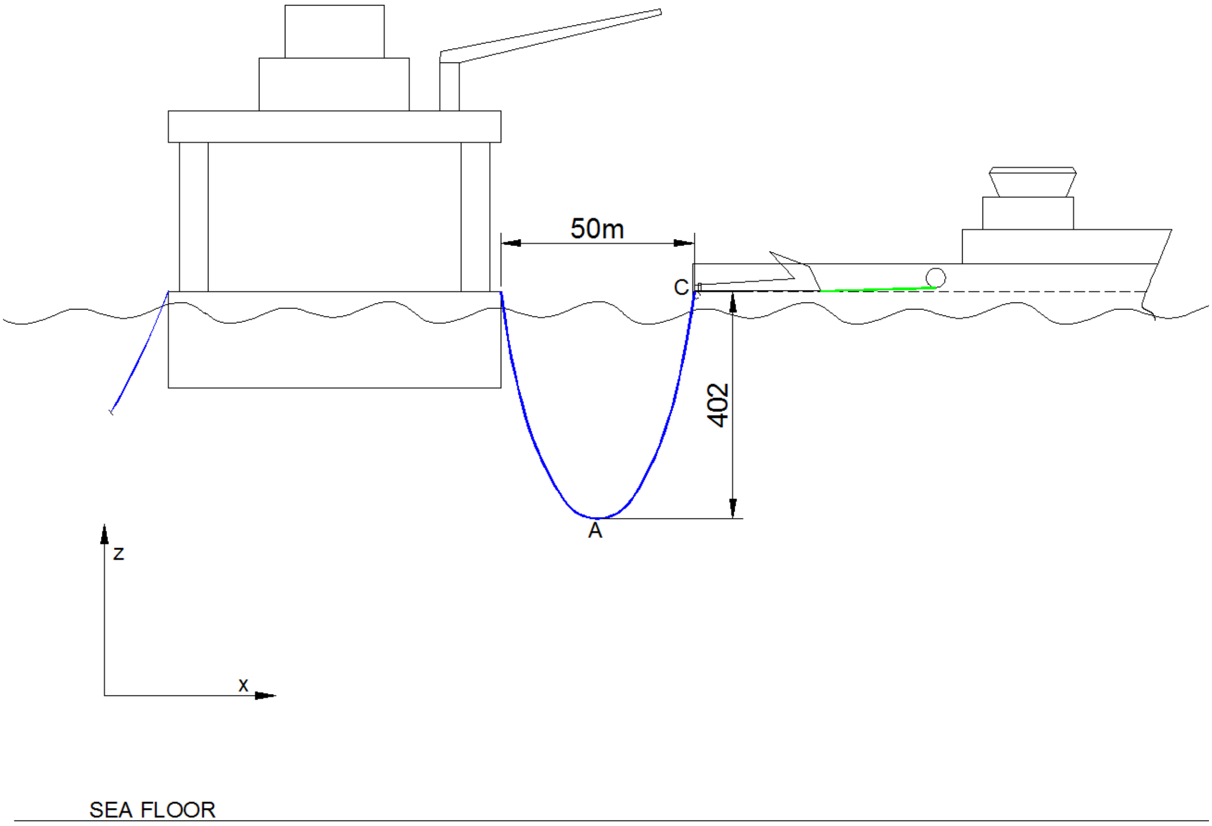


Figure 5.1: Anchor handling situation 1

Fig.5.1 above shows the situation when the vessel is close to the rig, and the anchor is located on the ship deck. The ship origo is in the zero point of the word coordinate system with heading zero degree. forward. This means that the points A and C is given in world coordinates.

The anchor line is modelled by using the basic model described in Ch.4.2.

Point A, is now the lowest point on the line. As the slope at point A is zero, this is a way to model the entire line.

The length of the line L, which forms half of the free hanging catenary was adjusted until the vertical force at the given point A, was found close to zero.

The gain values in the vessel position controller described in Ch.4.8, was tuned as low as possible to hold the vessel in position and with steady heading.

The resulting forces given from the propeller and thrusters was taken from the TF_B2B elements in the position control system (Ref.fig.4.7), and plotted in the world coordinate system.

Tab.5.1 below shows the line parameters used in the simulation, wave data, vessel heading where zero degree. is in x-direction, gain values for the position controller and coordinates for point A and C.

Situation 1:		Values	Unit	
Line length AC	L	412	m	
Line weight	w	388	kg/m	
Wave hight	H	0	m	
Wave period	t	-	s	
Waves direction		-	degr.	
Vessel heading		0	degr.	
Gain main prop: K1		-1.E+07		
Gain for sway: K2		-1.E+05		
Gain for yaw: K6		1.E+06		
		x	y	z
Connection point C		-34.9	5	2.39
Point A		-84.9	5	-400

Table 5.1:Parameters for Anchor handling situation 1

5.4. Situation 2-Vessel on way to drop position

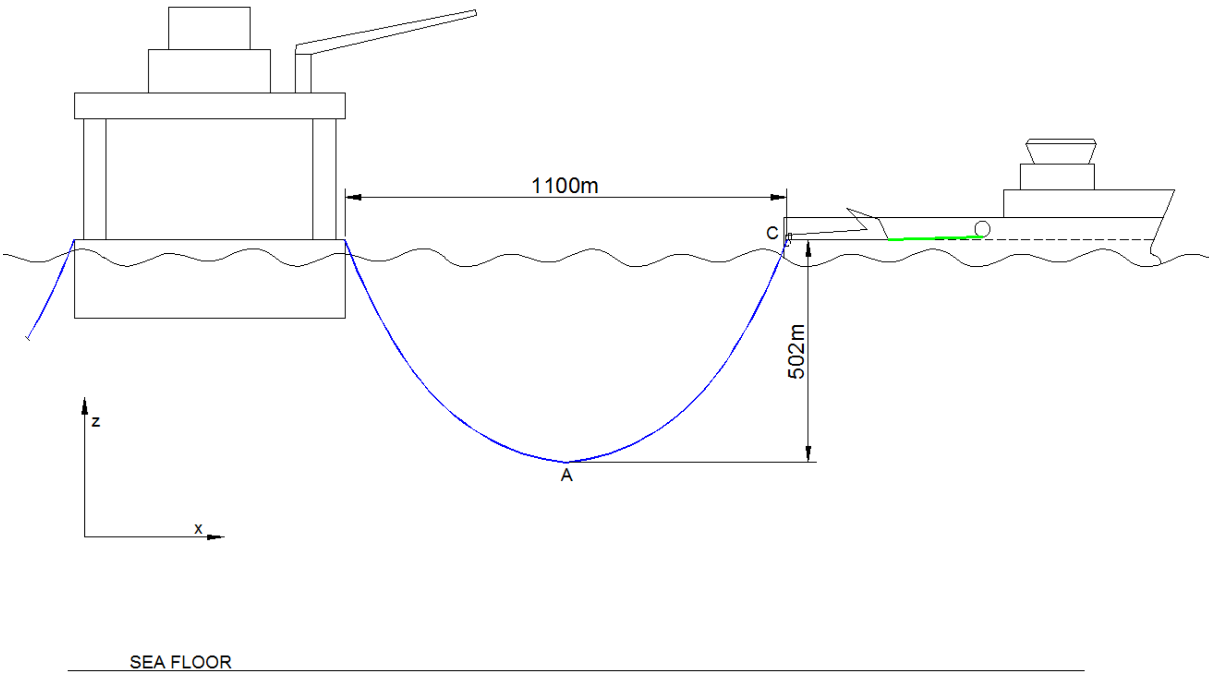


Figure 5.2: Anchor handling situation 2

Fig.5.2 above shows the vessel on way to the drop position.

The weight of the line was reduced until the simulation was found stable, and the result values was read after the motions was found regular and the heel angle within allowable limits (Ref.tab.6.2). One question in this situation was to find how the line tensions is varying for different line length L. This was obtained by running the simulation with varying z-coordinates for point A, and the rest of the variables as constants.

Situation 2:		**Values**	**Unit**	
Line length AC	L	836	m	
Line weight	w	120	kg/m	
Wave hight	H	2	m	
Wave period	t	10	s	
Waves direction		90	degr.	
Vessel heading		0	degr.	
Gain main prop: K1		-1.E+07		
Gain for sway: K2		-1.E+05		
Gain for yaw: K6		6.E+06		
		x	**y**	**z**
Connection point C		-34.9	5	2.39
Point A		-584.9	5	-500

Table 5.2: Parameters for anchor handling situation 2

5.5. Situation 3-Vessel at the anchor drop position

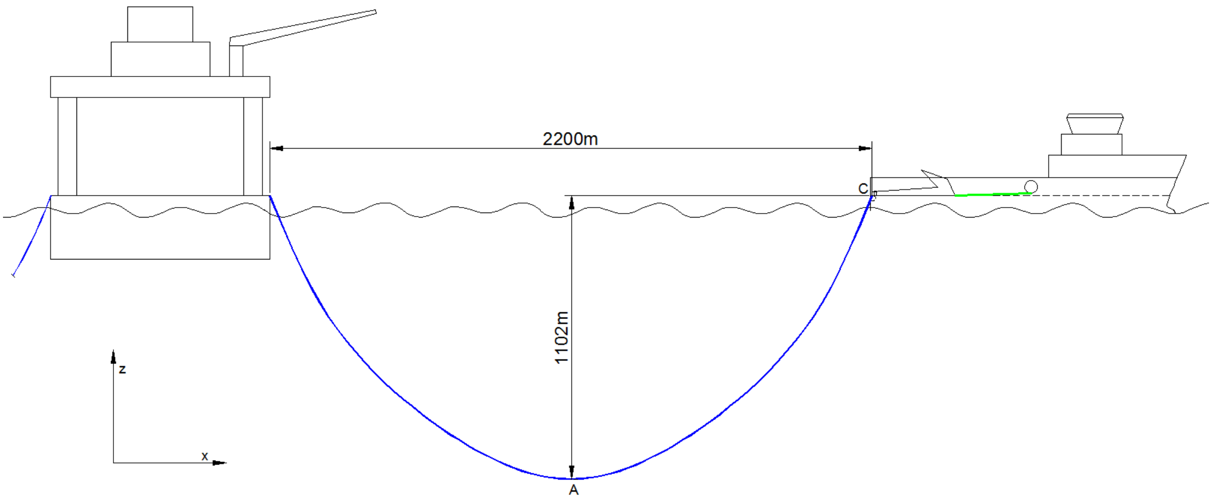


Figure 5.3: Anchor handling situation 3

Fig.5.3 above shows the vessel in position to drop the anchor. Due to drifting caused by difficult weather conditions the heading is changed 45 degree. relative to the line in order to obtain the correct position.

In this simulation the heel and roll motion when the line is connected 5m off centerline port, in vessel centerline and 2 m off ship centerline to starboard was studied. The heading angle is calculated from eq.5.2 below.

In this case, when the heading is different from zero degree, the angle Φ (Ref.tab.6.2) will also be different from zero. The angle Φ was calculated by using eq.5.1 below. Here Tcy and TCz is tension components from the line found in the simulation results. Please note that the angle Φ is independent of the resulting line tension.

When Φ is found, the expected biggest allowable force component TCz can be estimated by interpolating between the values given in tab.6.2. In the same manner, the expected corresponding heel angle and horizontal force component in y-direction can be found.

This estimations was done in order to see if the load from the line during the simulations is in same magnitude as found in the stability testing, when comparing the average roll angle in simulation with the heel angle from stability testing (Ref.tab.6.2)

The parameters used in the simulation, and coordinates for point A and C, is shown in tab.5.3 below.

$$\Phi = \arctan\left(\frac{TCy}{TCz}\right)$$

Equation 5.1

$$\text{Heading} = \arctan\left(\frac{ACy}{ACx}\right)$$

Equation 5.2

Situation 3:		**Values**	**Unit**	
Line length AC	L	1682	m	
Line weight	w	35	kg/m	
Wave hight	H	4	m	
Wave period	t	10	s	
Waves direction		90	degr.	
Vessel heading		45	degr.	
Gain main prop: K1		-1.E+07		
Gain for sway: K2		-1.E+05		
Gain for yaw: K6		5.E+06		
		x	**y**	**z**
Connection point C		-34.9	5/0/-2	2.39
Point A		812	783	-1100

Table 5.3: Parameters for anchor handling situation 3

5.6. Situation 4-Dropping the anchor

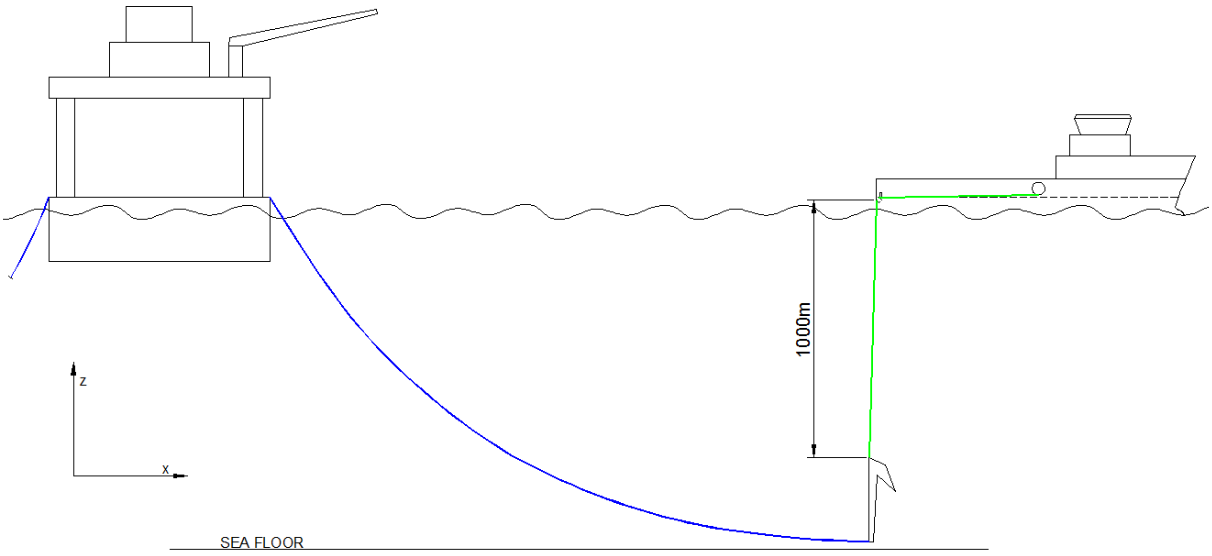


Figure 5.4: Anchor handling situation 4

Fig.5.4 above shows the situation when the vessel is in position and dropping the anchor. The basic vessel model without anchor line model is used here (Ref.fig.4.6). The vertical force is given as input to the vessel model as a vertical world fixed force (Se) Then the force is transformed from world to the vessel body coordinate system by using a transformer element (TF_G2B) and further from the vessel origo to the connection point at the stern by using a transformer (TF_B2B) element. Please see fig.5.5 below.

This is the content of the sub model "World fixed force" shown in fig.4.6. "J" is the 6x6-rotation matrix signal taken from the "Euler zyx" sub model in the same figure.

For this situation the propulsion forces is not studied or plotted, as the line force was assumed to be vertical only.

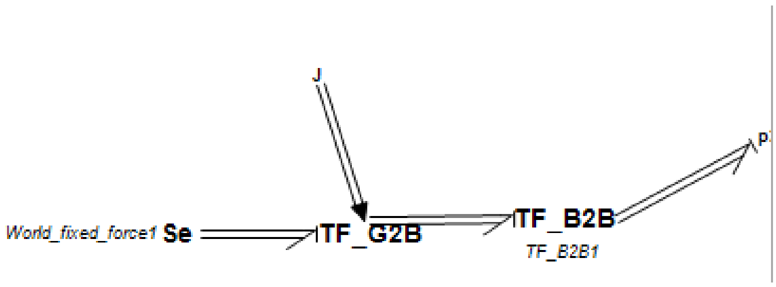


Figure 5.5: Sub model for transforming a World fixed force into body fixed coordinates

Situation 4:		Values	Unit	
Weight of winch wire	w*L	125	Ton	
Weight of anchor		20	Ton	
Wave hight	H	2	m	
Wave period	t	10	s	
Waves direction		90	degr.	
Vessel heading		0	degr.	
Gain main prop: K1		-1.E+05		
Gain for sway: K2		-1.E+05		
Gain for yaw: K6		5.E+05		
		x	y	z
Connection point C		-34.9	5	2.39
Anchor point A		-34.9	5	-1000

Table 5.4: Parameters for Anchor handling situation 4

Parameters used in the simulation is shown in tab.5.4 above. The weight of the winch wire and anchor is assumed. The gain values K1, K2 and K6 is set relative low as the force from the winch wire is assumed to have no horizontal components.

5.7. Situation 5-Anchor and line at the sea floor

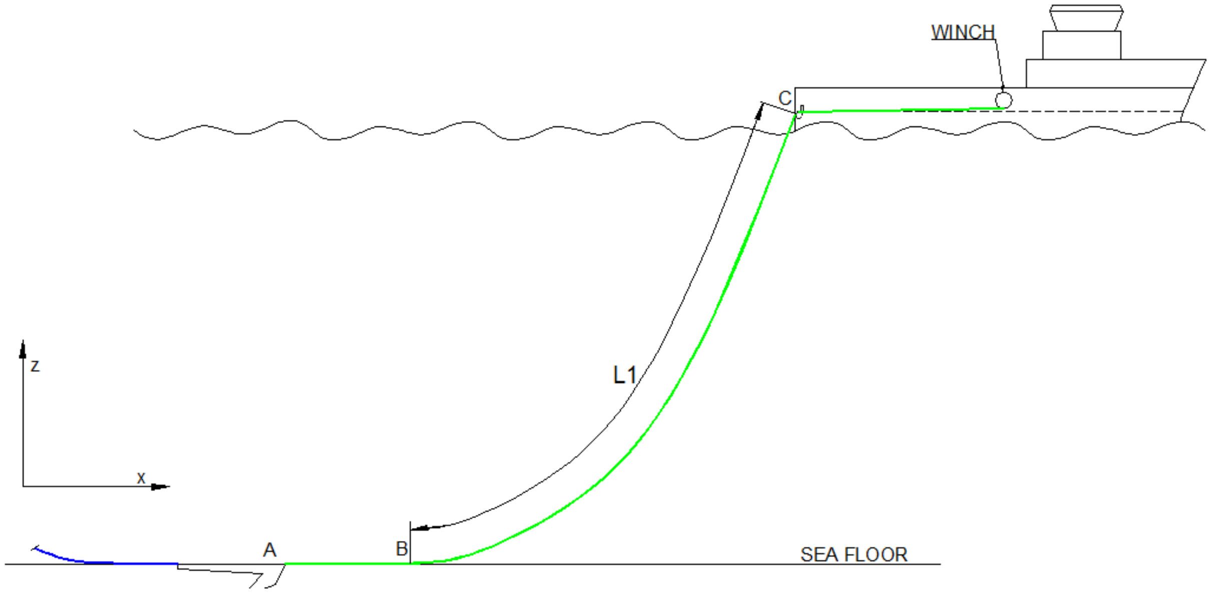


Figure 5.6: Anchor handling situation 5

Fig.5.6 above illustrates a thought situation when the anchor is laying on the seabed. In this situation, some part of the winch wire can lay on the sea floor, depending on the line length and vessel position. Here the anchor line model for seabed interaction as described in Ch.4.3 applied. The 20-sim sub model calculates the length of the free hanging length L1. Please see.tab.5.6 below for parameters used in the simulation.

