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Master's degree thesis

IP501909 MSc thesis, discipline oriented master

Assessment of Safety for Anchor Handling Operation

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Number of pages including this page: 53

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MASTER THESIS 2014

FOR

STUD.TECHN. Wenfeng Ni

ASSESSMENT OF SAFETY FOR ANCHOR HANDLING OPERATIONS

After the accident with the anchor handling vessel (AHTS) Bourbon Dolphin (which capsized in 2007), it became clear that the existing criteria for the anchor handling situation were insufficient. To evaluate the stability performance of an AHTS in operations, some modified limiting criteria were proposed. Because of the characteristics of the operations, the criteria may vary among different external conditions. In this work, the effects of these criteria are further studied.

In the project, the candidate will study the stability criteria for anchor handling vessels and establish a set of limitations for AHTS during anchor-handling operations. The static stability analysis will be carried out with the computer program Maxsurf.

The thesis work shall include the following:

- Describe several theory studies including:
  - Static stability criteria for general vessels
  - Additional criteria after accident of Bourbon Dolphin
  - Weather criteria
  - Dynamic stability criteria under drop of load, gust wind and beam waves
  - Evaluation of force between mooring lines and AHTS
- Describe typical anchor handling conditions of work vessels

- Establishes the model of AHTS of work conditions with software
- Analyze the floating state and buoyancy with the working condition
- Analyze the influence of the weight of anchor and mooring line to determine the allowable maximum mooring line tension.
- Carry out a sensitivity analysis to see how they will affect the stability during operation

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

In addition to the thesis, a research paper for publication shall be prepared.

Three weeks after start of the thesis work, a pre-study have to be delivered. The pre-study have to include:

- Research method to be used
- Literature and sources to be studied
- A list of work tasks to be performed
- An A3 sheet illustrating the work to be handed in.

A template for the A3 sheet is available on the Fronter website under MSc-thesis. This sheet should also be updated when the Master's thesis is submitted.

The thesis shall be submitted as two paper versions. One electronic version is also requested on a CD or a DVD, preferably as a pdf-file.

Supervision at AAUC: Karl H. Halse,

Karl H. Halse Wenfeng Ni

Program coordinator Stud. Techn

Delivery: 05/30/2014 Signature candidate: __ Wenfeng Ni________

Preface

This report is the result of my Master's thesis at The Aalesund University College (AUCC) at the spring of 2014.

The motivation for me to cover this topic at first is the guidance from my supervisor Karl H. Halse. Because I am interested in statistics, software and ship technology, so I choose the topic that can deeply study the vessel stability.

This thesis has given me an opportunity to go deeper into the field of vessel stability calculation that I had really weakness basis on. During the case study, I have learned more on the stability calculation, relevant knowledge and better use of Maxsurf. I need to mention here I am not good at English and there might be some grammar mistake or unclear expression that I feel sorry.

I would like to extremely thank my advisor Karl for excellent guidance and deep insight on the topic, during the study I through a time of lose myself and Karl didn't give up me and he there help me to uplift and inspire. Karl is really the best advisor. I would also like to thank my friend Jiang Zhu; he also helped me a lot.

Ålesund, December 19, 2013

Wenfeng Ni

ABSTRACT

The objective of this paper is to evaluate the stability performance of an AHTS in operations. After the accident with the anchor handling vessel (AHTS) Bourbon Dolphin (which capsized in 2007), it was clear that the existing criteria for the anchor handling vessel were no longer sufficient. There is an ongoing discussion that whether the criteria should be updated or not. The IMO criterion is the main criteria for special purpose vessel such as offshore supply vessel. But Bourbon Dolphin is a combined vessel with PSV and AHT. After that, NMD has suggested new criteria for the anchor handling vessel.

The most important thing is to evaluate the heeling moment during the operation. Several aspects regarding to operation should be studied. Because of the characteristics of the operations, the criteria may vary among different loading conditions. NMD report has proposed some suggestion for people to determine the characteristics of mooring load.

To describe the stability performance of an AHTS in operations, a computer program Maxsurf Stability is used to calculate the static stability curves and equilibrium data in various loading conditions.

The vessel stability mainly depends on the propulsion system, mooring load, external forces such as current, wind force or dynamical load. In the paper, there are some researches of mooring load parameters such as the angle beta between mooring line and center line and the angle alpha between mooring line and vertical axis. The angle alpha can be ignored while calculating the mooring load due to its small effect. After application of criteria, the maximum permissible tension will be figured out. These analyses are carried out under the vessel's working loading condition. In addition to this research, a sensitivity analysis based on modification of IMO weather criteria o can be studied. The results can be useful while designing work of anchor handling vessels and further work of analysis of AHTS.

TERMINOLOGY

Symbols

Δ	Displacement [t]
ϕ	Initial angle of heel Due to mooring Load [deg]
ϕ_1	Angel of roll to wind ward due to wave action [deg]
ϕ_0	Angle of heel under the action of steady wind speed [deg]
ϕ_C	Angelo f capsize under the action of gust wind speed [deg]
ϕ_V	Angle of vanishing stability [deg]
α	Angle between mooring line and vertical axis deg]
β	Angle of attack [deg]
a_{equil}	equilibrium - arm [m]
A_k	Total bilge keel area [m^2]
B	Breadth of the ship [m]
C_B	Block coefficient
D	Depth of the ship [m]
F_v	Vertical force component [t]
F_h	Horizontal force component [t]
F_{ML}	Force from the mooring line [t]
$F_{ML,XY}$	Horizontal force component [t]
$F_{ML,Z}$	Vertical force component [t]
GM_x	Transverse metacenter height [m]
GZ	Righting arm lever [m]
Hs	Significant wave height [m]
KB	Keel to buoyancy [m]
KG	Vertical center of gravity [m]

L	Water line length of the ship [m]
L_{pp}	Length between perpendiculars [m]
l_{w1}	Steady wing heeling arm [m]
l_{w2}	Gust wind arm [m]
M_t	Heeling moment due to mooring line [t*m]
M_H	Heeling moment due to horizontal force component [t*m]
M_V	Heeling moment due to vertical force component [t*m]
T	Draught [m]
T_p	Peak wave period [sec]
VCG	Vertical center of gravity [m]
y	distance between stern roller and ship's center line [m]
v	distance between stern roller and thruster's center line[m]

Abbreviations

IMO	International Maritime Organization
AHV	Anchor Handling Vessel
BP	Bollard pulls
AHTS	Anchor handling tug supply
BD	Bourbon Dolphin
CL	Centre Line
DNV	Det Noske Veritas
NMD	Norwegian Maritime Directorate
SOLAS	at Sea
SR	Stern roller
TR	Towing pin
WL	Water line

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1 Introduction

1.1 Background

Nowadays, all countries in the world are trying to exploring the resource from the endless ocean, even the Northern polar and the South Polar. With the great development of technologies, human nowadays have been able to drilling the oil and gas from the deeper sea. The offshore of semi-submerse, TLP and FPSO may work in the deep sea 3000 feet height. Those machineries usually work in the areas for a very long time without power plant, which means they need some other supply vessel work for them when they need to move or other action.

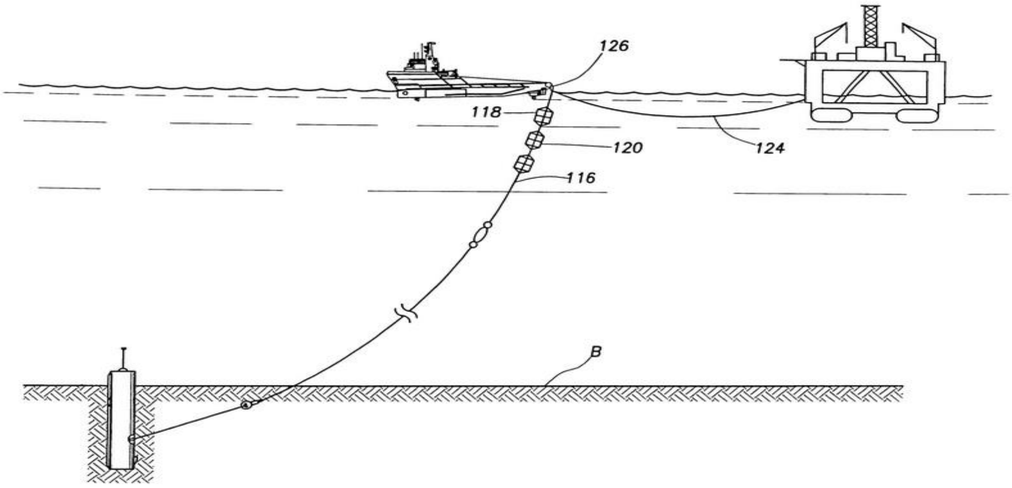

Figure 1 – Offshore vessel and platform

Platform supply vessel (PSV), offshore supply vessel (OSV) and Anchor handling tug (AHT) vessel are designed to serve these huge constructions. They are small size vessels but with large power and are equipped with cranes, mooring winches and some other machineries to server the drilling platform. Unfortunately, majority of the offshores are working under dangerous sea conditions. And small vessels are always with lower stability compare to large size vessels. And the actions and operations of supply vessels decrease the stability of the vessels seriously so that they are always with very high risk during working. In this paper, it will be place emphasise on the offshore supply vessels but with two different sizes. But anchor handling tug vessel will be discussed as well.

1.2 Anchor handling vessel

There is a disaster of Bourbon Dolphin1 on April 12, 2007. Bourbon Dolphin is a Norwegian AHTV and she capsized with 15 Norwegian sailors, while 5 are still missing and three of the ten are reported dead. This accident happens when she was anchoring the semi-submersible drilling platform. Therefore, to ensure the safety of operations for crew, vessel and ship equipment, it is important to make a criterion for the operation. After the disaster, the Norwegian Maritime Directorate (NMD) was on 10 April 2008 requested by the Ministry of Trade and Industry to follow-up the report and work after the accident. Anchor handling operations is a series of operations to deploy and retrieve anchors for rigs or drilling platform at a certain distance. Thus, definition and evaluation of stability criteria for anchor handling operation are very necessary to avoid another tragedy.

