TMR4900 - Master Thesis in Marine Structures

Analysis and monitoring of drilling risers on DP vessels

by

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Abstract

The object of this master thesis is to investigate a drilling riser exposed to currents, waves and vessel motions at different water depths. The aim is to develop an advisory system for vessel position based on the riser response and also to better predict the transition from operation to a potential disconnect. The advisory system will make use of *watch circles* which define the limits for normal operation, halt in operation and a possible disconnect.

As the most accessible oil reservoirs are exploited, there is a need for drilling operations at ever greater water depths and in harsher environments. The riser, and its interactions with the vessel and the blow-out preventer (BOP), is a crucial element in a drilling operation. In order to ensure a safe and productive operation, the riser top and bottom angles must be within acceptable limits. For excessive angles, a disconnect from the well is carried out. This will imply a major loss of income, and it is therefore highly undesirable to disconnect when not necessary. However, the consequences of *not* disconnecting when necessary are even more severe.

The riser is exposed to currents, waves and vessel motions which cause it to deflect. The effect from these influences must be investigated in order to predict the riser angles in various conditions and thereby develop watch circles taking these angles into account.

The riser has been modeled and analyzed in RIFLEX, a software program developed at MARINTEK for static and dynamic analysis of slender marine structures. In order to investigate the response in both shallow and deep waters, water depths of 300 and 2000 [m] have been applied. The riser is exposed to unidirectional current, regular waves and vessel motions. The top tension is kept constant for each water depth.

At 300 [m] water depth, the riser was found to be highly affected by vessel offsets, and the control objective for this depth must be to avoid any offset. At 2000 [m] water depth, however, both lower and upper angle will stabilize at acceptable magnitudes for the maximum static vessel offset studied in this thesis. The upper angle will however be excessive during the movement. The lower angle will not immediately respond to a motion at the top end of the riser, and it increases slowly for an increasing vessel offset. Hence, for a drive-off, which is an uncontrolled excursion of the vessel due to a failure in the DP system, the DP operator will have some time before a disconnect has to be carried out. The current affects the riser considerably more in deep waters compared to shallow waters. Also, first-order waves affect the upper angle significantly more than the lower angle, both in shallow and deep water.

The watch circles which have been developed prove that the limits for a halt in the operation and a possible disconnect are larger than the conventional guidance limits. By allowing the top angle to become excessive during a limited amount of time, one can uphold the operation for a longer period of time, and also avoid an unnecessary disconnect.

The main contributions in this thesis are the simulation study of the drilling riser and the proposed guidance limits for operation and disconnect.

Acknowledgements

This report represents my master thesis which has been carried out from January to June 2011 at the Department of Marine Technology at NTNU.

My supervisor Asgeir Sørensen has motivated and encouraged me during these months, and I would like to thank him for showing such enthusiasm towards my work, as well as for always taking his time to guide me when necessary. Carl Martin Larsen is appreciated for his help and advice, for providing me with RIFLEX files and for being available for my questions. I am also grateful to Anne Marthine Rustad for valuable feedback, discussion of results and for technical guidance as well as specific advice on report writing throughout the semester. Her expertise within the field of slender structures is utmost appreciated. I would also like to thank Elizabeth Passano who has helped me with RIFLEX and showed me its many possibilities.

Trondheim, June 2011 Anna Kringlen Ervik

Work description and scope of work

Work description

The productive time and safety of the dynamically positioned (DP) drilling operations of floaters depend on the loading and motions of the vessel, riser, blow-out preventer (BOP) and the well subject to varying operational and environmental conditions. The performance and reliability to several control systems such as the DP system, drilling control system including heave compensation and riser tensioner system and BOP control system have strong impact on the so-called well integrity and hence also productivity and profit. In this project we will focus on the behavior of the riser due to vessel motions at various water depths.

Scope of work

1. Review the necessary literature about the factors influencing the behavior of the riser; the DP system and heave compensator.
2. Review the technical specifications of the drilling riser, rig and heave compensation system of interest.
3. Carry out extensive RIFLEX analyses of motions and tension variations to identify time delays between vessel motions and riser response (top and bottom angles) for a set of water depths, current and vessel motion patterns (step-response, sinusoidal periodic motions).
4. Identify decision criteria for optimal set-point and riser disconnect.

The report shall be written in English and edited as a research report including literature study, description of mathematical models, description of control algorithms, simulation results, model test results, discussion and a conclusion including a proposal for further work. Source code should be provided on a CD with code listing enclosed in appendix. It is supposed that Department of Marine Technology, NTNU, can use the results freely in its research work, unless otherwise agreed upon, by referring to the student's work. The thesis should be submitted in three copies within June 14th 2011.

Notation

Some of the abbreviations and characters used in this report are listed and defined here.

Abbreviations

BOP	Blow-out preventer
DOF	Degree of freedom
DP	Dynamic positioning
DP3	Class notation for DP vessels where the DP system is fully redundant in addition to being fire and flood safe
LF	Low-frequency
LMRP	Lower marine riser package
MODU	Mobile offshore drilling unit
WF	Wave-frequency

Characters

Greek

$\boldsymbol{\eta}_1$, $\boldsymbol{\eta}_2$	Earth-fixed position vectors
θ	Inclination of each riser element relative to the global frame, **or** pitch angle
λ	Wave length
$\boldsymbol{\nu}_1$, $\boldsymbol{\nu}_2$	Body-fixed velocity vectors
ρ_s, ρ_f, ρ_w	Density of steel, internal fluid in riser and sea water
$\boldsymbol{\tau}_{wind}$, $\boldsymbol{\tau}_{wave2}$, $\boldsymbol{\tau}_{wave1}$, $\boldsymbol{\tau}_{thr}$	Wind load, second-order wave load, first-order wave load and control force vector
$\boldsymbol{\tau}_{vessel_{LF}}$, $\boldsymbol{\tau}_{vessel_{WF}}$	Low-frequency and wave-frequency vessel motion load (for riser modeling)
$\boldsymbol{\tau}_{3c}$	Horizontal-plane control law
$\boldsymbol{\tau}_{5c}$	Horizontal-plane control law with roll and pitch damping
ϕ	Roll angle
ψ	Yaw angle

Roman

A, A_e, A_i	Cross-sectional total, external and internal area of the riser
C	Wave propagation velocity
g	Gravity constant
E	Young's modulus
l_i	Length of each riser element in the mathematical model of the riser
l_r	Total length of riser
n	number of elements in the mathematical model of the riser
H_{max}	Wave height for a regular wave
H_s	Significant wave height
m_s	Mass of steel in riser
m_f	Mass of internal fluid in the riser
m_b	Mass of buoyancy modules
P_{top}	Top tension
T_{max}	Period for a regular wave
T_p	Peak period
w_e	Effective weight of riser per unit length
$w_{eff,i}$	Effective weight of each riser element
x, y, z	Longitudinal, lateral and vertical coordinate of vessel in the Earth-fixed frame
u, v, w	Surge, sway and heave velocities in Body-fixed frame
p, q, r	Roll, pitch and yaw velocities in Body-fixed frame
$\mathbf{f}_{top}$	Top tension vector
$\mathbf{f}_{drag}$	Drag force vector
$\mathbf{J}$	Rotation matrix
$\mathbf{k}_i$, $\mathbf{k}_{EAi}$, $\mathbf{k}_{Gi}$	Consistent total, elastic and geometric stiffness matrices for each riser element
$\mathbf{m}_i$, $\mathbf{m}_{si}$, $\mathbf{m}_{fi}$, $\mathbf{m}_{ai}$	Consistent total, structural, internal fluid and added mass matrices for each riser element
$\mathbf{M}$	System inertial matrix
$\mathbf{M}_r$	Riser system mass matrix
$\mathbf{K}_r$	Riser system stiffness matrix
$\mathbf{C}_r$	Rayleigh damping matrix
$\mathbf{T}_{0,i}^{f}$	Transformation matrix from i to f

Contents

1 Introduction

The retrieving of oil and gas is becoming more challenging as the reservoirs become more inaccessible. Since the start of the Norwegian oil adventure in 1969, the most accessible oil and gas reservoirs have been tapped, and the need for drilling on ever greater water depths and in harsher environments is increasing. However, according to estimates about 60% of the total resources on the Norwegian Continental Shelf are still unexploited ([1]). The need for more drilling on ever greater water depths, and in even harsher environments, is increasing.

1.1 Motivation

The productive time, i.e. the time available for drilling, is a crucial element in the drilling operation. Current day rate for a semi-submersible varies from $ 300 000 to $ 700 000. For a drilling rig with an expected production of 50.000 barrels per day, a 24 hours halt in the operation corresponds to a loss of revenue of approximately $ 5 000 000 (oil price $ 100 /barrel, price of March 2011). The economic consequences of a temporary break in the operation are thus severe, and it is undesirable to abort the operation when it is not strictly necessary. However, when an accident occurs because the operation was *n*ot aborted, the consequences may be fatal. In the wake of the Fukushima nuclear reaction accident in March this year, safety with regard to energy generation has been a topic in focus. In this context we shall bear in mind that statistics prove that oil and gas are still much more deadly energy sources, when rating number of lives lost versus each TWh output (Valmot, Hovland, and Nilsen [2]). The need for safer operations should therefore be obvious.

The productive time and safety of the dynamically positioned (DP) drilling operations of floaters depend on the loading and motions of the vessel, riser, blow-out preventer (BOP) and the well. In order to increase the time available for production and ensure a safe operation, the interactions between these components should be further investigated.

Being the connection between the vessel and the seabed, the riser is an important component in a drilling operation. The top and bottom angles must be within acceptable limits (2-4°) to prevent damage on the riser and/or the well head. In addition, bending stresses should be kept within certain limits in order to prevent wear and tear of the riser. Currents and vessel position result in a static force on the riser, while the dynamics in the DP system cause a dynamic force. The heave compensator system will also cause a dynamic force which is transmitted along the riser. Forces from incoming waves will induce dynamic response of the vessel which is transmitted to the riser and down to the BOP.

DP vessels use a watch circle system with color codes to indicate when the vessel offset is acceptable for operation (green zone) and when a disconnect should be prepared (yellow/red zone), see Figure 1.1. The transition from one zone to the next is based on the allowable top and bottom angles as well as the stress limits for the riser. It is critical that the red zone limit gives sufficient time for decision making and to allow emergency shut down (ESD) and safe disconnect from the well [3]. The assumption for calculating the transition limits is that the riser is inclined, though straight, when the vessel has an offset position.

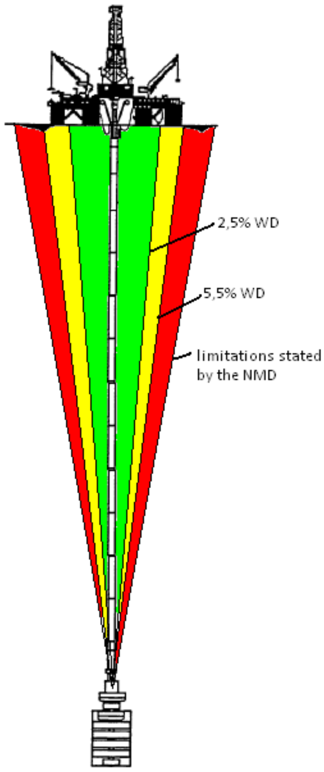
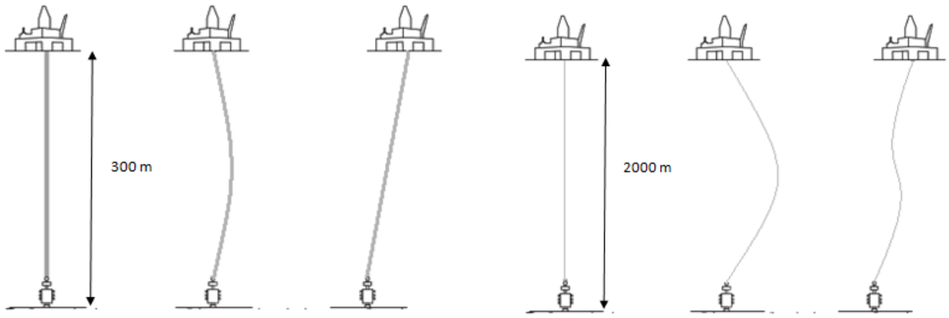


Figure 1.1: Watch circles for DP vessels (Djupesland, 2010)

Figure 1.2(a) shows a riser in shallow water when exposed to current and when the semi-submersible is moved to an offset position. The term *shallow* water has various definitions. Hydrodynamically, shallow water refers to the case where the water depth is *less* than half the wave length. By using this definition, shallow water, depending on the wave length, comprises water depths up to about 100 [m]. On the Norwegian Continental Shelf, the deepest fields (except from Ormen Lange) are not deeper than 400 [m], and when referring to these fields, the term *normal*, or even *deep*, water is used. However, in the Gulf of Mexico and outside Brazil, where drilling takes place at 2000-3000 [m] water depth, the term *shallow* water is used for water depths less than 1000 [m]. In this thesis, the term *shallow* water will refer to water depths less than 500 [m], while the term *deep* water will refer to water depths in excess of 500 [m].

In the case of shallow water, as illustrated in Figure 1.2(a), the assumption for calculating the angle at the offset position will give satisfying results, because the riser is rather straight when the rig is in an offset position. Figure 1.2(b) shows a riser in deep water when exposed to current and when moved to an offset position. In this case, the assumption about a straight and inclined riser is no longer valid. The angle at the bottom can be both larger and smaller, and limits for where the angels are unacceptable can not be concluded based on watch circles calculated on the assumption about a straight and inclined riser, see Figure 1.3. It is then a risk that the DP system will carry out actions based on wrong input. This affects both the operability and the safety.

In Figure 1.2(a) and 1.2(b) it is also indicated that the riser at deep water will be more affected by the current than the riser at shallow water. This will be further discussed in Section 4 in this report.



(a) Riser, shallow water (b) Riser, deep water

Figure 1.2: Riser behavior in shallow and deep water. The first frame in each subfigure shows the riser in its initial position. The second frame shows the riser exposed to current. The third frame shows the riser exposed to a vessel offset.

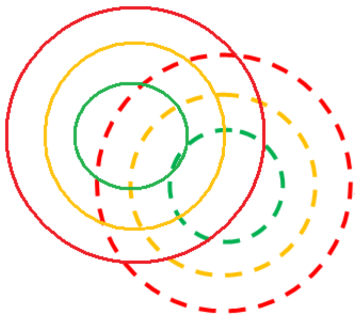


Figure 1.3: Watch circles seen from above. The solid circles show the assumed limits for the green, yellow and red zones, while the dashed circles indicate where the actual limits might be during operation

Complex mathematical models that account for the riser dynamics have been developed, and so-called *riser management systems* have been implemented on DP vessels. This will be further discussed in Section 1.2: *Previous Work*.

In this report, the interactions between the vessel and the riser will be studied. This will involve analyses of motions including time delays of a drilling riser for a set of varying water depths, currents and vessel motions. The object is to study which parameters that affect the riser behavior and *h*ow they affect the riser behavior. With a better knowledge and understanding of these interactions, an advisory system based on the riser angles can be developed.

1.2 Previous work

Several research papers have discussed and suggested methods for monitoring the drilling riser and using the data as reference for positioning of a drilling vessel. The object of these methods is to increase the time available for drilling by accurately determine actual disconnect limits and safety margins, as well as provide the maximum time to deal with an emergency situation. Disconnection of the riser is costly and will be avoided except in emergency situations. However, the consequences of not disconnecting when needed may be fatal. It is desirable to develop systems for monitoring of riser response that remove the uncertainty attached to whether or not to disconnect, reduce down-time and eventually wear and tear of the riser.

Seaflex Riser Technologies is a business unit in Kongsberg Oil and Gas Technologies which specializes within offshore riser technology. In cooperation with Kongsberg Maritime, Seaflex delivers Riser Management Systems (RMS) and the Riser Position Reference (RPR) system. The RMS is a monitoring and advisory system for optimum handling of drilling and work-over risers. It receives input from the upper inclinometer, the DP system, the BOP control system and the tensioner control system. An optimum position advice which limits the flex joint angles and well head loads is then provided.

Høklie, Jensen, Osen, and Ciatti [4] combine Kalman filtering technique with mathematical models of the vessel and the riser to derive vessel position estimates. The idea is that the measured riser response can reflect the dynamic behavior of the vessel and hence provide vessel position and velocity. The Kalman Filter uses both the measured data (vessel position and velocity, riser angles) and predicted values to provide an estimate of the true values. In the system proposed in Høklie et al., the current is first modeled as a linear profile in order to give a predicted value of the riser angles. Then, the riser inclinations and position measurements are used to update the current profile, and after this initial calibration, the only required input to the position estimator is the riser inclinations. The system, called Riser Position Reference, is an extension to the Riser Management System (RMS) described above.

In Sørensen, Leira, Strand, and Larsen [5], a hybrid dynamic positioning controller based on the riser angle offsets in three dimensions is presented. The object is to reduce the riser angle magnitude relative to the well head and at the top joint, which are stated to be the most limiting operational factors in drilling. Modeling a riser in three dimensions is complicated, as rotation at riser ends must be defined by both the direction of the inclination and the magnitude. Optimal set-point chasing is applied, which means that the target position of the vessel moves as a function of several parameters (current, riser top tension, etc). This demands for a reference model in order for the transition from one position to another to follow a smooth trajectory.

Leira, Sørensen, and Larsen [6] propose a reliability-based control algorithm for reducing the maximum riser angular response levels by dynamic positioning. It is found that positioning schemes based solely on mean values (application of a fixed reference set-point) are not able to capture the dynamic effects. A method for including both the mean value of the riser angle and the variance is needed. The reliability index is such a method.

In addition to the methods for monitoring the drilling riser, several research papers deal with the methodology for disconnect of the riser. Amongst these are Hock and Young [7] which describe a deepwater riser emergency disconnect system. The problem addressed is the controlling of the riser and the stored energy during an unplanned disconnect of the riser. Grytøyr, Rustad, Sødahl, and Bunæs [8] discuss the planned disconnect of *completion and work-over risers* (cwo). The method is based on an irregular wave approach, and this method gives a considerable increase in the operating window compared to regular wave analysis.

Another aspect with deep water drilling is the heave compensating system, which must maintain a near constant tension in the riser independent of rig motions. Force variations on heave compensating system for ultra-deepwater drilling is discussed in Sten, Hansen, Larsen, and Sævik [9].

1.3 Main contributions

The main contributions found in this project thesis are summarized here.

- In Section 4, the riser angles for various weather conditions and vessel motions are presented and discussed.
- In Section 5 an advisory system based on the riser angles is developed. The advisory system is based on watch circles and guidelines for operation and disconnect.

1.4 Organization of the thesis

The outline of the report is as follows:

Section 2 describes mobiles offshore drilling units, and especially the semi-submersible. A semi-submersible is applied as a case vessel in this thesis, and some general information about the vessel and the riser set-up is introduced.