Situation 5:		**Values**	**Unit**	
Line length	L	1400	m	
Length hanging line	L1	1231	m	
Line weight	w	60	kg/m	
Wave hight	H	4	m	
Wave period	t	10	s	
Waves direction		90	degr.	
Vessel heading		0	degr.	
Gain main prop: K1		-1.E+07		
Gain for sway: K2		-1.E+05		
Gain for yaw: K6		5.E+06		
		x	**y**	**z**
Connection point C		-34.9	5	2.39
Anchor point A		-600	5	-1100

Table 5.5: Parameters for Anchor handling situation 5

5.8. Comparing the vessel RAO

To check how the load at side of the stern roller is affecting the response amplitude operator (RAO) for the vessel in the situations described in Ch.5.1, 5.2 and 5.3 several simulations was performed. This was done by running a simulation for each chosen wave period between zero and thirty sec., for each of the situations. For each wave period Fossen's toolbox (Fossen, 2008) was used to transfer new vessel data to the 20-sim model.

To ensure that the roll response from the simulations is reliable, the roll response from the 20-sim simulations was compared with the RAO plot made in ShipX for different wave periods. The plot from this test can be found in appendix A.6.

6. Results for the stability calculations

6.1. Hydrostatics and intact stability

Tab.6.1 below shows the results after running the large angle stability check in Maxsurf as described in Ch.3.6. For a more detailed description for each criteria, please see Ch.2.3. Fig.6.1 below shows the plotted GZ curve.

6.2. Stability in the general loading condition

Stability criteria	Description	Actual	Status
IMO A.749-4.5.6.2.1	GZ area between 0 and angle of maximum GZ shall not be less than 3.1513 m.deg	17.34 m.deg	Pass
IMO A.749-4.5.6.2.2	Area 30 to 40 shall not be less than 1.7189 m.deg	4.87 m.deg	Pass
IMO A.749-4.5.6.2.3	Maximum GZ at 30 or greater shall not be less than 0.2m	0.57 m	Pass
IMO A.749-4.5.6.2.4	Angle of maximum GZ shall not be less than 15.0 deg	48.20 deg	Pass
IMO A.749-4.5.6.2.5	Initial GMt shall be greater than 0.15m	1.053 m	Pass

Table 6.1: Stability in the general loading condition

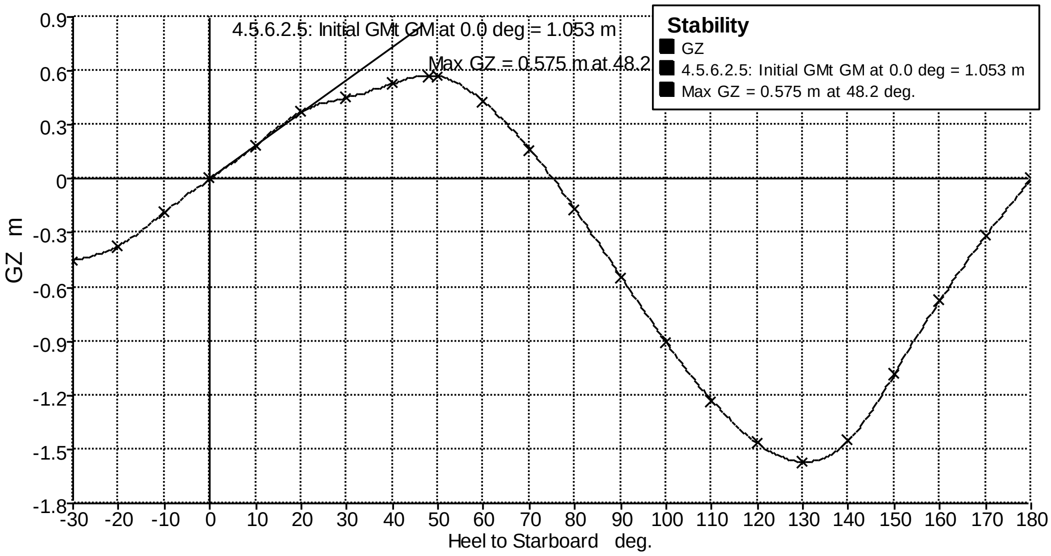


Figure 6.1: GZ curve for the general loading condition

6.3. Stability in anchor handling condition

Tab.6.2 below shows the results after including the external load as described in Ch.3.7. The criteria's described in Ch.2.4 is fulfilled as the actual heel is below 15 degree, not exceeding the angle at 50% of max GZ, and the deck corner aft is not below the water surface.

Calc.no	Max load Ton	Φ degr.	Φ rad.	Vertical comp.	Horisontal comp.	Transverse moment FY*8,3m	Max GZ based on the generel loadcase and vert.comp. of tension	Angle at 50% of Max GZ (Interpolated)	Actual Heel. Degr.
1	160	0	0.0000	160	0	0	0,30 at 49,1 degr.	16	7,5
2	145	15	0.2618	140	38	563	0,34 at 49,1 degr.	16,7	11,9
3	120	30	0.5236	104	60	900	0,403 at 48,2 degr.	16,3	13,6
4	105	45	0.7854	74	74	1114	0,453 at 48,2 degr.	16,0	14,3
5	95	60	1.0472	48	82	1234	0,496 at 48,2 degr.	15,8	14,5
6	90	75	1.3090	23	87	1304	0,35 at 50,0 degr.	15,6	14,2
7	90	90	1.5708	0	90	1350	0,37 at 50,0 degr.	28	14,2

Table 6.2: Stability results in anchor handling condition

In fig.6.2 below, the maximum possible tension for each angle Φ is illustrated.

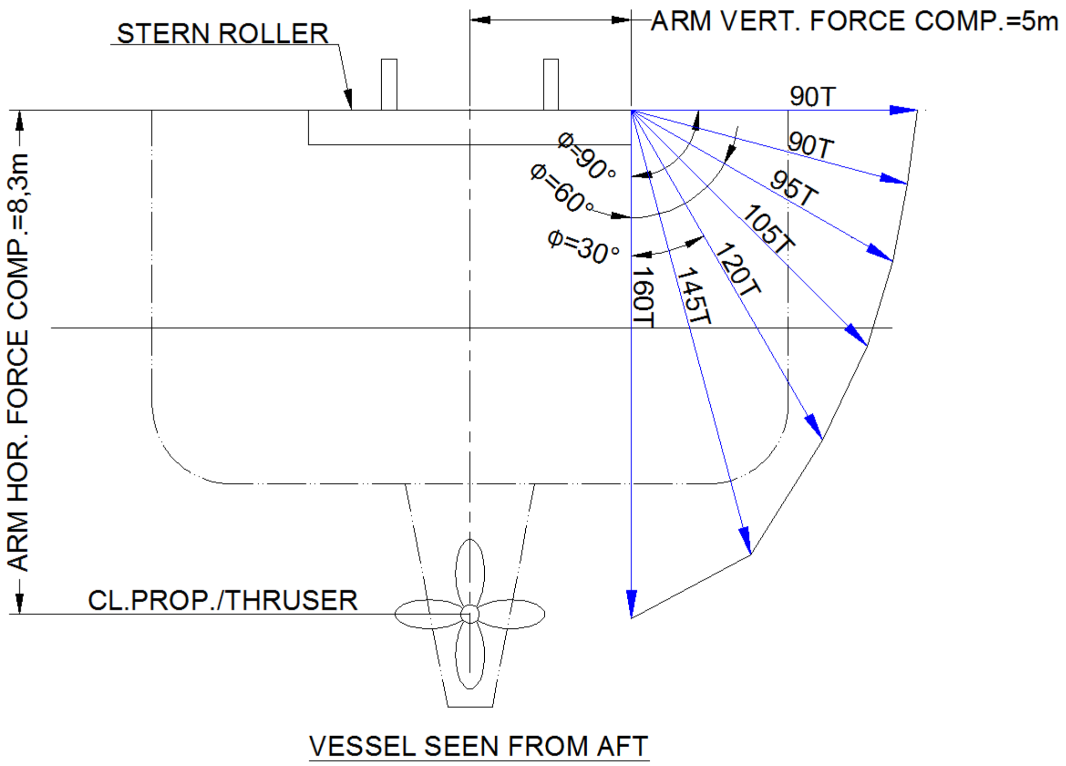


Figure 6.2: Illustration of maximum tension load from line attack at different angles

The NMD criteria regarding water on deck was checked visual by observing that the aft deck corner has some freeboard. This freeboard also was checked by observing that the deck edge freeboard in the report for equilibrium was positive. For an example stability report, please see appendix A.2.

7. Results for the case study simulations

In the following chapters is presented the results from the case study situations as described in Ch.5. To illustrate the motions, time series plots is used in Ch.7.1, 7.2, 7.3 and 7.6, while the results else is presented in tables and figures. To separate the simulations, it was aimed to have focus on some different findings for each chapter.

7.1. Simulation in the general loading condition

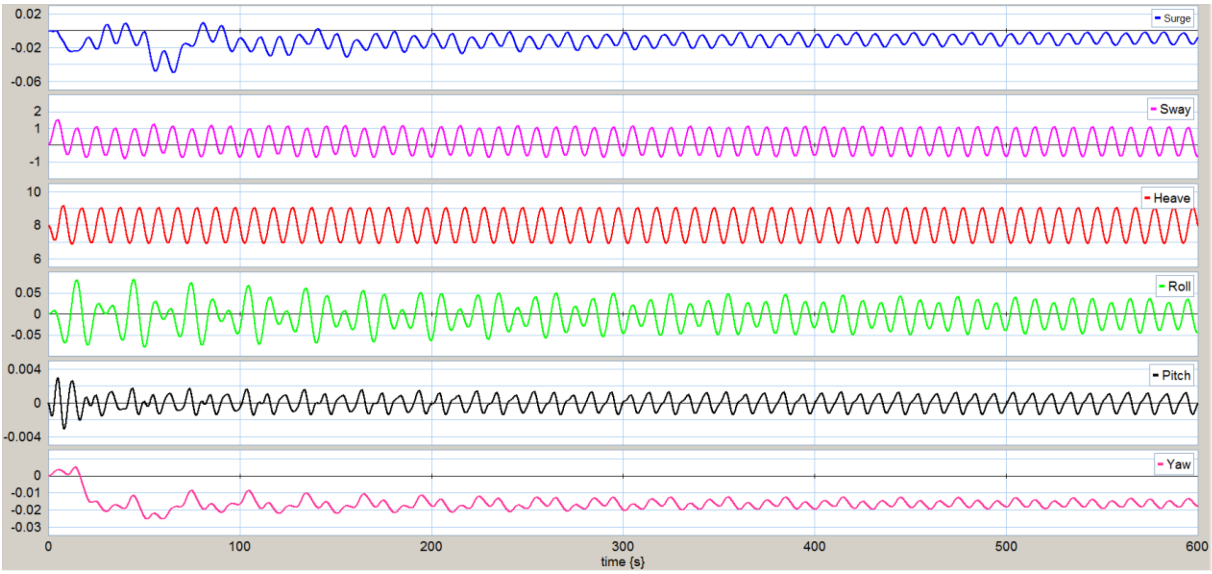


Figure 7.1: Result for simulation with ordinary load case

Fig.7.1 above shows the result motions in the 6 degrees of freedom. The roll, pitch and yaw motions is gradually damped after some time. As the waves coming from the side is the only external force acting on the system, especially the roll motion is having high response in the beginning. For the roll motion, the roll period for the vessel can be found to 10 sec. by measuring the time between each amplitude top.

7.2. Simulation with a vertical force at the stern

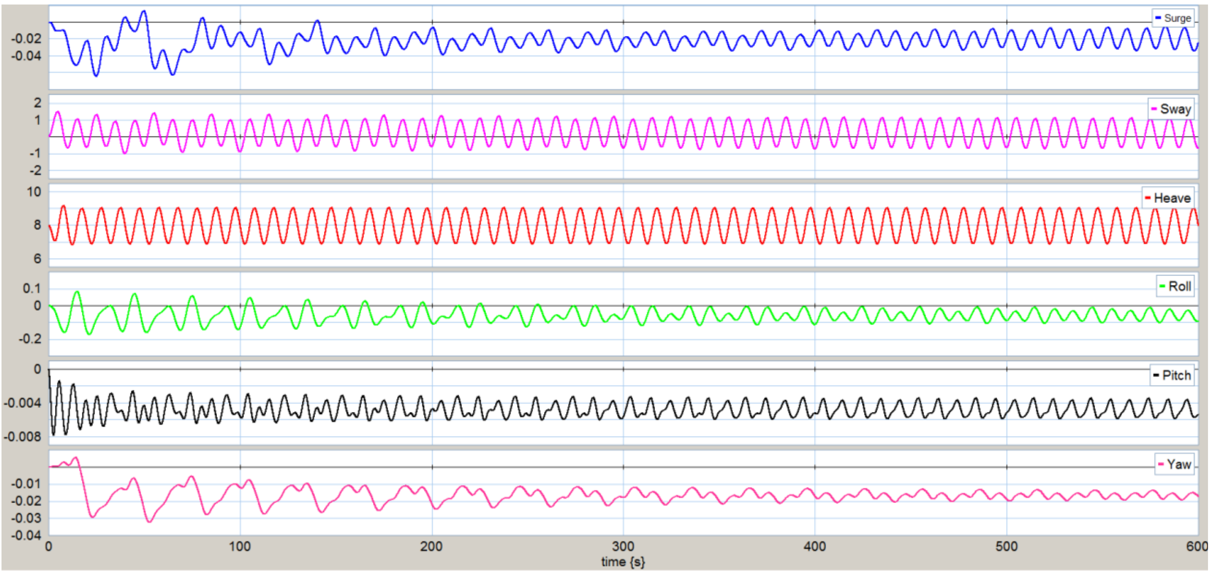


Figure 7.2:Simulation results from vertical force at stern

The fig.7.2 above shows the results when a World fixed vertical force of 50 Ton is applied in the stern 5m from the ship centerline. The average heel angle was found to be approximately 3,3 degree. and oscillating steady between 0,7 and 3,3 degree. after around 400 sec.

7.3. Situation 1 results-Vessel close to the rig

Vessel motions:

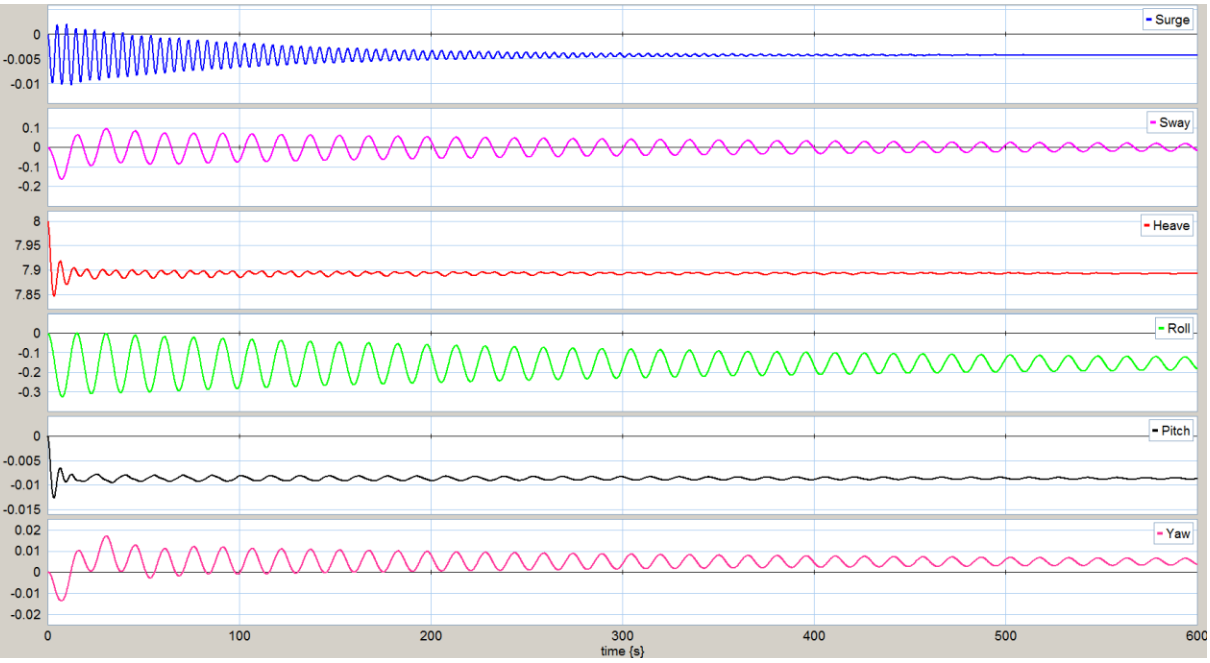


Figure 7.3:Vessel motions for anchor handling situation 1

Fig.7.3 above shows the oscillating vessel motions during the simulation time. After longer time the motion amplitudes is damping out towards zero, as it is no waves in this simulation.

Line tensions:

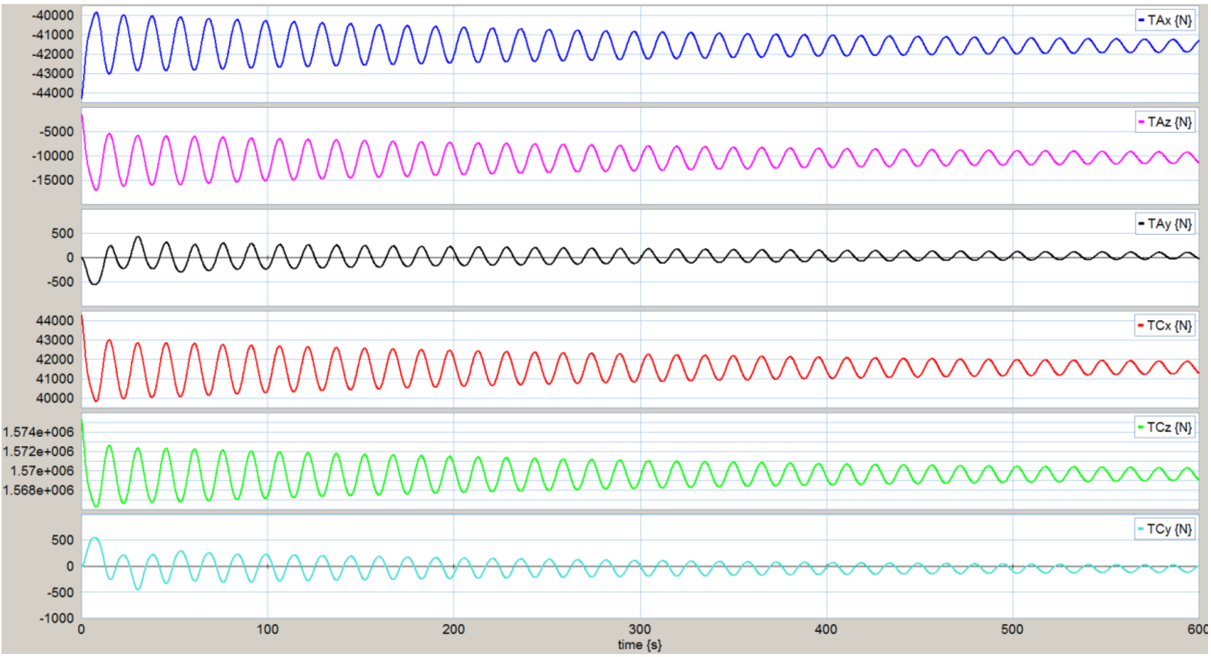


Figure 7.4:Anchor line tensions for anchor handling situation 1

Fig.7.4 above shows the oscillating tension in global x, y and z direction for point A and C.