Figure 2 – Bourbon Dolphin

Figure 3 Anchor handling operation

1.3 *Anchor Handling Equipment*

Anchor handling operation requires a set of equipment during two main missions of deploying anchor and recovering anchor. The mainly equipment affect the performance of vessel is presented as follow:

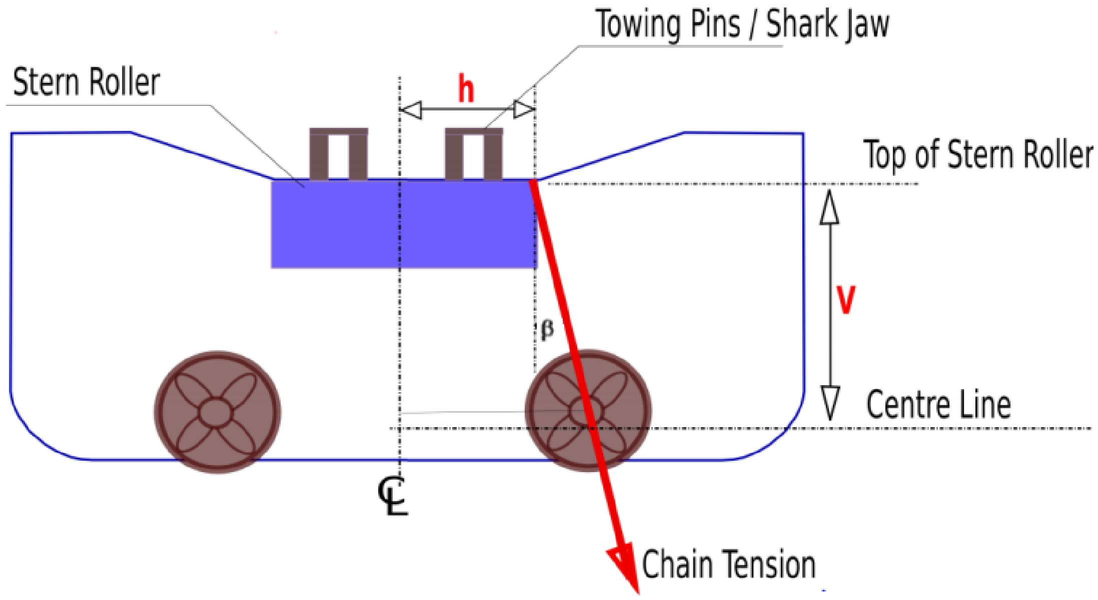

Figure 4 – Back views with equipment

- Work Wire

The work wire is connected with the winch and used for deploying and recovering anchor. Usually, the length of wire should be long and strong enough to reach the seabed.

- Winch

The winch contains both anchor handling drums and towing drums connected to the same drive system. The direction of rotation is normally over wind, so that the work wire has a small downwards angle to towards the stern.

- Stern Roller

The stern roller is a large cylindrical roller fitted at the stern edge of after deck to allow various awkward and heavy objects such as chains, anchors. It is primarily used to be hauled on board without causing excessive damage to the stern.

- Guide Pins

A guide pin is to keep the work wire in the centre line area of the vessel. There are several pins installed to locate the wire at the stern deck.

- Shark Jaw

Line and chain-handling device fitted in anchor handling tug forward of the stern roller to grip the chain or wire of the rig's anchor securely once it has been hauled on the vessel.

1.4 Anchor handling operations

Anchor handling operations are not very standard procedures, and a thorough plan in advance is a necessary procedure before operation. Several factors like sea state, tension of mooring load should have been considered in the plan. The report after the accident of the Bourbon Dolphin concluded several human errors leading to accident. But the capsizing is due to the inadequate stability.

1.4.1 Deploying the anchors

The anchor handling vessel tugs the wire from the rig to the anchor. When the wire is close to the anchor, the wire will be connected with the anchor and lowered down to the seabed. During to the operation, the vessel is under an external force from mooring line depending on how far away from the rig the anchor is to be deployed. In addition to mooring load, the current forces, wind forces and the dynamical loads on deck reduce the stability as well. Therefore, the anchor handling vessel need sufficient vessel to handle these conditions than other normal vessels. There are four phases during deploying the anchors:

1. Receiving a permanent chaser pendant
2. Deploying the anchor
3. Chasing back
4. Passing back the permanent chaser pendant

1.4.2 Anchor Recovery

The procedure of recovering of anchor is a reverse procedure of the anchor deploying procedure. The AHT vessel pulls the water depths of wire and tugs the anchor from the seabed. Until the anchor is above the water, the rig crane begins to pull it in the wire when the winch rolls up the anchor and reverses towards the rig.

2 Stability Theory

This chapter will describe the ships' intact stability which is the ability to withstand external effects. Subsequently, the characteristics of mooring line will be illustrated and discussed. The most important goal is to figure out the mathematic relations among these parameters.

2.1 Intact Stability[2]

Stability is the tendency of a vessel to rotate one way or another when forcibly inclined. The lifting force is called buoyancy force (B) and the weight of force of gravity is called force of gravity (G). When the ship is in upright position, buoyancy force and gravity force are in the same action line but opposite directions. When a ship is inclined, the center of buoyancy (B) shifts off centerline while the center of gravity (G) remains in the same position. Due to equal value forces of buoyancy and gravity and act along parallel action lines, but in opposite directions, a rotation is developed. This is called a couple, two moments acting simultaneously to produce rotation. This rotation returns the ship to where the forces of buoyancy and gravity balance out. The distance between the forces of buoyancy and gravity is called righting arm (GZ). In any heeling angle (θ) right moment (RM) is displacement times right arm (GZ). The right moment is the best measure of a ship's stability. It describes the ability of ship to resist inclination and return to equilibrium.

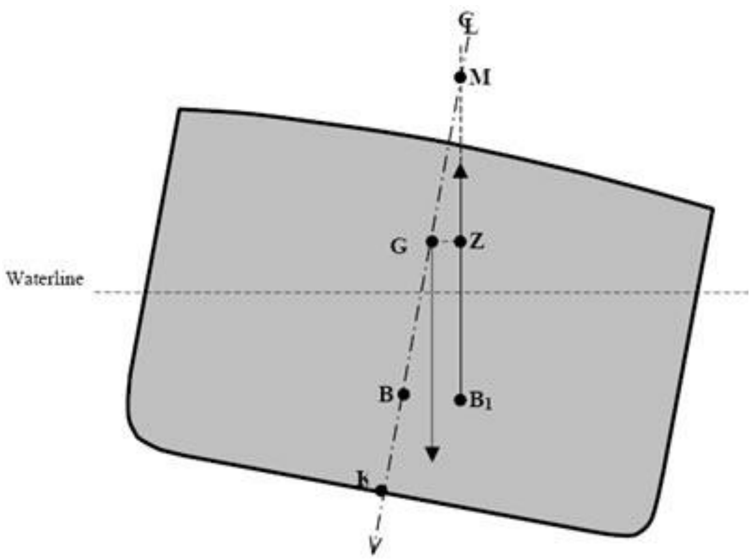

Figure 5 – A ship with heel seen from behind

With the increasing of heeling angle the righting arm (GZ) and right moment are increasing as well. But if the angle heel too large, the center of buoyancy (B) will move back to another side of force of gravity (G), therefore, an added heeling moment will be developed to take place of counteracting moment. This is the ship's maximum heeling angle which describes the capability of ship's stability. Metacentric Height (GM) is a measurement calculated by subtracting KG from KM (GM = KM - KG). GM is a measure of the ship's initial stability.

When a ship is inclined through all angles of heel, and the righting arm for each angle is measured, the statistical stability curve is produced. This curve is "snapshot" of the ship's stability at that particular loading condition.

2.2 *Relevant stability criteria*

Before the accident of Bourbon Dolphin, there were no specific internationally applicable stability criteria for anchor handling tug vessels. Since the disaster, engineers began to improve the requirements for the vessel working with specific proposes.

2.2.1 IMO Code on Intact Stability[3]

IMO intact stability criteria are a general requirement for all ships. The IS code covers some measures to against the capsizing regarding to metacentric height (GM) and righting lever (GZ); weather criteria (severe wind and rolling criterion); watertight integrity; IMO A.749(18) Ch4.5.6.2 offshore supply vessels indicates the static and dynamic criteria for offshore supply vessels. And a little requirement associated with anchor handling vessel stability is discussed when mentioned to mooring loads.

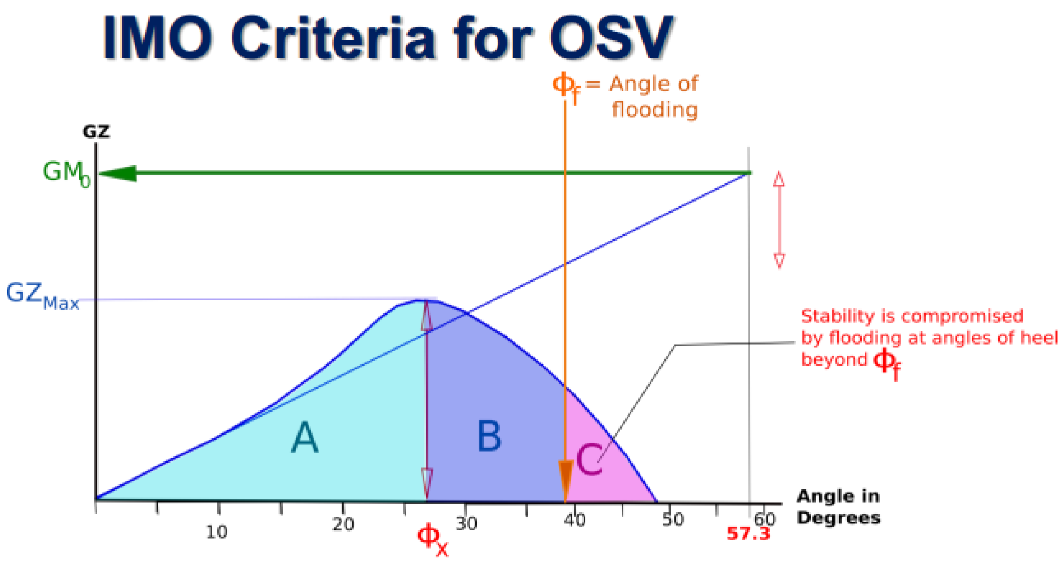

Figure 6 - IMO criteria for OSV

2.2.2 Norwegian Maritime Directorate (NMD)[4]

Norwegian Maritime Directorate (NMD) has provided new criteria for the AHTS regarding to calculation of permissible tension and maximum heeling angle. NMD Circular - Series V, RSV 04 – 2008, 14 July 2008.[5]

The list angle as a result of inflicted moments shall not exceed:

- 15° ： This angle is low enough to enable corrective action to be taken and make suspension of operation possible, at the same time as the angle is so large that it clearly indicates that the load is too high.
- Flooding angle: A freeboard requirement that makes work on deck possible in a critical static situation, at the same time as the ship's stability is significantly reduced beyond this angle.
- Angle for 50% of GZ_{max}: Provides a safety barrier with regard to the righting arm.

The Commission's recommendations indicate that the vessel needs some potential stability for the mooring line force during operation. The third requirement means that the maximum righting arm could not be decreased with more than 50% while mooring force is applied on the vessel.

From the commission's report, we could know that the general requirements for stability are accepted with small margin while stability reserve is small.

The NMD proposes an area requirement6 of 0.055 m*rad between heeling arm and righting arm up to the second intersection point, angle of flooding or 40°. The area requirement is based on the IACS area requirement for towing vessels, which is 0.09 m*rad, adjusted for a dynamic increase of 40%. The area requirement is expected to contribute to a greater extension of the GZ curve. Anchor handling vessels shall comply with the current towing requirements in relation to their maximum bollard pull.

2.3 Additional criteria for AHT vessel

2.3.1 Mooring load parameters

The NMD also recommends the requirement for the heeling moment. They suggest the heeling moment arm and righting moment arm should be located on the upper outer edge of the stern roller during calculation. On the general normal arrangements of towing pins and stern rollers, a lever arm greater than the distance between centerline and the outer edge of the stern roller is not necessary. But the smaller area between wire and chain may result a smaller moment arms. This condition should be considered and evaluated during design phase.