In **Section 3**, the analyses to be conducted in RIFLEX are discussed and defined.

Section 4 presents the simulation results from RIFLEX.

In **Section 5** an advisory system based on the riser angles is developed. The dynamic positioning system is explained, and mathematical models of the vessel and the riser are derived. Also, a horizontal-plane controller is formulated.

Appendix A describes the dividing of the riser into elements, in addition to the segment lengths and the component types.

Appendix B describes how the various analyses were carried out, using the input files in Appendix C.

In **Appendix C**, the RIFLEX input files are attached. This includes the inpmod, stamod and dynmod modules for the two water depths.

2 Case vessel and riser

2.1 Mobile offshore drilling units (MODUs)

Offshore drilling units can be classified in several ways. One of them is the ability to move from one location to another. Such units are referred to as mobile offshore drilling units (MODUs). The petroleum industry is dependent on mobile units in order to find and explore new reservoirs, and as the shallow water reservoirs are tapped, the need for drilling on greater water depths, and in harsher environment, is increasing.

Mobile offshore drilling units include jack-ups, drill ships and semi-submersibles. These units drill exploration and production wells and can be relocated to a new area either by means of towing or propulsion. In this section, a short evaluation of the different MODUs based on their sea keeping properties will be carried out. When considering marine vessels the terms *horizontal* and *vertical* degrees of freedom are frequently mentioned. The horizontal degrees of freedom are surge, sway and yaw, while the vertical degrees of freedom are roll, pitch and heave.

A jack-up platform is raised to a predetermined elevation above the sea surface by lowering its legs which are supported on the seabed (Vazquez et al. [10]). The legs can be supported by bottom pads, enlarged sections or they may penetrate the seabed. Jack-ups have small natural periods, but with increasing depth these periods increase and enter the domain of the wave periods. This is one of the reasons why jack-ups are limited to shallow waters (approximately 100 [m]).

Drill ships are marine vessels with the ability to drill for oil and gas. Drill ships can operate at far greater depths than jack-ups (up to 3000 [m]), and they maintain their position by means of mooring lines and dynamic positioning. However, heave is a limiting factor in drilling operations, and since the natural periods in heave for a ship is in the interval 4-16 [s], which is in the domain of the wave periods, the drilling operation is vulnerable to linear wave forces (Faltinsen [11]).

A semi-submersible obtains its buoyancy from ballasted, watertight pontoons located below the ocean surface and wave action. It has good stability and sea keeping properties, and the deep draft makes it resistant to wave loadings. For a semi-submersible, the horizontal degrees of freedom have large periods, typically in the range of 1-2 minutes. The vertical degrees of freedom are also in a range well above the periods of first order waves. Natural roll and pitch periods are in the range of 35-60 [s] (Sørensen and Strand [12]), while the natural heave period is greater than 20 [s] (Faltinsen [11]). The difference between the natural heave periods for semi-submersibles and drilling ships can easily be understood by regarding the water-plane areas of the two vessels. A drilling ship has a large water plane area, while the water-plane area of the semi-submersible is only the cross-sectional area of the pontoons. The restoring force in heave is proportional to the water-plane area, and to find the undamped and uncoupled resonance period we divide by the restoring force. Hence, a structure with a large water-plane area will have a smaller natural heave period than a structure with a small water-plane area. The semi-submersible is designed to have large periods in heave in order to avoid resonant heave motions. However, *swells* may be a problem for this kind of vessel. Swells are waves which have traveled out of the area where they were created. These have long periods, and will thus be in the same frequency domain as the natural heave period of the semi-submersible. Another aspect which one should keep in mind is the surge- and sway-induced pitch and roll motions that can occur for a dynamically positioned semi-submersible. Because of the previously discussed small restoring force, an unintentional coupling phenomena between the horizontal and vertical

(a) "Ocean Viking", built in 1966. (www.oilinfo.no) (b) "Deep Sea Bergen", built in 1983. (www.offshore.no) (c) "Aker Barents", built in 2009. (www.detnor.no)

Figure 2.1: Semi-submersibles from the sixties and up till to today. (a) The Aker rig "Ocean Viking" made the first economic petroleum discovery on the Norwegian Continental Shelf in 1969. (b)"Deep Sea Bergen" (Odfjell Drilling) is a 3rd generation semi-submersible currently carrying out drilling operations for Statoil in the Halten Nordland area on the Norwegian Continental Shelf. (c) "Aker Barents" (Aker Drilling) is a 6th generation semi-submersible. It is currently in operation on the Norwegian Continental Shelf for the rig operator Det Norske.

plane may occur for a semi-submersible. The natural periods in roll and pitch, as mentioned, are in the range of 35-60 [s], which is in the bandwidth of the positioning controller. The thruster system, which should act in the horizontal plane only, may induce large roll and pitch oscillations. When this happens, the riser risks to come in contact with the vessel, which is not desired. The surge- and sway-induced pitch and roll motions are discussed in Sørensen and Strand [12]. *Slow-drift motions* may also be an issue for a semi-submersible. Slow-drift motions are primarily resonance oscillations excited by non-linear interaction effects between the waves and the body motion (Faltinsen [11]). For a freely floating structure with low water-plane area, such as a semi-submersible, second-order slow-drift motions occur in all six degrees of freedom (surge, sway, heave, roll, pitch and yaw). The large horizontal excursions that occur can cause large forces in anchor lines and limitations in drilling operations (Faltinsen and Løken [13]). Slow-drift motions may also occur if there is a failure, or a mal-functioning, in the DP system. Hence, the vessel can start to move harmonically even in still water.

Despite the undesired effects from swells and thruster system, semi-submersibles are well-suited for drilling operations, and during the last years, semi-submersibles designed for special environments such as deep water and harsh weather, have been developed. Figure 2.1 shows three semi-submersibles from the 1960's and up till today. The currently built vessels are characterized as *sixth generation* semi-submersibles. These can operate at water depths up to 3000 [m] and in sea states with wave heights up till 12 [m].

2.2 Case vessel

The case vessel applied in this thesis is a sixth generation class DP3 semi-submersible designed for operations in deep waters (up to 3000 [m] water depth) and harsh environments. Main dimensions and operating data for the case vessel are found in Table 2.1.

In the present study, the semi-submersible will have either prescribed low-frequency motions in the horizontal plane, or it will have wave-frequency induced motions, or both.

Table 2.1: Vessel data

Length upper hull [m]	95
Breadth upper hull [m]	80
Pontoon length [m]	110
Pontoon height [m]	10
Columns number	4
Columns dimensions [m · m]	19x14
Operating draft [m]	23
Survival draft [m]	20

The software used to calculate vessel (and riser) response is RIFLEX, which has been developed at MARINTEK. In order to calculate vessel response for different weather conditions, or sea states, *transfer functions* for the specific vessel are needed. Transfer functions, or Response Amplitude Operators (RAOs), indicate the amplitude and phase of the vessel response in surge, sway, heave, roll, pitch and yaw for a set of wave directions and periods. In this way, the vessel response for a given wave can be calculated. Transfer functions, or RAOs, for a specific vessel are found either from model tests or computer programs.

2.3 Riser

The drilling riser is connected to the vessel at the upper end, and to the BOP at the lower end. To compensate for the vertical motions, the riser is connected to a tension system which keeps a constant tension in the riser. The riser tensioner system is a direct tension system with 6 cylinders. Table 2.2 shows the riser setup on the case vessel for a water depth of 1400 [m]. The buoyancy modules are included in order to reduce the needed top tension.

Table 2.2: Riser setup at 1400 m water depth, * means that the values are estimated.

Riser component	**Internal diameter [m]**	**External diameter [m]**	**Length [m]**	**Density of material [$\frac{kg}{m^3}$]**
Diverter flex joint	0.50	0.53	1.9	7850
Slip joint	Inner barrel: 0.50	Inner barrel: 0.53	32	7850
	Outer barrel: 0.61	Outer barrel :0.66	-	-
Riser joint	0.50	0.53	3.0	7850
Slick joint	0.50	0.53	23.0	7850
Riser joint w/buoyancy	0.50	1.35*	46.0	7850/400*
Riser joint w/buoyancy	0.50	1.35*	754.0	7850/400*
Riser joint w/buoyancy	0.50	1.35*	137.0	7850/400*
Slick joint	0.50	0.53	388.0	7850
LMRP	-	-	14	-

In this thesis, water depths of 300 [m] and 2000 [m] are investigated. Hence, the length of the longest riser segments in Table 2.2 has been modified to risers of length 300 and 2000 [m], respectively. Riser data for the two water depths can be seen in Appendix A. A segment of 50 [m] is added at the bottom of the risers, and will be under the sea bed.

3 Analyses: planning and set-up

In general, the term *analysis* is defined as the procedure by which we break down an intellectual or substantial whole into parts or components. In this section, the complex riser behavior for various influences will be divided into parts which are to be investigated in Section 4:*Results*.

A semi-submersible is subject to forces by environmental elements such as waves, wind and current, in addition to failures within the vessel itself. Wind, waves and current may result in offsets from the initial position. Both the possible offset and the forces from waves and current cause the riser to deflect. If the vessel uses dynamic positioning, a failure in the system may result in a *drive-off* or a *drift-off*. Drive-off is an uncontrolled excursion of the vessel which happens because a failure in the DP-system causes erroneous thruster commands. Drift-off happens in the event of total thrust loss because of a black-out. In this study, only drive-off will be studied. A drive-off is is normally more critical as full throttle on thruster may give the operator less time to assess and interact on the incident.

The analyses will be carried out in RIFLEX, which is a program developed at MARINTEK for static and dynamic analysis of slender marine structures.

The object of the RIFLEX analyses is to investigate the riser angles for different water depths, current and vessel motion patterns and hereby identify the time delays between a motion of the semi-submersible and the response of the riser as the water depth increases. Further, this will be used to develop guidance for positioning of the rig in various conditions.

3.1 Main questions to answer

The above formulation of the object can be divided into four main questions which the analyses are to answer:

1. What is the time delay between a motion of the rig and the response angle at bottom of the riser?
    - How is this coherent with the wave propagation velocity in a material?
2. What are the differences in response for shallow and deep water?
3. For which motions, current and waves - or combination of these - are the angles (either at the bottom or the top - or both) excessive?
4. How can the semi-submersible be positioned such that the bottom (and top) angle will be acceptable for a given condition?

The analyses carried out in this thesis thus have two main goals. Firstly, we want to investigate the behavior of the riser for different situations (waves, drive-off, current). Secondly, the possible use of this information must be identified. The task in this section is to find out which analyses that will have to be conducted - and how they will be conducted - in order to answer the questions above. In the following paragraphs, a systematic discussion of the previous questions will be made.

3.1.1 What is the time delay between a motion of the rig and the response at the bottom of the riser?

It is expected that the bottom part of the riser will use some time to respond to a motion at the top end. This is a fair assumption both for motions such as waves and a possible drive-off.

However, the effect of this time delay will be different for a wave and a drive-off. In fact, maybe waves do not propagate down to the bottom of the riser beneath a certain depth. In case of a drive-off, where the thrusters are commanded to give the vessel a velocity in a certain direction, one must expect the bottom of the riser to be affected, though after a while. The previous statements indicate that the effect of waves and drive-off should be examined separately - and then combined - in order to identify the effect that each motion will have on the riser. Further, to understand the effect of wave height and period of first-order waves, regular waves should be applied in the first round. The amplitude and period of the regular waves will be discussed in Section 3.2.2. Also, *slow drift motions* should be investigated. Slow drift motions are resonance oscillations excited by non-linear interaction effects between the waves and the body motion, see Section 2.1. A failure in the DP system, or a badly tuned DP, may also cause slow-drift motions of the rig. Furthermore, wind gusts may cause harmonic motions of the vessel. Slow-drift motions are illustrated by harmonic motions of the semi-submersible. The amplitude and period of these motions are discussed in Section 3.2.4. To illustrate a drive-off, the vessel is moved to an offset location. Different vessel speeds should be applied in the analyses. The time delay between a motion at the top end and the response of the bottom end may give quite different top and bottom angles for various speeds. The amplitude and velocity of the drive-off will be discussed in Section 3.2.3.

3.1.2 What are the differences in riser response for shallow and deep water?

In this report, the term *shallow* water is used to describe water depths up to 500 [m], while the term *deep* water refers to water depths exceeding 500 [m]. Introductory in this report, the differences between the riser behavior in shallow and deep water were discussed briefly. The main object of this discussion was to emphasize that the riser in deep water has a more complex behavior for a vessel offset than what is the case for the riser in shallow water. There are various reasons for the complex behavior; the fact that the riser is longer (and thus heavier), time delays (see Section 3.1.1) and buoyancy modules (see Section 5.3.2) are some. However, in shallow water even a relative small offset will cause critical riser angles. Hence, there will be less time to prepare for a disconnect at shallow water than for deep water. Some major differences between the riser response in shallow and deep water are thus established, but they should be further examined and compared in order to fully comprehend the effect of these differences. To represent shallow water, a water depth of 300 [m] is chosen, which is a typical depth on the Norwegian Continental Shelf. A water depth of 2000 [m] is used to investigate deep water. Water depths of 2000 [m] are common in the Gulf of Mexico and outside Brazil.

3.1.3 For which motions/scenarios are the angles excessive?

In Section 3.1.1 it was established that waves and drive-off should be examined separately, and then combined. Regular waves were found to be a good starting point for investigating the effect of first-order waves and their wave height and period. Further, moving the vessel to an offset position with different velocities will illustrate a possible drive-off. Until now, current has not been considered. Current will cause the riser to deflect, and combined with a drive-off, it may give excessive riser angles. Analyses combining waves and current, waves and drive-off, current and drive-off - and all together - should hence be conducted. Also, slow-drift motions of the rig will be investigated, with and without current. This will help us identify critical scenarios, and hopefully also spot situations where the moving of the vessel actually improves the riser angles. This is the topic for the last question in this section.

3.1.4 How can the semi-submersible be positioned such that the angles are acceptable?

Obviously, waves and current can not be controlled. Hence, for a given weather condition it is the task of the operator to position the vessel such that the riser angles will be within acceptable limits at all time. The desired outcome of this master thesis is to establish an advisory system which for a given weather condition may indicate optimal positions of the semi-submersible. This can only be done by systematically performing the analyses which have been derived by the previous discussions and thereafter carefully analyze and compare the results.

3.2 Parameters

In the previous section, the analyses necessary to perform have been defined. In this section we will look at specific values for various parameters. These are:

- Magnitude of top tension
- Waves and current (wave height, period, current velocity)
- Amplitude and period of harmonic low-frequency motions
- Amplitude and velocity of drive-off

The top tension prevents the riser from collapsing and is an important parameter in the analyses and in the real world. If the top tension is too small, the riser will buckle easily. However, an excessive top tension will cause wear and tear and damage the riser. Specific values for wave height, wave period and current velocity can be found from environmental data. Finally, the amplitude and velocity of the drive-off is decided according to the realistic speed of the semi-submersible as well as interesting offset positions.

3.2.1 Top tension

The required top tension P_{top} is calculated for each of the water depths. In shallow water depths there is no need for buoyancy modules, and the top tension is calculated as follows:

$$P_{top} = (m_s + m_f)g - \rho_w g V + 200[kN], \tag{3.1}$$

where m_s is the mass of the steel, m_f the mass of the fluid inside the riser, g is the acceleration of gravity, ρ_w is the density of water and V is the volume of the displaced fluid because of the presence of the riser. Finally, 200 [kN] is added in order to ensure sufficient tension at the lower end. This is not an accurate value of the required tension at the lower end, but simply an adequate estimate of what should be added in order to avoid damage on the BOP. In deep water, buoyancy modules are required to reduce the needed top tension in order to avoid tear of the riser. Buoyancy modules with density less than water are wrapped around a considerable part of the riser, and the effect is that a smaller force is required to support the riser. Also, the area of the riser will be larger, which both results in increased buoyancy and a larger drag force. The required top tension is calculated as:

$$P_{top} = (m_s + m_f + m_b)g - \rho_w g V + 200[kN], \tag{3.2}$$

where m_b is the mass of the buoyancy module. As for shallow water, 200 [kN] is added to keep the riser sufficiently tensioned at the lower end.

3.2.2 Waves and current

As discussed in Section 3.1.1, first-order wave loads should be investigated. First-order wave loads are represented by regular waves. This is obviously a simplification, as first-order waves can be said to comprise several regular wave components. The amplitude and period of the regular waves are given as environmental input in the analyses, and this will result in rig and riser motions. The second-order wave loads cause slow-drift motions of the vessel, and the method for introducing these loads is discussed in Section 3.2.4. In order to achieve realistic results when investigating the regular waves, environmental data for different locations are used in the analyses. Interesting locations are the North Sea, the Gulf of Mexico (GOM) and the sea outside Brazil. In Table 3.1, typical significant wave heights H_s, peak periods T_p and current velocities V_c for the North Sea and Brazil are listed. Unfortunately, satisfactory weather data for the Gulf of Mexico has not been obtained.

Table 3.1: Environmental data

Location	$\mathbf{H}_s$ [m]	$\mathbf{T}_p$ [s]	$\mathbf{V}_c$[m/s]
North Sea	[0.5 12.0]	[1.0 18.0]	[0.0 1.5]
Brazil	[0.5 7.0]	[1.0 18.0]	[0.0 1.5]

As we are to investigate regular waves, and not irregular waves, the notations H_{max} and T_{max} will be used rather than H_s and T_p, which are the parameters for irregular waves. All combinations of the wave heights and periods in Table 3.1 could be examined if wanted. However, by carefully chosing some of them we should be able to prove the same points. The selected wave heights and periods should be significant enough to affect the riser, but not extreme - as it is not realistic to operate above a certain significant wave height (Beaufort 10, which implies wave heights ranging from 9.0 to 12.5 [m] is often given as operation condition for semi-submersibles fitted for harsh environment). Wave heights in the interval [4 [m] 10 [m]] and wave periods in the range [10 [s] 30 [s]] represent probable, yet not insignificant, waves. Wave periods of 30 [s], which can occur for *swells* (waves from distant storms), are very rare - but as the periods for these waves risk to enter the natural periods in heave for the semi-submersible (see Section 2.1), it is interesting to study the effect of such waves. Considering the current, a starting point is a uniform and unidirectional current profile with velocity 0.6 $\frac{m}{s}$, while a sheared current profile (with surface velocity 0.6 $\frac{m}{s}$) will also be applied.