Propulsion forces:

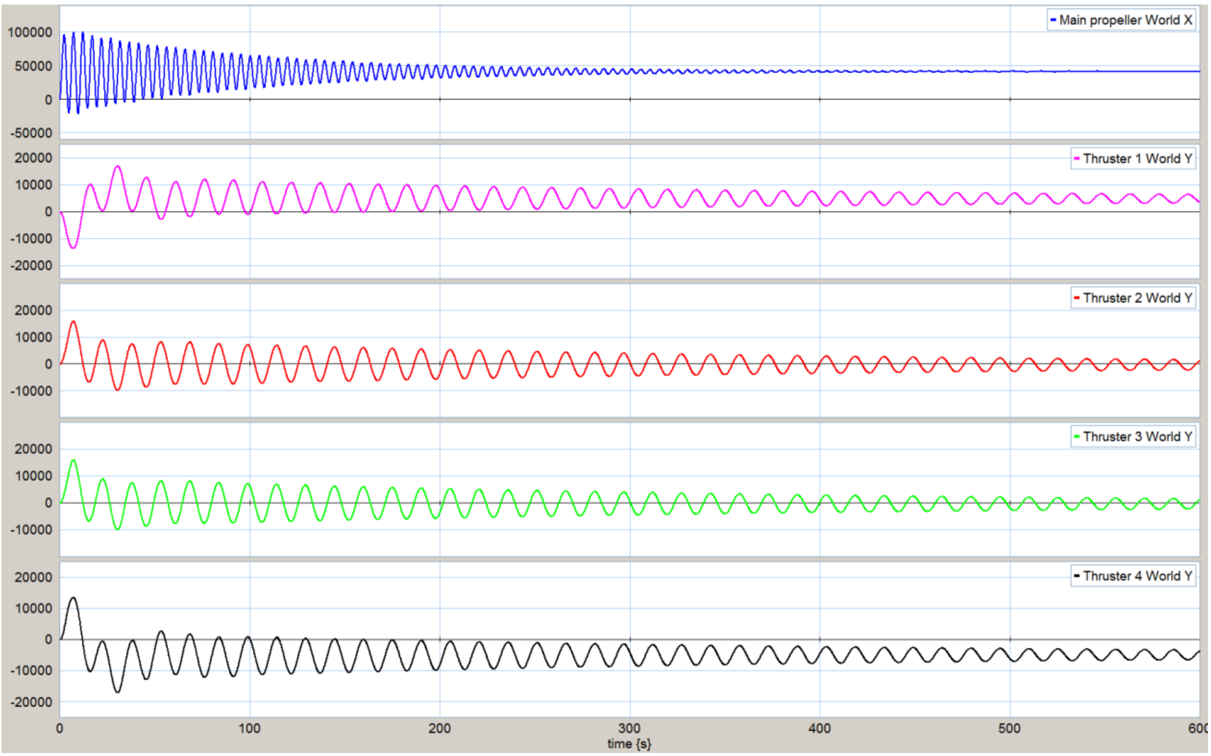


Figure 7.5:Propulsion forces for anchor handling situation 1

Fig.7.5 above shows the forces from the main propeller and thruster 1, 2, 3 and 4.

Average heel in sim. [Degr.]	8,6	ref.fig.7.3
Roll amplitude [Degr.]	0	ref.fig.7.3
Average pitch in sim. [Degr.]	-0,51	ref.fig.7.3
TCx [Ton] (Line tension in global X-dir.)	4,15	ref.fig.7.4
TCy [Ton] (Line tension in global y-dir.)	0	ref.fig.7.4
TCz [Ton] (Line tension in global z-dir.)	157	ref.fig.7.4
Force main fropeller (Surge correction)	-4,15	ref.fig.7.5
Force thruster 1&4 (Yaw correction)	0,48	ref.fig.7.5
Force thruster 2&3 (Sway correction)	0	ref.fig.7.5
Φ [Degr.]	0	ref.eq.5.1
Fz from stab calc. [Ton]	160	ref.tab.6.2
Heel from stab. Calc. [Degr.]	7,5	ref.tab.6.2

Table 7.1: Results case study situation 1

The results from the time series plots above is included in tab.7.1 above in order to give a better overview. Especially interesting in this situation is the relation TCx/TCy. The negative pitch means that the hull is trimming aft.

7.4. Situation 2 results-Vessel on way to drop position

Average heel in sim. [Degr.]	5,44	
Roll amplitude [Degr.]	2,16	
Average pitch in sim. [Degr.]	-0,34	
TCx [Ton] (Line tension in global X-dir.)	53,1	
TCy [Ton] (Line tension in global y-dir.)	0	
TCz [Ton] (Line tension in global z-dir.)	98,8	
Force main fropeller (Surge correction)	-53,1	
Force thruster 1&4 (Yaw correction)	3,46	
Force thruster 2&3 (Sway correction)	0	
Φ [Degr.]	0	ref.eq.5.1
Fz from stab calc. [Ton]	160	ref.tab.6.2
Heel from stab. Calc. [Degr.]	7,5	ref.tab.6.2

Table 7.2: Results case study situation 2

Tab.7.2 above shows the results from anchor handling situation no.2. The biggest line tensions is in this situation in x and z direction, as the vessel heading is zero degree. In fig.7.6 below is shown the resulting tensions when varying line length L from 683 to 1248m.

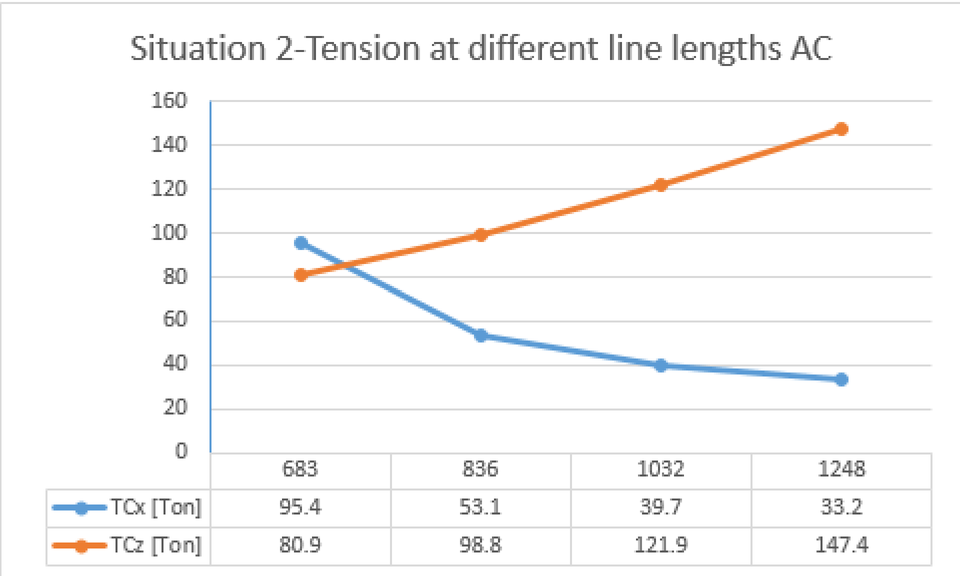


Figure 7.6: Line tension at different connection points at vessel stern

7.5. Situation 3 results-Vessel at the anchor drop position

Average heel in sim. [Degr.]	5,9	
Roll amplitude [Degr.]	4,72	
Average pitch in sim. [Degr.]	-0,28	
TCx [Ton] (Line tension in global X-dir.)	182	
TCy [Ton] (Line tension in global y-dir.)	16,7	
TCz [Ton] (Line tension in global z-dir.)	57,5	
Force main fropeller (Surge correction)	-182	
Force thruster 1&4 (Yaw correction)	13,40	
Force thruster 2&3 (Sway correction)	-16,9	
Φ [Degr.]	16	ref.eq.5.1
Fz from stab calc. [Ton]	138	ref.tab.6.2
Heel from stab. Calc. [Degr.]	12	ref.tab.6.2

Table 7.3: Results case study situation 3

Tab.7.3 above shows the results from the simulation in the drop position. It was found needed to reduce the line weight to 35 kg/m in order to obtain a stable simulation in waves, and for the stable roll motions not to exceeding the allowable heel angle from the stability calculation. This means a total line weight of approximately 59 Tons. (Ref.tab.5.3).

It should be noted that the horizontal tension TCx is more than three times the vertical tension TCz. Because the vessel has changed course, the horizontal force component TCy is also significantly increased. It can be seen from the propulsion plot that the forces from thruster 2 and 3, correcting the sway drift is increased, and in this situation the thruster influence on the roll motions is assumed significant.

Simulation with different line connection points

Tab.7.4 below shows the roll motion result from testing the line connection point at stern with different distances from the vessel centerline and line weight 35 kg/m.

The results shows that the worst situation occurs when the line is connected 5 m off centerline port, in the same direction as the vessel is heading in order to reach the drop position. An interesting finding in this situation was beside of increased heel, also increased roll amplitudes when the connection point is moved toward port side.

Point C pos. x,y,z [m]	**Average heel [degr.]**	**Biggest heel [degr.]**	**Lowest heel [degr.]**	**Amplitude [degr.]**
-34.9, 5, 2.39	-5,90	-10,65	-1,20	4,72
-34.9, 0, 2.39	-1,94	-4,85	0,97	2,91
-34.9, -2, 2.39	-0,68	-3,19	1,84	2,51

Table 7.4: Heel at different anchor line connection coordinates

7.6. Situation 4 results-Dropping the anchor

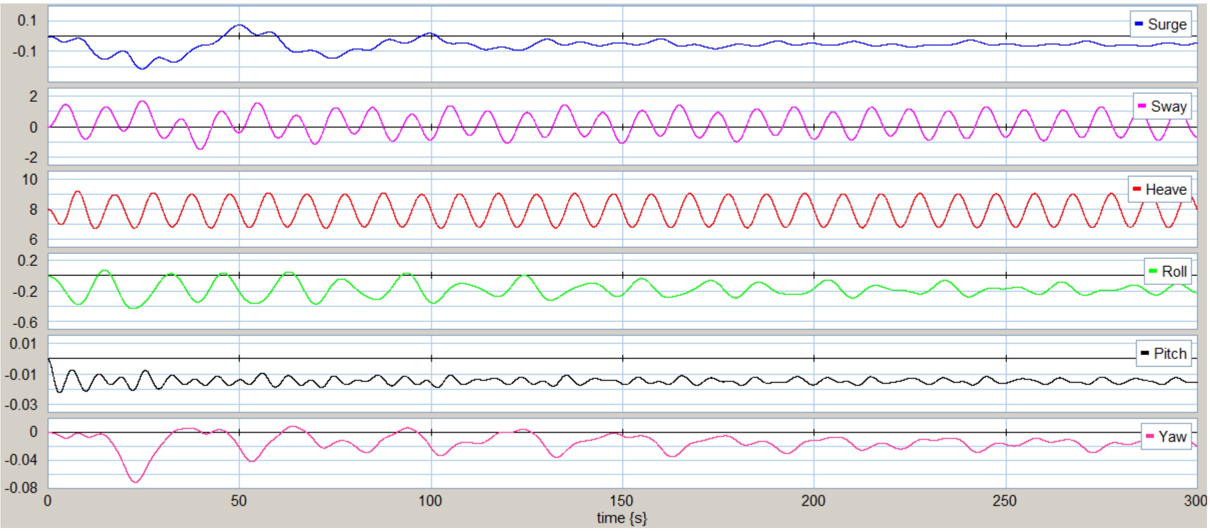


Figure 7.7: Vessel motions for anchor handling situation 4

Fig.7.7 above shows the results from the vessel motion simulation. It can be seen that the tuning of the gain for propulsion keeps the vessel surge, sway and yaw positions relative close to zero as the vessel heading is zero degrees forward.

7.7. Situation 5 results-Anchor and line at bottom

Average heel in sim. [Degr.]	3,4	
Roll amplitude [Degr.]	2,85	
Average pitch in sim. [Degr.]	-0,23	
TCx [Ton] (Line tension in global X-dir.)	8,10	
TCy [Ton] (Line tension in global y-dir.)	0	
TCz [Ton] (Line tension in global z-dir.)	72,5	
Force main fropeller (Surge correction)	-8,10	
Force thruster 1&4 (Yaw correction)	0	
Force thruster 2&3 (Sway correction)	0	
Φ [Degr.]		
Fz from stab calc. [Ton]	160	ref.tab.4.2
Heel from stab. Calc. [Degr.]	7,5	ref.tab.4.2

Table 7.5: Results for case study situation 5

Vessel motions:

Tab.7.5 above is showing the vessels motions in all 6 degrees of freedom. The line weight was reduced to 60 kg/m (Ref. tab 5.5), in order not to exceed the allowable heel angle from the stability calculations.

Line tensions:

The vertical force in the vessel connection point TCz was found to be 72,5 Ton. This is close the total weight of the free hanging line L1 (Ref.tab.5.5). The vertical force in the lifting point B is zero, and thus in accordance with the Catenary theory. The forces in y-direction is as expected close to zero as the vessel heading is zero degrees. In this situation, the tension in x-direction is approximately 10% of the force in z-direction TCz, which represents the weight of the free hanging line L1.

Propulsion forces:

The force from the main propeller is in average approximately 8,1 Ton, and corresponds well with the opposite directed force from the anchor line.

The thrusters only have small forces close to zero, and that is expected as the vessel heading is zero degree, and the force from the anchor line only is acting in the x-direction.

7.8. Comparing the vessel RAO

The grey line in fig.7.8 below is shown the vessel roll response for the 1m wave amplitude when the vertical load of 50 Ton is acting at stern 5m port of the ship centerline. The response with no vertical load at the same point at the stern is shown with orange line. It was found similar values for the RAO in this case.

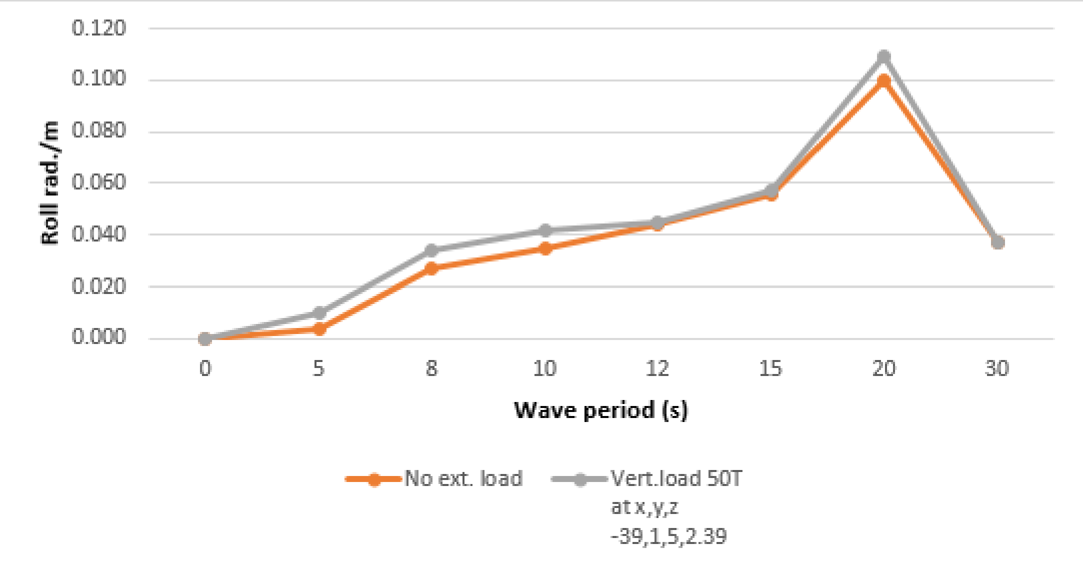


Figure 7.8: Vessel RAO for Vertical load 50T

Fig.7.9 below shows that the result for the load from the anchor line gives some bigger values for periods above 10 sec. This finding is discussed in Ch.9.8.

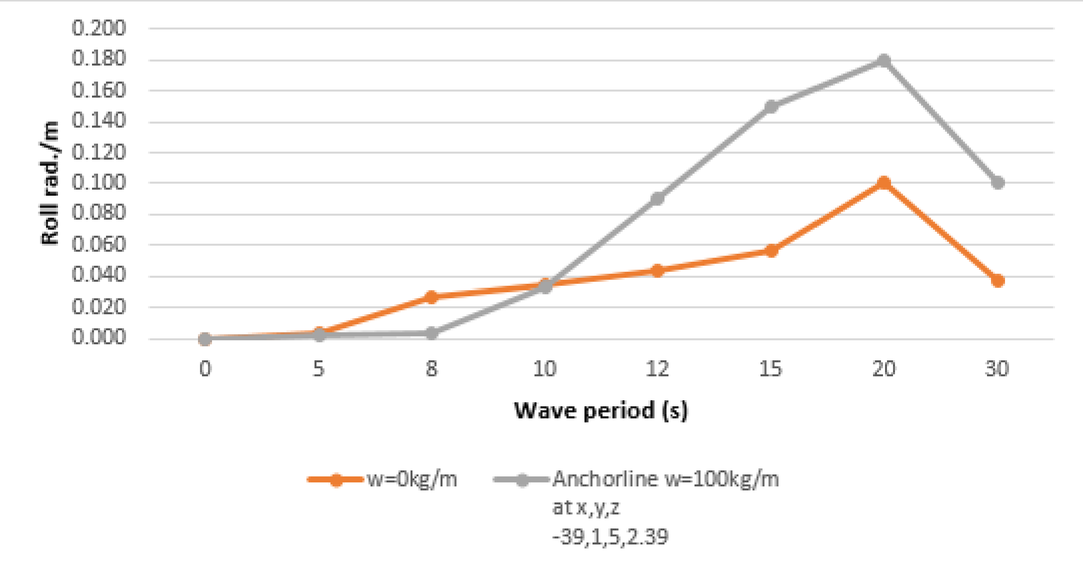


Figure 7.9: Vessel RAO for load from the anchor line

8. Discussion of the stability calculation results

8.1. Hydrostatics and intact stability

As the vertical center of gravity was estimated in the loading condition, this may be different from a real vessel in operation. AHTS vessels also usually has ballast tanks to regulate the center of gravity, and special roll damping tanks. This is not accounted for in this thesis.

8.2. Stability in the general loading condition

From tab.4.1, it can be seen that the stability criteria's is fulfilled with quite large margin. From the GZ curve in fig.6.1 it can be seen a small top in the curve at approximately 20 degr.heel. It is typical for this type of vessels to have a top early in the curve as the vessel has typical good stability before exceeding the angle where it is coming water on the working deck. Please see also fig.2.6.

8.3. Stability in the anchor handling condition

According to the NMD criteria's, the heeling moment shall be calculated as the total effect of the horizontal and vertical transverse components of tension in the line.
It was not found possible to add a horizontal force in MaxSurf. To find a way around, the moment from the horizontal component was recreated by adding a vertical force 100m from the ship centerline. This force is small is relatively small, and the change in trim by using this method was from MaxSurf found to be insignificant.

9. Discussion of case study simulation results

In general, it should be noted that tuning of the position control model described in Ch.4.8, may have influence on the results when doing simulations. Using too small or too big gain values may cause results that are not reliable. During the simulations this values was adjusted by looking at the simulator results and tuning the values until the vessel x, y distance and yaw angle from origo was found acceptable.

The estimation of Q shown in Ch.4.4 is assumed not to be very accurate because the angle between the line and a vertical line from point C can differ from the angle used in the method. Especially this is assumed the case when a large part of the total line length is laying on the bottom. Anyhow, this will not affect the results as long as the model is working.

The propulsion forces is plotted in the World coordinate system. This is not quite correct as the propellers is normally following the vessel coordinate system when the vessel is moving. However, as the position control system is tuned to keep the yaw motion close to zero, this is assumed to reduce some of the error. A simulation was done to test the difference between word and body fixed propellers, and the results was found to be quite similar. A plot from this test can be found in appendix A.5.

As it can be seen from the time series plots in Ch.7.3, the line tension and corresponding forces from the propulsion is oscillating because of the external wave force. In a real propulsion system, the forces may have not these oscillations. It may be assumed that this may have some influence on the simulations results compared to a real situation.