2.3.2 Angles on the mooring line

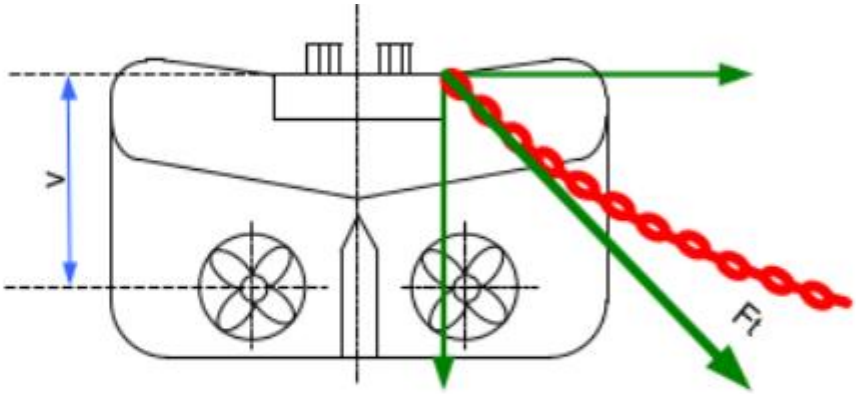

Figure 7 - Back view of vessel

Due to the special propose of AHT, tensions on the vessel will be the most dangerous key points affecting the capability of vessel. Thus, NMD defined the angles for the mooring line to calculate the maximum tension on the vessel during operation.

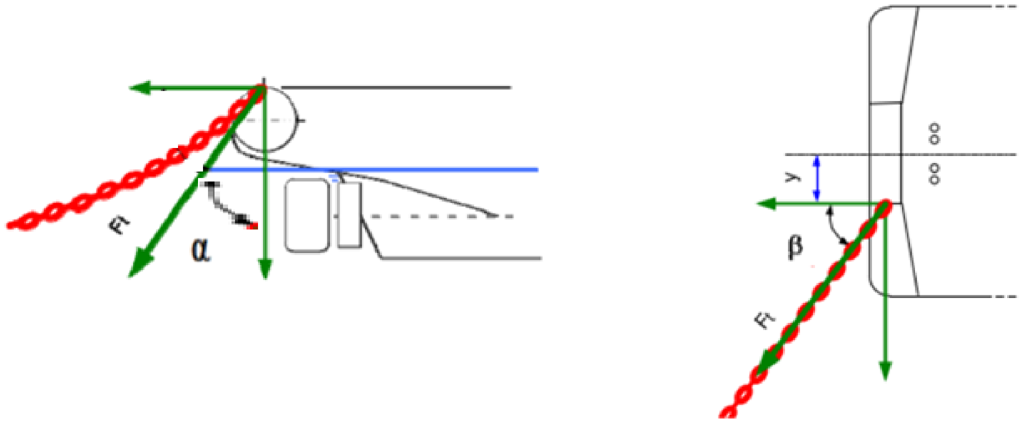

Figure 8 mooring load in the horizontal and vertical planes

α – the attack angle between the ship's horizontal plane and the mooring line. And it will be given based on three variables: the distance between point of attack on the line to the point where the line leaves the rig; the run – out line's composition; the length of the run – out chain.

β – the angle between the ship's centerline and the mooring line in the horizontal plane. It will be given when the angle between the line's defined point of attack to the point where the line leaves the rig and vessel's heading.

2.4 Internal force

Obviously, the most important force is the mooring loads which consist of several parameters. Mooring line force is not a constant force which is a combined force and it increases while the wire is running – out. Mooring load will increase a ship's trim and heeling. The figure show below will help understand the principle.

Basically, the mooring line force can be divided into three force components in three directions. As is showed in figure below, the longitudinal direction is X-axis. Y-axis is along the transverse direction. Z-axis is the vertical direction. As mentioned in Ch2.1.2, Y, V, α and β have been defined by the criteria.

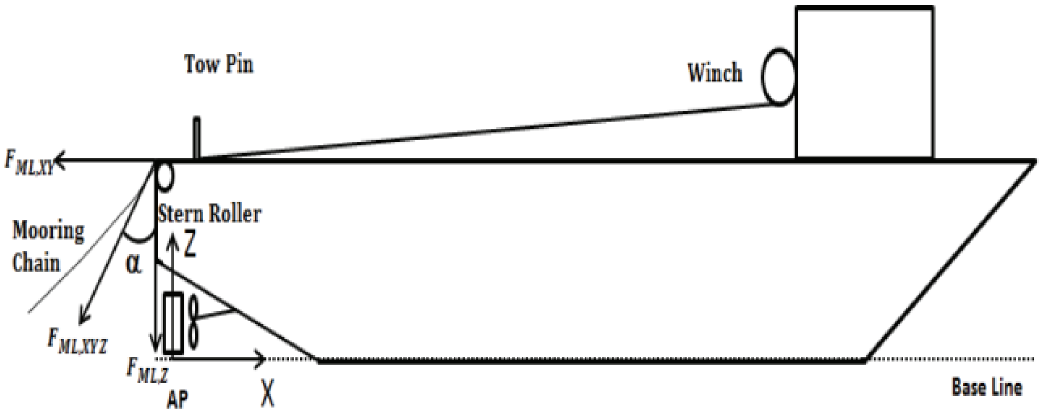

Figure 9 - A profile view of AHT

$$F_{ML,XYZ} = F_t \tag{2.1}$$

$$F_{ML,XY} = F_{ML,XYZ} \times \sin\alpha \tag{2.2}$$

$$F_{ML,Z} = F_{ML,XYZ} \times \cos\alpha \tag{2.3}$$

Where $F_{ML,XYZ}$ and F_t are the total forces from mooring chain.

$F_{ML,Z}$ is the vertical force component.

$F_{ML,XY}$ is the horizontal force component.

α is the angle between mooring line and Z-axis.

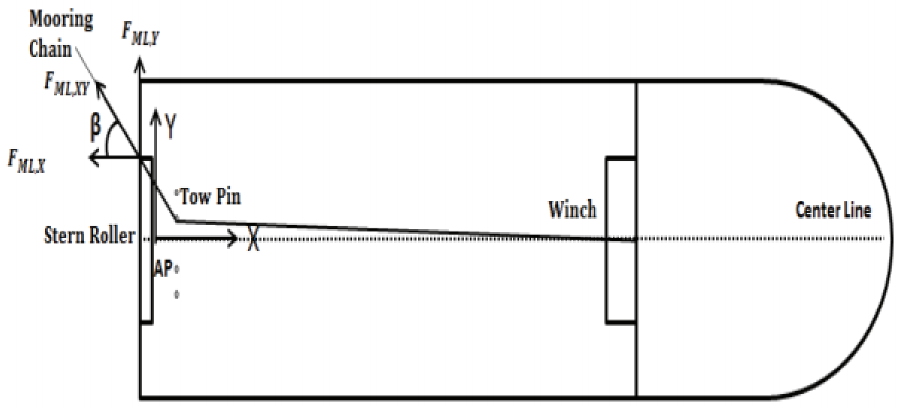

Figure 10 - A plan view of AHT

$$F_{ML,X} = F_{ML,XY} \times \cos\beta = F_t \sin\alpha \cos\beta \tag{2.4}$$

$$F_{ML,X} = F_{ML,XY} \times \sin\beta = F_t \sin\alpha \sin\beta \tag{2.5}$$

Where $F_{ML,XYZ}$ and F_t are the total forces from mooring chain.

$F_{ML,Z}$ is the vertical force component.

$F_{ML,XY}$ is the horizontal force component.

β is the angle between mooring line and center line in the horizontal plane.

With the equation above, the relations among total force and three force components are clearly described.

In various loading conditions, the effect of stern forces on trim and displacement shall be taken into account. There will be pressure due to the concentrated load in the ship's centerline in the upper edge of stern roller. Alternatively, more accurate and iterative methods can be used to calculate the stern force. The NMD suggests that initial test calculations to test whether the effect of free trim regardless of axis has a significant impact on certain types of vessels.

2.5 Heeling moment analysis

The most important factor affecting the stability is the heeling moment. Normally, it is due to external force such as transverse force component from mooring line, waves and wind forces. Due to the influence of transvers forces, vessel rolls on the sea and the chain line will be deviated to port side or starboard. When the chain will smack over against from one side outer pin to the other side, the list moment will increase dramatically. And if the rotating direction is the same as the list moment, it will be the most dangerous conditions during anchor handling.

The heeling moment M_{ML} can be calculated as equation:

$$M_{ML} = (F_t \cdot \sin\alpha \sin\beta \cdot v) + (F_t \cdot \cos\alpha \cdot y) \tag{2.6}$$

Where v is the distance between out-edge of stern roller and center line of the thruster

y is the distance between out-edge of stern roller and center line of the vessel

M_{ML} is the heeling moments from

F_t is the force from mooring chain

According to another report[7], the angle α can be represented as a function of β ,as showed below:

$$\alpha = \arctan\left(\sin\beta \frac{v}{y}\right) \tag{2.7}$$

2.6 Curves for maximum permissible moment[8]

To determine the maximum tension on the vessel, a curve should be defined. The value of force is a function of the displacement/draught and vertical center of gravity (VCG) to meet the stability criteria. The dynamic additional forces should be taken account to while calculating the maximum permissible tension.

The limit curves should exceeding the maximum permissible moment, thus means the vessel has enough stability for entitle range of anchor handling operations. The angles α and β will be various while pulling an anchor or running – out of chain. When it comes to pulling an anchor handling as the vessel is located straight above the anchor's position at the bottom, α will be small and β will be close to 90°. While running – out of chain, β will be vary and α will be kept small. The maximum permissible moment can be calculated back to a maximum tension by using a selected angle interval when the tension appears as the minimum pulling power in the intervals.

2.7 Tension directions and heeling moments

This is a table shows the relations tension directions and heeling moments. The angle alpha and beta are various from 0 to 90 degrees. This method will describe the influence of angle α and β .

In the calculation, the tension is assumed to be 150 tones. The distance of v and length of y are 6.4m and 3m. According to the equation (2.6) and (2.7), the heeling moments are showed below:

Table 1- Tension directions vs Heeling moments

α (deg) \ β (deg)	β = 0	β = 15°	β = 30°	β = 50°	β = 70°	β = 90°
α = 0	450	450	450	450	450	450
α = 5°	448	470	490	512	527	532
α = 30°	390	514	630	757	841	870
α = 35°	369	511	644	790	886	919
α = 40°	345	504	653	817	924	962
α = 45°	318	494	657	838	956	997
α = 50°	289	480	657	852	980	1025
α = 55°	258	462	651	860	997	1044
α = 60°	225	440	641	862	1006	1056
α = 65°	190	415	625	856	1008	1060
α = 70°	154	387	605	845	1001	1056
α = 80°	78	323	551	802	967	1024
α = 90°	0	249	480	735	902	960

According to the table, the effects on the heeling moment from angle α and β is obvious. When the α increases, the heeling moment is decreasing. As the angle β increases, the heeling moment is increasing. Thus, the heeling moments distribution for a given angle β could be plotted as follow figure