3.2.3 Amplitude and velocity of drive-off

By *amplitude* of drive-off is meant the magnitude of the offset of the semi-submersible when it drives off. We know that if the semi-submersible is allowed to drive off location without being restrained at a certain point, the angles at the top and bottom of the riser will undoubtedly grow excessive. The target of the analyses with drive-off is both to find out for which offset the angles are excessive, and to see *how* they develop as the vessel moves away from its initial position. Therefore, reasonable amplitudes should be applied in the analyses. However, a reasonable offset at 2000 [m] water depth may be critical at 300 [m] depth. For instance, an offset of 20 [m] at 2000 [m] will most probably not cause any trouble - but of course, the reason for the offset is a problem in itself because it should not occur. At 300 [m] water depth, on the other hand, an offset of 20 [m] is an offset of nearly 7 % of the water depth, which would result in a riser disconnect. In shallow water, the criteria for disconnect - and hence also the time available for preparation for disconnect - is much smaller than for deep water. In Sørensen et al. [5], this is mentioned as an argument against dynamic positioning of vessels in shallow water. An immediate idea is to use different amplitudes of drive-off for the two water depths in the analyses. However, the probability for the vessel to drive off with a high enough speed to reach an offset of, say, 100 [m] is not larger for a larger water depth.

Further, the velocities with which the semi-submersible drives off location should be realistic. In the analyses, the vessel will drive off with increasing velocity, and four different scenarios in which the time used to reach the offset varies are studied. Dividing the magnitude of the offset by the time used to reach it gives an average velocity, and this will not exceed 2 $[\frac{m}{s}]$.

3.2.4 Amplitude and period of low-frequency harmonic motions

Slow-drift motions of the semi-submersible are caused by second-order wave, current and wind loads. Also, a failure in the DP system may give undesired harmonic motions of the vessel. In order to simulate the effect of these motions, the vessel is given prescribed harmonic motions with high periods (1-2 minutes). The amplitude of the motion will be in the interval [20 40] [m]. The reader should keep in mind that - even though the slow-drift motions are prescribed in this analysis - these motions are in real life caused by non-linear interaction effects between the waves and the body motion, or a failure in the DP system. Also, we will use the term *low-frequency harmonic motions* when referring to these motions, as real-life slow-drift motions always come with waves (except when they are caused by the DP system). In the analyses, however, waves will *not* be present in all analyses with low-frequency harmonic motions.

3.3 Periods of interest

When performing analyses of a system consisting of several components it is crucial to consider the natural periods for each component. In Figure 3.1, natural periods for environmental loads, different structures and the DP system are shown. As stated in Section 2, semi-submersible does not risk to get excited by wind generated waves. However, the periods of swells may be in the same period domain as the natural period in heave, roll and pitch of the semi-submersible. The DP system may also excite the heave, roll and pitch motions of the vessel through the control of the horizontal motions. This phenomena is described in Sørensen and Strand [12].

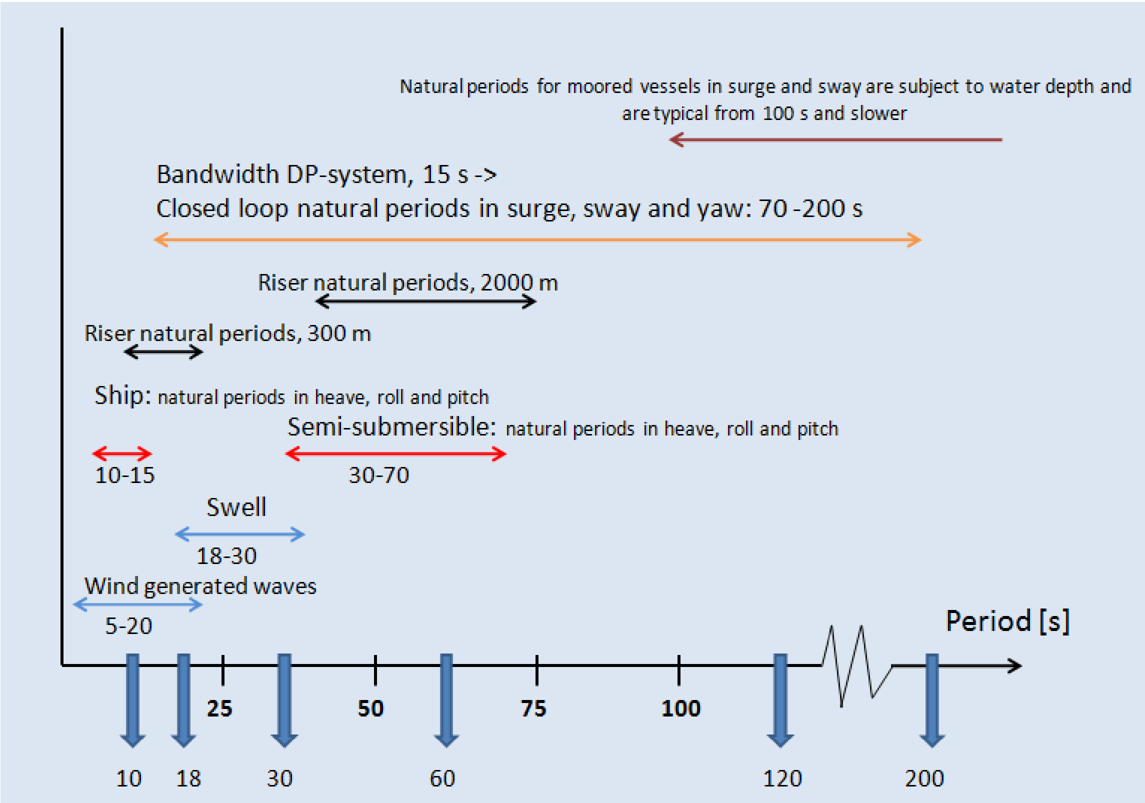


Figure 3.1: Overview of eigenperiods and selected periods

The arrows indicate which periods which are investigated in the analyses. Also, the natural periods of the riser must be considered. These periods are dependent on water depth and top tension. In RIFLEX, natural periods are calculated for each water depth. In Table 3.2 the first and second eigenperiod for the riser at 300 and 2000 [m] water depth can be seen.

Table 3.2: Natural periods (eigenperiods) for the riser in shallow and deep water

	Water depth [m]	
	300	**2000**
First eigenperiod [s]	16	74
Second eigenperiod [s]	8	37

For the riser in shallow water, for instance, it is interesting to see whether the response is larger for regular waves with period of 8 [s] and 16 [s] than elsewhere. In deep water, the response to a low-frequency motion with period close to 74 [s] may be investigated.

3.4 Set-up

With reference to Section 3.1.1 and 3.1.3 the analyses in RIFLEX should be carried out in such a way that the effect of waves, current and drive-off is first studied separately, and then combined so that critical scenarios can be identified. Low-frequency harmonic motions, with and without current and regular waves, are studied at the end of Section 4:*Results*. The order in which the analyses will be accomplished (and discussed) is as follows:

1. Riser exposed to **current**.
2. Riser exposed to **regular waves**.
3. Riser exposed to **vessel drive-off** to a specified location during different spaces of time.
4. Riser exposed to **regular waves** and **current**.
5. Riser exposed to **vessel drive-off** and **current**.
6. Riser exposed to **regular waves** and **vessel drive-off**.
7. Riser exposed to **regular waves**, **current** and **vessel drive-off**.
8. Riser exposed to **low-frequency harmonic motions** of the semi-submersible.

In the first analysis, there will be no waves, and the vessel is in its initial position at all times. The riser is *only* exposed to current. This also applies for the remaining analyses; only the listed item(s) influence(s) the riser, in addition to the top tension - of course - which supports the riser. The top tension for each of the water depths is calculated according to Equations (3.1) and (3.2), and this will be constant for each water depth. Both 300 and 2000 [m] water depth will be applied in most analyses.

The results from the listed analyses will be presented in Section 4:*Results*.

4 Results

In this section, results from the analyses in RIFLEX will be presented and discussed. The aim is to find out how the riser responds to various influences such as current, waves, vessel drive-off and slow-drift motions. Furthermore, the results of interest will be used as background information when developing an advisory system for the semi-submersible in Section 5.

The focus will be on the riser top and bottom angles. These must not exceed certain values in order to ensure a safe operation. If the top angle becomes excessive, the riser risks to get into contact with the rig. An excessive bottom angle may result in damage on the BOP and, in the worst case, a blow-out. Different research papers establish different limits for the riser angles. Leira et al. [6] give the following intervals for the riser angles (both lower and upper):

- 2-4°: may imply that the drill-pipe within the riser gets into contact with the ball-joint or the well-head.
- 4-6°: interruption of operation
- 6-7°: controlled disconnect of the riser

Meanwhile, Sørensen et al. [5] state that riser angles within ± 2° are optimal for operation. Furthermore, riser angles larger than 5-8°are classified as *fatal*. Based on this, a fair approach is to allow the lower angle to reach 2° and the upper angle to reach 4° before a disconnection should be prepared. The reason why the top angle has a higher limit than the lower angle is that a severe angle at the bottom has more critical consequences than a severe angle at the top. A wider moonpool may allow for greater top angles. The reader should keep in mind that the limits of 2° and 4° are *absolute* magnitudes. A more specific way to state the limits is to say that the lower angle must be kept within ± 2°, while the upper angle must be kept within ± 4°.

In the following analyses, riser top angles in excess of ± 4° will be referred to as *critical* or *excessive*. Similarly, bottom angles above ± 2° are classified as *critical* or *excessive*. Excessive top and/or bottom angles implies that the operation must stop and that a disconnect should be prepared.

4.1 Calculation of riser angles from displacements

Before presenting the results from the analyses, some important features of the resulting riser angles should be clarified. The reader should keep in mind that it is the angle between the BOP and the bottom of the riser, as well as the angle between the vessel and the top of the riser, that are the crucial angles. The angles at the bottom and at the top of the riser are calculated from the resulting dynamic displacements from RIFLEX. From trigonometric relations, the following formula is derived:

$$\alpha = arctan(dx/dz), \tag{4.1}$$

where dx and dz are defined in Figure 4.1. The angles are hence given as the inclination of the element compared to the global z-axis. This is adequate when considering the effect of current and drive-off. The angle between the global z-axis and the bottom of the riser will always be a good representation of the angle between the BOP and the bottom of the riser. Furthermore, the vessel will not tilt, such that the angle between the global z-axis and the top of the riser can represent the angle between the vessel and the top of the riser. However, when there are first-order waves acting on the semi-submersible, the vessel itself will tilt, and in this case, the angle between the vessel and the top of the riser is not the same as the angle between the global z-axis and the top of the riser. The top angle compared to the global z-axis will in this case not be interesting, because it can not indicate whether the top of the riser gets into contact with the vessel or not. Also, the inclination according to the riser itself is the inclination compared to the object to which the riser is attached; in this case the vessel. In the following, the plots of the angles will always indicate which top angle which is presented. The top angle compared to the global z-axis is always red, while the top angle compared to the vessel is magenta.

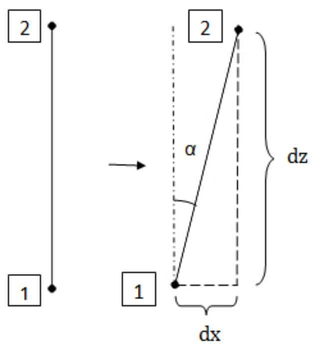


Figure 4.1: Calculation of riser angles from displacements.

4.2 Sequence of analyses and case data

In the previous chapter, the following sequence of analyses was presented:

1. Riser exposed to **current**.
2. Riser exposed to **regular waves**.
3. Riser exposed to **vessel drive-off** to a specified location during different spaces of time.
4. Riser exposed to **regular waves** and **current**.
5. Riser exposed to **vessel drive-off** and **current**.
6. Riser exposed to **regular waves** and **vessel drive-off**.
7. Riser exposed to **regular waves**, **current** and **vessel drive-off**.
8. Riser exposed to **low-frequency harmonic motions** of the semi-submersible.

The riser needs to be supported by a top tension. For each water depth, the required top tension has been calculated and the values can be seen in Table 4.1.

Table 4.1: Top tension

Water depth [m]	Top tension [kN]
300	1650
2000	4000

The riser segment numbering can be seen in A.1, while the complete riser segment data for the two water depths can be found in A.2.

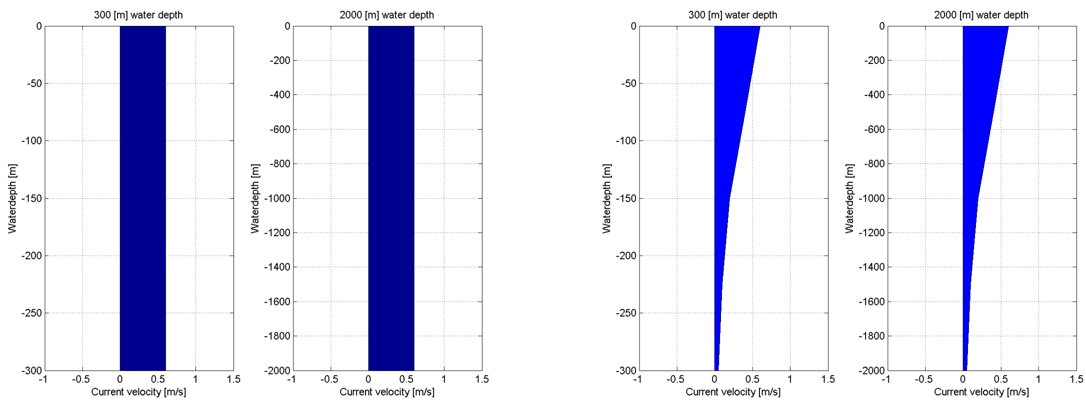
In the following sections, results from these analyses will be presented and discussed.

4.3 Results from analyses 1, 2 and 3

The effect of current, regular waves and a vessel drive-off will be studied separately in order to understand the riser response for each of these influences. The external influences (current and waves) will be studied first. The vessel drive-off has its source in the semi-submersible itself, and is analyzed at the end. The vessel drive-off will in this analysis be demonstrated by a displacement of the vessel from its initial position to an offset position. However, a displacement of the vessel may also be a controlled action in order to compensate for current forces. This will be further explored in Section 4.4.1.

4.3.1 Effect of current

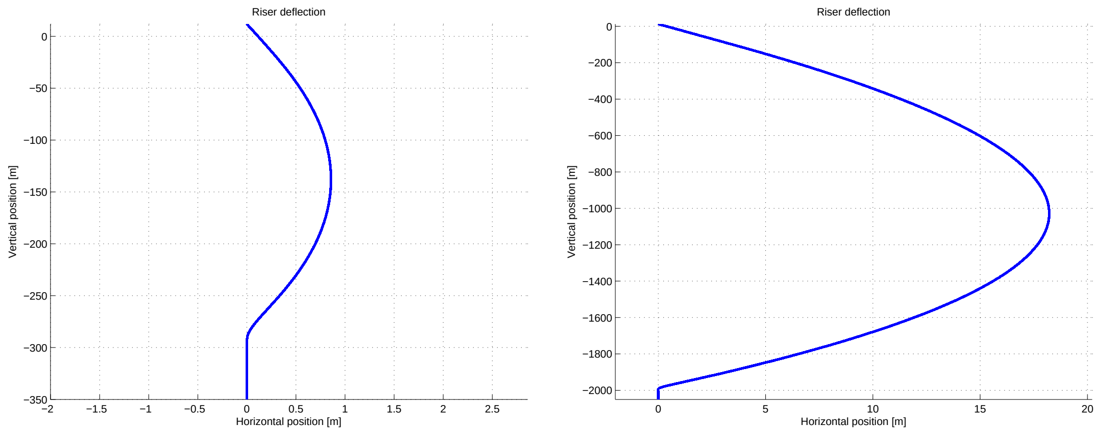
In the introduction of this report, the effect of current in shallow in deep water was shortly presented (see Figure 1.2(a) and 1.2(b)). It was indicated that the riser will be more deflected in deep water than in shallow water when exposed to current. The riser becomes more flexible when it becomes longer, and the increased area because of the buoyancy modules will cause the drag force to increase. In this section, results from a riser exposed to current in shallow and deep water are presented. The riser is first exposed to a uniform current with velocity 0.6 $[\frac{m}{s}]$. The current has a velocity in the positive x-direction. The uniform current profile can be seen in Figure 4.2(a).



(a) Uniform current (b) Sheared current

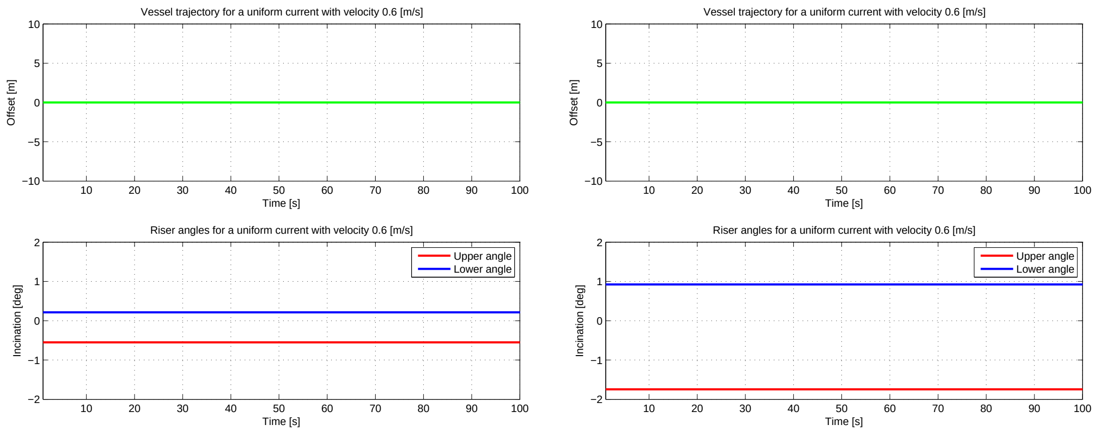
Figure 4.2: Current profiles at 300 and 2000 [m] water depth

The static deflection of the riser is shown in Figure 4.3. The riser in shallow water (300 [m] water depth) is very little affected by this current, while the riser in deep water (2000 [m] water depth) is clearly deflected. Please note that different scales are applied on the x- and z-axes in order to better visualize the deflections. Therefore, the actual deflections are not as alarming as indicated in Figure 4.3(a) and 4.3(b). However, Figure 4.4(a) and 4.4(b) present the riser top and bottom angles, and it can be seen that the riser in deep water will actually have rather significant - though not severe - top and bottom angles. The top angle is almost -2°, while the bottom angle is approximately 1°. At both water depths, a segment of 50 [m] is below the sea bed and will not be deflected due to the current.