In anchor handling situation 1,2 and 3 the basic Catenary described in Ch.4.1 was applied. The coordinates for point A was applied, and L adjusted until the gradient in point A was zero. This is not appropriate in a real operation as L is known, and the z-coordinate for A will be a function of L. This is about causality in the Catenary equation used. If more time available it would be more appropriate to use a basic equation for a free hanging Catenary line between the rig and the ship.

The rig was assumed to be fixed by other mooring lines, and the situations on way to the dropping point is simplified and made to illustrate the vessel behavior at the different coordinates and headings.

9.1. Simulation in the general loading condition

From fig.7.1, it can be seen that the roll motion is oscillating around zero degrees. Slightly bigger amplitudes was found towards negative direction. This was assumed to be reliable as the waves has positive direction towards the hull.

9.2. Simulation with a vertical force at stern

From fig.7.2 the average heel was found to be 3,3 degree. Compared with the 7,5 degree heel found for 160 Ton in the anchor handling condition (Ref.tab.6.2), this was assumed reliable in terms of the load of 50 Ton used in this situation.

9.3. Situation 1-Vessel close to the rig

The vertical tension component TCz was found close the total weight of the line of 160 Ton used in this simulation (Ref.tab.5.1). From the stability results in tab.6.2, one should expect the largest allowable heel angle to be approximately 7,5 degree. for a vertical tension of 160 Ton, which is some lower than 8,6 degree. found in the simulations. The reason for this discrepancy was assumed that MaxSurf takes into account the change in hull shape when the ship is heeling. The assumption is supported from the in advance testing of 20-sim vs. MaxSurf. Please see appendix A.4.

In this case, the line hanging from the vessel is close to vertical in the x-z plane, and from tab.7.1, it can be seen that the horizontal force TCx is approximately only 3 % of the vertical component TCz. It can also be seen that the vessel aft trim is considerable caused by the big vertical tension.

The forces in global y-direction is opposite directed and small as expected, since the vessel heading is zero degrees.

The main propeller was found to give thrust equal and opposite of the line tension in x-direction as expected. The yaw moment compensated by thruster 1 and 4, is a consequence of the anchor line connected 5m from the vessel centerline. Thruster 2 and 3 is correcting the sway motion and is small since the force from the line is only acting in the x-z plane.

9.4. Situation 2-Vessel on way to drop position

From the stability results for anchor handling condition the maximum allowable line weight still is 160 Ton as the line is vertical and corresponding heel angle 7,5 degree. The simulation was not stable with that load over longer time, but compared the found 4,5 degrees was assumed credible, as the line weight in the simulation was 90 Ton (Ref.tab.5.2).

Compared to situation 1, the horizontal force in the vessel heading direction TCx has increased to 40% of the vertical tension component TCz (Ref.tab.7.2).

As in situation 1, the force from the main propeller is balancing the opposite directed force of 53 Ton from the line (TCx), and the correcting forces from the thrusters is small since the vessel course still is straight forward. The connection point C for the line is 5m from the vessel centerline, so thruster one and four will also in this situation correct the yaw drift. Thruster two and tree gives approximately zero force, and is assumed to have minimal influence on the roll motions in this case. Increased roll motion may be caused from the TCx

force because the anchor line is connected out of the ship centerline and the waves is making the vertical component TCz oscillating.
Please note that thruster 1 and 4 is assumed not to affect the roll motion as they is acting in opposite direction and thus not creating any heel moment.

9.5. Situation 3-Vessel at the anchor drop position

The vertical force TCz acting on the vessel connection point C is close to 58 Ton, which is close to the total weight of the line length L. (Ref.tab.5.3).
The angle Φ was found to be 16 degree. By interpolating between the results from the stability results in tab.6.2, the biggest allowable vertical force and corresponding allowable heel angle is 138 Ton and 12 degree. respectively. That means a line weight w=86kg/m. Simulating this load in waves was not stable over longer time, and the line weight therefore had to be reduced to 35 kg/m. The 5,9 degree. average roll angle found for this load was assumed credible compared to the stability calculation result, as both this angle and corresponding weight is close to 50% of the allowable (Ref.tab.6.2).
The increased roll amplitude for the connection point 5m from cl. shown in tab.7.4 was assumed to be a consequence of the increased heel angle. Please see fig.9.1 below where the strong line shows the amplitude when the line is connected 5m off vessel centerline port, compared to line connected in vessel centerline as shown by the weak line.
Compared to situation 2, the wave high in this simulation was set to 4m, which is, due to increased roll motions assumed to have some influence on the need to reduce the line weight to 59 Ton. The biggest impact is anyhow assumed to be caused by the increased line tensions in the x-y plane.

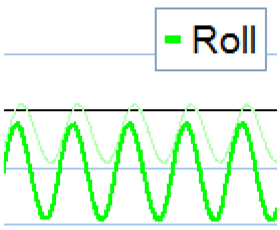


Figure 9.1: Roll amplitudes

9.6. Situation 4-Dropping the anchor

In a real situation the vessel, have to use some thrust forward to compensate for the horizontal tension from the anchor line from the rig. In this thesis, this component is assumed small, and therefore neglected. In reality, the horizontal component TCx may be assumed to be close to zero only if vessel is not compensating the drift in x-direction by using the main propeller.

9.7. Situation 5-Anchor and line at the sea floor

As in situation one and two, the angle Φ in this situation also is zero degrees, as the vessel heading is zero degree. forward. As for situation one and two, the allowable vertical force component is 160 Ton, and corresponding heel angle 7,5 degree.

In the simulation, the average heel angle was found to approximately 8,5 degree. for a line weight of 130 kg/m. Here 130 kg/m is calculated from 160Ton/L1.

The simulation was found more stable compared with situation 2 and 3, because the horizontal component TCx is approximately only 1,2% of the vertical component TCz. No force component in y-direction is present. This means that the thrusters do not need to compensate with big forces that increasing the roll amplitudes, and the static heel angle.

9.8. Comparing the vessel RAO

The anchor line model in this thesis does not take drag forces into account and either not inertia forces or geometrical stiffness of the anchor line. Therefore, the line should in the theory not give different RAO.
In fig.7.9 the results anyhow shows that the RAO is some bigger for the situation when the line is connected to the vessel. In this situation, the line tension x-component is acting 5m from the ship centerline, and together with the x-force from the main propeller, it will create a yaw moment.

From fig.7.5 it can be seen that thruster one and four is giving some thrust to counter the yaw moment, but since this forces is in opposite direction this should not give roll moment.

It may also be assumed that the oscillating force from the main propeller while countering the line tension in x-direction will increase the roll motion because the z-component of the line tension then will be increased, as the line is connected out of the vessel centerline.

Please note that in the situation three, it will be an additional y-component in the line tension and it may be assumed that thruster two and three will increase the roll motion further as they is acting in the same direction, and in that manner a heel moment. Please see fig.9.3 below.

Fig.7.8 and fig.7.9 shows that the biggest RAO is for a wave frequency of approximately 20 sec. From the figure in appendix A.3, the natural period for roll was found to be around 15 sec, and with a higher RAO value. The difference was assumed related to the reading of the time series plots, where the amplitudes for wave periods close to the natural frequency has much variations. The roll amplitudes in fig.7.8 and 7.9 was read after some time when the amplitudes was smaller and stable, while the figure in appendix A.3 is based on the bigger amplitudes in the start of the simulation. Please see fig.9.2 below.

How the RAO was affected in situation three was not studied, but the transversal forces in that situation may be assumed to have influence as well.

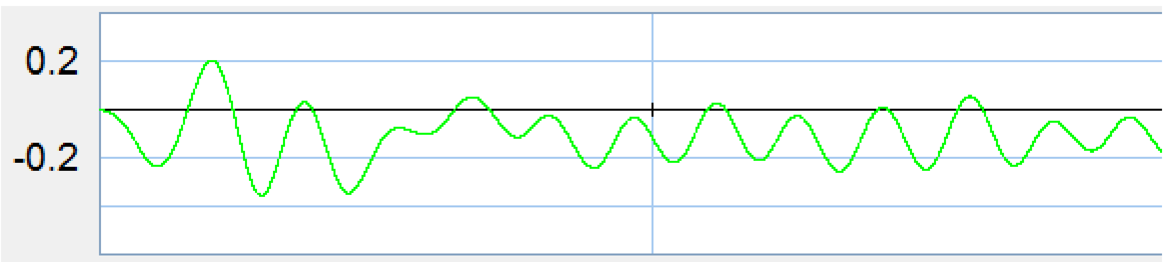


Figure 9.2-Roll amplitudes for 15 sec wave frequency

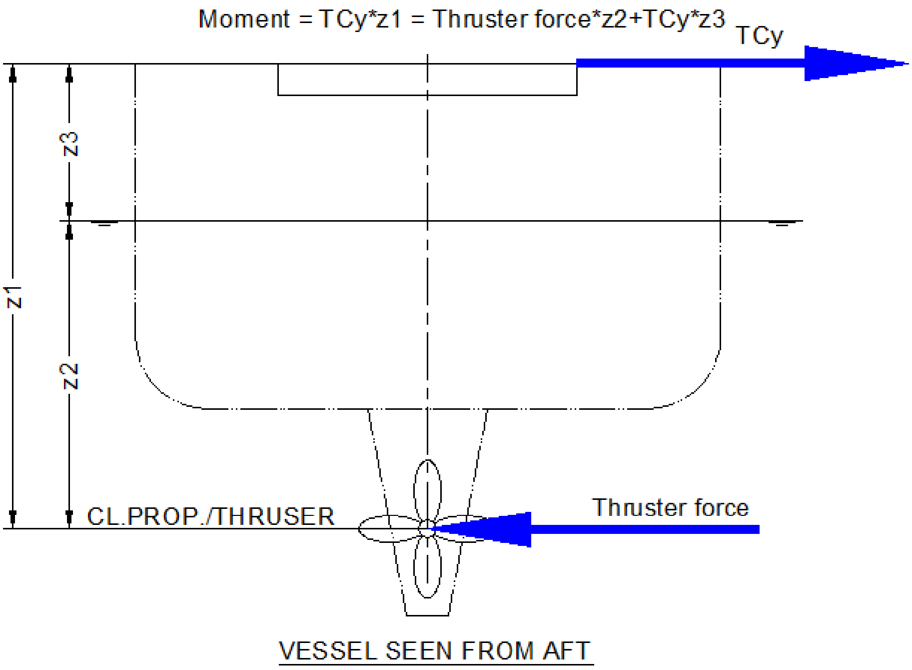


Figure 9.3-Heel moment from line and thrusters

10. Conclusion for stability calculations

10.1. Stability in the general loading condition

The general stability for the hull in this thesis was found to fulfill all criteria's according to IMO.

10.2. Stability in the anchor handling condition

The stability during anchor handling was found to fulfill all criteria's according to NMD, as well as the IMO criteria's.

11. Conclusion for case study simulations

Below is presented the conclusions from the different case studies. This thesis is a simplified approach to a real anchor-handling situation. As the mass, stiffness and inertia effect is not included in the anchor line model, the result may be assumed realistic only if the anchor line stiffness, inertia forces and drag from ocean currents may be neglected.

11.1. Simulation in the general loading condition

The results from the simulation without external load was found reliable as the vessel is kept close to the wanted position and the motion amplitudes was found stabile.

11.2. Simulation with vertical force at stern

This simulation was performed to have some basic results as foundation for the anchor handling situations below. The results was found reliable by comparing with the heel from the stability calculation results.

11.3. Situation 1-Vessel close to the rig

In this situation, the vessel can handle line load up to the limit found in the stability calculations, and the simulation is stable because of only small horizontal tension components. The heel was found to comply well with results from the stability calculations.

11.4. Situation 2-Vessel on way to the drop position

The horizontal tension in x-direction is increasing and depending on the length of line in the sea. The ability to handle line weight is some reduced but not critical as the vessel heading is forward. Reducing the line length will relatively rapid increase the horizontal force components from the line, which has negative influence on the vessel motions and heel.

11.5. Situation 3-Vessel at the anchor drop position

Because of the horizontal force component in y-direction caused by the changed ship course, this was found to be the most critical situation.
Moving the connection point sideways on the vessel stern gives increased roll amplitudes, which in addition to the static heel, may quickly exceed the allowable heel angle found from the stability calculations.
Compared to the Bourbon Dolphin accident this is not an identical situation, but the line length and depth at the accident is approximately the same. The big reduction in the vessel ability to handle line weight in situation three may be compared to the accident, as a helping vessel was needed to lift the line in order to reduce the load on Bourbon Dolphin. The average chain dimension in the sea at the accident is assumed to be 76mm, and with weight 125 kg/m. (DNV GL AS, 2016). Assuming that the helping vessel removed 50% of the line weight acting on Bourbon Dolphin, and that the line in the accident was guided by a pin closer to the ship centerline in that case (Ruano, 2013), the found line weight possible to handle in situation three may be assumed to be a rough comparison.

11.6. Situation 4-Dropping the anchor

This simulation is similar to the simulation with the vertical force at stern. In a real operation, the tension from the anchor line is assumed considerable and as situation 3, this is a dangerous phase of the operation. Especially is the vessel is exposed from transversal force tension from the anchor line as in situation 3.

11.7. Situation 5-Anchor and line at the sea floor

This situation is also very simplified, but the simulation gives results as expected according to the Catenary model with seabed interaction described in Ch.4.3. The winch wire is assumed normally not to be as heavy as the anchor line.

11.8. Comparing the vessel RAO

The anchor line alone is assumed not to have influence on the vessel RAO for roll since forces from drag, inertia and line stiffness is not included in the anchor line model. However, from the results in Ch.9.8, it indirectly may be concluded that the force components and moment around the z-axis in x-y plane, from the line, is countered by the propulsion and in that way creating moments that increases the vessel roll motion as well as the static heel. Comparing fig.7.8 and 7.9 supports the conclusion that the increased line weight and corresponding propulsion forces is indirectly affecting the RAO.

12. Recommendations for further work

- By modelling the anchor line in Matlab, the simulation will be possible to make better visualized.
- Modelling the anchor line with a method as finite element, is assumed to be a better method for including drag, inertia and stiffness and making the simulation more realistic.
- Study more the oscillations from the propellers to find how this is working compared to a real propulsion system (Ref.Ch.9).
- Perform a sensitivity analysis to find how the gain values for the positioning controller is affecting the roll amplitudes.

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Appendix A

1. Hydrostatics

Hydrostatics - AHTS_2016_a7

Stability 19.0, build: 16
Model file: \\laks.hials.no\student\130517\2016 Master Thesis\AHTS_2016\AHTS_2016_a7 (Medium precision, 64 sections, Trimming off, Skin thickness not applied). Long. datum: MS; Vert. datum: Baseline. Analysis tolerance - ideal(worst case): Disp.%: 0.01000(0.100); Trim%(LCG-TCG): 0.01000(0.100); Heel%(LCG-TCG): 0.01000(0.100)

Damage Case - Intact

Fixed Trim = 0 m (+ve by stern)
Specific gravity = 1.025; (Density = 1.025 tonne/m^3)

Draft Amidships m	0.000	0.922	1.844	2.767	3.689	4.611	5.533	6.456	7.378	8.300
Displacement t	15.69	581.2	1251	1986	2782	3648	4593	5606	6653	7719
Heel deg	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Draft at FP m	0.000	0.922	1.844	2.767	3.689	4.611	5.533	6.456	7.378	8.300
Draft at AP m	0.000	0.922	1.844	2.767	3.689	4.611	5.533	6.456	7.378	8.300
Draft at LCF m	0.000	0.922	1.844	2.767	3.689	4.611	5.533	6.456	7.378	8.300
Trim (+ve by stern) m	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
WL Length m	59.329	65.591	67.585	69.453	74.581	75.779	76.050	74.509	74.000	74.000
Beam max extents on WL m	14.851	17.171	17.200	17.200	17.200	17.200	17.200	17.200	17.200	17.200
Wetted Area m^2	37.646	732.709	889.654	1042.929	1212.137	1393.715	1596.541	1782.154	1941.995	2096.816
Waterpl. Area m^2	23.328	667.419	745.359	807.140	878.899	955.906	1041.545	1093.908	1119.389	1136.946
Prismatic coeff. (Cp)	0.121	0.563	0.579	0.593	0.578	0.596	0.622	0.664	0.694	0.715
Block coeff. (Cb)	0.017	0.259	0.367	0.428	0.449	0.485	0.523	0.571	0.607	0.635
Max Sect. area coeff. (Cm)	0.995	0.969	0.984	0.989	0.992	0.993	0.995	0.995	0.996	0.996
Waterpl. area coeff. (Cwp)	0.026	0.593	0.641	0.676	0.685	0.733	0.796	0.854	0.879	0.893
LCB from zero pt. (+ve fwd) m	-26.567	0.922	1.201	1.089	0.740	0.153	-0.662	-1.560	-2.306	-2.822
LCF from zero pt. (+ve fwd) m	-23.017	1.635	1.215	0.554	-0.866	-2.692	-4.878	-6.161	-6.274	-5.793
KB m	-0.459	0.458	0.958	1.458	1.967	2.487	3.020	3.558	4.087	4.605
KG m	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
BMt m	8.769	20.167	11.155	7.905	6.230	5.248	4.746	4.391	3.917	3.443
BML m	72.929	206.927	122.835	94.149	85.791	81.904	79.699	71.842	63.639	57.215
GMt m	8.310	20.625	12.113	9.364	8.197	7.734	7.765	7.949	8.004	8.048
GML m	72.470	207.385	123.793	95.607	87.758	84.391	82.719	75.400	67.725	61.821
KMt m	8.310	20.625	12.113	9.364	8.197	7.734	7.765	7.949	8.004	8.048
KML m	72.470	207.385	123.793	95.607	87.758	84.391	82.719	75.400	67.725	61.821
Immersion (TPc) tonne/cm	0.239	6.841	7.640	8.273	9.009	9.798	10.676	11.213	11.474	11.654
MTc tonne.m	0.167	17.672	22.715	27.835	35.802	45.145	55.706	61.976	66.068	69.971
RM at 1deg = GMt.Disp.sin(1) tonne.m	2.276	209.194	264.548	324.486	398.021	492.468	622.446	777.664	929.315	1084.276
Max deck inclination deg	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
Trim angle (+ve by stern) deg	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000

2. Typical Maxsurf stability report

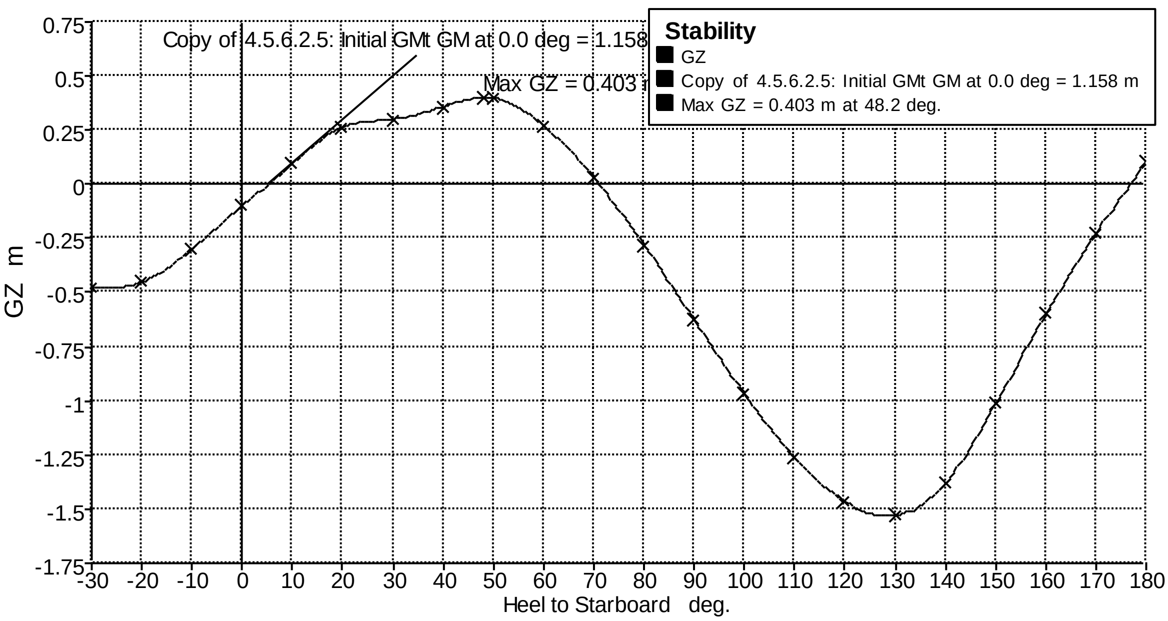
Stability Calculation - AHTS_2016_a7

Stability 19.0, build: 16
Model file: \\laks.hials.no\student\130517\2016 Master Thesis\AHTS_2016\AHTS_2016_a7 (Medium precision, 64 sections, Trimming off, Skin thickness not applied). Long. datum: MS; Vert. datum: Baseline. Analysis tolerance - ideal(worst case): Disp.%: 0.01000(0.100); Trim%(LCG-TCG): 0.01000(0.100); Heel%(LCG-TCG): 0.01000(0.100)