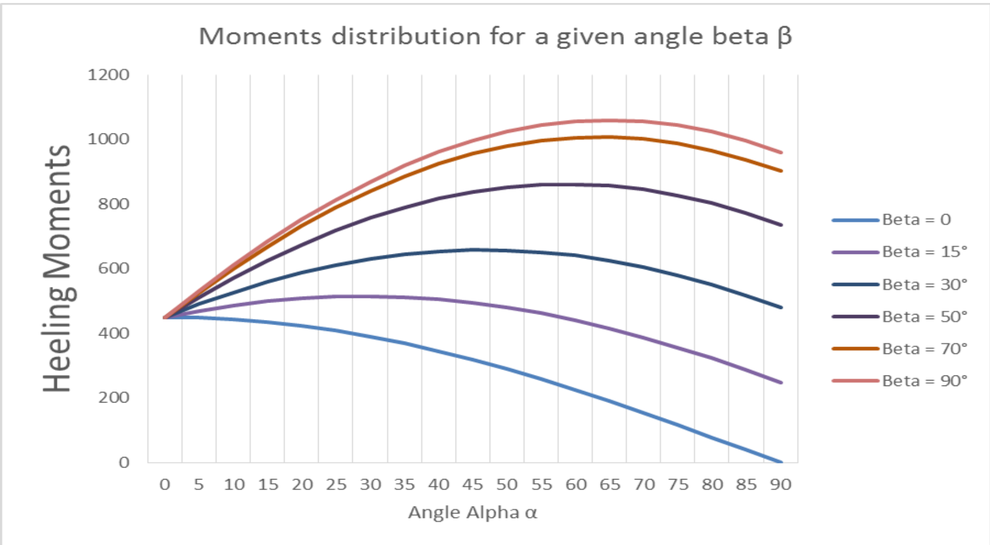

Figure 11 - Moments with angle β

Table 2- Tension for a given beta when moment is fixed

Alpha\beta	β = 0	β = 15°	β = 30°	β = 50°	β = 70°	β = 90°
α = 0	233.33	233.33	233.33	233.33	233.33	233.33
α = 5°	234.22	223.44	214.25	204.95	199.30	197.40
α = 25°	257.43	204.76	171.98	146.16	133.10	129.09
α = 30°	269.39	204.33	166.79	138.67	124.92	120.75
α = 35°	284.79	205.45	163.10	132.88	118.54	114.24
α = 45°	329.85	212.61	159.71	125.31	109.85	105.33
α = 55°	406.52	227.44	161.25	122.06	105.33	100.54
α = 60°	466.24	238.52	163.91	121.86	104.37	99.40
α = 65°	551.43	252.75	167.97	122.59	104.21	99.03
α = 85°	2654.38	365.93	202.91	136.04	111.94	105.44
α = 90°	293012.06	422.19	218.69	142.76	116.37	109.33

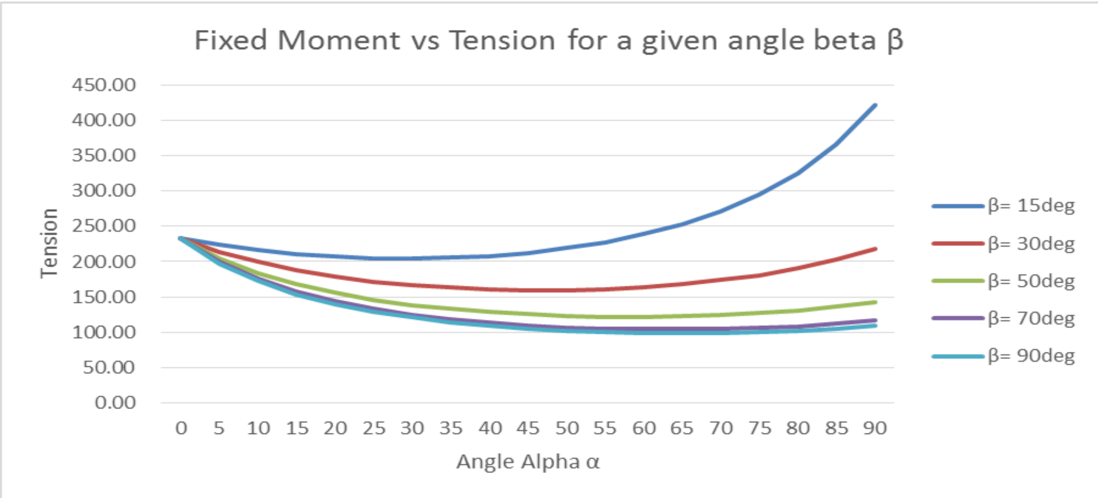

Figure 12 - Tension for a given beta when moment is fixed

2.7.1 Conclusion

This figure shows that the heeling moment could reach to an unacceptable level as β is increasing. Obviously, the heeling moment mainly depends on the angle β, the effect of α can be ignored. This conclusion will be applied on the next chapter during research the vessel stability. And in the chapter 4, a sensitivity analysis on program will be carried out to prove this conclusion.

3 Study Case

In the Maxsurf Stability program, it is not available to define a given mooring load with various directions. This chapter indicates how to use the program to simulate the anchor handling operation and evaluate the stability of the vessel. IMO and NMD criterion will be applied during evaluation. Subsequently, a table of maximum allowable tensions is plotted as a liming curve. Finally, a sensitivity analysis is carried out to determine that how far the influence of mooring load parameters is able to affect the stability of offshore vessel during anchor handling operation.

3.1 3D model in the program

A computer program Maxsurf, version 19.0 is used to build the 3D model for a vessel and simulate it in varies loading conditions to generate static stability curves. This program is able to track the equilibrium position of the ship in still water by adjusting the load and buoyancy for a given model with weight and center of gravity. This program takes account for the changes of deck immersions, center of gravity, buoyancy and opening positions. In this paper, the main goal is to determine the method to simulate the anchor handling operation in Maxsurf before evaluation of stability. And the sensitivity analysis mainly focuses on roll angle and the capsizing angle. The flooding angle usually depends on its position and ship model data. This paper is no longer an intact stability report. Therefore, the down flooding points will not be considered in this paper.

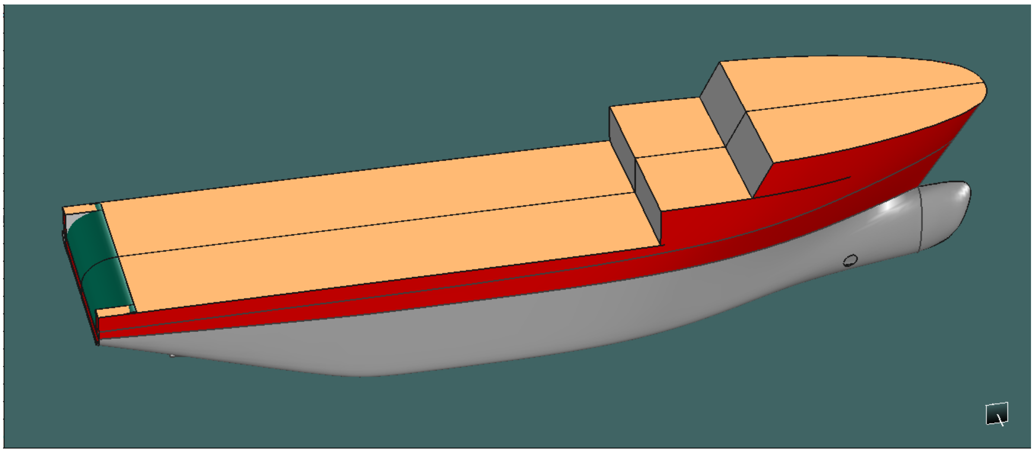

Figure 13 – 3D model in Maxsurf

3.2 The particulars of anchor handling vessel (AHV)

In this paper, the main interest is to discuss the effects from angles of mooring line and tensions. These results will be varies due to different vessels. The AHV model I used is provided by the model library from documents of Maxsurf. And program also provides departure mud loading condition for this ship. Due to these original default data for program, the simulation and results will be more reality than setting loading conditions by users.

3.2.1 Principle particulars of anchor handling vessel

The follow main dimensions are used throughout the rest of the paper. This model modified from the OSV parent ship model which is provided by Maxsurf documents. The winch capacity is defined according to the statics of several vessels which has the similar size. And the statics also indicates that the bollard pull capacity is always no more than 50% of the winch capacity.

Table 3- Principle particulars

Overall length	L_{OA} = 61m
Length between particulars	L_{pp} = 56 m
Breadth	B = 14 m
Draft	T = 5.4 m
Displacement	∇ = 3124t
Depth	D = 8.00 m
Bollard pull Capacity	180 tones
Winch capacity	400 tones

3.2.2 Initial loading condition

Maxsurf provides two arrangements for loading conditions in the model. The assumption is that the departure mud loading condition is the initial loading condition for the AHT vessel before operation. The departure-mud loading condition is presented in the appendix.

3.2.3 Working loading condition

In this part, the working loading condition is discussed. The method of simulation in program is indicated as well.

3.2.4 Trim analysis:

The vertical force component of the mooring load decreases the trim and freeboard of the vessel. That means the vertical force component of the mooring load should be taken account of when calculating the floating position as well.

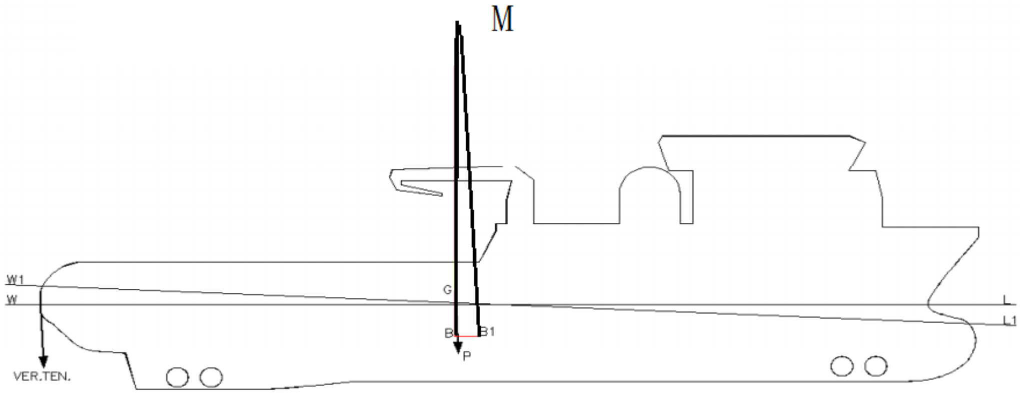

Figure 14 – trim and floating position

3.2.5 Heeling moment analysis

As mentioned before, in the Maxsurf Stability, it is not allowed to define a given mooring load with a specific direction directly. To simulate the working loading condition, the method applied in the trimming moment could be useful as well. Determining a new equilibrium-arm with previous vertical force component is to take place of heeling moment of transvers mooring load.