(a) 300 m water depth (b) 2000 m water depth

Figure 4.3: Riser deflection in a) shallow and b) deep water for a uniform current with velocity 0.6 $[\frac{m}{s}]$

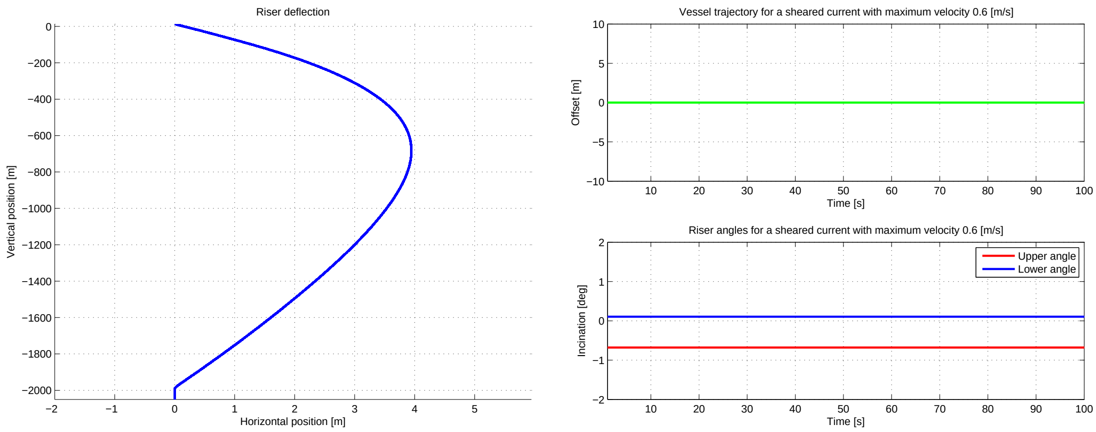


(a) 300 m water depth (b) 2000 m water depth

Figure 4.4: Riser angles in a) shallow and b) deep water for a uniform current with velocity 0.6 $[\frac{m}{s}]$

However, most ocean currents are not uniform. They can be sheared, bidirectional or they may have quite complicated profiles. In order to study a more representative current, a sheared current profile is applied. In Figure 4.2(b) the current velocities along the current profile for 300 and 2000 [m] water depth are shown. As it has already been established that a unidirectional current does not have a significant impact on the riser in shallow water, only results from the riser in deep water will be presented for the sheared current in Figure 4.2(b).

Figure 4.5(a) and 4.5(b) show the riser deflection and riser angles when the riser is exposed to the sheared current profile in Figure 4.2(b). The deflection is considerably smaller, which is confirmed by the riser angles. The top angle is approximately -0.7°, while the bottom angle is just over 0.1°.



(a) Riser deflection

(b) Vessel position and riser top and bottom angles

Figure 4.5: Riser deflection and riser angles for a sheared current with surface velocity 0.6 [$\frac{m}{s}$] (see Figure 4.2(b))

The results and discussion in this section will be valuable as the current is introduced in combination with waves and drift-off in the coming sections. The reader should keep in mind that only unidirectional current is applied. In further studies, current should enter from more than one direction. Also, current profiles developed through measurements on different locations should be applied.

4.3.2 Effect of regular waves

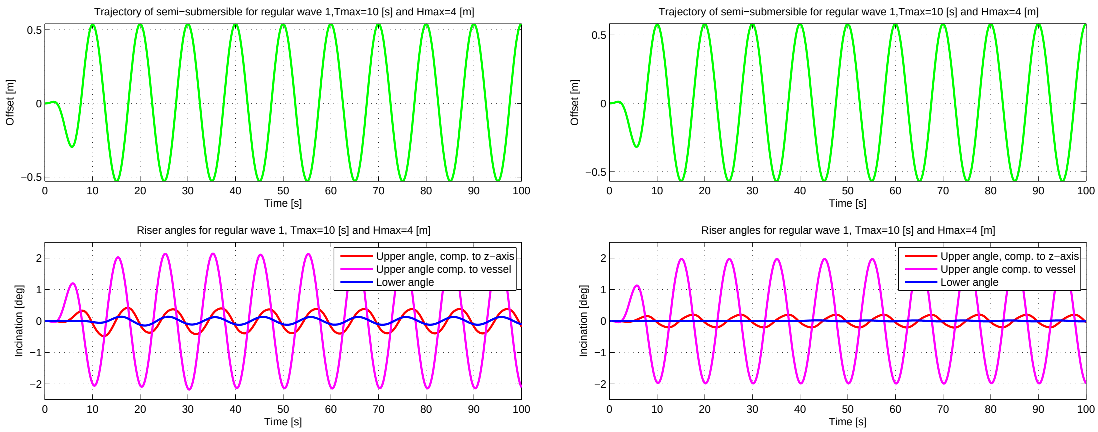
In this section, the vessel and the riser are exposed to regular waves with wave heights and periods as listed in Table 4.2. The regular wave case with wave height 4 [m] and period 10 [s] is referred to as *regular wave case 1*, and similarly the regular wave case with wave height 8 [m] and period 18 [s] is referred to as *regular wave case 4*, as indicated in Table 4.2.

Table 4.2: Regular wave cases

T_{max}/H_{max}	4 [m]	8 [m]	10 [m]
10 [s]	1	2	-
18 [s]	3	4	5
30 [s]	-	6	7

When exposed to regular waves, the semi-submersible will incline, hence the pitch angle will be non-zero. In this case, the angle between the top of the riser and the global z-axis may differ from the angle between the top of the riser and the vessel. It is the latter which is interesting, because an excessive top angle compared to the vessel may result in contact between the riser and the vessel, which is not desirable. Hence, the angle between the top of the riser and the vessel is used when presenting the results, and the curve representing this angle is magenta. The top angle compared to the global z-axis is also included, however, in order to illustrate the difference between these two angles.

Regular wave case 1 (see Table 4.2) is first investigated. In Figure 4.6(a) and 4.6(b) the vessel trajectories and riser angles for regular wave case 1 at 300 and 2000 [m] water depth are shown.



(a) Riser angles, 300 m

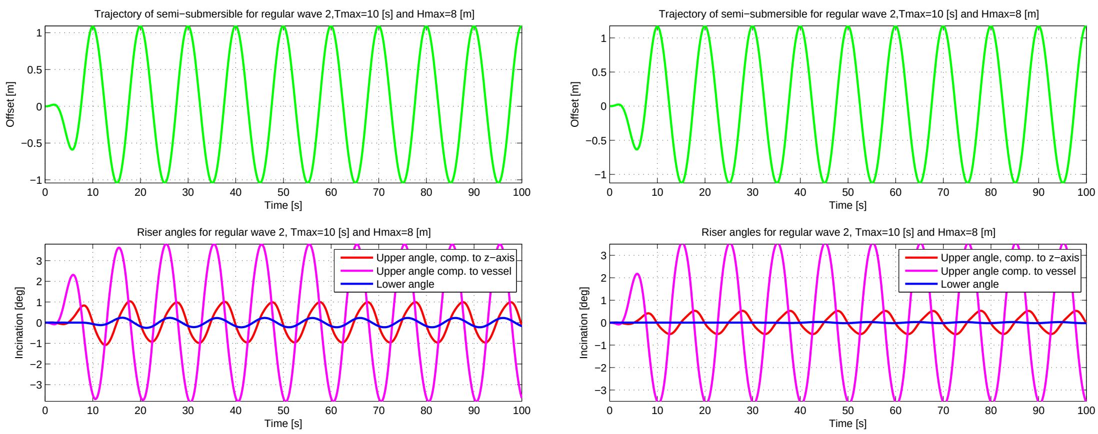
(b) Riser angles, 2000 m

Figure 4.6: Riser angles for a regular wave with period of 10 [s] and wave height of 4 [m]

The motion of the vessel is harmonic with the same period as the wave. The amplitude, however, is quite small. The vessel seems to move slightly more at 2000 [m] than at 300 [m], though just marginally. However, the difference in magnitude of the motion is due to the way in which this information has been obtained: it is the motion of the top node of the riser which is presented. This motion is fixed to the vessel horizontally, but not vertically. The difference in riser response in shallow and deep water results in different vertical motions of the top end, and hence also the horizontal displacements will be different. It is however wrong to say that the riser affects the vessel motion; the vessel moves equally in shallow and deep water, but the top end of the riser does not. Despite the fact that it is actually the trajectory of the top end of the riser, and not that of the vessel, which is shown in the following figures, this trajectory will still be called the vessel trajectory. This gives a more practical understanding of the situation which is analyzed, and the error is insignificant.

Considering the angles, it is evident that the bottom angle is only marginally affected by the regular wave, both in shallow and deep water. At 300 [m], the bottom angle responds after 9 [s], approximately. At 2000 [m] it can be found (when studying the time series) that the bottom angle takes an insignificant inclination after 35 [s], approximately. Further, the importance of considering the top angle of interest appears in both Figure 4.6(a) and 4.6(b). The inclination between the top of the riser and the global z-axis (represented by the red line) is rather small in both figures. The inclination between the top of the riser and the vessel (represented by the magenta-colored line), however, is more severe. Still, an inclination of 2° between the vessel and the riser is not necessarily as bad as an inclination of 2° at the lower end of the riser. The reason why the top angle compared to the vessel is much bigger than the top angle compared to the z-axis is the vessel inclination, which was discussed in Section 4.1. The vessel responds to the wave according to its transfer functions (see Section 2.2), and this may not coincide with the response of the riser. Hence, the inclination of the vessel compared to the global z-axis may be negative while the inclination of the riser compared to the same axis is positive. This obviously results in large riser angles compared to the vessel.

Figure 4.7 shows the vessel trajectory and the riser angles at 300 and 2000 [m] when the vessel is exposed to a regular wave with the same period as the previous case, but with a wave height which is twice as big - regular wave case 2. The amplitude of the vessel amplitude is roughly the double of the motion amplitude in Figure 4.6(a) and 4.6(b). The period of the motion is still the same, however, as the wave period is the same for regular wave 1 and 2. The result of this is that the distance traveled by the vessel is twice as long, but the time used to travel the distance is the same. This results in a higher vessel velocity. Comparing the top angles in Figure 4.7 with the top angles in Figure 4.6, we see that they are larger. Seen that only the wave height, and hence the vessel offset and the vessel velocity is different in the two cases, this leads to the conclusion that the top angle is dependent on the vessel velocity; the higher vessel velocity, the more excessive top angle. The velocity dependence is also reflected in the top angle lapse. The top angle compared to the global z-axis (the red line) reaches the maximum value when the vessel trajectory crosses the x-axis. From basic trigonometry we know that the derivative (and hence the velocity in this case) is greatest where the function (in this case the vessel offset) is zero. The top angle compared to the vessel reaches its maximum a little after this point. This angle is also dependent on the inclination of the vessel, and it will be at its maximum when the vessel inclination is maximum. Hence, the point where the top angle compared to the vessel reaches its maximum is a combination of the vessel velocity and the vessel inclination. Considering the bottom angles, these are still very small, and the time delay is the same as for regular wave 1. Indeed, the offset of the vessel is twice as big as in the previous case, but an offset of 1 [m] is far too small to cause an excessive bottom angle, even in shallow water.



(a) Riser angles, 300 m

(b) Riser angles, 2000 m

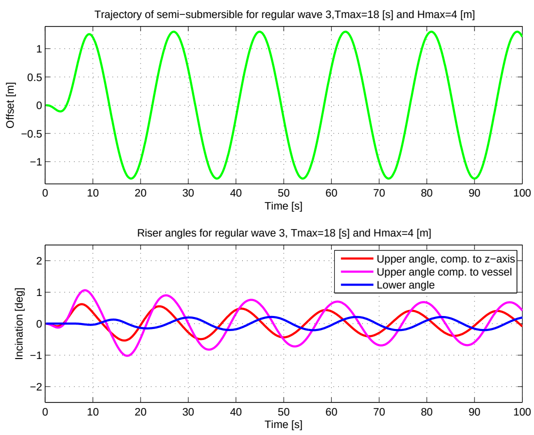
Figure 4.7: Riser angles for a regular wave with period of 10 [s] and wave height of 8 [m]

It has been found that a greater wave height causes a larger vessel motion amplitude, but that the period of motion is the same when the wave period does not change. Hence, the vessel velocity and the top angle increase.

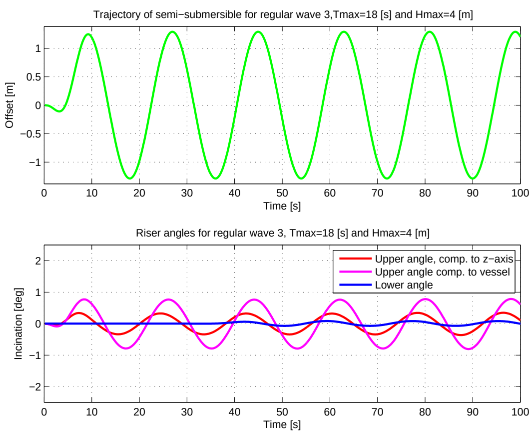
The effect of a greater period will be studied. In Figure 4.8 the vessel trajectory and riser angles for a regular wave with period 18 [s] and wave height 4 [m] (regular wave case 3) are shown. The amplitude of the vessel motion is nearly the same as for regular wave case 2, but the period of the motion is 18 [s], and not 10 [s], as the wave period is now 18 [s]. Thus, the vessel velocity is smaller, and this is reflected by the top angles which are less critical. Comparing the angles in Figure 4.8(a) and 4.8(b) with the angles in Figure 4.6(a) and 4.6(b) (regular wave case 1) - where the wave height is the same, but the period is smaller - it is seen that a greater period apparently causes smaller top angles compared to the vessel, while the top angles compared to the global z-axis are larger. Calculating the average vessel velocity for the two wave cases we find that the vessel moves faster when the period is 18 [s]. Hence, the top angles compared to the z-axis are in accordance with the vessel velocity dependency identified earlier in this section. However, the riser seems to have a smaller inclination compared to the vessel for this period. When studying the vessel inclination, it is found that this is smaller for regular wave case 3 compared to regular wave case 1, and this results in smaller top angles compared to the vessel. This leads to the conclusion that the top angles are dependent on the inclination of the vessel, as well on its velocity.

The bottom angles are still quite insignificant, and they have the same time delay as for the other waves.

A fourth wave, regular wave case 4, is introduced. This is both higher and longer than the first wave, with wave height 8 [m] and period 18 [s]. The resulting vessel motions and riser angles for the two water depths are seen in Figure 4.9. The amplitude of the vessel motions for 300 and 2000 [m] are approximately 2.5 [m] for both water depths, and the period of motion is 18 [s], which is the same as the wave period. Considering the top angles, these are smaller than for regular wave case 1 and 2 (Figure 4.6 and 4.7), but larger than for regular wave case 3 (Figure 4.8). The bottom angles, however, are larger than for all the other cases. Yet, these are still insignificant. Compared to regular wave case 3, which has the same period but only half the wave height, the top angles are roughly twice as big. In shallow water (Figure 4.9(a)) it is noticed that both upper angles have large magnitudes at the start of the vessel motion before they stabilize at a slightly lower magnitude.

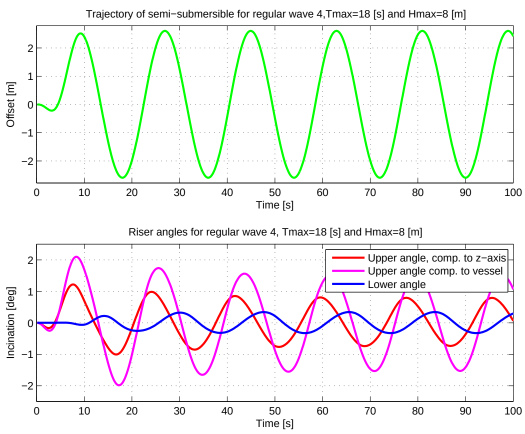


(a) Riser angles, 300 m

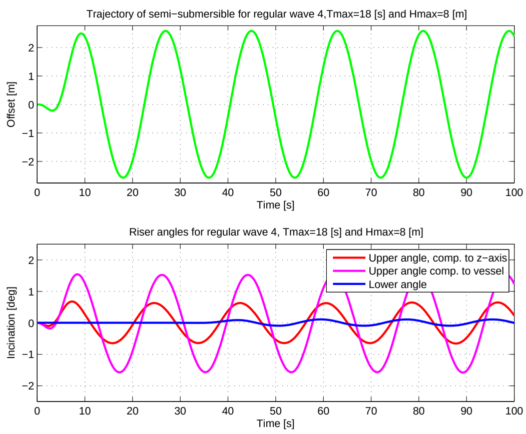


(b) Riser angles, 2000 m

Figure 4.8: Riser angles for a regular wave with period of 18 [s] and wave height of 4 [m]



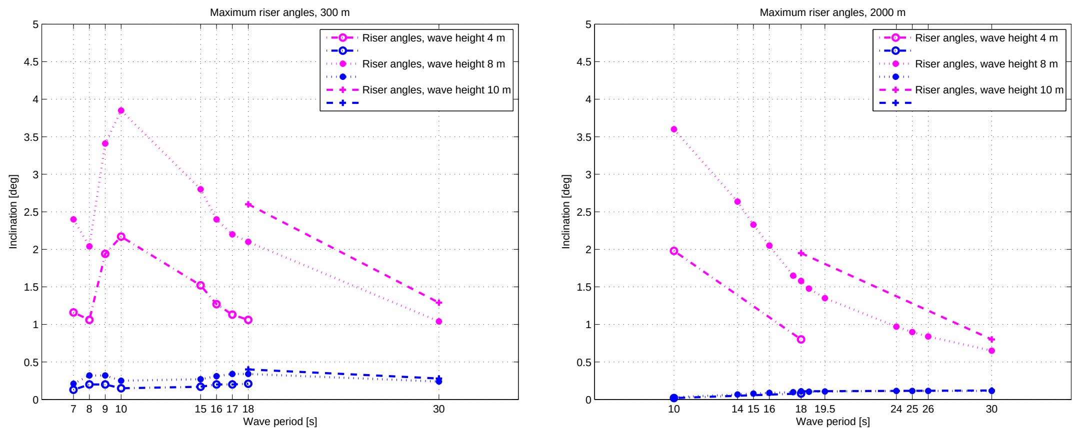
(a) Riser angles, 300 m



(b) Riser angles, 2000 m

Figure 4.9: Riser angles for a regular wave with period of 18 [s] and wave height of 8 [m]

Figure 4.10(a) and 4.10(b) summarize the maximum absolute lower and upper angles for the four regular wave cases that have been studied so far. In addition, results from regular wave case 5,6 and 7 in Table 4.2 are also included. For 300 [m] water depth, wave periods corresponding to the first and second eigenperiod of the riser (16 and 8 [s]) are included. The riser angles for these periods will be discussed later in this section. In the figures, the maximum lower and upper angles are displayed as function of the wave period for each wave height. In the figures, *upper angle* refers to the upper angle compared to the vessel, as this is more relevant than the top angle compared to the global z-axis.



(a) Maximum riser angles, 300 m (b) Maximum riser angles, 2000 m

Figure 4.10: Maximum absolute lower (blue line) and upper (magenta line) angles as function of the wave period for each wave height.