Loadcase - Loadcase 1
Damage Case - Intact

Free to Trim
Specific gravity = 1.025; (Density = 1.025 tonne/m^3)
Fluid analysis method: Use corrected VCG

Item Name	Quantity	Unit Mass tonne	Total Mass tonne	Unit Volume m^3	Total Volume m^3	Long. Arm m	Trans. A m
Lightship	1	5000.000	5000.000			-1.033	
Anchor line_vertical	1	104.000	104.000			-39.100	
Anchor line_horisontal	1	0.000	0.000			-39.100	10
Total Loadcase			5104.000	0.000	0.000	-1.809	
FS correction							
VCG fluid							



Heel to Starboard deg	-30.0	-20.0	-10.0	0.0	10.0	20.0	30.0	40.0	50.0	60.0	70.0	80.
GZ m	-0.477	-0.454	-0.298	-0.102	0.097	0.262	0.301	0.357	0.401	0.274	0.031	-0.
Area under GZ curve from zero heel m.deg	10.5804	5.8458	2.0038	-0.1852	-0.0247	1.8566	4.7271	7.9759	11.8526	15.3642	16.9607	15.7
Displacement t	5104	5104	5104	5104	5104	5104	5104	5104	5104	5104	5104	5
Draft at FP m	5.657	5.744	5.681	5.637	5.682	5.745	5.658	5.291	4.431	3.059	0.520	-7.
Draft at AP m	6.175	6.012	6.172	6.264	6.172	6.012	6.174	6.669	7.499	8.853	11.425	19.
WL Length m	76.048	76.019	76.029	76.038	76.028	76.019	76.048	76.137	76.274	75.898	75.131	76.
Beam max extents on WL m	19.844	18.304	17.465	17.200	17.465	18.304	19.844	20.470	18.145	16.050	14.792	14.
Wetted Area m^2	1810.680	1743.390	1687.851	1698.786	1687.849	1743.414	1810.646	1853.695	1883.581	1900.848	1909.408	1910.
Waterpl. Area m^2	942.858	1002.835	1077.110	1085.720	1077.091	1002.837	942.885	926.286	877.357	808.531	757.382	714.
Prismatic coeff. (Cp)	0.648	0.652	0.644	0.640	0.644	0.652	0.648	0.636	0.611	0.596	0.588	0.

Heel to Starboard deg	-30.0	-20.0	-10.0	0.0	10.0	20.0	30.0	40.0	50.0	60.0	70.0	80.
Block coeff. (Cb)	0.365	0.438	0.519	0.525	0.519	0.438	0.365	0.330	0.359	0.403	0.448	0.
LCB from zero pt. (+ve fwd) m	-1.832	-1.823	-1.835	-1.842	-1.833	-1.822	-1.831	-1.866	-1.912	-1.973	-2.022	-2.
LCF from zero pt. (+ve fwd) m	-0.299	-3.108	-5.346	-5.971	-5.345	-3.108	-0.299	2.167	4.021	4.744	4.915	4.
Max deck inclination deg	30.0021	20.0011	10.0082	0.5274	10.0081	20.0011	30.0021	40.0082	50.0201	60.0298	70.0311	80.0
Trim angle (+ve by stern) deg	0.4352	0.2248	0.4126	0.5274	0.4113	0.2241	0.4337	1.1575	2.5756	4.8561	9.0850	20.9

Key point	Type	Immersion angle deg	Emergence angle deg
Margin Line (immersion pos = -38.1 m)		13.6	n/a
Deck Edge (immersion pos = -38.1 m)		14.2	n/a

Code	Criteria	Value	Units	Actual	Status	Margin %
My criterias	Copy of 4.5.6.2.1: GZ area between 0 and angle of maximum GZ				Pass	
	from the greater of					
	spec. heel angle	0.0	deg	0.0		
	to the lesser of					
	angle of first GZ peak	48.2	deg			
	angle of max. GZ	48.2	deg	48.2		
	lower heel angle	15.0	deg			
	required GZ area at lower heel angle	4.0107	m.deg			
	higher heel angle	30.0	deg			
	required GZ area at higher heel angle	3.1513	m.deg			
	shall not be less than (>=)	3.1513	m.deg	11.1212	Pass	+252.91
My criterias	Copy of 4.5.6.2.2: Area 30 to 40				Pass	
	from the greater of					
	spec. heel angle	30.0	deg	30.0		
	to the lesser of					
	spec. heel angle	40.0	deg	40.0		
	first downflooding angle	n/a	deg			
	angle of vanishing stability	71.1	deg			
	shall not be less than (>=)	1.7189	m.deg	3.2488	Pass	+89.01
My criterias	Copy of 4.5.6.2.3: Maximum GZ at 30 or greater				Pass	
	in the range from the greater of					
	spec. heel angle	30.0	deg	30.0		
	to the lesser of					
	spec. heel angle	90.0	deg			
	angle of max. GZ	48.2	deg	48.2		
	shall not be less than (>=)	0.200	m	0.403	Pass	+101.50
	Intermediate values					
	angle at which this GZ occurs		deg	48.2		
My criterias	Copy of 4.5.6.2.4: Angle of maximum GZ				Pass	
	limited by first GZ peak angle	48.2	deg	48.2		
	shall not be less than (>=)	15.0	deg	48.2	Pass	+221.21
My criterias	Copy of 4.5.6.2.5: Initial GMt				Pass	
	spec. heel angle	0.0	deg			
	shall be greater than (>)	0.150	m	1.158	Pass	+672.00

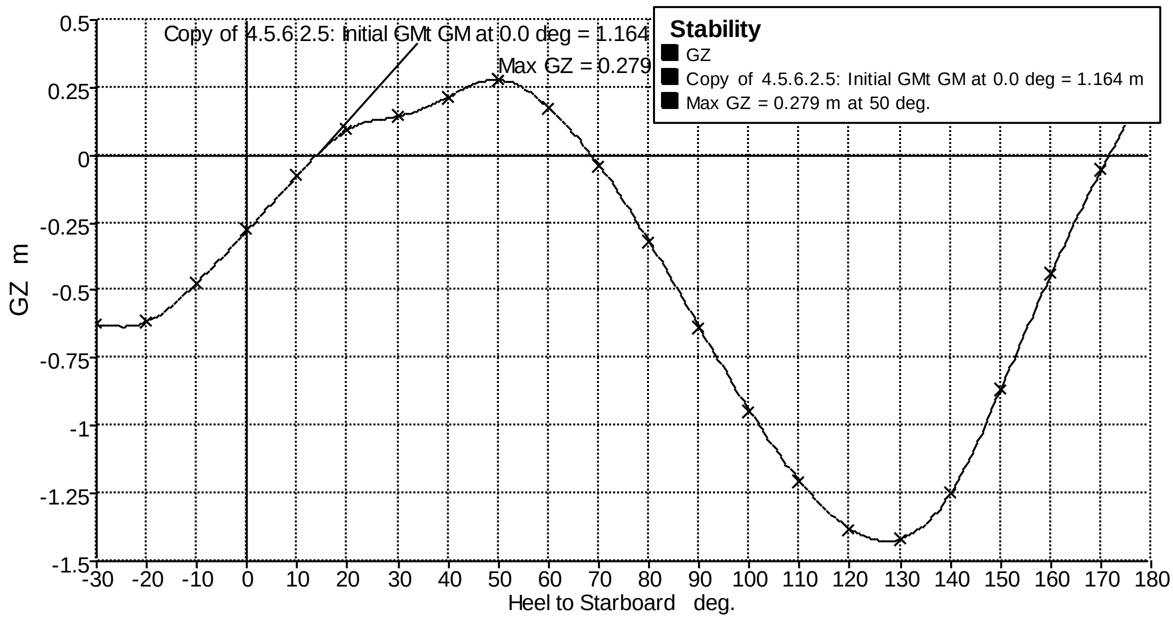
Stability Calculation - AHTS_2016_a7

Stability 19.0, build: 16
Model file: \\laks.hials.no\student\130517\2016 Master Thesis\AHTS_2016\AHTS_2016_a7 (Medium precision, 64 sections, Trimming off, Skin thickness not applied). Long. datum: MS; Vert. datum: Baseline. Analysis tolerance - ideal(worst case): Disp.%: 0.01000(0.100); Trim%(LCG-TCG): 0.01000(0.100); Heel%(LCG-TCG): 0.01000(0.100)

Loadcase - Loadcase 1
Damage Case - Intact

Free to Trim
Specific gravity = 1.025; (Density = 1.025 tonne/m^3)
Fluid analysis method: Use corrected VCG

Item Name	Quantity	Unit Mass tonne	Total Mass tonne	Unit Volume m^3	Total Volume m^3	Long. Arm m	Trans. A m
Lightship	1	5000.000	5000.000			-1.033	
Anchor line_vertical	1	104.000	104.000			-39.100	
Anchor line_horisontal	1	9.000	9.000			-39.100	10
Total Loadcase			5113.000	0.000	0.000	-1.874	
FS correction							
VCG fluid							



Heel to Starboard deg	-30.0	-20.0	-10.0	0.0	10.0	20.0	30.0	40.0	50.0	60.0	70.0	80.
GZ m	-0.624	-0.617	-0.472	-0.278	-0.075	0.095	0.143	0.214	0.279	0.177	-0.037	-0.
Area under GZ curve from zero heel m.deg	15.5819	9.2958	3.7599	-0.5049	-1.7675	-1.5852	-0.3455	1.3938	3.9416	6.3564	7.1267	5.3
Displacement t	5113	5113	5113	5113	5113	5113	5113	5113	5113	5113	5113	5
Draft at FP m	5.622	5.715	5.657	5.614	5.658	5.716	5.624	5.252	4.386	3.002	0.437	-7.
Draft at AP m	6.232	6.053	6.204	6.294	6.204	6.053	6.230	6.741	7.591	8.979	11.615	19.
WL Length m	76.055	76.025	76.034	76.044	76.034	76.025	76.055	76.146	76.264	75.858	75.097	76.
Beam max extents on WL m	19.845	18.304	17.465	17.200	17.465	18.304	19.845	20.490	18.145	16.050	14.792	14.
Wetted Area m^2	1813.745	1746.895	1689.455	1700.467	1689.453	1746.909	1813.689	1856.549	1886.839	1903.516	1912.044	1912.
Waterpl. Area m^2	941.240	1000.900	1078.106	1086.867	1078.084	1000.911	941.295	924.997	876.765	807.382	756.062	713.
Prismatic coeff. (Cp)	0.649	0.653	0.644	0.640	0.644	0.653	0.649	0.635	0.611	0.597	0.588	0.
Block coeff. (Cb)	0.365	0.439	0.518	0.524	0.518	0.439	0.365	0.329	0.359	0.403	0.448	0.

Heel to Starboard deg	-30.0	-20.0	-10.0	0.0	10.0	20.0	30.0	40.0	50.0	60.0	70.0	80.
LCB from zero pt. (+ve fwd) m	-1.903	-1.892	-1.904	-1.910	-1.901	-1.891	-1.900	-1.934	-1.978	-2.037	-2.083	-2.
LCF from zero pt. (+ve fwd) m	-0.268	-3.071	-5.368	-5.998	-5.367	-3.071	-0.269	2.185	4.050	4.752	4.915	4.
Max deck inclination deg	30.0030	20.0017	10.0102	0.5719	10.0101	20.0017	30.0029	40.0095	50.0219	60.0317	70.0327	80.0
Trim angle (+ve by stern) deg	0.5125	0.2839	0.4601	0.5719	0.4585	0.2827	0.5093	1.2509	2.6902	5.0082	9.3083	21.3

Key point	Type	Immersion angle deg	Emergence angle deg
Margin Line (immersion pos = -38.1 m)		13.4	n/a
Deck Edge (immersion pos = -38.1 m)		13.9	n/a

Code	Criteria	Value	Units	Actual	Status	Margin %
My criterias	Copy of 4.5.6.2.1: GZ area between 0 and angle of maximum GZ				Pass	
	from the greater of					
	spec. heel angle	0.0	deg	0.0		
	to the lesser of					
	angle of first GZ peak	50.0	deg			
	angle of max. GZ	50.0	deg	50.0		
	lower heel angle	15.0	deg			
	required GZ area at lower heel angle	4.0107	m.deg			
	higher heel angle	30.0	deg			
	required GZ area at higher heel angle	3.1513	m.deg			
	shall not be less than (>=)	3.1513	m.deg	3.9416	Pass	+25.08
My criterias	Copy of 4.5.6.2.2: Area 30 to 40				Pass	
	from the greater of					
	spec. heel angle	30.0	deg	30.0		
	to the lesser of					
	spec. heel angle	40.0	deg	40.0		
	first downflooding angle	n/a	deg			
	angle of vanishing stability	68.5	deg			
	shall not be less than (>=)	1.7189	m.deg	1.7393	Pass	+1.19
My criterias	Copy of 4.5.6.2.3: Maximum GZ at 30 or greater				Pass	
	in the range from the greater of					
	spec. heel angle	30.0	deg	30.0		
	to the lesser of					
	spec. heel angle	90.0	deg			
	angle of max. GZ	50.0	deg	50.0		
	shall not be less than (>=)	0.200	m	0.279	Pass	+39.50
	Intermediate values					
	angle at which this GZ occurs		deg	50.0		
My criterias	Copy of 4.5.6.2.4: Angle of maximum GZ				Pass	
	limited by first GZ peak angle	50.0	deg	50.0		
	shall not be less than (>=)	15.0	deg	50.0	Pass	+233.33
My criterias	Copy of 4.5.6.2.5: Initial GMt				Pass	
	spec. heel angle	0.0	deg			
	shall be greater than (>)	0.150	m	1.164	Pass	+676.00

Equilibrium Calculation - AHTS_2016_a7

Stability 19.0, build: 16
Model file: \\laks.hials.no\student\130517\2016 Master Thesis\AHTS_2016\AHTS_2016_a7 (Medium precision, 64 sections, Trimming off, Skin thickness not applied). Long. datum: MS; Vert. datum: Baseline. Analysis tolerance - ideal(worst case): Disp.%: 0.01000(0.100); Trim%(LCG-TCG): 0.01000(0.100); Heel%(LCG-TCG): 0.01000(0.100)

Loadcase - Loadcase 1
Damage Case - Intact

Free to Trim
Specific gravity = 1.025; (Density = 1.025 tonne/m^3)
Fluid analysis method: Use corrected VCG

Item Name	Quantity	Unit Mass tonne	Total Mass tonne	Unit Volume m^3	Total Volume m^3	Long. Arm m	Trans. A m
Lightship	1	5000.000	5000.000			-1.033	
Anchor line_vertical	1	104.000	104.000			-39.100	
Anchor line_horisontal	1	9.000	9.000			-39.100	10
Total Loadcase			5113.000	0.000	0.000	-1.874	
FS correction							
VCG fluid							

Draft Amidships m	5.911
Displacement t	5113
Heel deg	13.6
Draft at FP m	5.686
Draft at AP m	6.136
Draft at LCF m	5.944
Trim (+ve by stern) m	0.450
WL Length m	76.028
Beam max extents on WL m	17.693
Wetted Area m^2	1686.065
Waterpl. Area m^2	1078.778
Prismatic coeff. (Cp)	0.647
Block coeff. (Cb)	0.491
Max Sect. area coeff. (Cm)	0.761
Waterpl. area coeff. (Cwp)	0.802
LCB from zero pt. (+ve fwd) m	-1.898
LCF from zero pt. (+ve fwd) m	-5.033
KB m	3.434
KG fluid m	6.833
BMt m	4.754
BML m	75.992
GMt corrected m	1.257
GML m	72.496
KMt m	8.055
KML m	77.307
Immersion (TPc) tonne/cm	11.057
MTc tonne.m	54.351
RM at 1deg = GMt.Disp.sin(1) tonne.m	112.193
Max deck inclination deg	13.5643
Trim angle (+ve by stern) deg	0.3779

Key point	Type	Freeboard m
Margin Line (freeboard pos = -38.1 m)		-0.01
Deck Edge (freeboard		0.064

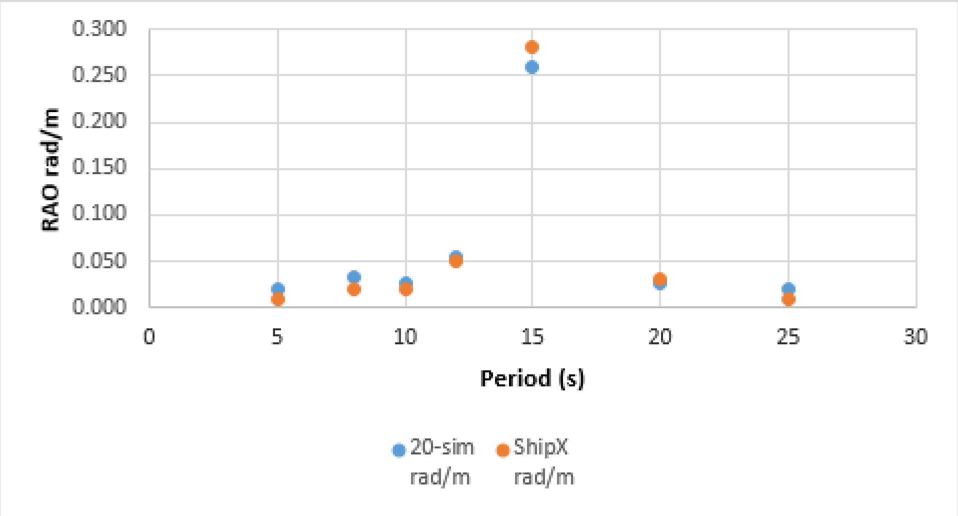
Key point	Type	Freeboard m
pos = -38.1 m)		

Code	Criteria	Value	Units	Actual	Status	Margin %
My criterias	Value of heel at equilibrium				Pass	
	the angle of	Heel				
	shall be less than (<)	15.0	deg	13.6	Pass	+9.60
My criterias	Value of heel at equilibrium for 50%GZ max				Pass	
	the angle of	Heel				
	shall be less than (<)	13.6	deg	13.6	Pass	+0.30

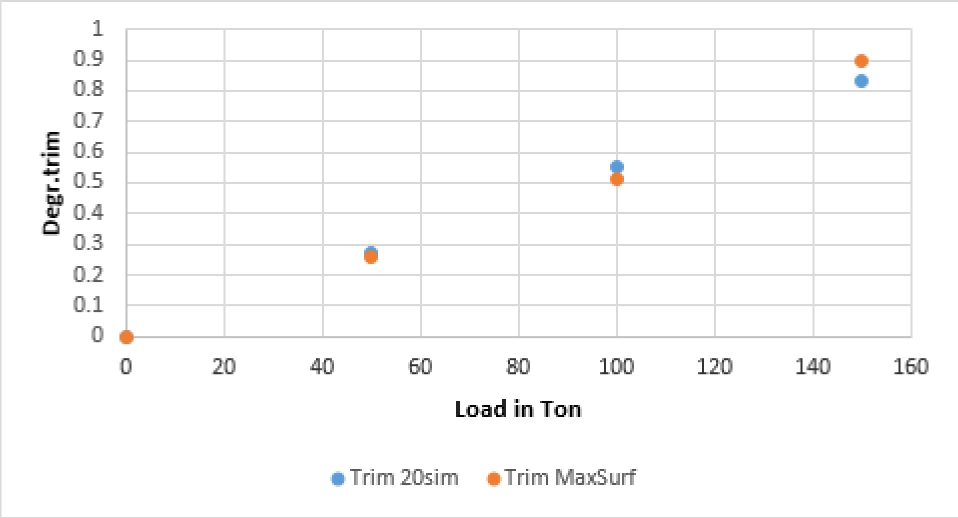
3. Comparing roll response in 20-sim with RAO from ShipX

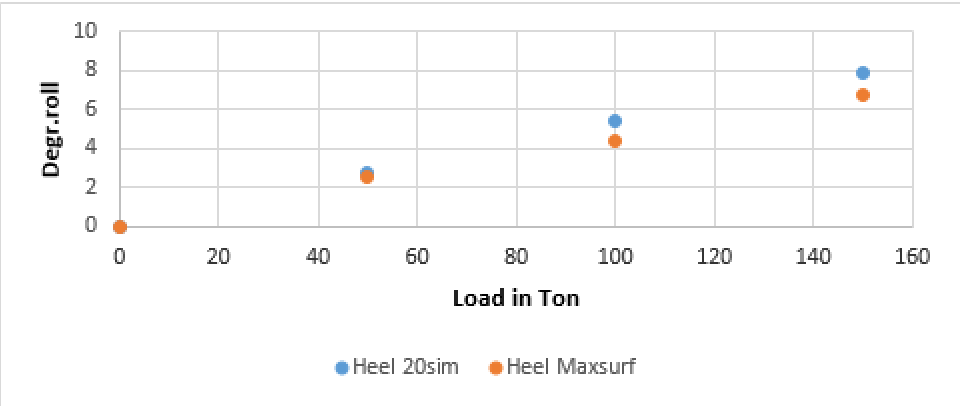
Compariation of RAO ShipX-20SIM AHTS L=77m (No external load)
Waves H=2m (1m amplitude) frome side 90degr.