Due to the ignored effect of angle α on the heeling moments, which has been proved in last chapter, and to make the method simple while setting values in program, the influence of α would not be considered during this chapter. Thus, the heeling moments should be calculated as follow equations:

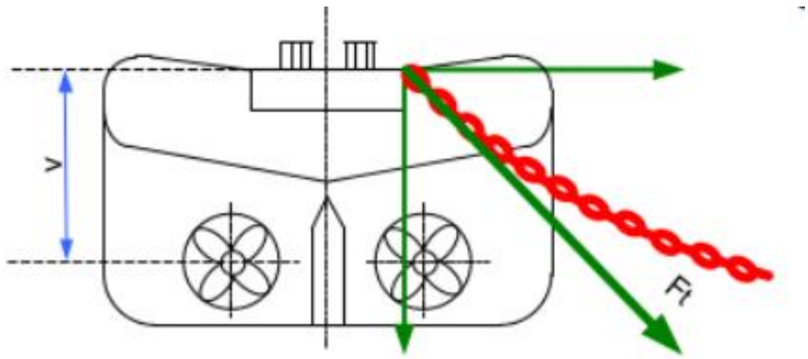

Figure 15 mooring line in transverse plane

The mooring force in transverse plane can be divided into vertical force F_V and horizontal force component F_h .

$$F_h = F_t \times \sin \beta \quad (3.1)$$

$$F_v = F_t \times \cos \beta \quad (3.2)$$

Where F_h *is the horizontal force component*

F_v *is the vertical force component*

F_t *is the value of mooring load*

The additional heeling moment can be divided into two components due to the horizontal force component and vertical force component.

$$M_H = F_h \times v \tag{3.3}$$

$$M_V = F_v \times y \tag{3.4}$$

$$M_t = M_H \times M_V \tag{3.5}$$

Where M_H *is the horizontal heeling moment*

M_V *is the vertical heeling moment*

Thus, the total heeling moment can be taken place by a new heeling moment composed of previous vertical force component and a new equilibrium arm.

$$M_{total} = F_{vertical} \times a_{equilibrim} \tag{3.6}$$

$$a_{equil} = \frac{M_{total}}{F_{vertical}} \tag{3.7}$$

Where a_{equil} is equilibrium-arm.

Table 4-mooring load parameters

y	3 m
v	6.4 m
DF	1.3
β	(1, 15, 30, 45, 60, 75, 89) degrees
Tension of mooring line	50t, 100t, 150t, 200t

When calculating the 0 and 90 degrees, excel can’t be recognized, thus use 1 degree and 89 degrees to take place of 0 and 90 degrees. The calculation is presented in the Appendix B.

Table 5 equilibrium-arm regarding to angle β

β	0	15°	30°	45°	60°	75°	90°
Arm - equilibrium	3.1 m	4.7 m	6.7 m	9.4 m	14.1 m	26.9 m	369.7 m

According to the results above, the new equilibrium - arm can be calculated with equation (3.7). Subsequently, the arm - equilibrium should be transferred into Y-axis to a new loading condition. This is the simple way to simulate a working loading condition with given mooring loads in various angle β. The new arrangements of new loading conditions are presented in the appendix.

3.3 Criterion study

3.3.1 NMD Criteria

As can be seen, the heeling moment decreases the possibility of passing the criteria due to the change of level of stability.According to the NMD criteria, the maximum heeling angle should not exceed:

- 15 degrees
- Immersion angle : the angle occurs at water on deck
- The angle regarding to 50% maximum GZ value

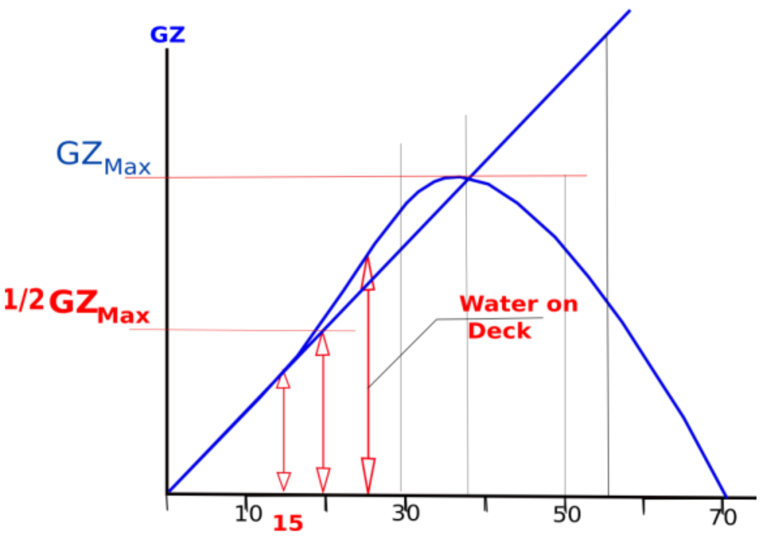

Figure 16 – NMD criterion for maximum heeling angle

As has been mentioned before, the trim of the vessel should be taken account while measuring the maximum heeling angle. But according to the report from G R S Gunnu and T Moan[9], the influence of angle (α) between mooring load and vertical axis is negligible. Therefore, only the angle (β) is considered while calculating the maximum heeling angle and α is assumed to be 0. The detailed results are presented in the appendix and Excel file.

3.3.2 Check the IMO criteria

IMO A.749 (18).Ch4.5 is the criteria for offshore supply vessel. As mentioned before, bourbon dolphin is a combined PSV and AHT designed vessel. Thus means IMO A.749 (18).Ch4.5 should be a part of basic requirements for an AHT vessel. In the Maxsurf Stability, the vessel is able to be checked by several criterion including IMO criteria. The results are showed in the table below. The introduction of IMO A.749 (18).Ch4.5 is presented in the appendix.

Table 5 – Results of vessel checked by IMO

Tension	Attack angle (β)	IMO Criteria	Tension	Attack angle (β)	IMO Criteria
50t	0°	All Pass	150t	0°	All Pass
	15°			15°	
	30°			30°	
	60°			60°	
	90°			90°	
Tension	Attack angle (β)	IMO Criteria	Tension	Attack angle (β)	IMO Criteria
100t	0°	All Pass	200t	0°	Pass
	15°			15°	Fail
	30°			30°	
	60°			60°	
	90°			90°	

According to the table above, the vessel almost meets the IMO requirements while mooring load no more than 150 tones. It is not fulfill the criteria when the tension increased to 200 tones with the attack angle (β) over 15 degrees.

3.3.3 Water on deck

The angle at water on deck is a necessary criterion when evaluating the stability of vessel. According to NMD criteria, the maximum heeling angle should be the minimum values among three angles.

3.4 Results

3.4.1 When the tension is 50tones:

Table 6 - Results when mooring load is 50t

Attack angle （β）	50%GZmax	angle(deg)	＜ 15°	immersion angle(deg)
0°	0. 32	20. 0	No	7. 1
15°	0. 30	20. 9	No	7. 2
30°	0. 29	21. 6	No	7. 6
45°	0. 29	22. 2	No	8. 2
60°	0. 29	22. 5	No	9. 0
75°	0. 29	22. 6	No	9. 9
90°	0. 31	22. 3	No	10. 8

According to the table above, when the line tension is 50tones, the angles corresponding to 50% maximum GZ values are all over 15 degrees. Thus means, the maximum heeling angle for this vessel is depending on the immersion angle which ranges from 7.1 degrees to 10.8 degrees.

3.4.2 When the tension is 100tones:

Table 7 - Results when mooring load is 100t

Attack angle （β）	50%GZmax	angle(deg)	＜ 15°	immersion angle(deg)
0°	0. 25	20. 9	No	3. 7
15°	0. 22	22. 6	No	3. 9
30°	0. 20	24. 1	No	4. 6
45°	0. 19	25. 1	No	5. 7
60°	0. 19	25. 7	No	7. 1
75°	0. 20	25. 8	No	8. 9
90°	0. 23	25. 7	No	10. 8

According to the table above, when the line tension is 100 tones, the angles corresponding to 50% maximum GZ values are all over 15 degrees. Thus means, the maximum heeling angle for this vessel is only depending on the immersion angle which ranges from 3.7 degrees to 10.8 degrees.

3.4.3 When the tension is 150tones:

Table 8 - Results when mooring load is 150t

Attack angle(β)	50%GZmax	angle(deg)	< 15°	immersion angle(deg)
0°	0.24	25.6	No	0.3
15°	0.19	23.8	No	0.6
30°	0.16	25.9	No	1.6
45°	0.15	27.3	No	3.1
60°	0.16	28.0	No	5.2
75°	0.19	28.1	No	7.8
90°	0.23	27.7	No	10.5

According to the table above, when the line tension is 150tones, for this vessel, the angles corresponding to 50% maximum GZ values are all over 15 degrees. Thus means, the maximum heeling angle for this vessel is depending on the immersion angle which ranges from 0.3 degree to 10.5 degrees.

3.4.4 When the tension is 200tones:

Table 9 - Results when mooring load is 200t

Attack angle(β)	50%GZmax	angle(deg)	< 15°	immersion angle(deg)
0°	0.22	21.7	No	0
15°	0.16	25.2	No	0
30°	0.13	28.0	No	0.3
45°	0.12	29.7	No	0.7
60°	0.14	30.4	No	3.5
75°	0.18	30.2	No	6.7
90°	0.24	29.6	No	10.3

According to the table above, when the line tension is 200tones, the angle occurs at water on deck is 0 which means that the deck is lower than the water line while mooring load is 200t. So the vessel could not work safely during operation.

3.4.5 Conclusion

According to these results, the vessel has less potential stability as an AHT during anchor handling. Because the angles associated with 50% GZ_{max} are higher than 15 degrees. The immersion angles with mooring loads are small.

3.5 *Tables for maximum permissible tension*

To work safely during operation, it is necessary to determine a limitation curve during operation. And the maximum allowable force curve should be given as curves exceeding the maximum permissible moment. As mentioned before, the moment due to the mooring load had been replaced of a new moment which consists of a vertical force component and a new equilibrium – arm. According to the results, the equilibrium – arm is a constant value associated with a constant angle β . That provides users a simply way to figure out a maximum heeling moment by only setting vertical force component. Eventually, the maximum allowable tension could be calculated by the equation

$$T_{\max} = \frac{F_{vertical(\max)}}{\cos\beta \times DF} \tag{3.8}$$

3.5.1 Check the IMO A.749 (18).Ch4.5

As can be seen, IMO is a basic criterion for AHT vessel. Firstly, checking the mooring load varied from 50t to 200t is a simple way to find an approximate magnitude of tension for a given attack angle β .

Table 10 - 3.5.1 Check the IMO A.749 (18).Ch4.5

Angle(β)	Mooring load	Maximum heeling angle(deg)	IMO Criteria
0°	50t	7.1	Pass
	100t	3.7	Pass
	150t	0.3	Fail
	200t	0.0	Fail
15°	50t	7.2	Pass
	100t	3.9	Pass
	150t	0.6	Fail
	200t	0.0	Fail
30°	50t	7.6	Fail
	100t	4.6	Pass
	150t	1.6	Pass
	200t	0.3	Fail
45°	50t	8.2	Pass
	100t	5.7	Pass
	150t	3.1	Pass
	200t	0.7	Fail
60°	50t	9.0	Pass
	100t	7.1	Pass
	150t	5.2	Pass
	200t	3.5	Fail
90°	50t	10.8	Pass
	100t	10.8	Pass
	150t	10.5	Pass
	200t	10.3	Fail

According to this figure, while β is less than 15 degrees, the vertical force component decreases the trim too much.