Considering the top angles in Figure 4.10(a) and 4.10(b), it is evident that the top angle increases for an increasing wave height while it decreases for an increasing wave period. The exception is the top angle for the second eigenperiod for 300 [m] water depth, and this will be discussed later in this section. The top angle compared to the vessel is both dependent on the vessel velocity and the vessel inclination. A short and high wave causes higher vessel velocity than a short and low wave. While the top of the riser is forced to follow the vessel motion, the lower end will stay behind when the vessel moves rapidly. This causes instant large top angles. Also, the vessel inclines less as the wave period increases. This can be deducted from the vessel transfer functions, where the response amplitude decreases with increasing period. The longer the wave period, the more will the system approach a quasi-static behavior, and the vessel will follow the wave instead of inclining. The lower angles are very small both at 300 and 2000 [m] water depth. While the top angle follows the same pattern in both shallow and deep water, the lower angle has a different development in shallow and deep water. In shallow water, the lower angle seems to reach the "worst angle" for a wave height of 10 [m] and a period of 18 [s], and in the transition from this wave period to a wave period of 30 [s] the angle decreases slightly. In deep water, the lower angle is nearly unchanged for an increased wave period over 18 [s]. Furthermore, the riser in shallow water experiences larger angles than the riser in deep water. One reason for larger bottom angles in shallow water is that a greater part of the energy from the harmonic motion of the vessel is transmitted down to the bottom of the riser in shallow water. In deep water, the harmonic motion is significantly reduced at the bottom of the riser. Also, the vessel offsets, which occur because of the regular wave, affect the riser more in shallow water than in deep water. In Figure 4.10 it is evident that the regular wave with period 10 [s] and height 8 [m] causes significant, though not critical, top angles. For first-order waves of a corresponding magnitude one should possibly initiate a temporary halt in the operation.

Considering the riser angles for the eigenperiods for the riser at 300 [m] water depth, we find that for the second eigenperiod, 8 [s], the upper riser angle compared to the vessel obviously reaches a local minimum. Meanwhile, the lower angle seems to reach a local maximum for this period. The first eigenperiod, 16 [s], does not seem to cause as significant effects. For waves in the vicinity of the eigenperiod of the riser, one would expect *higher* response than for the other periods. However, the riser angle compared to the vessel may not be the best angle to consider when investigating resonance effects. In Figure 4.11, the upper angle compared to the z-axis for wave height 4 and 8 [m] and the same wave periods in Figure 4.10(a) is shown. It is evident that the top angle compared to the z-axis is large in the vicinity of the eigenperiod. Because the top angle compared to the vessel both is dependent on the vessel inclination and the top angle compared to the z-axis, a large top angle compared to the z-axis may give smaller top angles compared to the vessel. The local minimum at 8 [s] for the top angle compared to the vessel does coincide with the peak at 8 [s] for the top angle compared to the z-axis. For the first eigenperiod, 16 [s], we see ambiguous effects when studying the three riser angles, and there is little sign of resonance in the vicinity of this period.

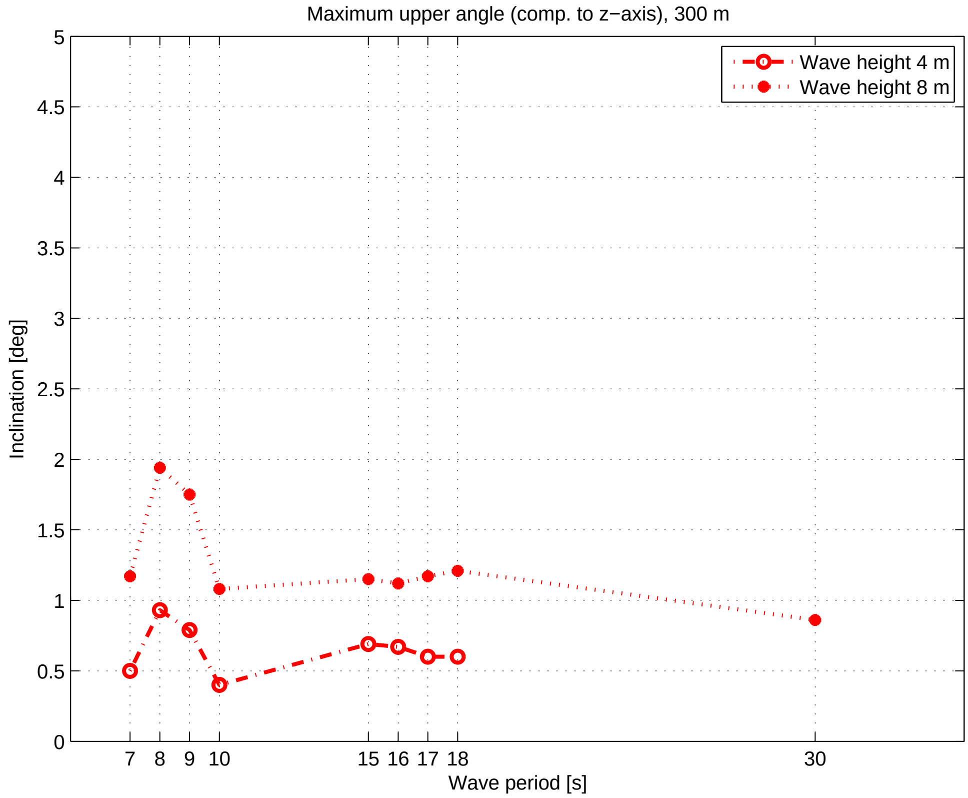


Figure 4.11: Upper angle compared to z-axis at 300 [m]

The first and second eigenperiod in deep water (74 and 37 [s]) are too large to be excited by first order waves. Even swells do not have such long periods. However, the third, fourth and fifth eigenperiod are included in Figure 4.10(b). These do not seem to give any resonance. Nonetheless, they give a more detailed picture of the riser angles for different wave periods.

Figure 4.10(a) and 4.10(b) prove that the top angle is much more affected by a regular wave than the bottom angle, both in shallow and deep water. They also indicate that a high and short wave is the most critical case considering the top angle. By "short" is here meant a wave with period of 10[s]. Shorter waves have less probability of reaching a wave height of significance. From fundamental wave theory we know that a wave breaks when the relationship between the wave height H and the wave length λ exceeds $\frac{1}{7}$, or, mathematically written:

$$\frac{H}{\lambda} > \frac{1}{7} \tag{4.2}$$

Using the relation between wave length and period T in deep water, λ=1.56T^2, one finds that a wave with height 8 [m] will break for a wave period of 6 [s], approximately. Hence, a wave period of 10 [s] is the lower limit for wave periods in this study, as shorter waves most probably will have smaller wave heights and hence have little impact on the semi-submersible.

It has also been found that for the riser in deep water it takes approximately 35 [s] for the bottom angle to respond to the harmonic motion at the top end. This response is also smaller than the response of the lower angle in shallow water, which responds to the top end motion after 9 [s]. The wave propagation velocity C in a tensioned riser can be calculated using the following relation:

$$C = \sqrt{\frac{P_{top}}{m}}, \tag{4.3}$$

where P_{top} is the top tension applied for each water depth in order to prevent the riser from collapsing (see Table 4.1), and m is the mass of the riser (including buoyancy modules and mud). At 300 [m] water depth, C is found to be 55 [$\frac{m}{s}$], which implies that the time required for a wave to reach the lower end of the riser is 5.5 [s]. At 2000 [m] water depth, C is 81 [$\frac{m}{s}$]. This implies a that a wave uses 25 [s] to reach the bottom end of the riser. Comparing the calculated time delays with the observed time delays we find that the magnitudes of the time delay agree. The difference between the calculated time delay and the simulated time delay may have its origin in several error sources, such as in accuracies when calculating mass of riser and top tension. Also, it might be that the wave is transmitted to the bottom of the riser at an earlier point that what we have been able to see in the time series.

In future analyses including regular waves, the notation in Table 4.2 will be applied when referring to the regular wave of interest.

Only regular waves have been considered. Irregular waves may give more complex results closer to reality. However, it is believed that the effect from different wave heights and periods is best captured using regular waves. In further studies, irregular waves should be applied.

4.3.3 Effect of drive-off

Drive-off is an uncontrolled excursion of the vessel, which may happen because of a failure in the DP system (Sørensen [14]). If the riser is not disconnected fast enough, a drive-off may result in damage on the riser and the BOP, and the worst-case scenario is a well blow-out. As stated in Section 3.2.3, a drive-off may be more critical at shallow water compared to deep water, because there is less time available for preparation for disconnect as the radiuses of the watch circles (see Figure 1.1) are smaller.

In this section, the effect of drive-off will be investigated. There is no current and no waves included in the analysis. The vessel will reach an offset position of 100 [m]. The time to reach this position will vary, though, from 50 [s] to 500 [s]. Figure 4.12 shows the four different trajectories for drive-off. The semi-submersible starts in its initial position with a velocity of 0 [$\frac{m}{s}$] and will then pick up speed which increases depending on the scenario. The trajectories are meant to illustrate the following situation:

1. A failure in the DP system causes the thrusters to give the semi-submersible a velocity in the x-direction.

2. The vessel picks up speed and drives off. The velocity increases with time.

3. The operator manages to get in control and the vessel stops at an offset of 100 [m].

For instance, the solid line in Figure 4.12, represents a drive-off where the vessel has a velocity of 0.2 [$\frac{m}{s}$] after 10 [s], 0.7 [$\frac{m}{s}$] after 30 [s] and 2 [$\frac{m}{s}$] after 85 [s]. Since it is more realistic that the velocity of the semi-submersible will decrease before the vessel stops when the velocity is this high, the semi-submersible will change its speed from 2 [$\frac{m}{s}$] to a constant speed of 0.9 [$\frac{m}{s}$] the last 15 [s] before it stops at an offset of 100 [m]. Likewise, for the drive-off during 50 [s], the vessel will have a smaller and constant velocity the last 10 [s] before it stops. For the drive-offs during 300 and 500 [s], the velocity is sufficiently low after 100 [s] for the vessel to stop almost immediately (0.2 and 0.08 [$\frac{m}{s}$], respectively), so no transition velocity is included.

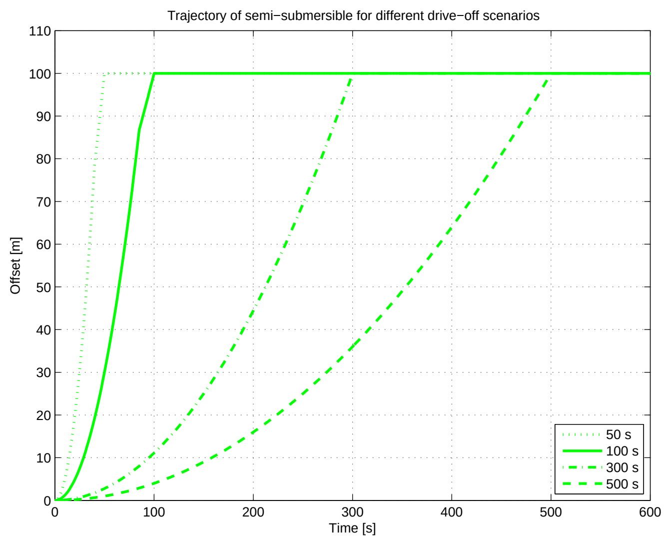
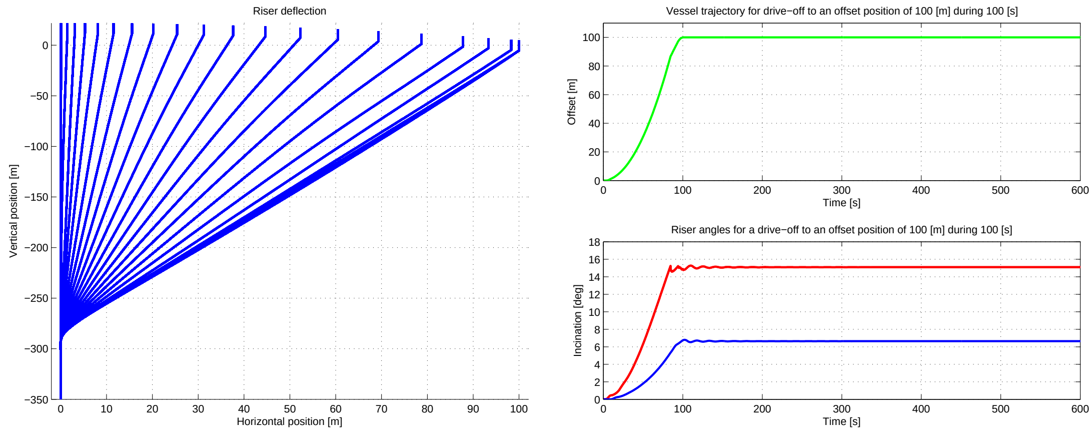


Figure 4.12: Trajectory of the vessel drive-off for four different scenarios. The time to reach the offset position of 100 [m] ranges from 50 [s] to 500 [s], which gives average vessel velocities in the range [0.2 2] [$\frac{m}{s}$].

There are two interesting characteristics to study in this analysis. Firstly, there is the difference in riser behavior in shallow and deep water. An offset position of 100 [m] at a water depth of 2000 [m] does not have to be critical, and it is expected that both angles will stabilize at acceptable values (below 2° for the lower angle and below 4° for the upper angle). At 300 [m], however, an offset of 100 [m] is far above the accepted offset, and a disconnect would have been executed at a much earlier point. Therefore, it is more interesting to study the development of the riser angles as the vessel drives off rather than considering the stationary riser angles when the vessel has reached its offset position. Secondly, the time delay between the motion at the top end and the response of the bottom of the riser must be investigated. In the previous section, it was found that, for a water depth of 2000 [m], the bottom angle did not respond until 35 [s] after the motion of the vessel, resulting from a regular wave, started. This time delay is expected to exist also for a vessel drive-off.

Figure 4.13 shows the riser at 300 [m] water depth for a drive-off to 100 [m] during 100 [s]. An instant remark is that both angles become excessive before the vessel has reached its offset position. The time delay between the motion at the top end of the riser and the response of the bottom end is about 9 [s]. It can be seen that the top angle increases more rapidly than the bottom angle, and it reaches its limit of 4° after 45 [s], approximately. The top and bottom angles increase parallelly, almost, until they reach their stationary values of 15° and 6.6° , respectively. It is seen that, as the vessel velocity decreases at 85 [s], the top angle responds immediately by decreasing before it oscillates slightly and thereafter stabilizes.

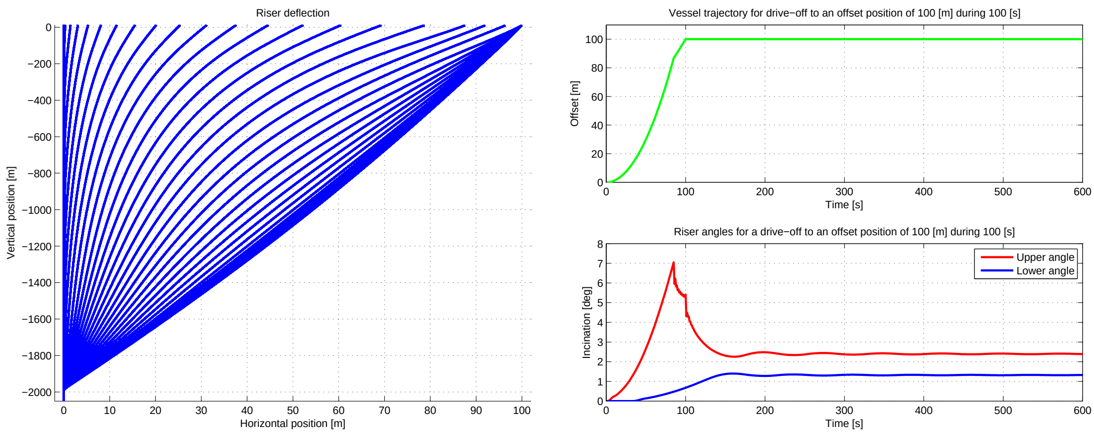


(a) Riser deflection (b) Riser angles

Figure 4.13: Riser deflection and angles for drive-off to an offset position of 100 [m] during 100 [s]. The water depth is 300 [m].

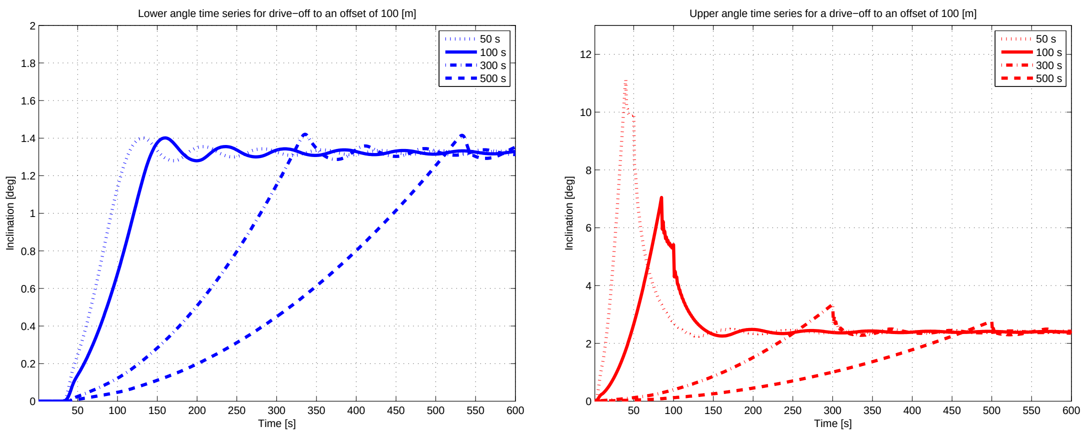
In Figure 4.14(a) and 4.14(b), the riser deflection and riser angles for an offset to 100 [m] during 100 [s] at a water depth of 2000 [m] can be seen. The top angle increases with the increasing velocity and offset, and it becomes excessive (above 4°) after 60 [s], approximately. It reaches a maximum value of 7°. For the bottom angle, however, it takes about 35 [s] before any response is seen. At 85 [s], when the vessel speed decreases to a constant value, the top angle clearly responds and decreases before it reduces even more when the vessel stops. From the point where the vessel is no longer moving, it takes another 50 [s] before the top angle has decreased to an angle in the vicinity of the stationary value. This is because the magnitude of the top angle will indirectly be affected by the magnitude of the bottom angle; the more the lower end of the riser manages to follow the motion, the smaller top angle during the motion. Because of the time delay the lower angle continues to increase after the maximum offset has been reached. The top and lower angle then approach each other almost synchronically. This is also the case for the three other drive-off scenarios. In this case, the top angle stabilizes at 2.5°, approximately, while the bottom angle stabilizes at 1.3°. In Figure 4.15, the bottom and top angle for the four different scenarios can be seen. The top angle is most critical for a step to 100 [m] during 50 [s]. Both for 50 and 100 [s] the top angle increases to an excessive value before it decreases when the vessel velocity decreases, and even more when the vessel stops. For a drive-off to 100 [m] during 50 [s] the top angle will in fact reach just above 11°. In all cases, the bottom angle has a time delay of about 35 [s]. From Figure 4.15 it is revealed that the magnitude of the top angle is dependent on the velocity of the vessel drive-off. The higher velocity, the higher top angle. When the riser moves in water, the riser itself experiences an incoming water flow. The velocity of the water flow increases with increasing vessel speed and prevents the riser from fully following the motion of the vessel. The bottom end of the riser will thus stay behind, and this causes large top angles. In Figure 4.15 this is reflected by the excessive top angles for drive-offs during 50 and 100 [s]. For all the scenarios, the top angle peaks for the maximum velocity. The maximum velocity occurs either just before the velocity decreases (for the drive-off during 50 and 100 [s]) or just before the vessel stops (for the drive-off during 300 and 500 [s]).