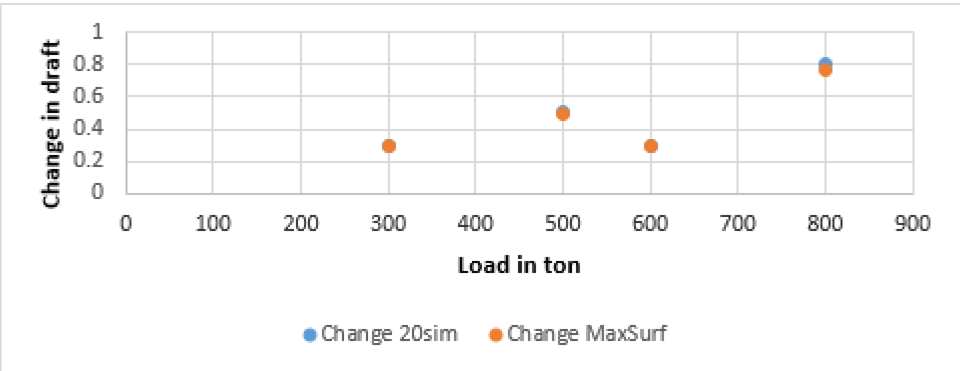
Period (s)	20-sim rad/m	ShipX rad/m
5	0.020	0.010
8	0.033	0.020
10	0.026	0.020
12	0.055	0.050
15	0.260	0.280
20	0.026	0.030
25	0.020	0.010



4. In advance testing of the hull response in 20-Sim and MaxSurf

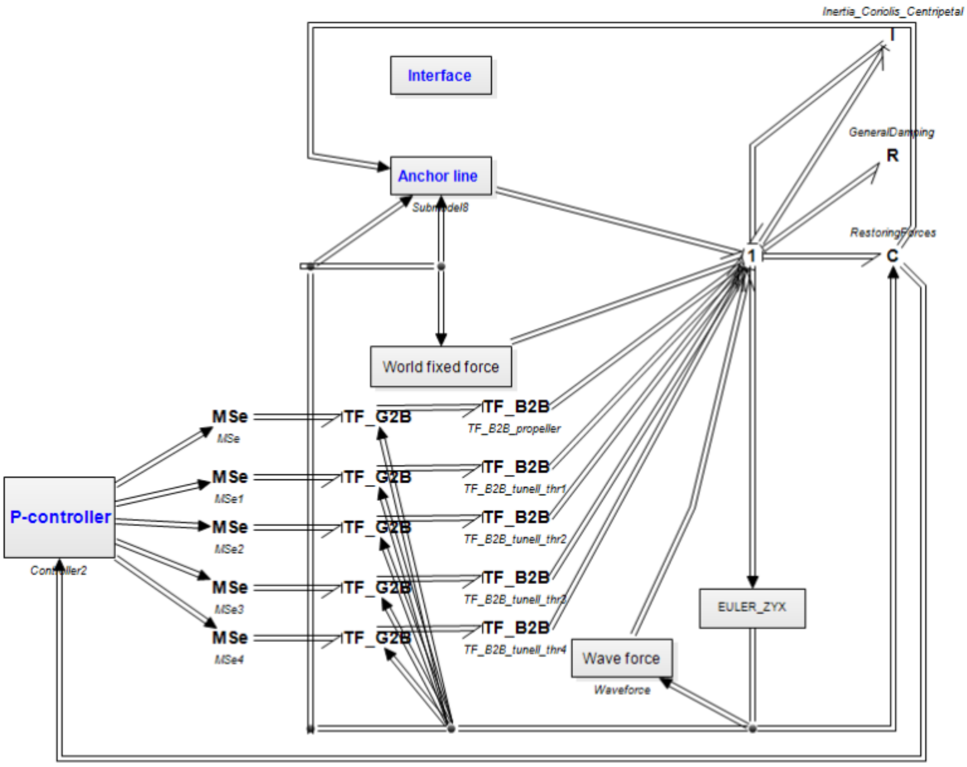


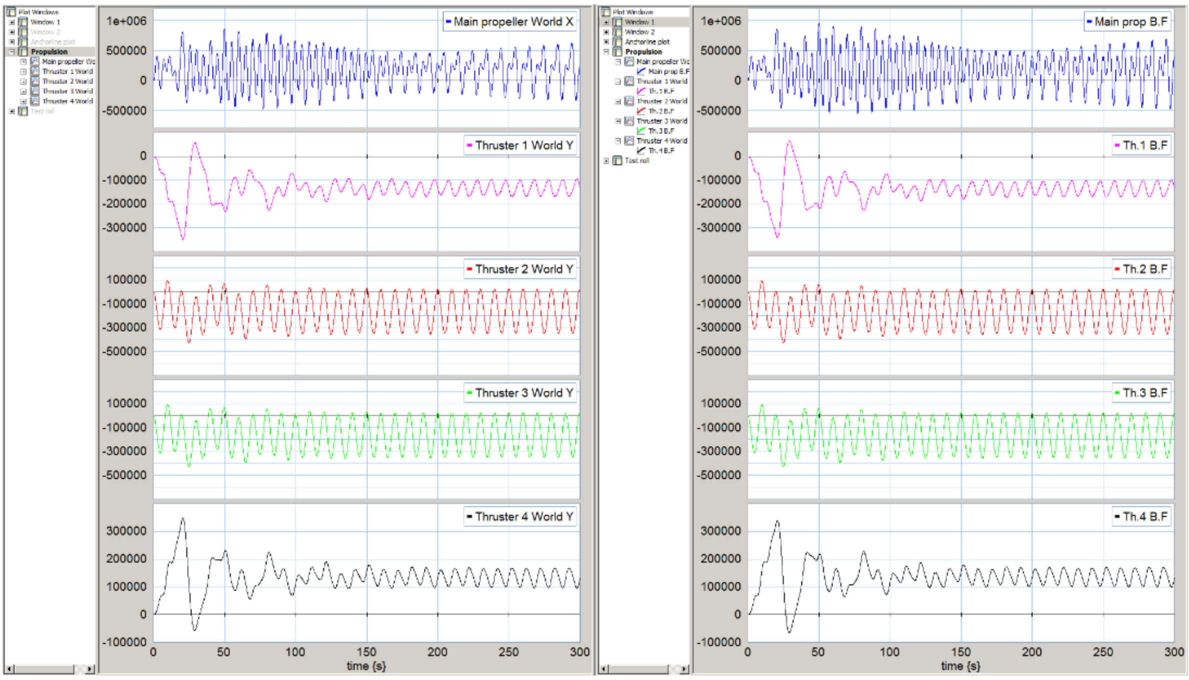




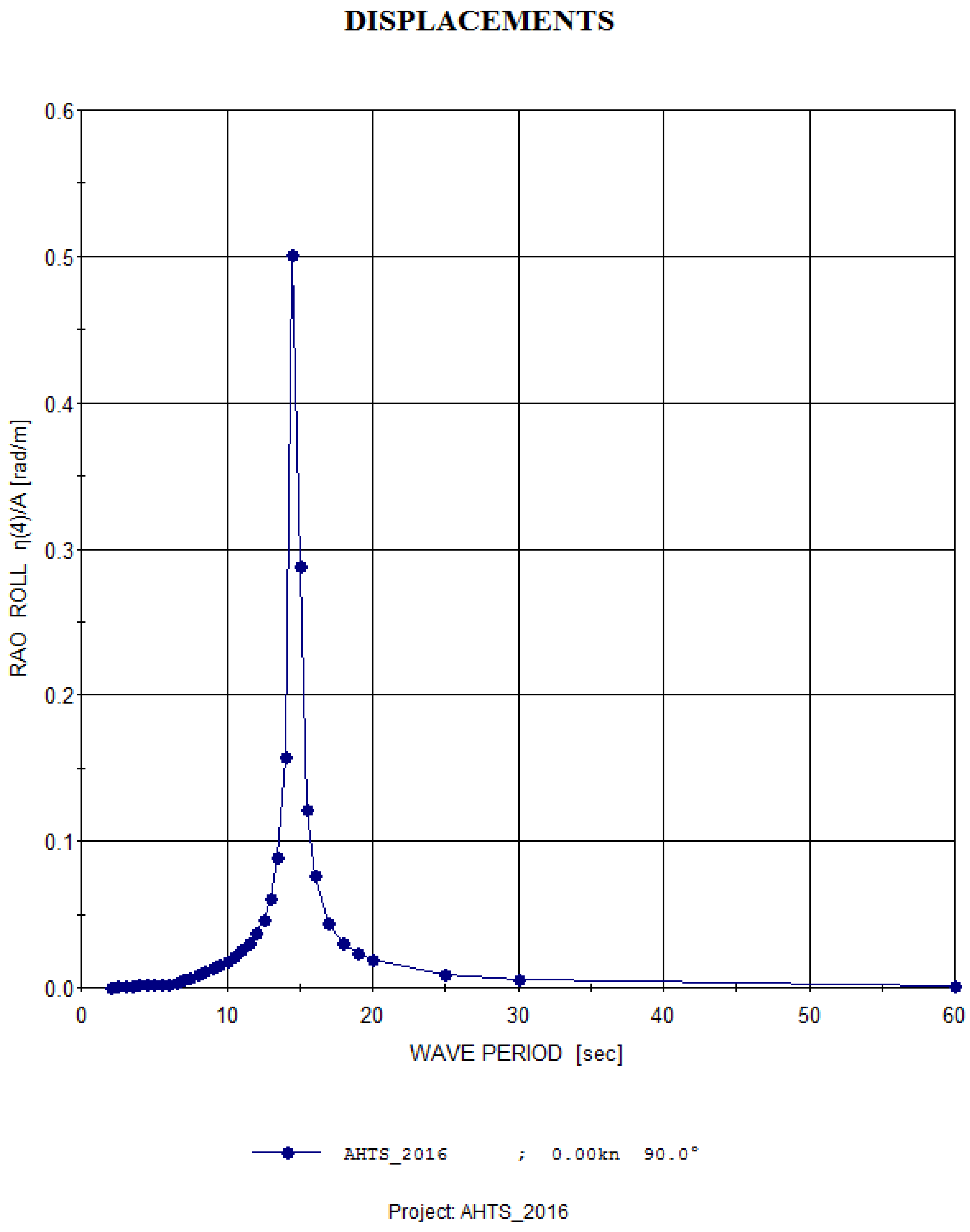
5. World fixed vs. Body fixed propulsion testing

In the figures below is shown the test model for body fixed propulsion and the test result from world vs. body fixed propulsion.





6. RAO plot from ShipX



Appendix B

1. Matlab script for transferring data from Matlab to 20-sim

(Xu, 2014)

```
clear;
%% Connect to 20 SIM
xxsimConnect();clc

% Open the model Simple vessel.emx
fprintf('Please select a 20SIM model,press [Enter] to continue\n');
fprintf('\n');
pause;
[modelname,modelpath] = uigetfile({'*.emx','20SIM-Model(*.emx)'},'Select 20SIM Model');

% Check if the user pressed cancel on the dialog.
if isequal(modelname,0) || isequal(modelpath,0)
    disp('Program cancelled');
    return
else
    disp(['User selected:', fullfile(modelpath, modelname)]);
end
xxsimOpenModel(fullfile(modelpath,modelname));

% process the model
xxsimProcessModel();
% Load *.mat data file
fprintf('Please select a SHIPX data, press [Enter] to continue\n');
fprintf('\n');
pause;
[dataname,datapath] = uigetfile({'*.mat','Matlab-data(*.mat)'},'Select SHIPX data');

% Check if the user pressed cancel on the dialog.
if isequal(dataname,0) || isequal(datapath,0)
    disp('Program cancelled');
    return

else
    disp(['User selected:', fullfile(datapath, dataname)]);
end
load(fullfile(datapath,dataname));
%% Select condition
% Define target vessel speed
knot = vessel.velocities/1.852*3.6;
fprintf('\nThe vessel speeds in knots are [');
fprintf('%g ',knot);
fprintf('\b].\n');
vel = str2num(input('Choose target vessel speed in knots:','s'));
for i=1:length(vessel.velocities)
    if abs(vel-knot(i))<0.1
        velno=i;
    break
    end
end
% Define target wave period
wp = 2*pi./vessel.freqs;
fprintf('\nThe wave periods are [');
fprintf('%g ',wp);
fprintf('\b].\n');
period = str2num(input('Choose wave period:','s'));
for j=1:length(vessel.freqs)
    if abs(period-wp(j))<0.1
        freqno=j;
    break
    end
end
% Define target wave heading
hd = vessel.headings*180/pi;
fprintf('\nThe wave headings are [');
fprintf('%g ',hd);
fprintf('\b].\n');
head = str2num(input('Choose wave heading:','s'));
for k=1:length(vessel.headings)
    if abs(head-hd(k))<0.1
        headno=k;
    break
    end
end


% MotionRAO
motionRAOamp = zeros(6,1);
motionRAOphase = zeros(6,1);
for i=1:6
    motionRAOamp(i,1) = vessel.motionRAO.amp{i}(freqno,headno,velno);
    motionRAOphase(i,1) = vessel.motionRAO.phase{i}(freqno,headno,velno);
end
%% Curve for Ca and Cd of the object
% Za=rand(7,8); % CFD matrix for Ca, function of period and amplitude
% Zd=rand(7,8); % CFD matrix for Ca, function of period and amplitude
% p=3;
% q=3;
% aaCa=fitting(p,q,Za); % Curve fitting of Ca
% aaCd=fitting(p,q,Zd); % Curve fitting of Cd
Ca=1; % Added mass coefficient
Cd=1.2; % Damping coefficient
%% Set parameters
% Transfer nested variables
```

Edited part:

```
  xxsimSetParameters({'GeneralDamping\DsubL','Gravity\g',...
  'Inertia_Coriolis_Centripetal\MRB',...
  'Inertia_Coriolis_Centripetal\Ma','RestoringForces\C',...
  'Wave_force_world_fixed\forceRAOamp','Wave_force_world_fixed\forceRAOw','Wave_force_world_fixed\forceRAOphase'},{vessel.B(:,:,freqno,...
   velno),vessel.main.g,vessel.MRB,vessel.A(:,:,freqno,velno),...
   vessel.C(:,:,freqno,velno),forceRAOamp, vessel.forceRAO.w(1,freqno),forceRAOphase});
```

```
%% Run the model
xxsimRun();
```

2. 20-sim code for the basic anchor line model

```
//Basic anchor line model
parameters
   real L=150 {m};    //Length of free hanging part the line
   real w=10  {};     //weight of line kg/m
   real g=-9.81;

variables
   real Q {};         //=H0/w
   real pA[2]{m};     //x and z pos values for point A
   real pB[2]{m};     //x and z pos values for point B
   real k {m};        //x distance between A and B
   real h {m};        //z distance between A and B
   real TA[2] {N};    // Tension on point A
   real TB[2] {N};    // Tension on point B
   real C1;
   real C2;
   real C21;
   real dzdx_A;
   real dzdx_B;
   real dzdx;
   real interesting plotz;
   real interesting plots;
equations
   pA=int(port1.f);  //integrates the vel. in x and z dir. to find pos.A
   pB=int(port2.f)+[100;100]; //integrates the vel. in x and z dir. to find pos.B

   k=pB[1]-pA[1];
   h=pB[2]-pA[2];

   Q=(k^3/(24*((L^2-h^2)^0.5-k)))^0.5;

   C1=arcsinh(h/(2*Q*sinh(k/(2*Q))))-k/(2*Q);
   C2=-Q*cosh(C1);

   TA[1] = Q*w*g;
   TB[1] = 0-TA[1];
   dzdx_A=sinh((0/Q)+C1);  //x=k
   dzdx_B=sinh((k/Q)+C1);  //x=0
   dzdx = sinh((time/Q+C1));

   TA[2]=TA[1]*dzdx_A;
   TB[2]=TB[1]*dzdx_B;

   port1.e=-TA;
   port2.e=-TB;

   plots = int((1+dzdx^2)^0.5);
   plotz = Q*cosh((time/Q)+C1)+C2;
```