3.5.2 Test and determine the maximum vertical force component.

The maximum $F_{vertical}$ force needs to be tested by the program repeatedly to find the accurate values. Finally, the maximum mooring load can be calculated by the equation (3.9)

Attack angle (β)	0°	15°	30°	45°	60°	75°	90°
Arm - equilibrium	1.0 m	4.7 m	6.7 m	9.4 m	14.1 m	26.9 m	369.7 m
Maximum F-vertical	184t	130t	98t	74t	50t	27t	2t
Maximum Mooring load	141.6t	103.5t	87t	80.5t	76.9t	80.2t	88.2t

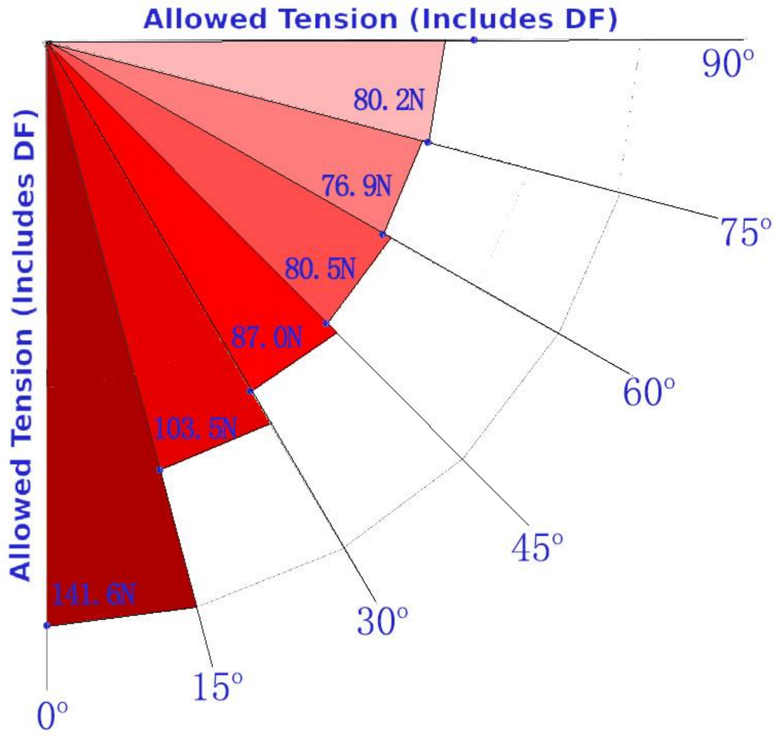

Figure 17 - Maximum allowable tension associated with angle β

As has been plotted in chapter 2.7, the maximum moment happens when β is close to 60 degrees. While β is large than 65 degrees.

3.6 Conclusion

In this chapter, a simple way to determine the mooring load in Maxsurf Stability has been introduced. The main principle is to define a new load point to simulate the trimming and heeling moment. As can be seen, the heeling moments is increasing as angle β increases. Meanwhile, heeling moments is decreasing while angle α increases. That means only β needs to be considered during calculating the maximum allowable tension.

4 Sensitivity Analysis

In this part, the primary aim is to calculate the allowable roll angles and vanishing angles by IMO weather criteria. As has been discussed in Ch2, that the heeling moment mainly influenced by angle beta. Thus, a sensitivity analysis will be carried out to find that how far the mooring load parameters could affect the vessel. In addition to the mooring load, the wind forces and currents are external effects as well. Wind forces and waves create sudden heeling moments in the heeling direction. It is not easy to determine the effect of current and wind force. A practical way to analysis is using an experience method to describe ships motions in waves. The IMO Weather Criterion provides a recognized method to describe the influence on ship from wind and waves.

4.1 IMO Weather Criterion[10]

IMO in 1985 (Res.A.562 (14)) is a severe wind and rolling criteria. The objective is to determine the ability of a ship to withstand severe wind and rolling from a beam sea by comparing heeling and righting moment.

The principle of the criterion is to measure the ship's recovering moment to restore its equilibrium position when the vessel is rolling due to external forces. The area "b" showed in figure below is considered as additional heeling energy. The area "a" means the recovering energy. It is an energy balance, where the total amount of energy "a" used to roll the ship from external forces shall not exceed the ships' remaining potential energy "b". The figure below can help give a better understanding of the criterion.

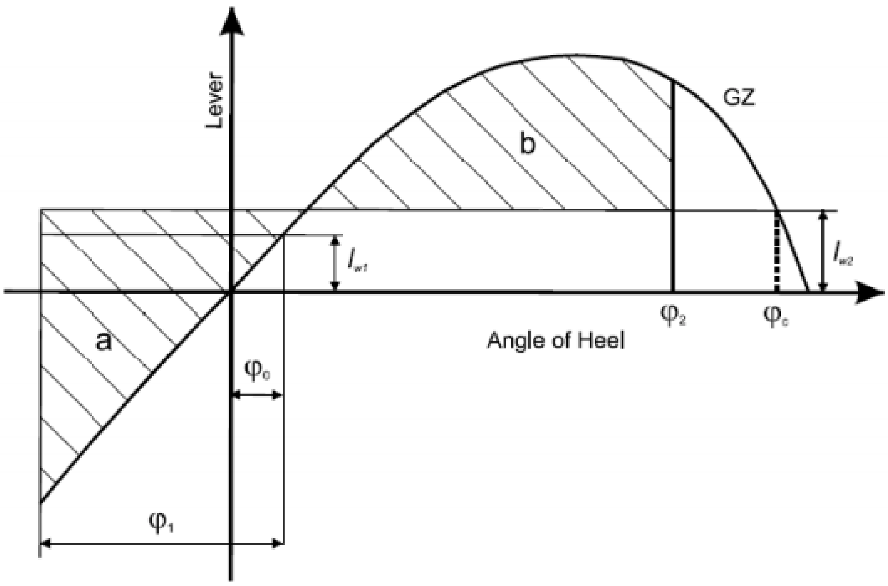

Figure 18 - Severe wind and rolling criteria

During the ship rolling action, ship is assumed that there is an initial heeling angle ϕ_0 caused by beam steady wind represented by a lever arm l_{w1}. Subsequently, ship is rolling windward due to waves to ϕ_1. Finally, ship rolls back due the combined effects from waves and gust wind represented by the lever arm l_{w2}. Therefore, ϕ_2 is the maximum allowable roll angle for the vessel. The area "b" should not be less than area "a".

The wind heeling arm due to steady wind (lw1) and gust wind (lw2) for each tilt angle must be calculated through the following expressions:

$$l_{w1} = \frac{P \times A \times Z}{1000 \times g \times \Delta} (m) \qquad (4.1)$$

$$l_{w2} = 1.5 \times l_{w1} (m) \qquad (4.2)$$

Where P = 504 N/m^2,

A - side area projected above the ships load line (m^2),

Z - vertical distance between the area "A" centroid and a point located approximately at half draft (m)

Δ= displacement,

g= 9.81 m/sec^2.

The roll angel ϕ_1 should be calculated through the following equation

$$\phi_1 = 109 \times k \times X_1 \times X_2 \times \sqrt{r \times s} (\deg) \qquad (4.3)$$

where, X_1 is the factor obtained from (Figure 2) and X_2 is the factors obtained from figure below.

Table 11 - Values of factors X1 &X2

B/d	X1
⩽2.4	1.00
2.5	0.98
2.6	0.96
2.7	0.95
2.8	0.93
2.9	0.91
3.0	0.90
3.1	0.88
3.2	0.86
3.4	0.82
⩾3.5	0.80

Cb	X2
⩽0.45	0.75
0.50	0.82
0.55	0.89
0.60	0.95
0.65	0.97
⩾0.70	1.00

k is the factor that presents the following values:

k= 1 for the ships with rounded bilge keel, without bilge keel or plate keel. k= 0.7 for ships with chain bilge, k should be obtained in table below for ships with bilge keels and plate keels.

$$r = 0.73 \pm 0.6 \times OG / d \tag{4.4}$$

Where, OG is the distance between the center of gravity and the floating line (m) (positive if the center of gravity is above the floating line and negative if it is below), d the mean moulded draught of the ship in (m). And “s” is the factor should be obtained from table below.

T = roll period (sec), calculated through the following expression:

$$T_{\phi} = \frac{2 \times C \times B}{\sqrt{GM_x}} \tag{4.5}$$

$$C = 0.373 + 0.023 \times (B / d) - 0.043 \times (L / 100) \tag{4.6}$$

Where, B is the breadth of the ship.

The table and formulae are based on data from the following parameters:

- B/d should be smaller than 3.5

- (KG/d-1) between -0.3 and 0.5;
- T should be smaller than 20 seconds.

Table 12 - Values of factors k, s

$\frac{A_k \times 100}{L_{WL} \times B}$	k
0	1. 00
1. 0	0. 98
1. 5	0. 95
2. 0	0. 88
2. 5	0. 79
3. 0	0. 74
3. 5	0. 72
⩾4. 0	0. 70

T	s
⩽6	0. 1
7. 0	0. 098
8. 0	0. 093
12	0. 065
14	0. 053
16	0. 044
18	0. 038
⩾20	0. 035

4.1 Anchor handling vessel initial loading condition

Load condition –departure mud condition from the Maxsurf Stability advanced[11] is considered as an initial loading condition. The static stability characteristics associated with initial loading condition are illustrated in Table below.

Table 13- Initial loading condition

Displacement	4003 tones
Transverse center of gravity	0.00 m
Draft at AP	5.695 m
Initial trim	0.16 degrees(forward)
Metacenter	1.11 m
Vanishing angle	77°
Maximum GZ	0.769 m
Angle at maximum GZ occurs	37.3 degrees
Vertical center gravity	5.486 m

Parameters of the case vessel for a given loading condition (without considering mooring load effect):

Table 14-mooring parameters

y	3 m
v	6.4 m
DF	1.3
β	(0, 15, 30, 45, 60, 75, 90) degrees
Tension of mooring line	25t, 50t, 100t, 200t

4.2 Results and discussion

The angle of vanishing due to gust wind and allowable roll angle while subjected to waves and wind speed in addition to the above parameters. The stability of vessel can be improved by limiting the influence of these data. To research the static stability of AHT during anchor handling vessel, it is necessary to present these levels of influence associated with parameters on stability. Therefore, a parametric study will be carried out mooring loads range from 25 tonnes to 100 tonnes. The attack angle β is considered to vary from 0 to 60 degrees. The attack angle 0 means that the mooring line is along with the center line and parallel to deck when it is 90degrees. But from other report, the maximum attack angle should not exceed 57 degrees because the transom at stern acts as a barrier while increasing the angle.

In the program, it is not allow defining a mooring load with angles in the loading condition configuration. Thus, there is able to simulate the mooring load by setting the load in separate procedures.

4.2.1 Parametric study

1. The first parametric study is carried out on the influence of α . Setting the angle β equal to 30 degrees and the mooring load (T) varies from 25t, 50t, 75t, to 100t.

   The results of angle is presented in the appendix C.