In the introduction of this section it was stated that both angles were assumed to stabilize at acceptable values for the riser in deep water. The lower angle does not exceed 1.5° in any of the cases, and the top angle stabilizes at 2.5°. These angles are not optimal, but they are within the established limits for the lower and upper and of the riser. In reality, a preparation for disconnect would be executed. However, knowing that the angles will not worsen, a disconnect could be avoided. This is obviously not the case if the vessel continues to drive off after the offset of 100 [m] has been reached. Also, the magnitudes of the top angle peaks for the drive-offs during 50 and 100 [s] would normally initiate a disconnect, even though they exist for a limited period of time.



(a) Riser deflection (b) Riser angles

Figure 4.14: Riser deflection and angles for a drive-off to an offset position of 100 [m] during 100 [s]. The water depth is 2000 [m].



(a) Lower angle (b) Upper angle

Figure 4.15: Riser angles for drive-off to an offset position of 100 [m] with various vessel speeds (see Figure 4.12). The water depth is 2000 [m]

It can be concluded that a drive-off is much more critical in shallow water than in deep water. In shallow water, both angles increase to an excessive magnitude and stabilize at this magnitude. This is not the case in deep water. The top angle increases with the vessel velocity, and decreases when the vessel stops, and even further as the lower angle approaches its static magnitude. Thus, the top angle will only be excessive for a certain amount of time before it improves. Also, the top angle is most critical for a rapid vessel drive-off, because the top end is forced to follow the vessel while the lower end stays behind. The time delay between the motion at the top end and the response of the lower end is found to be 9 [s] in shallow water and 35 [s] in deep water. These time delays are the same as for the riser exposed to regular waves, analyzed in Section 4.3.2. An important observation from these analyses is that in case of a drive-off in deep water, the lower angle will not respond immediately, and even when it responds to the motion, it increases slowly. Hence, the operator has time to make a decision before the lower angle becomes excessive and causes damage to the BOP and the well.

4.4 Results from analyses 4,5 and 6

The three separately investigated cases (riser exposed to current, regular waves and vessel drive-off) will be combined as described in Section 4.2. This will hopefully give a profound understanding of the riser response due to several influences and the complexity of the riser dynamics. This section comprises three sets of analyses where current, regular waves and vessel drive-off are combined in pairs. The combination of all three cases will be investigated in Section 4.5.

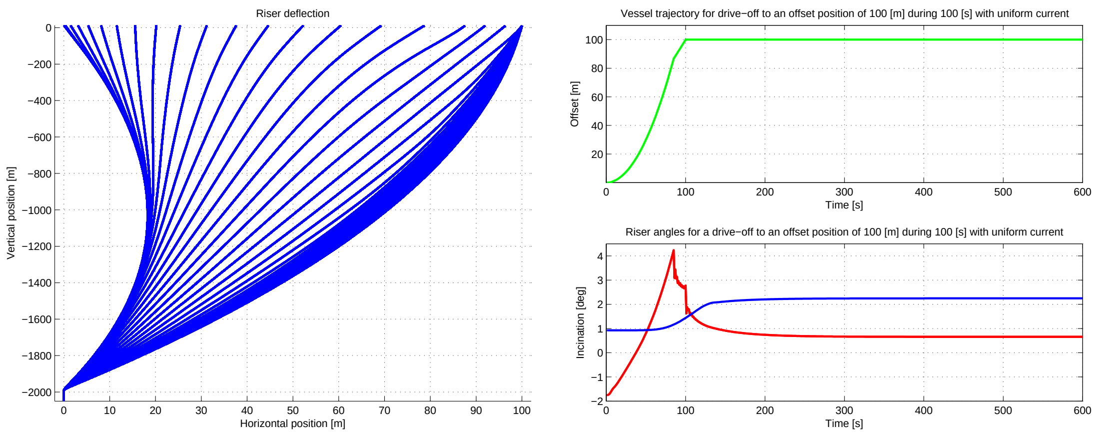
4.4.1 Combination of drive-off and current

In Section 4.3.1 the effect of current was studied, while the effect of a drive-off was investigated in Section 4.3.3. The current was found to only marginally influence the riser in shallow water, see Figure 4.3(a). In the drive-off analysis, it was found that the riser top and bottom angles quickly become excessive for a riser in shallow water, while the riser angles in deep water will stabilize within their respective limits. In this section, the combination of current and drive-off will be studied.

First, the rig will drive off in the same direction as the current velocity, and we call this a drive-off to a *positive* offset. Thereafter, the rig will move in the opposite direction compared to the current, and this is called a *negative* offset. The two analyses will be carried out for a water depth of 2000 [m], only, as the current has an insignificant impact on the riser at 300 [m] water depth. Hence, only trivial differences in the riser deflection are expected when introducing current to the riser in Figure 4.13(a). A uniform and a sheared current (as shown in Figure 4.2(b)) will successively be introduced at 2000 [m] water depth. The drive-off is represented by a movement of the semi-submersible to an offset of 100 [m] during 100 [s]. The reason for chosing this particular vessel drive-off out of the drive-off scenarios in Figure 4.12 is that it causes significant riser top angles, but not too excessive, as the drive-off during 50 [s].

The reader should keep in mind that the analyses in this section are not only performed to find out how critical a possible drive-off is combined with current. Another aspect of these analyses is that moving the vessel to an offset position may be more optimal for a given weather condition (see Section 3.1.4). In the case where the semi-submersible is moved to an offset position in order to improve the riser angles, the movement of the semi-submersible is not a drive-off, but a controlled transfer from one location to another. However, the behavior of the vessel will in practice be the same. A combination of current and drive-off in the same direction will most likely result in an excessive bottom angle, and only an analysis which confirms this will be conducted. Then, analyses with current and drive-off in opposite directions will be performed, as this is believed to result in smaller bottom angles.

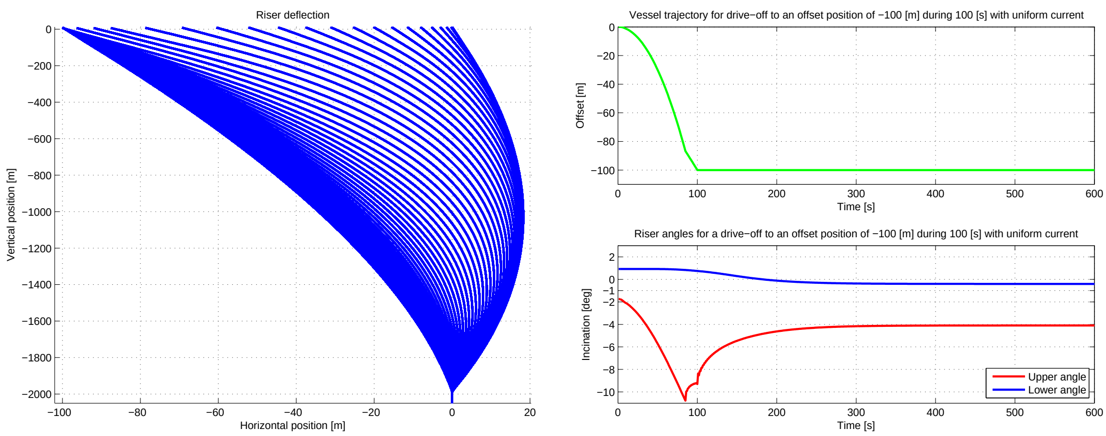
Figure 4.16 shows the riser and the riser angles at 2000 [m] when exposed both to a uniform current with velocity 0.6 $[\frac{m}{s}]$ and a drive-off in the same direction as the current. Both angles are non-zero at the start of the simulation because of the current (see Figure 4.3(b)). As the vessel begins to move, the top angle increases, while the bottom angle will not respond until after 35 [s], and then only marginally. Compared to Figure 4.14, where there is no current, the top angle stabilizes at a smaller value, and the bottom angle reaches a larger value. In fact, the lower angle will reach almost 2.3°, which is above the critical limit stated in the introduction of this section. The current can be thought of as an extra contribution to the deflection of the riser in the positive x-direction. In fact, the top angle will benefit from the current, because the riser is further "pushed" in the positive x-direction, and this contributes to straightening out the riser. Furthermore, the magnitude of the top angle is dependent on the water particle velocity experienced by the riser, as revealed in Section 4.3.3. When the riser and current move in the same direction, the experienced velocity of the water is smaller than in the case where the riser moves in water without current. Hence, the lower end of the riser is less prevented from following the vessel displacement. Despite the positive effect from the current on the top angle, the combination of both drive-off and a uniform current is a critical case, as the bottom angle exceeds 2°.



(a) Riser deflection (b) Riser angles

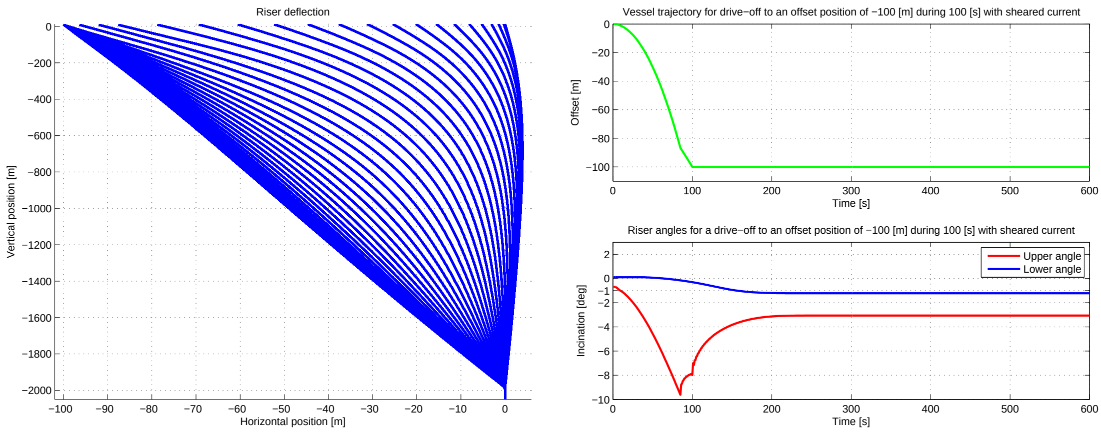
Figure 4.16: Riser deflection and angles for a drive-off to an offset position of 100 [m] during 100 [s] in combination with a uniform current with a velocity of 0.6 [$\frac{m}{s}$]. The water depth is 2000 [m].

In the next analyses, the combination of current and drive-off to a *negative* offset will be studied. Both uniform and sheared current is introduced. Figure 4.17 and 4.18 show riser deflection and angles for a drive-off to a negative offset combined with uniform and sheared current, respectively.



(a) Riser deflection (b) Riser angles

Figure 4.17: Riser deflection and angles for a drive-off to an offset position of -100 [m] during 100 [s] in combination with a uniform current with a velocity of 0.6 [$\frac{m}{s}$]. The water depth is 2000 [m].



(a) Riser deflection (b) Riser angles

Figure 4.18: Riser deflection and angles for a drive-off to an offset position of -100 [m] during 100 [s] in combination with a sheared current with a maximum velocity of 0.6 [$\frac{m}{s}$]. The water depth is 2000 [m].

In a uniform current, as seen in Figure 4.17 it is evident that the negative offset has a positive effect on the bottom angle, as it will decrease and stabilize at a magnitude just below 0°. However, the improvement of the bottom angle is little beneficial for the top angle, as this will sink to just below -10° before it stabilizes at -4°, which is the limit for this angle. When the vessel moves in the negative current direction, the velocity of the fluid experienced by the riser is in fact the sum of the current velocity and the vessel velocity. This results in excessive top angles because, while the top end of the riser is attached to the vessel and hence will be forced to follow the vessel, the lower end will be prevented and thus stay behind. In conformity with the observation for the positive offset, the top angle immediately decreases when the velocity is reduced, and even more as the velocity becomes zero. In a sheared current, as in Figure 4.2(b), the transfer of the rig to the negative offset position will in fact worsen both angles, see Figure 4.18. Since the sheared current used in these analyses has a very small velocity at the sea bottom, the bottom angle experiences little force from the current. Also, since it is critical for the top angle that the vessel is being moved against the current we once again see that this angle is excessive, though less excessive than for the uniform current. This is because the bottom of the riser is less prevented from following the top of the riser when there is less current force acting.

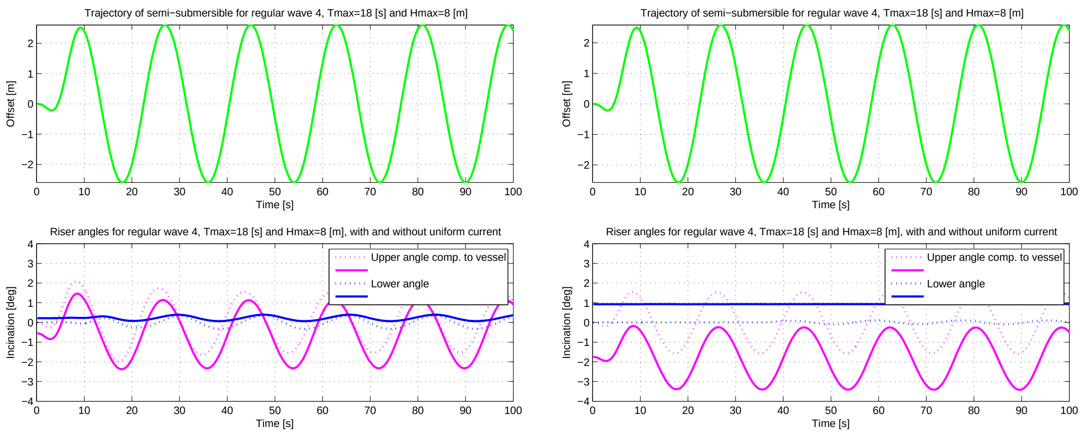
The analyses in this section proves that the combination of current and drive-off has a large impact on the riser in deep water. If the current has the same direction as the vessel drive-off, even a relative small offset compared to the water depth will give an excessive bottom angle. Moving the semi-submersible in the negative current direction will improve the bottom angle because the forces from the current and the vessel motion act in opposite directions and will result in a lower bottom angle. However, this improvement of the bottom angle takes place on the cost of the top angle. When the bottom of the riser is prevented from following the motion of the vessel, the top of the riser will obviously experience increasing inclinations. This observation leads us to the preliminary conclusion that the optimization of the riser angles must include a compromise between the two angles.

4.4.2 Combination of regular waves and current

The effect of current was studied in Section 4.3.1, while the effect of regular waves was investigated in Section 4.3.2. It was shown that current affects the riser in deep water more than the riser in shallow water. At 300 [m] water depth, a rather strong current (0.6 [$\frac{m}{s}$]) has little impact, see Figure 4.3(a). When studying regular waves it was found that high and short waves are critical for the top angle, while the bottom angle is less affected, both in shallow and deep water. The response of the bottom angle is also time delayed, and this time delay is 9 [s] at 300 [m] water depth, and 35 [s] at 2000 [m] water depth.

In this section, current and regular waves will be combined. The vessel and the riser are exposed to regular waves with height and period as in Table 4.2 in addition to a uniform current with velocity 0.6 [$\frac{m}{s}$].

Figure 4.19 shows the riser in shallow and deep water exposed to regular wave case 4 (wave height 8 [m], wave period 18 [s]) and a uniform current. The riser angles for the same wave, but without current, are also included, in dotted lines. When exposed to a uniform current the riser deflects statically as shown in Figure 4.3. In deep water, this static deflection causes a rather large static negative top angle. Hence, the sinusoidal top angle lapse is shifted below 0°.



(a) Riser angles, 300 m (b) Riser angles, 2000 m

Figure 4.19: Riser angles for a regular wave with period of 18 [s] and wave height of 8 [m] in combination with a uniform current with velocity 0.6 [$\frac{m}{s}$] (solid line), compared to riser angle for the same regular wave and no current acting (dotted line).

The difference in response is evident in deep water, where the current affects the riser significantly. Considering the bottom angle with and without current for a regular wave in Figure 4.19(b), it is seen that this angle no longer has a harmonic lapse when the riser is exposed to current. The current results in a static bottom angle, and the harmonic motion of the top end of the riser is prevented from being transmitted to the bottom.

In shallow water, the difference between the response with and without current is less considerable. As for the riser in deep water, the top angle lapse is shifted down, but only marginally. The harmonic motion of the bottom angle is damped, but we still see an oscillation.

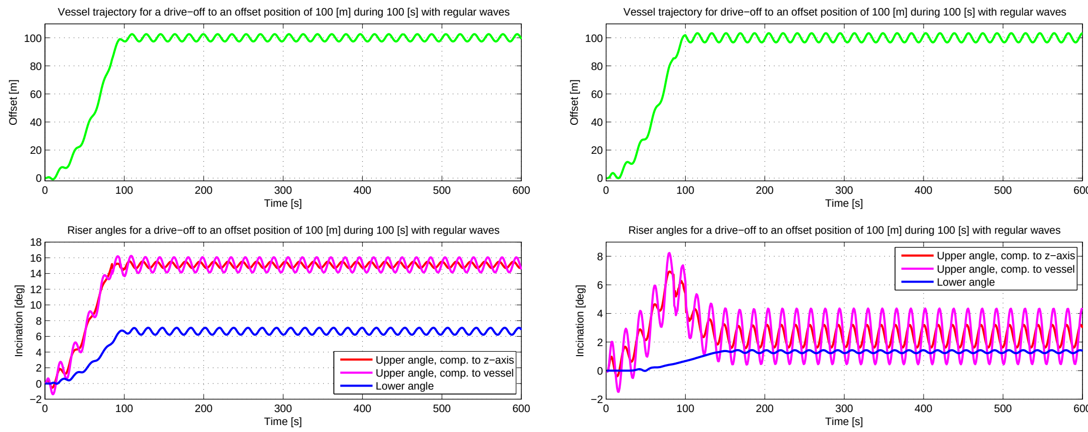
When exposed to both regular waves and a uniform current, the riser in deep water will experience rather large top angles. However, the combination of a regular wave with height 8 [m] and period 18 [s] will not result in top angles in excess of 4°, which is used as a limit for the top angle in these analyses. The lapse of the top angle is approximately the same as for the case without current - only shifted below 0°. Meanwhile, the lower end of the riser in deep water will only have a static inclination. The harmonic motion of the top end of the riser is more damped along the riser then what was the case without current, and the bottom angle will not oscillate. In shallow water, the angles are only marginally affected by the current, and the difference in response with and without current is not significant.