3. 20-sim code for the 3D Anchor line model

```
//Anchor line model 3D. Used in the Anchor handling case study situation no.1,2 and 3

parameters
   real global L;    //Total lenght of line. Input from the interface submodel
   real global w;    //Line weight kg/m in water. Input from the interface submodel
   real g=-9.81;     //gravity constant

variables
   real Q {};        //=H0/w
   real pA[3]{m};    //Anchor Point. Found by integrating velocity+initial pos. as given in the interface
   real pC[3]{m};    //Connection point transformed from the vessel origo by the "Pos transfer" submodel
   real TA[6] {N};   //Array containing tension and moments on point B. Ref.eq.4.5(Q=Tx/w)
   real TC[6] {N};   //Array containing tension and moments on point C
   real C1;          //Integration constant. Ref.eq.4.10
   real C2;          //Integration constant. Ref.eq.4.19
   real i;           //Iteration number used in Newtons method and in animation
   real x_anim[20];  //Array for x used for animation
   real y_anim[20];  //Array for y used for animation
   real z_anim[20];  //Array for z used for animation
   real plotz;       //Variable used for plotting the line curve. Ref.eq.4.15
   real plots;
   real k[2];        //Array containing distance between anchor point(A) and vessel connectiong point(C)in the x-y plane
   real h;           //Vertical distance in z-direction between anchorpoint(A) and vessel connecting point(C)
   real rC;          //Distance between A and C an the xy plane.
   real dzdr_A;      //The slope for the line at point A. Ref.eq.4.6
   real dzdr_C;      //The slope for the line at the vessel connection point C. Ref.eq.4.6
   real ACr;         //Distance between point(A) and connection point(C). (Ref.eq.4.26)
   real segment_l;   //Used for animation. A part of the total line length L

//Please see the parameters and variables descriptions above.
equations
   pA=int(port1.f[1:3])+AnchorPoint;
   pC=pos_C;
   h=pC[3]-pA[3];
   k=pC[1:2]-pA[1:2];
   rC=sqrt(k[1]^2+k[2]^2);

//Checking if total line length is possible,and that the ship is not too close the anchor:
   if (rC^2+h^2)^0.5>L then stopsimulation ('Total length of line,L, is too short');end;
   if (rC+h)<L then stopsimulation ('Total length of line,L, is too long');end;
   if  rC<20 then stopsimulation ('The anchorpoint is too close the connection point');end;

//Finding Q,C1 and C2;
   Q=(rC^3/(24*((L^2-h^2)^0.5-rC)))^0.5;
   C1=arcsinh(h/(2*Q*sinh(rC/(2*Q))))-rC/(2*Q);
   C2=-Q*cosh(C1);
```

```
   dzdr_A=sinh((0/Q)+C1);
   dzdr_C=sinh((rC/Q)+C1);
   ACr=-C1*Q;

//Tension at point A and C in x,y and z direction
   TA[1]=Q*w*g*k[1]/rC;
   TA[2]=Q*w*g*k[2]/rC;
   TA[3]=sqrt(TA[1]^2+TA[2]^2)*dzdr_A;
   TC[1]=0-TA[1];
   TC[2]=0-TA[2];
   TC[3]=sqrt(TC[1]^2+TC[2]^2)*dzdr_C;

//Moments in the connection points of anchorline:
   TA[4]=0;TA[5]=0;TA[6]=0;TC[4]=0;TC[5]=0;TC[6]=0;
   // Reaction force & moment to the ship and anchor
   port1.e=-TA;
   port2.e=-TC;

//Plotting of the line shape:
   plotz=Q*cosh((time/Q)+C1)+C2;

//3D Animation:
   segment_l=L/(20-1);
   for i=1 to 20 do
         x_anim[i]=(Q*(arcsinh((segment_l*(i-1)-ACr)/Q)-C1))*k[1]/rC+pA[1];
         y_anim[i]=(Q*(arcsinh((segment_l*(i-1)-ACr)/Q)-C1))*k[2]/rC+pA[2];
         z_anim[i]=Q*sqrt(1+((segment_l*(i-1)-ACr)/Q)^2)+C2+pA[3];
      end;
   end;
```

4. 20-sim code for 3D Anchor line model with bottom interaction

```
//Anchorline model 3D with bottom interaction. Used for anchor handling case study situation no.5
parameters
   real global L;    //Total lenght of line. Input from the interface submodel
   real global w;    //Line weight kg/m in water. Input from the interface submodel
   real g=-9.81;     //gravity constant
   real alfa1=1.2;   //for Q estimation. Ref.Ch.4.4
   real alfa2=0.005; //Used for Q estimation. Ref.Ch.4.4

variables
   real beta;          //Variable for estimation of Q. Ref.eq.4.39
   real gamma;         //Variable for estimation of Q. Ref.eq.4.40
   real AB;            //Used for estimating Q.Distance between point A and B.
   real TH;            //Used for estimating Q.Tension in horisontal direction. Ref.eq.4.47
   real TZ;            //Used for estimating Q.Tension in vertical direction. Ref.eq.4.45
   real L1_est;        //Used for estimating Q.Length of the lifted part of the line. Ref.eq.4.44
   real Q_estim;       //Estimated Q. Ref.eq.4.47
   real a;             //Used for estimating Q. a,b and c is roots in quadric formula. Ref.Ch.4.4
   real b;
   real c;
   real Q {};          //=H0/w
   real pA[3]{m};      //Anchor Point. Found by integrating velocity+initial pos. as given in the interface
   real pB[3]{m};      //Lifting Point (B)
   real pC[3]{m};      //Connection point transformed from the vessel origo by the "Pos transfer" submodel
   real TB[6] {N};     //Array containing tension and moments on point B. Ref.eq.4.5
   real TC[6] {N};     //Array containing tension and moments on point C
   real C1;            //Integration constant. Ref.eq.4.34
   real C2;            //Integration constant. Ref.4.21
   real i;             //Iteration number used in Newtons method and in animation
   real x_anim[20];    //Array for x used for animation
   real y_anim[20];    //Array for y used for animation
   real z_anim[20];    //Array for z used for animation
   real plotz;         //Variable used for plotting the line curve.Ref.eq.4.35
   real k[2];          //Array containing distance between anchor point(A) and vessel connectiong point(C)in the x-y plane
   real h;             //Vertical distance in z-direction between anchorpoint(A) and vessel connecting point(C)
   real L1;            //Length of the lifted part of the line. Ref.eq.4.31
   real Z;             //Variable used in Newton's method.
   real rC;            //Distance between A and C an the xy plane.
   real dzdr_B;        //The slope for the line at the lifting point (B). Ref.eq.4.6
   real dzdr_C;        //The slope for the line at the vessel connection point (C). Ref.eq.4.6
   real ABr;           //Distance between the anchor point(A) and the lifting point(B). Ref.eq.4.26
   real segment_l;     //Used for animation. A part of the total line length L

//Please see the parameters and variables descriptions above.
equations
   pA=int(port1.f[1:3])+AnchorPoint;
   pC=pos_C;
   h=pC[3]-pA[3];
   k=pC[1:2]-pA[1:2];
   rC=sqrt(k[1]^2+k[2]^2);
```

```
//Checking if total line length is possible,and that the ship is not too close the anchor:
   if (rC^2+h^2)^0.5>L then stopsimulation ('Total length of line,L, is too short');end;
   if (rC+h)<L then stopsimulation ('Total length of line,L, is too long');end;
   if  rC<20 then stopsimulation ('The anchorpoint is too close the connectionpoint');end;

//Estimation of Q.
   beta=-2*rC;
   gamma=rC^2+h^2;
   a=alfa1^2-1;
   b=alfa1^2*beta+2*L;
   c=alfa1^2*gamma-L^2;
   AB=(-b+sqrt(abs(b^2-4*a*c)))/(2*a);
   L1_est=L-AB;
   TZ=L1_est*w*9.81;
   TH=TZ*alfa2*(rC-AB)/h;
   //TH=TZ*0.005*1/sqrt(tanphi^2+1);
   Q_estim=TH/w;

//Interation to solve Q by using Newtons method.
   Q=Q_estim;
   for i=1 to 10 do
      Z=Q-(Q*cosh(rC/Q+((h^2+2*h*Q)^0.5-L)/Q)-h-Q)/(cosh(rC/Q-(L-(h^2+2*Q*h)^0.5)/Q)+Q*sinh(rC/Q-
       (L-(h^2+2*Q*h)^0.5)/Q)*((L-(h^2+2*Q*h)^0.5)/Q^2-rC/Q^2+h/(Q*(h^2+2*Q*h)^0.5))-1);
      Q=Z;
   end;

   C1=((h^2+2*h*Q)^0.5-L)/Q;
   C2=-Q;
   ABr=-C1*Q;
   L1=L-ABr;

   dzdr_B=sinh((ABr/Q)+C1);
   dzdr_C=sinh((rC/Q)+C1);
   pB[1:2]=ABr*k/rC+pA[1:2];
   pB[3]=pA[3];

//Tension at point B and C in x,y and z direction
   TB[1]=Q*w*g*k[1]/rC;
   TB[2]=Q*w*g*k[2]/rC;
   TB[3]=sqrt(TB[1]^2+TB[2]^2)*dzdr_B;
   TC[1]=0-TB[1];
   TC[2]=0-TB[2];
   TC[3]=sqrt(TC[1]^2+TC[2]^2)*dzdr_C;
   //TC[3]=TC[1]*dzdr_C;
```

```
//Tension at point B and C in x,y and z direction
  TB[1]=Q*w*g*k[1]/rC;
  TB[2]=Q*w*g*k[2]/rC;
  TB[3]=sqrt(TB[1]^2+TB[2]^2)*dzdr_B;
  TC[1]=0-TB[1];
  TC[2]=0-TB[2];
  TC[3]=sqrt(TC[1]^2+TC[2]^2)*dzdr_C;
  //TC[3]=TC[1]*dzdr_C;

//Moments in the connection points of anchorline:
  TB[4]=0;TB[5]=0;TB[6]=0;TC[4]=0;TC[5]=0;TC[6]=0;
  // Reaction force & moment to the ship and anchor
  port1.e=-TB;
  port2.e=-TC;

//Plotting of the line shape:
  if abs(time)>ABr then
  plotz=Q*cosh((time/Q)+C1)-Q;
  else
  plotz=0;
  end;

//3D Animation:
  segment_l=L/(20-1);
  for i=1 to 20 do
    if (segment_l*i)>ABr then
      x_anim[i]=(Q*(arcsinh((segment_l*(i-1)-ABr)/Q)-C1))*k[1]/rC+pA[1];
      y_anim[i]=(Q*(arcsinh((segment_l*(i-1)-ABr)/Q)-C1))*k[2]/rC+pA[2];
      z_anim[i]=Q*sqrt(1+((segment_l*(i-1)-ABr)/Q)^2)+C2+pA[3];
    else
      x_anim[i]=(i-1)*segment_l*k[1]/rC+pA[1];
      y_anim[i]=(i-1)*segment_l*k[2]/rC+pA[2];
      z_anim[i]=pA[3];
    end;
  end;
  end;
```

5. 20-sim code for the P-controller model

```
parameters
    real setpos[6]= [0;0;0;0;0;0];
    real K1= -1e7;  //gain for surge (thrust in x-dir.)
    real K2= -1e5;  //gain for sway (thrust in y-dir.)
    real K6=  1e6;  //gain for yaw

variables
    real main[6];
    real thrust1[6];
    real thrust2[6];
    real thrust3[6];
    real thrust4[6];
    real corrpos[6];

equations
    corrpos = MV-setpos;
    //main propeller:
    main[1] =corrpos[1]*K1;
    main[2] =0;
    main[3] =0;
    main[4] =0;
    main[5] =0;
    main[6] =0;

    //tunell thruster1:
    thrust1[1] =0;
    thrust1[2] =corrpos[6]*K6; //correcting yaw motion
    thrust1[3] =0;
    thrust1[4] =0;
    thrust1[5] =0;
    thrust1[6] =0;

   //tunell thruster2:
    thrust2[1] =0;
    thrust2[2] =corrpos[2]*K2; //correcting sway motion
    thrust2[3] =0;
    thrust2[4] =0;
    thrust2[5] =0;
    thrust2[6] =0;

    //tunell thruster3:
    thrust3[1] =0;
    thrust3[2] =corrpos[2]*K2; //correcting sway motion
    thrust3[3] =0;
    thrust3[4] =0;
    thrust3[5] =0;
    thrust3[6] =0;

    //tunell thruster4:
    thrust4[1] =0;
    thrust4[2] =corrpos[6]*K6; //correcting yaw motion
    thrust4[3] =0;
    thrust4[4] =0;
    thrust4[5] =0;
    thrust4[6] =0;

    //signal output:
    output1=main;
    output2=thrust1;
    output3=thrust2;
    output4=thrust3;
    output5=thrust4;
```

6. Matlab code for differentiation of equation used in Newton's method

```
syms f Q L C1 xC zC
clc
zC=Q*cosh(xC/Q+((zC^2+2*zC*Q)^0.5-L)/Q)-Q;
%pretty(zC)

diff(zC,Q)

%pretty(diff(f,Q))
```

```
ans =

cosh(xC/Q - (L - (zC^2 + 2*Q*zC)^(1/2))/Q) + Q*sinh(xC/Q - (L - (zC^2 + 2*Q*zC)^(1/2))/Q)*((L - (zC^2 + 2*Q*zC)^(1/2))/Q^2 - xC/Q^2 + zC/(Q*(zC^2 + 2*Q*zC)^(1/2))) - 1

>>
```

Appendix C

1. Files in the enclosed CD-rom

Description:	**Filename:**
Master thesis_Kjell Lennart Nygård	Master thesis_Kjell Lennart Nygård.pdf
Master thesis_Kjell Lennart Nygård	Master thesis_Kjell Lennart Nygård.doc
Research paper draft	Research draft.pdf
Research paper draft in Word format	Research draft.doc
20-sim model for the basic anchor line	Basic anchor line model.emx
3D 20-sim model basic	3D model basic.emx
3D 20-sim model with bottom interaction	3D model with bottom interaction.emx
Data file from ShipX	AHTS_2016a.mat
Matlab, Newton's method basic	Q_iterative.m
Newton's method for seabed interaction	Newton's_Method_for_seabed_interaction.m
Derivation for Newton's method	Derivation for Newton's method_seabed.m
MaxSurf modeller design file	AHTS_2016_a7.msd
MaxSurf stability design file	AHTS_2016_a7.hmd
MaxSurf stability criterias	Criteria.txt
MaxSurf stability criterias	My criterias.hcr
Excel speed sheet	Calculations AHTS_2016_d.xlsx
AutoCAD 2D drawings	Drawing_2D.dwg
AutoCAD 3D drawings	3D_models.dwg
ShipX database	"AHTS_2016" file folder

Appendix D

1. Article draft

Effect of anchor line tension on an AHTS vessel at sea

Stud. Kjell Lennart Nygård

NTNU Ålesund, Postbox 1517, 60025 Ålesund (Norway)

Abstract

Key Words: Anchor line, Catenary, Anchor handling, 20-sim, Simulation

In this thesis, the aim was to simulate a typical anchor-handling situation in order to study the influence from an anchor line. With today's computer power and simulation programs simulations be performed at reasonable cost and and many different scenarios may be studied without any safety issues.

Main problems

Due to limited time, it was agreed not to include forces from drag, inertia or line stiffness in the anchor line model. Particularly in deep-water operations the drag caused by strong ocean currents are assumed to have considerable influence on the results.
Tuning of the propulsion forces to keep the vessel at position has influence on the results, and it was needed to find reasonable values for the controller gain without overcompensating.

Main results

From the simulations, it was found that moving the line sideways on the vessel stern has large influence on the average roll angle, and some influence on the roll amplitudes. In the critical anchor handling situation the weight of anchor line possible to handle had to be reduced with more than 50% compared to the results from the stability calculations alone.

The anchor line model does not include drag, inertia and line stiffness, so the line motions should not influence the RAO. Anyhow, some bigger RAO in the case when the anchor line connected to the vessel was found.

Main conclusion

The main conclusion is that the load from the anchor line is affecting the limits for safe operation when operating in difficult situations.
It was concluded that the increased RAO is caused by the moments made by the propulsion that are compensating the external forces from the line in x-y plane to keep the vessel at position and compensating the yaw moment from the line.
In this thesis, the results must be read as simplifications, but still it may point out some critical moments due to ship stability and motions during anchor handling.

Introduction

An anchor line that is connected to a ship will not only have impact for the ship stability, but also the ship response in waves.
In waves, a ship will move in 6 degrees of freedom, and in this work, the focus is mainly on the roll motion. The drag effect from current, inertia force or anchor line stiffness was not included in this thesis.

Background

General

In this work a typical anchor handling operation at deep water was selected as a plan case as shown in fig.1 below.
When doing such operations it is important to be aware of how the force from the anchor line is affecting the ship motions and stability

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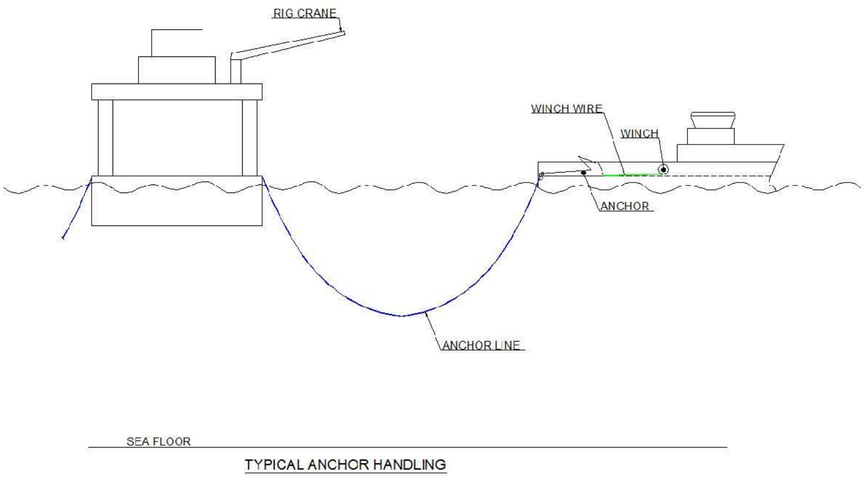

Figure 1

Figure 2

Ship intact stability

A common measure for the ship stability is the GZ value. This comes from Atwoods formula $\boldsymbol{GZ = BoR - BoG * sin\varphi}$ (Johansen, 1975). From this formula, GZ for different heeling angles can be plotted as the GZ curve.

The stability was checked against two different set of criteria's. IMO A.749 4,5 is a set of criteria's for offshore supply vessels. These criteria's was used as they are predefined in Maxsurf stability (Bentley Systems, 2012).

The second set of criteria's is the NMD criteria's (NMD, 2007) for anchor handling. According to this criteria's the maximum tension on the wire must be calculated so that the vessel's maximum heeling is limited to one of the following angles, whichever occurs first:

- Heeling angle equivalent to a GZ-value equal to 50 % of GZ-max.
- The angle of flooding, which results in water aft on working deck when the deck is calculated as flat.
- 15 degrees.

It should be noted that the vertical force from the tension shall be included in the loading conditions, upon which calculations of trim and GZ-curve is based.

The vessel model

In order to study the dynamic motions of the vessel a vessel model (Xu, 2014) has been used as basic model in this thesis. This is a 6 degree of freedom bond graph model made in 20-sim.

General methodology

Ship hull and vessel data

An existing ship hull for a typical AHTS vessel is used in the study. After reading the hull geometry into MaxSurf computer program (Bentley Systems, 2012), a typical loading condition for this hull was established by assuming a weight displacement and center of gravity. This loading condition and corresponding waterline was then used both for checking the ship stability and to generate vessel data used in the 20-sim vessel model. The coefficients (for added mass, damping and inertia) was generated by using ShipX computer program (MARINTEK AS, 2015). Further, the vessel data was saved to Matlab by using a Matlab toolbox for this purpose (Fossen, 2008). From Matlab the coefficients was further transferred to 20-sim by using an existing Matlab script (Xu, 2014).

Hydrostatics and intact stability

By using MaxSurf stability computer program the intact stability for the ship hull was checked against the stability criteria's described in the background. The stability calculations the general loading condition is performed to ensure that the ship hull has sufficient stability when the hydrodynamic coefficients was transferred to ShipX. For later use in the simulations, also the limiting tension on the anchor line was checked. This calculation was done by varying the tension (T) until the maximum tension without failing on any of the criteria's from IMO and NMD as described in the background. This was done for each angle ϕ in steps between 0 and 90 degree. Please see fig.3 below.