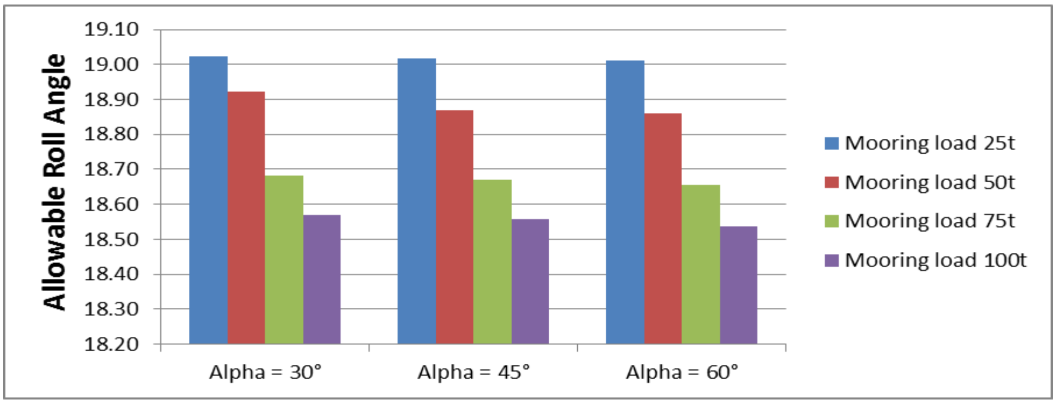

Figure 19 - Allowable roll angle, β = 30 degrees

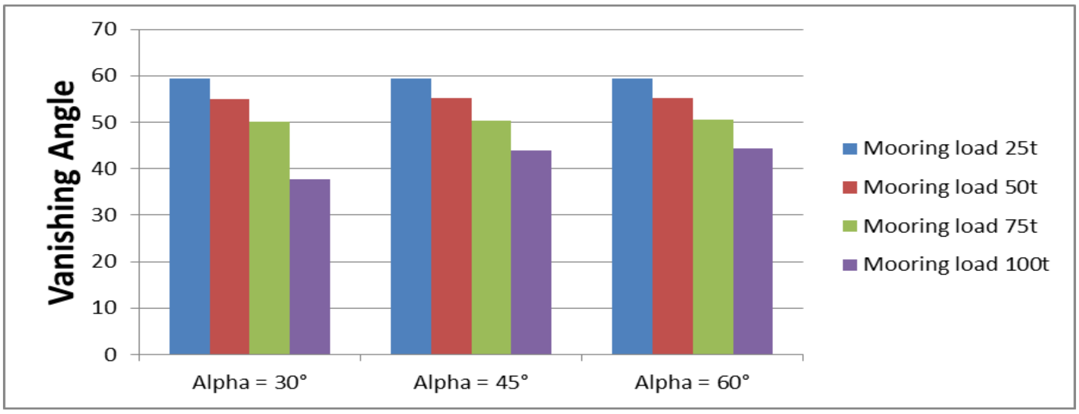

Figure 20 - Vanishing angle when β is 30 degrees

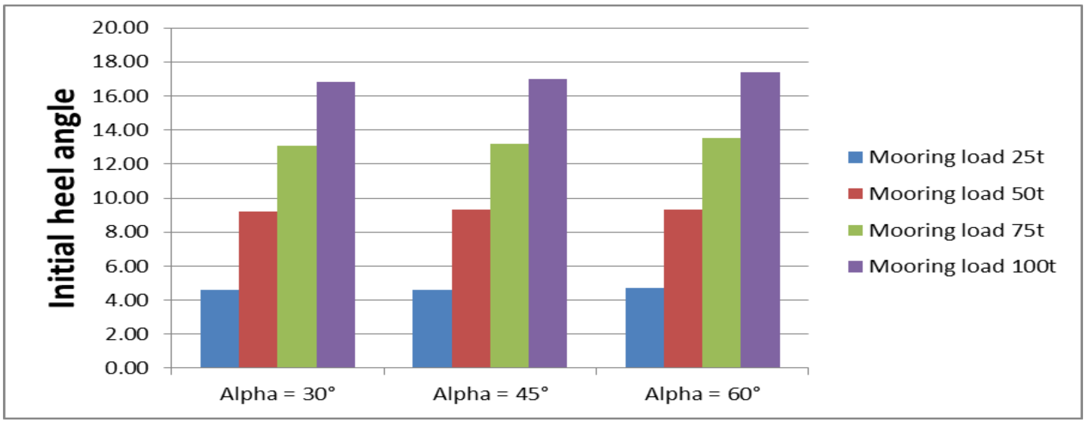

Figure 21 - Initial heel angle when β is 30 degrees

According to the table below, α is varies from 30 degrees to 60 degrees. The comparisons for the allow able roll angle and angle at vanishing angle were drawn for variable α and variable mooring loads. The variation with respect to α is insignificant for a given T. The reason of the fact is observed from bar graph below. By increasing α, the amplitude of variation in allowable roll angle and vanishing angle is so small that it can be negligible. Therefore, it can be concluded that the influence associated with α is negligible.

2. The second parametric study is carried out on the influence of β. Setting the angle α equal to 30 degrees and the mooring load (T) varies from 25t, 50t, 75t, to 100t.

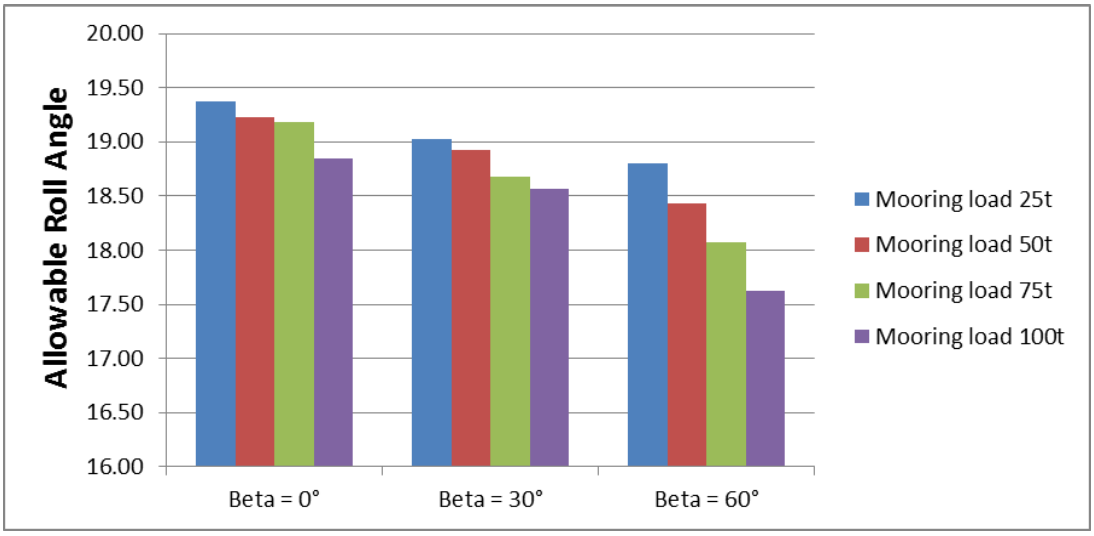

Figure 22 - Allowable roll angle when α is 30 degrees

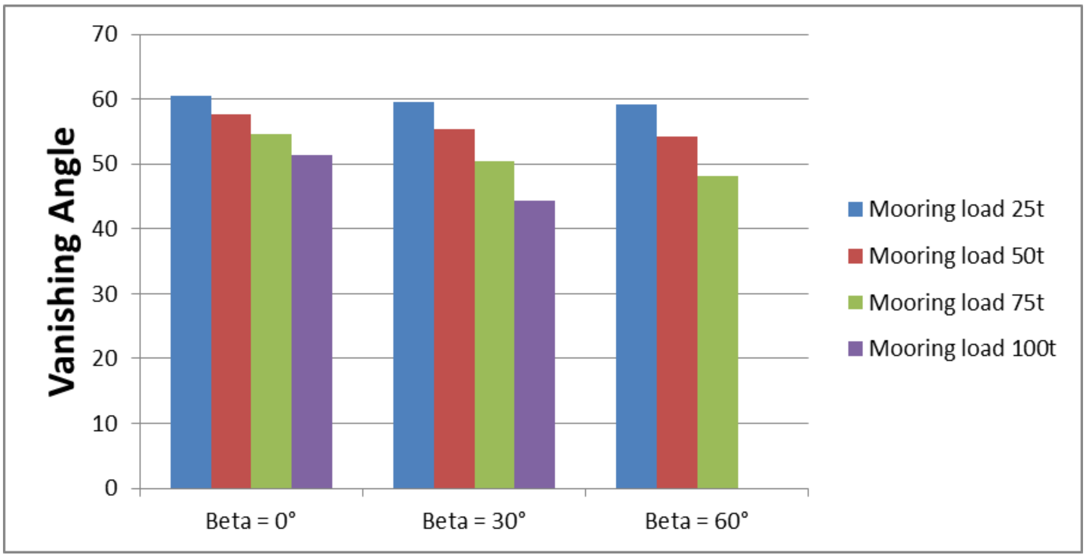

Figure 23 - Vanishing angle when α is 30 degrees

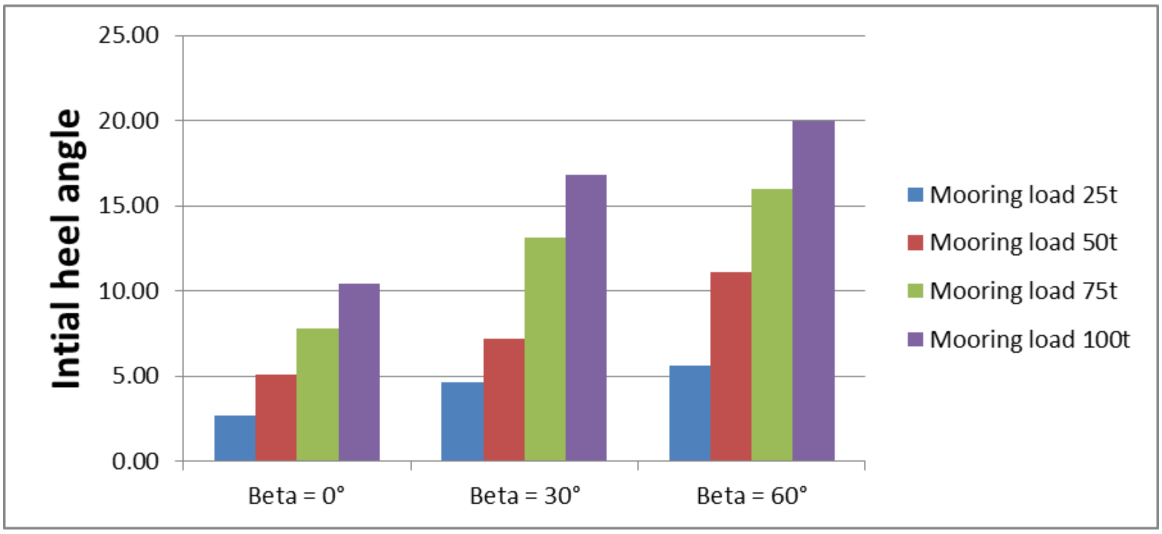

Figure 24 - Initial heel angle when α is 30 degrees

According to the table above, β is varies from 0 degrees to 60 degrees. The comparisons for the allowable roll angle and angle at stability vanishing were drawn for variable β and variable mooring loads. The variation with respect to β is significant for a given T. The reason of the fact is observed from bar graph below. By increasing β, the amplitude of variation in allowable roll angles, vanishing angles and initial heeling angles are so much larger that in first parametric study. Therefore, it can be concluded that the influence associated with β is obviously.

4.2.2 Conclusion

In this chapter, the sensitivity analysis has been determined by a modified IMO weather criterion to evaluate the influence of mooring load. Actually, the weather criteria are experience results only suitable for normal vessel. There are no specific weather criteria for anchor handling vessel. There is expected be more realistic criteria than assessing the AHT vessel by IMO weather criteria. Through this parametric, we can conclude that:

- The influence of angle (α) is negligible
- The effects from mooring load and angle of attack (β) have much more influence on vessel stability

This conclusion can be useful when ship designer is designing the stability of the AHT vessel.

It is also useful for the operator to plan and assessing the risk of anchor handling operation procedure.

5 Conclusions

The five objective points can be concluded as

1. The major forces which will influence the vessel during operation are mooring load, beam wind force, waves and. Mooring load is the largest one among them and have much influences more than other forces.