Both in shallow and deep water, the bottom angle will not reach a critical value when the riser is exposed to regular waves and current. For the range of regular waves in Table 4.2, the lower angle for the riser in deep water will have a maximum value of **0.9°** when the riser is exposed to a uniform current with velocity 0.6 [$\frac{m}{s}$]. This maximum angle is the same for all regular wave cases in Table 4.2. In shallow water, the maximum bottom angle will occur for regular wave case 7 (wave height 10 [m] and wave period 30 [s]), where the inclination reaches **0.6°** . The top angle, however, reaches a critical value for regular wave case 2 for both water depths, where the wave height is 8 [m] and the wave period is 10 [s]. This maximum value is **4.4°** at 300 [m] and **5.4°** at 2000 [m]. These inclinations are in excess of the top angle limit of 4° established in the introduction of this section.

4.4.3 Combination of drive-off and regular waves

The effect of a vessel drive-off in combination with regular waves is to be investigated. In shallow water, the drive-off caused both riser angles to increase to unacceptable values. In deep water, the drive-off resulted in an excessive top angle during the vessel motion, but both angles stabilized at acceptable values. None of the regular waves applied for the two water depths resulted in top angles in excess of 4° or bottom angles in excess of 2°.

The vessel drives off to an offset position of 100 [m] during 100 [s]. Simultaneously, there are incoming regular waves with wave height 8 [m] and period 18 [s] (regular wave case 4) acting on the vessel and the riser. The vessel trajectory as well as the riser top and bottom angles can be seen in Figure 4.20.



(a) Riser angles, 300 m (b) Riser angles, 2000 m

Figure 4.20: Riser angles for a drive-off to an offset position of 100 [m] during 100 [s] in combination with a regular wave with period 18 [s] and wave height 8 [m].

The riser angles in shallow water (Figure 4.20(a)) are excessive without the presence of waves, and the regular waves will simply increase the angles even further. However, compared to the magnitude of the angles for a drive-off without current, the increase is not significant. In deep water, the top angle will be even more excessive in the beginning of the drive-off compared to the case without waves, but it stabilizes at a maximum magnitude just above the limit of 4° . The lower angle is not significantly affected by the waves, and it is still below the limit of 2° . A regular wave which is not critical in itself can thus be critical when combined with other influences, such as a drive-off.

4.5 Combination of regular waves, current and drive-off

In this section, the combination of current, waves and drive-off will be investigated. From the previous analyses, some interesting observations have been made. The most important observations are summarized below.

- Current affects the riser significantly in deep water, but only marginally in shallow water.

- Regular waves have little impact on the lower angle for both water depths. They will however affect the top angle, and a short and high wave is found to be the most critical case.

- A vessel drive-off to an offset of 100 [m] is very critical for the riser in shallow water as both angles become excessive. In deep water, the drive-off is not as critical.

- The top angle is dependent on the velocity of the vessel. The higher vessel velocity, the higher top angle.

- The top angle is also dependent on the inclination of the vessel caused by incoming waves.

- The lower angle is affected by current and vessel offset. The combination of these two influences cause excessive lower angles in deep water.

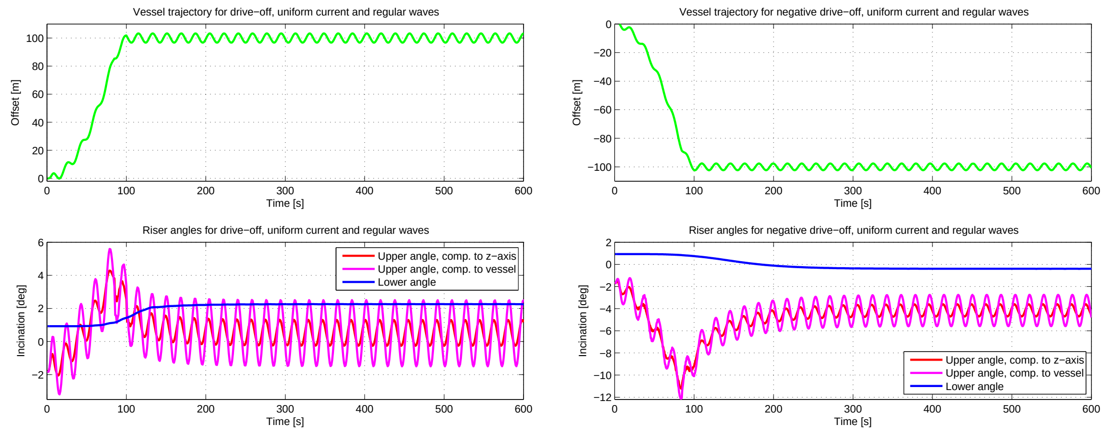
- The lower angle is improved when the current and vessel motion act in opposite directions, but at the cost of the upper angle.

- In deep water, the lower angle will use approximately 35 [s] to respond to any motion at the top end, and it increases more slowly than the top angle. Hence, in case of a drive-off, the time for the lower angle to become excessive is longer than for the upper angle.

The following analyses will be performed for the riser in deep water (2000 [m] water depth), only. This follows from the observation about the effect of current in shallow water. The combination of regular waves and drive-off has been analyzed for the riser at 300 [m] water depth, and no significant changes are expected with the presence of a uniform current.

The analyses are performed with regular waves with wave height of 8 [m] and period 18 [s] (regular wave case 4), a uniform current with velocity 0.6 [$\frac{m}{s}$] and a drive-off to an offset of 100 [m] during 100 [s].

Figure 4.21 shows the riser angles in deep water for a positive and negative drive-off. A negative drive-off implies that the vessel motion and the current act in opposite directions. Please notice that the values on the y-axes are different for the two cases.



(a) Riser angles for waves, current and positive drive-off

(b) Riser angles for waves, current and negative drive-off

Figure 4.21: Riser angles in deep water for regular wave case 4 (H_{max}=8 [m] and T_{max}=18 [s]), uniform current and drive-off.

In Figure 4.21(a), the riser angles for a uniform current, regular waves and a positive drive-off (in the same direction as the current velocity) can be seen. The lower angle is excessive as a result of the current and the vessel offset. The top angle (compared to the vessel) reaches a maximum value of almost 6° for the maximum vessel velocity (which is reached just before 85 [s]), but will stabilize at a maximum magnitude slightly above 2°. It can also be seen that, while the top angle lapse will oscillate due to the harmonic motion of the vessel caused by the waves, the harmonic motion of the vessel will not reach down to the bottom of the riser.

Figure 4.21(b) shows the riser angles for a uniform current, regular waves and a negative drive-off (in the opposite direction of the current velocity). In this case, the lower angle stabilizes at -0.4°. The top angle, however, reaches a maximum inclination of -12°before it stabilizes at a maximum inclination of almost -6°. If the displacement of the vessel is deliberate in order to improve the angles when there is current and waves acting, a displacement to an offset of -100 [m] during 100 [s] is not optimal. The velocity of the vessel during the displacement is too high, and this results in an excessive top angle during the displacement. Also, the maximum inclination will not stabilize below 4°, which is set as the limit for the top angle in this study.

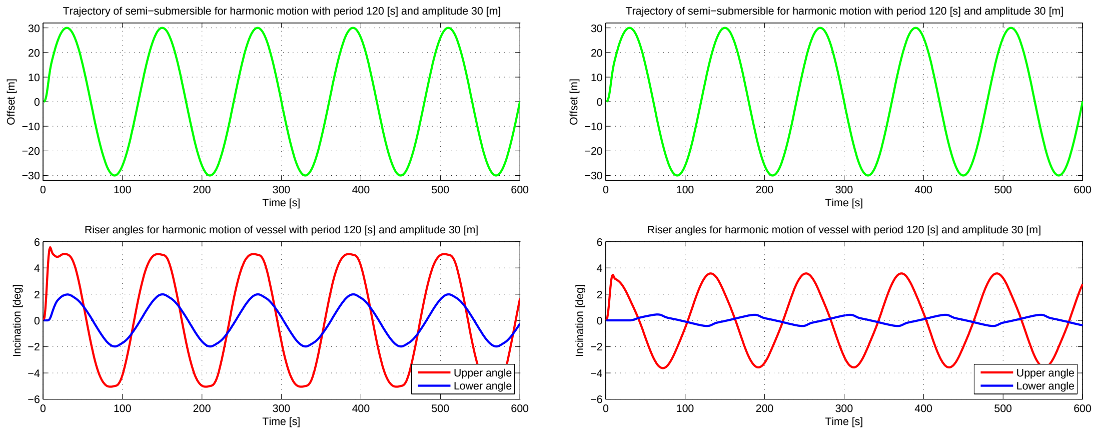
When introduced to all three influences (current, waves and drive-off) at the same time, the riser in deep water experiences excessive angles. For a drive-off in the direction of the current, the lower angle will be excessive. When the vessel is displaced in the opposite current direction, the top angle will be excessive. Hence, an optimal position of the vessel for a given weather will necessarily involve a compromise between the two angles. This will be further discussed in Section 4.7:*Synthesis*.

4.6 Effect of low-frequency harmonic motions

Eventually, the effect of low-frequency harmonic vessel motions will be studied. Such motions may occur because of interaction effects between the vessel and waves, and also because of a malfunction in the DP system. Traditionally, the limit for where to disconnect at 300 [m] water depth is when the vessel has an offset of 12 [m], or somewhere close to this value. At water depths more than 1000 [m] the limit is 25 [m]. These values are obtained from a working document from Statoil/Hydro, and they are only indicative. Seen the major economic consequences of a disconnect, it is interesting to investigate whether a disconnect is really necessary at the given limits. The bottom angle is the most crucial factor in this analysis; if it exceeds 2°, the riser must be disconnected. The top angle is allowed to reach 4°.

Low-frequency harmonic motions of the vessel are either caused by resonance effects resulting from interaction between the waves and the vessel *or* malfunctions in the DP system. In this section, the effect of such motions are investigated. The vessel is given prescribed harmonic motions with an amplitude of 20, 30 and 40 [m] and periods of 60, 120, 200 and 300 [s]. The motivation for choosing these periods are that resonance oscillations between the waves and the vessel often will have periods in this frequency domain. Also, oscillations resulting from resonance effects between the vessel and the DP system will be in this domain, see Figure 3.1 in Section 3. In the first analysis, there are no waves and no current acting. Then, a uniform current with velocity 0.6 $[\frac{m}{s}]$ is introduced. A regular wave will also be introduced, in order to investigate whether the combination of a rather non-critical wave and the harmonic motions of the vessel may result in excessive angles.

Figure 4.22 shows the riser angles at 300 and 2000 [m] water depth for a harmonic vessel motion with amplitude 30 [m] and period 120 [s]. Since there are no waves acting, the angle between the top of the riser and the global z-axis is adequate to describe the angle between the top of the riser and the vessel.



(a) Riser angles, 300 m

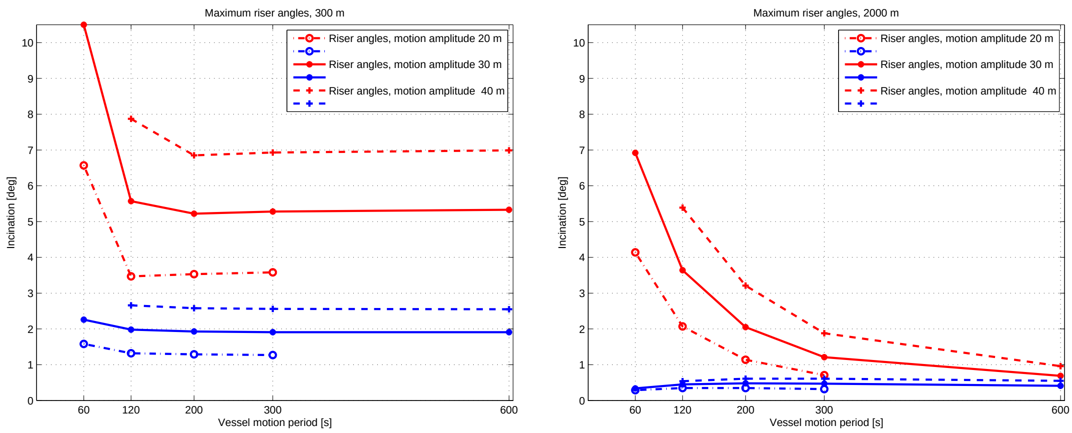
(b) Riser angles, 2000 m

Figure 4.22: Riser angles for a harmonic vessel motion with amplitude 30 [m] and period 120 [s]

In both Figure 4.22(a) and 4.22(b), the top angle is much more severe than the bottom angle, as was the case with the regular waves in Section 4.3.2. In deep water (Figure 4.22(b)), the lower angle is little affected by the harmonic vessel motion (maximum inclination ≈ 0.5°), while the top angle reaches 3.6°. In shallow water (Figure 4.22(a)), the lower angle reaches 2°, which is the limit for when the riser has to be disconnected. The top angle is above its limit of 4°;its maximum value is 5.5°. In this case, the riser in shallow water should be disconnected, while there is no need for such dramatic action for the riser in deep water. The velocity dependence of the top angle is reflected in the fact that it is maximum when the vessel trajectory crosses the x-axis, where the velocity of the vessel is on its highest. It can also be seen that the lower angle reaches the maximum inclination in the vicinity of the maximum vessel offset. The time lags between the maximum vessel offset and the maximum lower angles in shallow and deep water are in accordance with the time delays identified in Section 4.3.2, where the effect of regular waves was analyzed. The time delay is 9 [s] for the riser in shallow water and 35 [s] for the riser in deep water.

This analysis demonstrates the advantage of drilling in deep water versus shallow water. Even for a harmonic motion which causes the vessel to reach an offset above the limit for disconnect stated introductory in this section, the riser angles in deep water will not reach the critical values. In shallow water, however, the same harmonic motion causes excessive angles both at the top and the lower end, and a disconnect should be prepared.

Figure 4.23 shows the maximum riser angles for increasing vessel motion periods and amplitudes in shallow and deep water. Please keep in mind that these are maximum *absolute* values, hence the inclination may be negative even though the displayed maximum is positive. An interesting observation for 2000 [m] water depth is this; if the critical angles for the top and the bottom of the riser is 4° and 2°, respectively, the vessel may have offsets larger than 20 [m] as long as the period of motion is relatively large. For a motion amplitude of 30 [m], the top angle is acceptable for all motion periods larger than 120 [s]. Furthermore, even a vessel motion amplitude of 40 [m] is non-critical when the period of motion is larger than 200 [s]. At 300 [m] water depth, the angles are excessive for most of the motion amplitudes and periods. The top angle is only acceptable for a motion amplitude of 20 [m] and motion periods greater than 120 [m]. The lower angle is acceptable in most cases. Hence, the top angle is the limiting factor both in shallow and deep water.



(a) Maximum riser angles, 300 m (b) Maximum riser angles, 2000 m

Figure 4.23: Maximum absolute lower (blue line) and upper (red line) angles as function of the vessel motion period for each vessel motion amplitude.

In Figure 4.23(b), the maximum angles (both upper and lower) in deep water seem to approach a stable value as the vessel motion period increases even further. It is likely that when the period goes towards infinite, the maximum riser response approaches the response for a static offset as the dynamics in the system will approach the behavior of a steady-state system. In Figure 4.24, the riser angles for a vessel motion amplitude of 30 [m] and periods up to 1200 [s] in deep water can be seen. The response angles at 2000 [m] water depth for a static offset of 30 [m] are found to be 0.7° for the top angle and 0.4° for the lower angle. Studying the riser angles in Figure 4.24, we find that they actually stabilize at these values as the period of motion increases. In shallow water (Figure 4.23(a)) the top angle stabilizes at a constant magnitude much quicker. The response angle for a static offset of 30 [m] at 300 [m] water depth is found to be 5.3° for the top angle and 1.9° for the lower angle. The solid lines in Figure 4.23(a), which represents the maximum riser angles for a harmonic motion with amplitude 30 [m], clearly converge towards these values.

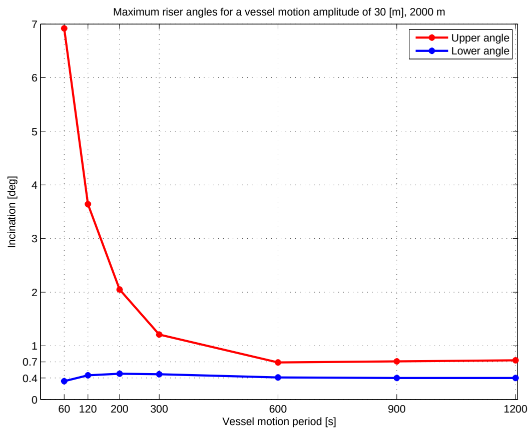
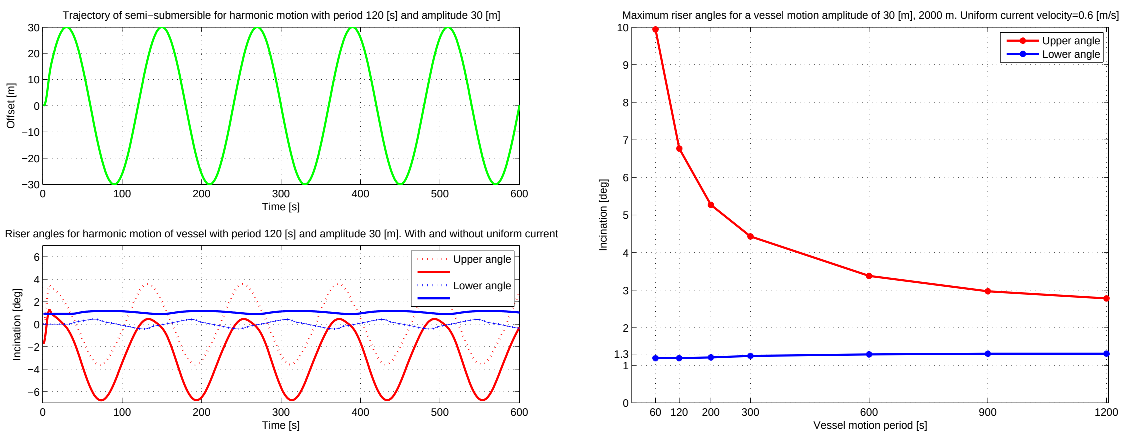


Figure 4.24: Maximum lower and upper angles as function of the vessel motion period for a vessel motion amplitude of 30 [m]. The water depth is 2000 [m]

The riser angles in deep water are not alarming for most of the harmonic vessel motions investigated so far. However, the presence of a current may change the picture. In the next analyses, a uniform current with velocity 0.6 $[\frac{m}{s}]$ will be introduced. As we have already revealed that most of the low-frequency harmonic vessel motions at 300 [m] water depth, even without current and waves, cause excessive angles, no further analyses for this water depth will be performed. Figure 4.25(a) shows the riser angles in deep water for a vessel motion amplitude of 30 [m] and motion period of 120 [s]. The solid lines represent the response when there is a uniform current acting, while the dotted lines represent the responses without the presence of current. Figure 4.25(b) shows the maximum riser angles for a motion amplitude of 30 [m] and increasing vessel motion periods combined with the uniform current.