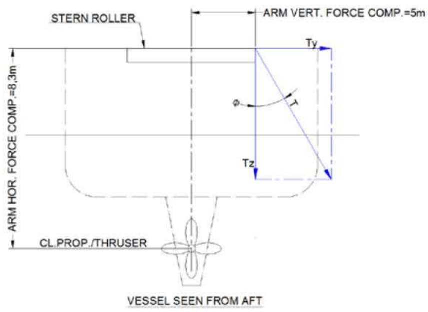

Figure 3

Model development methodology

Model for the submerged anchor line

The anchor line was modelled as an inelastic static catenary line. In fig.4 below the line is shown with seabed interaction.

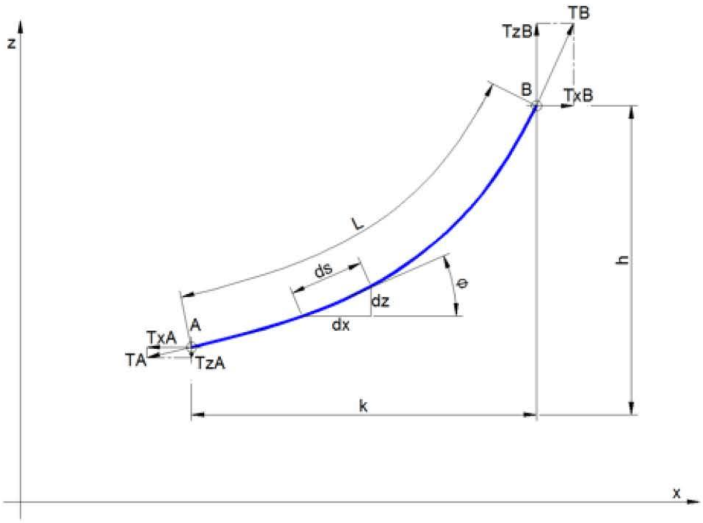

Figure 4

For a segment of the line to be in equilibrium, it requires the forces in x direction, T_xA and T_xB to be equal. In addition, the forces in z direction must be equal as shown in eq.1 below.

$$T_{Z(S)} = T_{Z(0)} + \int_0^S w\,ds$$

Equation 1

By using the relation $ds = \sqrt{dx^2 + dz^2}$ and second order differentiation, equation 1 can be written as in eq.2 below:

$$T_x \frac{dz^2}{dx^2} = w * \sqrt{1 + (\frac{dz}{dx})^2}$$

Equation 2

This is a second order differential equation, and by integrating and assume that the curve has a hyperbolic shape the resulting expression for z is shown in eq.3.

$$z = Q * \cosh\left(\frac{x}{Q} + C1\right) + C2\,,$$
$$where\ Q = \frac{T_X}{w}$$

Equation 3

By using the relations in eq.4, and eq.5 below, an equation for L can be written as shown in eq.6

$$(\frac{dz}{dx})^2 = sinh^2\left(\frac{x}{Q} + C1\right)$$

Equation 4

$$sinh^2\left(\frac{x}{Q} + C1\right) = cosh^2(\frac{x}{Q} + C1)$$

Equation 5

$$L = \int_0^k \sqrt{1 + \left(\frac{dz}{dx}\right)^2}\,dx$$
$$= \int_0^k \cosh(\frac{x}{Q} + C1)\,dx$$

Equation 6

After integrating from zero to k, eq.6 becomes:

$$L = Q * \sinh\left(\frac{k}{Q} + C1\right) - Q * \sinh(C1)$$

Equation 7

By inserting the points A(0,0) from fig.4, into eq.3, C2 can be written as in eq.8 below.

$$C2 = -Q * \cosh(C1)$$

Equation 8

In addition, in the same manner by using point B(k,h) from fig.4, h will become as shown in eq.9 below.

$$h = Q * \cosh(\left(\frac{k}{Q}\right) + C1) + C2$$

Equation 9

For a small segment in fig.4 the following relation exist:

$$k^2 = L^2 - h^2$$

Equation 10

Then by using eq.10 and calculation rules for hyperbolic functions, eq.11 below is obtained.

$$L^2 - h^2 = 2 * Q^2 * sinh^2(\frac{k}{2Q})$$

Equation 11

Finding the constant Q from eq.11 can be found in two ways, either non-iterative, or by using Newton's method which is iterative. The non-iterative solution for Q can be written as in eq.12 below, similar to (Journee & Massie, 2001):

$$Q = \sqrt{\frac{k^3}{24 * ((L^2 - h^2) - k)}}$$

Equation 12

By inserting C2 from eq.8 into eq.9, h may be written as shown in eq.13 below.

$$h = Q * \left[\cosh\left(\frac{k}{Q}\right) + C1\right) - \cosh(C1)]$$

Equation 13

By introducing a new variable P as shown in eq.14, the expression for h can be simplified to as shown in eq.15 below. This was done by using the calculation rules for hyperbolic functions.

$$P = C1 + \frac{k}{2Q}$$

Equation 14

$$h = 2 * Q * \sinh\left(\frac{k}{2Q}\right)\sinh(P)$$

Equation 15

From eq.15, P may be written as shown in eq.16 below.

$$P = sinh^{-1}(\frac{h}{2Qsinh(\frac{k}{2Q})})$$

Equation 16

Using eq.14 and eq.16, C1 may be found as shown in eq.17 below.

$$C1 = sinh^{-1}\left(\frac{h}{2Qsinh\left(\frac{k}{2Q}\right)}\right) - \frac{k}{2Q}$$

Equation 17

Supplementations to the existing 20-sim model

Fig.5 below shows an overview of the complete model after implemented the sub models for the anchor line and the vessel positioning system. In the following a short introduction to these models will be given.

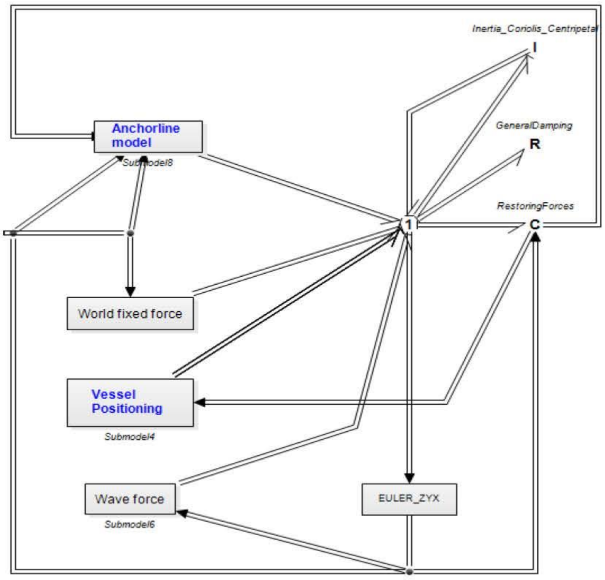

Figure 5

The vessel position control model

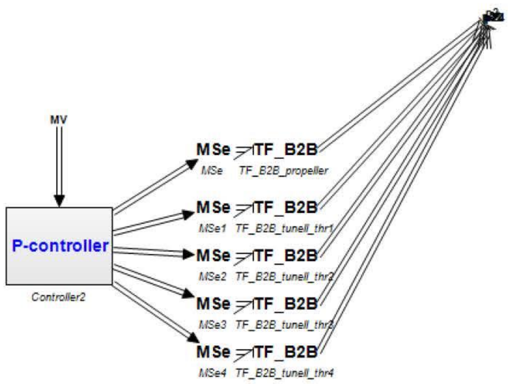

Figure 6

Fig.6 above shows the sub model that is imploded inside the vessel positioning sub model in the overview. The model is not meant to be a DP system, but a simple solution, which only purpose is to keep the vessel at a fixed position.

The P_controller sub model is from the MV signal receiving the distance that the vessel is moving away from the zero position and linear to the discrepancy in the surge, sway and yaw and given gain values for surge, sway and yaw it gives signal to the Mse elements representing the propeller and thrusters. The Mse elements is making the signal to efforts witch in the TF_B2B elements is transformed from the ship origin to the body fixed position for each thruster/propeller. Thruster 2(aft) and 3(fore) is receiving the same effort, and as they are located at equal x-distance from the ship origo, they will not create any moment and the force will correct the discrepancy in y-direction (Sway) from the zero point in the world fixed coordinate system. Thruster 1(aft) and 4(fore) also receives equal effort, but here the effort is set to negative in the MSe4 element so the created moment will correct the ship Yaw motion. The TF-B2B_propeller is correcting the vessel surge motion. The B2B elements is transforming the effort from the ship origin to the location of the thrusters/propeller by using a transformation matrix.

The anchor line model

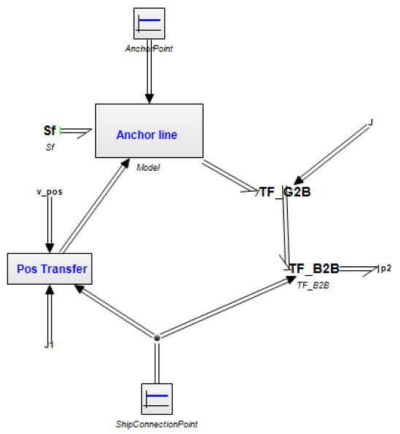

Figure 7

In fig.7 above is shown the sub models inside the Anchor line model in shown in fig.5. Connection to the vessel is done by using a transformer (TF_G2B) to transform the power from the global coordinate system to the vessel origo. Then the power is transferred from the vessel origo to the connection point for the line on the vessel. The "Anchor Point" sub model gives in the world fixed coordinates for the anchor, which is used as initial values for the anchor point A (ref.fig.4).

The "Pos Transfer" sub model is transferring the connection point for the line from the vessel origo to point C. This is done by using the position transformation matrix, shown as signal J1, from inside the EULER ZYX sub model shown in fig.5.
The "v_pos" signal is the vessel position in world coordinates given from the vessel C-element. "Sf" represents the anchor velocities.

Case study simulations

Fig.8 below shows the vessel in an anchor handling operation, and is situation no.3 shown in tab.1. The operation was splitted into three different situations as shown in tab.1. To study the vessel response amplitude operator (RAO) for roll, the roll response was measured for different wave periods between 5 and 30 sec. This was also done by simulating the basic vessel model without external load, and by attaching a line with self-weight of 100kg/m in situation 1. The angle Φ (ref.fig.9) in situation 3 was found from eq.18 by using the force components from the simulation result.

$$\Phi = \arctan\left(\frac{TCy}{TCz}\right)$$

Equation 18

The gain K1,K2 and K6 for the propulsion compensation was tuned until the vessel was keeping its position. Please see tab.1 for the used gain values. In situation 3, the heel and roll motion when the line is connected 5m off centerline port, in vessel centerline and 2,0 m off ship centerline to starboard also was tested. Please see fig.8 below.

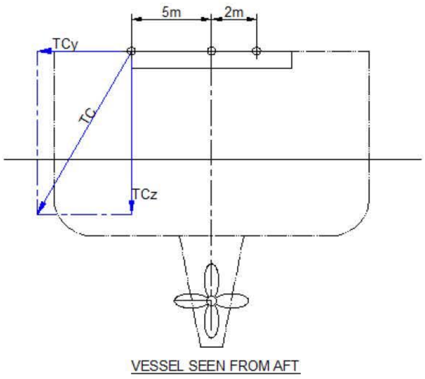

Figure 8

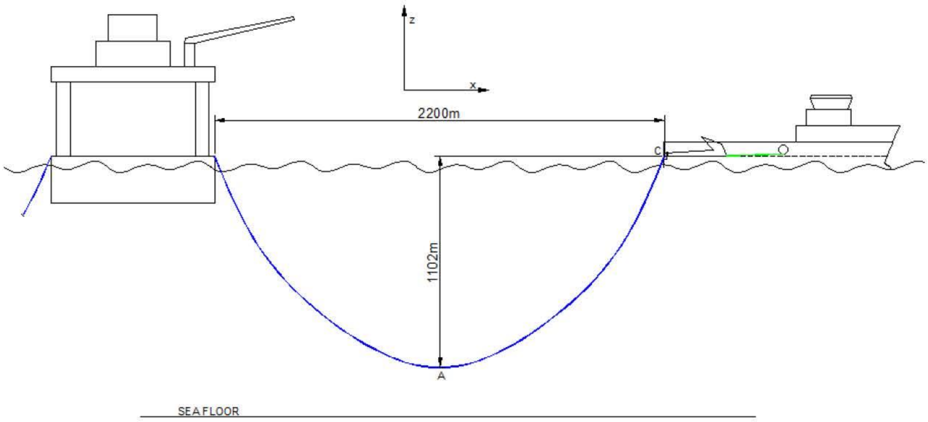

Figure 9

	Abbrevation	Situation 1	Situation 2	Situation 3	Unit
Distance rig-vessel		50	1100	2200	m
Line length AC	L	412	836	1682	m
Line weight	w	388	120	35	kg/m
Wave hight	H	0	2	4	m
Wave period	t	-	10	10	s
Waves direction		-	90	90	degr.
Vessel heading		0	0	45	degr.
Gain main prop: K1		-1.E+07	-1.E+07	-1.E+07	-
Gain for sway: K2		-1.E+05	-1.E+05	-1.E+05	-
Gain for yaw: K6		1.E+06	6.E+06	5.E+06	-

Table 1

Results

Stability in the general loading condition

In tab.2 below is shown the main result for the different stability criteria's. This is presented to show that the vessel model has sufficient stability.

Stability criteria	Description	Actual	Status
IMO A.749-4.5.6.2.1	GZ area between 0 and angle of maximum GZ shall not be less than 3.1513 m.deg	17.34 m.deg	Pass
IMO A.749-4.5.6.2.2	Area 30 to 40 shall not be less than 1.7189 m.deg	4.87 m.deg	Pass
IMO A.749-4.5.6.2.3	Maximum GZ at 30 or greater shall not be less than 0.2m	0.57 m	Pass
IMO A.749-4.5.6.2.4	Angle of maximum GZ shall not be less than 15.0 deg	48.20 deg	Pass
IMO A.749-4.5.6.2.5	Initial GMt shall be greater than 0.15m	1.053 m	Pass

Table 2

Stability in anchor handling condition

The results for stability check in anchor handling condition is shown in fig.9 below. From the result, it can be seen that the maximum allowable force T is decreasing relatively fast as the angle ∅ is increasing.

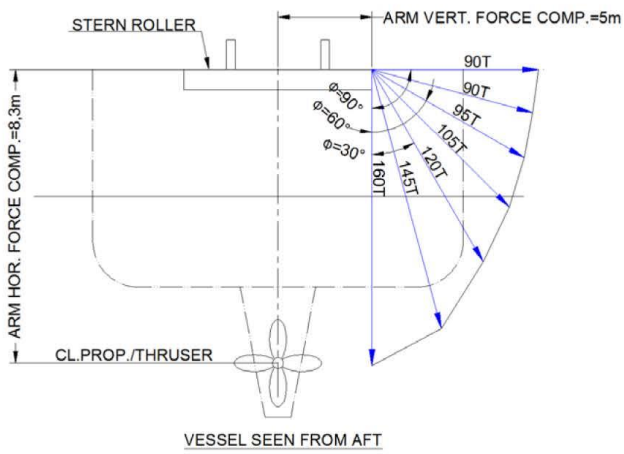

Figure 10

Case study simulations

	Situation 1 close to rig	Situation 2 On way to drop	Case study 3 At drop position
Distance vessel to rig [m]	50	1100	2200
Line length AC [m]	412	836	1682
Line weight, L*w [Ton]	160	100	58,8
TCx [Ton]	4,15	53,1	182
TCy [Ton]	0	0	16,7
TCz [Ton]	157	98,8	57,5
Force main fropeller [Ton]	-4,15	-53,1	-182
Force thruster 1&4 [Ton]	0,48	3,46	13,40
Force thruster 2&3 [Ton]	0	0	-16,9
Φ [Degr.]	0	0	16
Fz from stab calc. [Ton]	160	160	138
Heel from stab. Calc. [Degr.]	7,5	7,5	12
Average heel in sim. [Degr.]	8,6	5,44	5,9
Roll amplitude [Degr.]	0	2,16	4,72
Average pitch in sim. [Degr.]	0,51	0,34	0,28

Table 3

Fig.12 above shows the result from the case study simulations. It can be seen that the horizontal tension TCx is increasing, as the vessel is moving away from the rig. In situation 1, the vessel can handle a line weight close to the 160 Ton found from the stability calculation (Ref.fig.9). In situation 2, when the vessel is half way to the drop position, TCx has increased and the main propeller is compensating to keep the vessel in position. Now the line weight had to be reduces to 100 Ton in order for the ship not to exceed the allowable heel angle.

In situation 3, the vessel has changed course, and now the anchor line is not vertical but has an angle Ø of 16 degrees from the vertical. This is causing a horisontal force component from the line of 16,7 Ton, and the thrusters have to compensate for yaw and sway.

The result from using different connection point for the anchor line on the vessel is shown in tab.4. In the worst case, when the anchor line is connected 5m from ship centerline port. It was found significant increased heel amplitudes in addition to increased heel angle.

Point C pos. x,y,z [m]	Average heel [degr.]	Biggest heel [degr.]	Lowest heel [degr.]	Amplitude [degr.]
-34.9, 5, 2.39	-5,90	-10,65	-1,20	4,72
-34.9, 0, 2.39	-1,94	-4,85	0,97	2,91
-34.9, -2, 2.39	-0,68	-3,19	1,84	2,51

Table 4

Comparing the RAO

In fig.13 below is shown the result from the ROA compilation between the case with the vessel model alone, and with the line fixed on the stern. It was measured some bigger values for the case with the anchor line added to the model for wave periods above 10 sec.

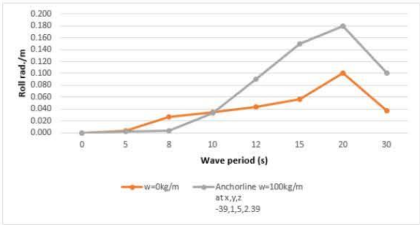

Figure 11

Discussion

Vessel stability:

The results for stability is dependent on among other factors, the location for the vertical center of gravity. In a thesis this location was estimated, and the results therefore not directly comparable with a real AHTS vessel.

The case study simulations:

In general, it should be noted that tuning of the position control model described in fig.6 might have influence on the simulations. Using too small or too big gain values may cause the simulation to fail, or give incorrect results.

In situation 1 (ref.tab.3), it can be seen that the heel in the simulation is 8,6 degree. which is close to expected heel from the stability calculations of 7,5 degree. The reason for this is assumed that MaxSurf takes the change in hull shape when the ship is heeling into account.

In situation 2 and 3, the maximum line weight in the simulation had to be reduced in order to not exceed the allowable heel angle from the stability calculations. The line weight possible to handle is influenced by the horizontal force components from the anchor line. In situation 2 the vertical force component is oscillating because the main propeller is compensating for surge drift, and this is increasing the heel angle and the roll amplitudes.
In situation 3, the vessel has changed course, and therefore it is a transversal force component from the anchor line. This is needed to be compensated by thruster 2 and 3, which will contribute to increase the heel moment. The moments created by the propulsion was also found to influence the RAO indirectly, since the anchor line model itself has not forces from inertia, drag or geometrical stiffness included. In situation 3 it also was found increased roll amplitude by moving the anchor line connection point towards port. This was assumed to be a consequence of the increased heel angle.

Conclusion

Operation in waves and big horizontal force components from the anchor line was found to reduce the possible anchor line weight possible for the vessel to handle due to the compensation from the propulsion.

The anchor line alone should not have direct influence on the vessel RAO. This because forces from drag, inertia and line stiffness is not included in the anchor line model,
But it was concluded that the components and moment around the z-axis in x-y plane from the line, is countered by the propulsion, and in that way the propulsion

is creating moments that increases the roll motion amplitudes as well as the static heel angle.

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