2. For the mooring load, five factors have effects on it. They are angle α, angle β, magnitude of mooring load, height between stern roller and thruster and distance between stern roller and ship's center line. Obviously, the influence of angle α can be ignored. But the effects of magnitude of mooring load and angle β are very high. By limiting the wind speed, the capsize angle will be increased for a given set of mooring load.

3. There is no suitable weather criterion for AHT vessel. The IMO "severe wind and rolling criteria" is criteria for normal vessels. But it could be useful when the IMO weather criteria are modified. The principle is that the added moment due to wind should be caused by the mooring line.

4. Maxsurf is able to evaluate the static stability for AHT vessel, but the loading condition need to be modified. The principle is similar to the way to modify the IMO weather criteria. A simple method is to exchange the force couple from mooring load into a new force moment. And the most effective way is to consider the angle β and ignore the angle α.

5. The large bow and highly located winch results a high KG. This high KG decreases the GZ curve. For some offshore vessels, their angles at 50%GZ_{max} are all more than 15 degrees. The limiting of maximum heeling angles are immersion angles.

6. Bollard pull capacity is always no more than 50% of the winch capacity. And the test of bollard pull should include a test of the available side thrust at the same time. This is because with the bollard pull and thrusts, ship is able to withstand the extreme conditions. Usually, it is very rare that the heel caused by the wind or waves can lead the vessel to capsize. The most dangerous conditions is due to the combination of gust wind, waves and mooring load.

6 Appendix

6.1 Appendix A – Initial Loading Condition arrangement

Loadcase - OSV_Departure_Mud 25t with alhpa

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	Long. Arm m	Trans. Arm m	Vert. Arm m
Lightship	1	1400,000	1400,000	26,136	0,000	6,000
Superstructure	1	60,000	60,000	51,736	0,000	13,282
beta = 0 deg	0	130,000	0,000	0,000	3,000	8,000
beta = 15 deg	0	125,600	0,000	0,000	4,700	8,000
beta = 30 deg	0	112,600	0,000	0,000	6,700	8,000
beta = 45 deg	0	91,900	0,000	0,000	9,400	8,000
beta = 60 deg	0	65,000	0,000	0,000	14,100	8,000
beta = 75 deg	0	33,600	0,000	0,000	26,900	8,000
beta = 90 deg	0	2,300	0,000	0,000	369,700	8,000
beta 30 & Alpha 30	0	28,100	0,000	-2,200	6,700	8,000
beta 30 & Alpha 45	1	28,100	28,100	1,300	6,700	8,000
beta 30 & Alpha 60	0	28,100	0,000	6,500	6,700	8,000
alpha 30 & beta 0	0	28,100	0,000	6,700	3,600	8,000
alpha 30 & beta 30	0	28,100	0,000	6,700	6,700	8,000
alpha 30 & beta 60	0	28,100	0,000	6,700	8,100	8,000
Total LightShip			1488,100	26,699	0,127	6,331

6.2 Appendix B – Calculate the heeling moment for several given β

Table 15 - Calculate the heeling moment β

Y =	3.0 m		DF =	1.3
V =	6.4 m			
T=50t	β	T-ver(N)	T-hor(N)	M-incl(N*m)
65	15°	62.8	16.8	296.0
65	30°	56.3	32.5	376.9
65	45°	46.0	46.0	432.0
65	60°	32.5	56.3	457.8
65	75°	16.8	62.8	452.3
65	90°	1.1	65.0	419.3
T=100t	β	T-ver(m)	T-hor(m)	M-incl(n*m)
130	15°	125.6	33.6	592.0
130	30°	112.6	65.0	753.7
130	45°	91.9	91.9	864.1
130	60°	65.0	112.6	915.5
130	75°	33.6	125.6	904.6
130	90°	2.3	130.0	838.7
T=150t	β	T-ver(m)	T-hor(m)	M-incl(n*m)
195	15°	188.4	50.5	888.1
195	30°	168.9	97.5	1130.6
195	45°	137.9	137.9	1296.1
195	60°	97.5	168.9	1373.3
195	75°	50.5	188.4	1356.9
195	90°	3.4	195.0	1258.0
T=200t	β	T-ver(m)	T-hor(m)	M-incl(n*m)
260	15°	251.1	67.3	1184.1
260	30°	225.2	130.0	1507.5
260	45°	183.8	183.8	1728.2
260	60°	130.0	225.2	1831.1

260	75°	67.3	251.1	1809.2
260	90°	4.5	260.0	1677.4

6.3 Appendix C – Calculate the allowable roll angle by IMO weather criteria

Beta=30	Alpha=30			
Φ1(roll angle)	T=25t	T=50t	T=75t	T=100t
d (m)	4.03	4.05	4.068	4.084
B/d	3.48	3.46	3.4	3.4
X1	0.8	0.81	0.82	0.82
Cb	0.508	0.481	0.444	0.413
X2	0.82	0.8	0.75	0.75
k	1	1	1	1
r	0.982929	0.983014	0.983097	0.983869
KG	5.726	5.755	5.784	5.812
OG	1.698	1.707	1.716	1.728
GMt	1.102	1.163	1.279	1.449
C	0.42714	0.426745	0.426354	0.426044
T(period)	11.39299	11.07993	10.55586	9.910112
s	0.072	0.073	0.079	0.078
Allowable roll angle	19.02	18.92	18.68	18.57
Beta=30	Alpha=45			
Φ1(roll angle)	T=25t	T=50t	T=75t	T=100t
d (m)	4.03	4.052	4.073	4.091
B/d	3.5	3.5	3.4	3.4
X1	0.8	0.8	0.82	0.82
Cb	0.509	0.481	0.444	0.413
X2	0.82	0.8	0.75	0.75
k	1	1	1	1
r	0.982506	0.982172	0.98205	0.982408
KG	5.726	5.755	5.784	5.812
OG	1.696	1.703	1.711	1.721
GMt	1.097	1.151	1.268	1.44
C	0.427101	0.426667	0.426257	0.425909
T(period)	11.41787	11.13549	10.59913	9.937885
s	0.072	0.0745	0.079	0.078
Allowable roll angle	19.02	18.87	18.67	18.56
Beta=30	Alpha=60			
Φ1(roll angle)	T=25t	T=50t	T=75t	T=100t
d (m)	4.033	4.057	4.081	4.101
B/d	3.5	3.5	3.4	3.4
X1	0.8	0.8	0.82	0.82

Cb	0.511	0.481	0.443	0.403
X2	0.82	0.8	0.75	0.75
k	1	1	1	1
r	0.981872	0.981122	0.98038	0.980329
KG	5.726	5.755	5.784	5.812
OG	1.693	1.698	1.703	1.711
GMt	1.089	1.138	1.251	1.43
C	0.427041	0.426569	0.426102	0.425717
T(period)	11.45814	11.19634	10.66702	9.968078
s	0.072	0.0745	0.079	0.078
Allowable roll angle	19.01	18.86	18.66	18.54

Alpha=30	Beta=0			
Φ1(roll angle)	T=25t	T=50t	T=75t	T=100t
d (m)	4.04	4.064	4.091	4.12
B/d	3.47	3.44	3.4	3.4
X1	0.81	0.81	0.82	0.82
Cb	0.516	0.505	0.497	0.472
X2	0.82	0.82	0.82	0.79
k	1	1	1	1
r	0.98145	0.979656	0.978301	0.976408
KG	5.726	5.755	5.784	5.812
OG	1.691	1.691	1.693	1.692
GMt	1.08	1.069	1.081	1.121
C	0.427002	0.426432	0.425909	0.425355
T(period)	11.50471	11.54833	11.46997	11.24882
s	0.073	0.072	0.07	0.073
Allowable roll angle	19.38	19.23	19.18	18.85
Alpha=30	Beta=30			
Φ1(roll angle)	T=25t	T=50t	T=75t	T=100t
d (m)	4.03	4.05	4.068	4.084
B/d	3.48	3.46	3.4	3.4
X1	0.8	0.81	0.82	0.82
Cb	0.508	0.481	0.444	0.413
X2	0.82	0.8	0.75	0.75
k	1	1	1	1
r	0.982929	0.983014	0.983097	0.983869
KG	5.726	5.755	5.784	5.812
OG	1.698	1.707	1.716	1.728
GMt	1.102	1.163	1.279	1.449
C	0.42714	0.426745	0.426354	0.426044
T(period)	11.39299	11.07993	10.55586	9.910112
s	0.072	0.073	0.079	0.078

Allowable roll angle	19.02	18.92	18.68	18.57
Alpha=30	Beta=60			
Φ1(roll angle)	T=25t	T=50t	T=75t	T=100t
d (m)	4.032	4.055	4.074	4.09
B/d	3.5	3.5	3.4	3.4
X1	0.82	0.82	0.82	0.84
Cb	0.511	0.464	0.422	0.392
X2	0.82	0.75	0.75	0.75
k	1	1	1	1
r	0.982083	0.981541	0.981841	0.982616
KG	5.726	5.755	5.784	5.812
OG	1.694	1.7	1.71	1.722
GMt	1.097	1.18	1.369	1.067
C	0.427061	0.426608	0.426238	0.425929
T(period)	11.41681	10.99629	10.20019	11.5455
s	0.067	0.077	0.074	0.067
Allowable roll angle	18.80	18.43	18.07	17.62

6.4 *Appendix D – Parametric study*

Table 16 – Results of allowable roll angle when β is 30 degrees

	Alpha = 30°	Alpha = 45°	Alpha = 60°
Mooring load 25t	19.02	19.02	19.01
Mooring load 50t	18.92	18.87	18.86
Mooring load 75t	18.68	18.67	18.66
Mooring load 100t	18.57	18.56	18.54

Table 17- Results of vanishing angle when β is 30 degrees

	Alpha = 30°	Alpha = 45°	Alpha = 60°
Mooring load 25t	59.3	59.4	59.5
Mooring load 50t	54.90	55.10	55.30
Mooring load 75t	50.10	50.30	50.50
Mooring load 100t	37.70	44.00	44.30

Table 18- Initial angle when β is 30 degrees

	Alpha = 30°	Alpha = 45°	Alpha = 60°

Mooring load 25t	4.60	4.60	4.70
Mooring load 50t	9.2	9.30	9.30
Mooring load 75t	13.10	13.20	13.50
Mooring load 100t	16.80	17.00	17.40

Table 19 - Results of allowable roll angle when α is 30 degrees

	Beta = 0°	Beta = 30°	Beta = 60°
Mooring load 25t	19.38	19.02	18.80
Mooring load 50t	19.23	18.92	18.43
Mooring load 75t	19.18	18.68	18.07
Mooring load 100t	18.85	18.57	17.62

Table 20 - Results of vanishing angle when α is 30 degrees

	Beta = 0°	Beta = 30°	Beta = 60°
Mooring load 25t	60.50	59.50	59.10
Mooring load 50t	57.60	55.30	54.20
Mooring load 75t	54.60	50.50	48.20
Mooring load 100t	51.40	44.30	0.00

Table 21 - Results of Initial angle when α is 30 degrees

	Beta = 0°	Beta = 30°	Beta = 60°
Mooring load 25t	2.70	4.60	5.60
Mooring load 50t	5.10	9.20	11.10
Mooring load 75t	7.80	13.10	16.00
Mooring load 100t	10.40	16.80	20.00

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