(a) Riser angles, 2000 m (b) Maximum riser angles, 2000 m

Figure 4.25: Riser angles for harmonic vessel motion with amplitude 30 [m] and period 120 [s] (With uniform current: solid line. Without current: dotted line) - and maximum lower and upper angles as function of the vessel motion period for a vessel motion amplitude of 30 [m]

In Figure 4.25(a), it can be seen that the top angle lapse is shifted downwards when the current is introduced, while the bottom angle lapse is shifted upwards. The amplitude of the oscillation of the bottom angle is also smaller, because the current contributes in damping the harmonic motion as it is transmitted along the riser. While the magnitude of the bottom angle is not significantly affected by the current, the top angle will be critical in this case (approximately -6.5°). Considering the maximum riser angles for the motion amplitude of 30 [m] and increasing periods, it is evident that the riser top angle is excessive for periods smaller than 600

[s] (Figure 4.25(b)). The lower angle is acceptable. The static riser angles for an offset of 30 [m] with current is 1° for the top angle and 1.3° for the lower angle. Comparing the maximum riser angles for the highest period in this figure (1200 [s]) with these values, we find that the maximum lower angle approaches the static offset angle. The maximum top angle, however, does not stabilize at the static offset angle. When there is current present, the velocity of the motion must apparently be even lower in order for the system dynamics to approach the steady state condition.

In Section 4.3.2 it was among other factors established that a regular wave with period 18 [s] and wave height 8 [m] will not represent a critical situation for the riser in deep water. Furthermore, in this section it has been found that low-frequency harmonic vessel motions (without current) are not necessarily critical for the riser in deep water. A harmonic motion with amplitude of 30 [m] and period of 120 [s] is combined with a regular wave with height of 4 [m] and 18 [s] in order to see whether the combination of these two may result in excessive angles. In Figure 4.26 the riser angles are shown.

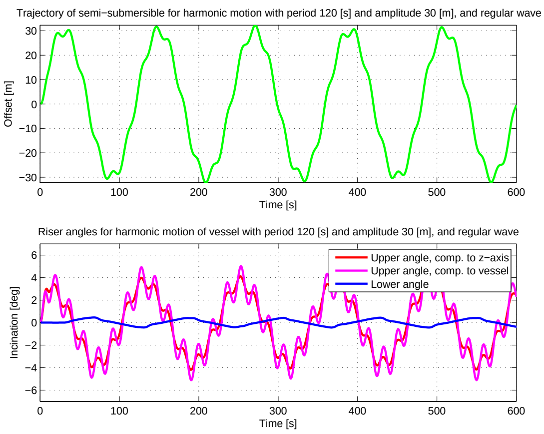


Figure 4.26: Riser angles for a harmonic vessel motion with amplitude 30 [m] and period 120 [s] in combination with regular waves with wave height 8 [m] and period 18 [s].

While the regular waves have little effect on the magnitude of the lower angle, the top angle will in fact be excessive (above 4°) for the combination of the harmonic vessel motion and the regular wave. Hence, even though the top angle was non-critical for each of these influences when studied separately, the combination is a critical case.

4.7 Synthesis

While the term *analysis* refers to the procedure by which a problem is broken into parts, the term *synthesis* is defined as the procedure by which we combine separate elements or components in order to form a coherent role. Thus, the terms *analysis* and *synthesis* complement each other. In this section, the separate parts discovered in the previous simulations will be put together to form a whole.

Simulations including different environmental loads and vessel motions have been carried out. The three influences investigated in the previous simulations are

- Current, uniform and sheared
- Regular waves
- Vessel offset - caused by either drive-off or low-frequency harmonic vessel motions

Based on the effect of these influences, a synthesis of riser response in shallow and deep water will be made. The main target is to identify optimal positioning of the vessel for various weather conditions, and also to decide when a disconnect should be performed. Hence, the main target is divided into two parts by means of their applications. Under normal conditions, it is desirable to formulate a control strategy which positions the vessel optimally for the given weather. In abnormal conditions, we want to develop rules for when and how to disconnect, and when not to disconnect. Especially in deep water, the traditional limits for disconnect are possibly too conservative.

While performing the simulations, it was also found that the vessel velocity affects the riser significantly. This will be further explored in the following discussion.

4.7.1 Riser response: shallow water

In the previous simulations, critical, as well as non-critical situations have been revealed. In shallow water, critical situations comprise drive-off and low-frequency harmonic vessel motions. Because of the "short" riser, the angles are highly sensitive to vessel offsets. Vessel offsets of 30 [m] due to harmonic vessel motions (see Figure 4.22(a)) will result in an excessive top angle and a lower angle just below the accepted 2°. Hence, offsets of 30 [m] or more should initiate preparation for disconnect. In combination with waves, the limit will be smaller. A drive-off is a very critical case, as the vessel will reach 30 [m] shortly after the beginning of the drive-off if the thrusters give full throttle in one direction. The time to prepare for a disconnect is thus limited. As even small offsets from the initial position are critical, the question is not whether or not to disconnect in the case of a drive-off. Current will not affect the riser significantly, while regular waves are seen to cause significant anglers, though not excessive ones.

In Table 4.3 maximum lower and upper angles for current, waves, drive-off and slow-drift motions at 300 [m] water depth can be seen.

Table 4.3: Riser angles for various influences at 300 [m] water depth. Red numbers indicate excessive values. *Worst regular wave = regular wave case 2, which causes the most severe upper angle. All harmonic vessel motions have period 120 [s]*

	Maximum lower angle [°]	**Maximum upper angle [°]**
Uniform current	0.2	-0.5
Worst regular wave	0.3	3.8
Regular wave case 4	0.3	2.1
Drive-off to 100 [m] during 100 [s]	6.6	15.0
Harmonic vessel motion, 20 [m]	1.3	3.5
Harmonic vessel motion, 30 [m]	2.0	5.5
Harmonic vessel motion, 40 [m]	2.7	7.9

It is evident that any offset, either caused by drive-off or harmonic vessel motions, will cause significant, and in most cases, excessive angles. Hence, the objective in shallow water must be to avoid offsets. In Table 5.4 is shown static riser angles at 300 [m] water depth for various offset positions with and without current.

Table 4.4: Static riser angles at 300 [m] water depth for different vessel offsets. The uniform current has a velocity of 0.6 [$\frac{m}{s}$]. Red numbers indicate excessive angles.

		Vessel offsets [m]				
		0	10	20	25	30
Static lower angle [°]	No current		0.8	1.3	1.8	2.0
	Uniform current, positive offset	0.2	0.9	1.6	1.9	2.2
	Uniform current, negative offset		-0.5	-1.1	-1.7	
Static upper angle [°]	No current		2.1	3.6	4.1	5.4
	Uniform current, positive offset	-0.6	1.6	3.2	4.1	4.9
	Uniform current, negative offset		-3.0	-5.1	-7.0	

Table 5.4 shows that the current has a marginal, but still not negligible effect on the riser in shallow water, and that even small offsets cause excessive angles. The top and bottom angles are well within acceptable limits when there is uniform current acting but no offset. Also, since the angles are sensitive to offsets, one should not position the vessel at an offset location in order to improve one of the angles in case of a current. However, the allowable offset limits will be smaller when there is current, and this should be taken into account when establishing watch circles for this water depth.

4.7.2 Riser response: deep water

In deep water, the most severe angles occur for drive-off in combination with a uniform current and harmonic vessel motions in combination with current or waves. Current is a critical factor for the riser in deep water, as the riser is longer and thus more flexible, and the current forces will act on a larger area. When the riser moves in water with current, the current will either benefit the top angle or the lower angle, on the cost of the other, depending on the direction of the vessel. The top and bottom angles respond differently to the influences. The analyses reveal that while the top angle is mainly dependent on the vessel velocity, the lower angle is only dependent on the vessel offset. In the cases where there are waves acting, the top angle is also dependent on the vessel inclination. Because motions from waves are damped along the riser, the lower angle will not respond significantly to first order waves. The top angle, however, will experience large angles for a short and high wave.

Table 4.5 presents the maximum lower and upper angle for current, waves, drive-off and low-frequency harmonic vessel motions at 2000 [m] water depth. Combinations of drive-off and current, harmonic vessel motions and current and harmonic vessel motions and regular waves are also included.

Table 4.5: Riser angles for various influences at 2000 [m] water depth. Red numbers indicate excessive values. *Worst regular wave = regular wave case 2, which causes the most severe upper angle. All harmonic vessel motions have period 120 [s]*

	Maximum lower angle [°]	**Maximum upper angle [°]**
Uniform current	0.9	-1.7
Sheared current	0.1	-0.7
Worst regular wave	0.0	3.6
Regular wave case 4	0.1	1.6
Drive-off to 100 [m] during 100 [s]	1.3	7.0
Harmonic vessel motion, 20 [m]	0.4	2.0
Harmonic vessel motion, 30 [m]	0.5	3.6
Harmonic motion, 40 [m]	0.5	5.4
Positive drive-off with uniform current	2.3	0.7
Negative drive-off with uniform current	-0.4	-4.0
Harmonic vessel motion, 30 [m] with unif. current	1.2	-6.8
Harm. vessel mot., 30 [m] with regular wave case 4	0.4	5.1

As can be seen in Table 4.5, the maximum top angle will be 7° for a drive-off to 100 [m]. This maximum angle occurs during the movement, and the top angle stabilizes at 2.5° once the vessel velocity is zero. Hence, an offset of 100 [m] does not result in excessive angles once the vessel has reached its position. However, during the movement, the top angle is critical due to the vessel velocity. Hence, in case of a drive-off the decision to disconnect is not as easy as for shallow water. The top angle will probably improve if the operator manages to take control over the vessel and stop the drive-off before the vessel offset reaches 100 [m]. In addition, the margins for the static lower and upper angles are good; an even larger offset than 100 [m] may still result in non-critical stationary angles. The critical factor is the velocity during the drive-off. If a uniform an relative strong current is present however, and the drive-off takes place in the positive current direction, the lower angle will, if the vessel stops at 100 [m], stabilize at a magnitude in excess of 2°. In the opposite case, where the vessel drives off in the negative current direction, the top angle will grow excessive during the movement and stabilize at 4°.

Hence, with uniform current present, an offset of 100 [m] in either directions will most likely be critical for one of the angles, and a disconnect must be prepared and carried out. In table 5.6 the static lower and upper riser angles for different offsets and with and without uniform and sheared current are presented.

Table 4.6: Static riser angles at 2000 [m] water depth for different vessel offsets. The uniform current has a velocity of 0.6 [$\frac{m}{s}$], while the sheared current has a velocity of 0.1 [$\frac{m}{s}$] at the sea bottom and 0.6 [$\frac{m}{s}$] at the surface. Red numbers indicate excessive angles.

		Vessel offsets [m]							
		0	20	40	50	60	70	100	150
Static lower angle [°]	No current					0.8		1.3	2.0
	Uniform current, positive offset	0.9	1.2	1.5	1.6	1.7	1.9	2.3	3.0
	Uniform current, negative offset			0.4	0.3	0.1	0.0	-0.4	-1.0
	Sheared current, positive offset	0.1					1.0	1.4	2.1
	Sheared current, negative offset			-0.4	-0.6			-1.2	-1.9
Static upper angle [°]	No current					1.5		2.5	3.5
	Uniform current, positive offset	-1.7	-1.3	-0.8	-0.6	-0.3	-0.1	0.7	1.8
	Uniform current, negative offset			-2.6	-2.9	-3.2	-3.4	-4.0	-5.3
	Sheared current, positive offset	-0.7					1.0	1.7	2.9
	Sheared current, negative offset			-1.6	-1.9			-3.1	-4.2

The reader should keep in mind that the riser angles in Table 5.6 are *static* angles for the different vessel offsets. The top angle will in most cases be excessive (above 4°) during the vessel movement. However, the static magnitudes indicate that, in deep water, it is not necessarily the offset which is critical. Only for the vessel offset of 100 [m] and above with uniform current do we see a critical lower angle, and the top angle will only be excessive for the negative vessel offset of 100 [m] and more with the same current. Regarding the optimal positioning of the vessel for a given current, we notice that for a uniform current, the static lower angle is 0° when the vessel has an offset of 70 [m] in the negative direction. This is an improvement compared to the magnitude of 0.9° when the vessel has zero offset. However, the corresponding top angle is then -3.4°. This magnitude is below the critical limit of 4°, but still significant. In Figure 4.27, the absolute static riser angles for different offset positions and uniform current can be seen.

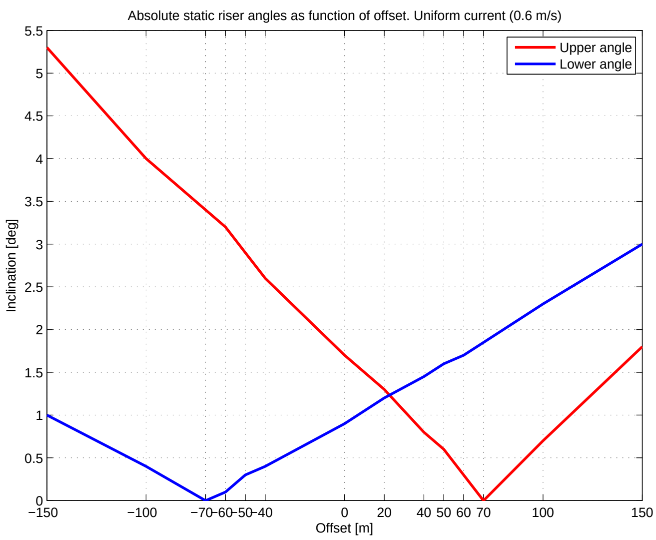


Figure 4.27: Absolute static riser angles for different vessel offsets and uniform current with velocity 0.6 [$\frac{m}{s}$].

Figure 4.27 indicates that in a uniform current in deep water, both angles can not be optimal at the same time. Hence, the optimization of the angles must include a compromise. This will be further explored in Section 5.6.2.

While even small vessel offsets will cause excessive angles in shallow water, the vessel offset is not necessarily a very critical situation in deep water. At 2000 [m] water depth, however, current is a critical factor. Also, the vessel velocity during vessel movements may cause excessive top angles, and this is further worsened if the vessel moves in the opposite direction of the current.

The question which arises for a drive-off in deep water is whether or not one should allow for excessive angles for a limited amount of time. The top angle will grow excessive during the vessel movement because of the increasing vessel velocity. The maximum magnitude of the top angle during this motion is dependent on the vessel velocity, and it may reach as much as 7° in the case of a drive-off to 100 [m] during 100 [s]. This is clearly in excess of the critical value, and the operation should stop, and a disconnect should be prepared. However, as the vessel velocity decreases and goes towards zero, the top angle stabilizes at a magnitude of 2.5°, which is non-optimal, but still acceptable. There are two aspects to consider in this case. Firstly, the time used to disconnect must be addressed. As it is possible that the operator does not succeed to take control over the vessel and stop is from driving off, a further increase of the angle is likely. As the offset increases, the lower angle will also become excessive, and if the disconnect is not carried out fast enough, the worst-case scenario is a blow-out. Secondly, the effect of a temporary excessive top angle must be considered. In the case where the operator does manage to take control and stop the drive-off the top angle will as mentioned decrease and eventually become acceptable. However, one must assume that a temporary contact between the moonpool and the riser is not desirable, and this could cause damage on both parts. In Figure 4.28, the riser top angle for a slow movement of the vessel to 100 [m], positive or negative, with or without uniform and sheared current, can be seen. The velocity of the vessel increases from zero to a constant velocity of 0.4 [$\frac{m}{s}$] until it reaches the offset position. This takes about 4 minutes and 20 seconds.

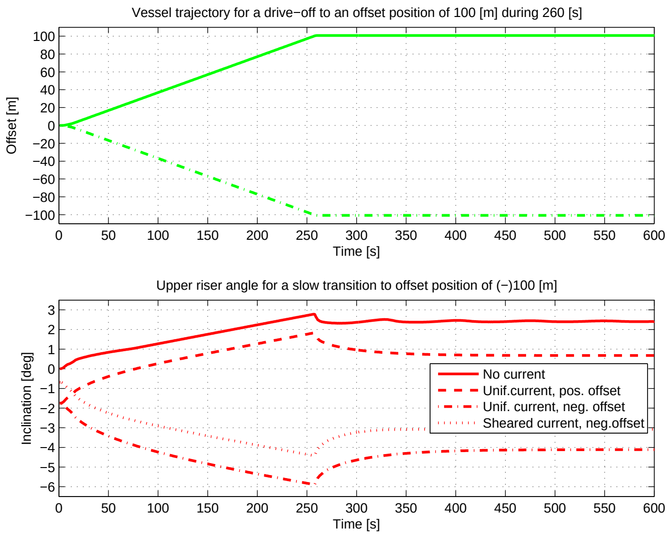


Figure 4.28: Upper riser angle for a slow vessel movement to an offset position (positive of negative) of 100 [m]. Constant vessel velocity: 0.4 [$\frac{m}{s}$]. Uniform current velocity: 0.6 [$\frac{m}{s}$]. Sheared current velocity at bottom: 0.1 [$\frac{m}{s}$], at surface: 0.6 [$\frac{m}{s}$]

The upper angle will not become excessive when the vessel moves without current in any direction to an offset position of 100 [m]. In a uniform current, the angle is non-critical when the vessel moves in the same direction as the current. When the vessel movement takes place in the negative current direction, however, the angle increases to an absolute magnitude of 5.3° . In a sheared current, the negative offset will also result in an excessive top angle, but slightly smaller; it is approximately -4.4° at most. However, Figure 4.28 tells us that the excessive top angle during the vessel movement in deep water can be avoided by decreasing the vessel velocity. In case of a vessel drive-off, the vessel velocity is obviously not controlled, but if it for some reason is sufficiently low (below 0.5 [$\frac{m}{s}$], based on the results in Figure 4.28), the top angle will not increase to a magnitude far beyond the critical limit. Also, in the case where the vessel is moved in order to optimize one or both angles, the vessel velocity should be very low in order to avoid excessive angles during the transition.

4.7.3 Categorizing of riser angle magnitudes

Previously, the limits for the lower and upper riser angles have been set to 2° and 4°, respectively. At these magnitudes, the operation should stop and a preparation for disconnect should be carried out. In order to classify the effect from vessel offset, current and waves, the riser angle magnitudes should be further categorized. In Table 5.3 categories for the lower and upper angle are presented. The following categories are used:

- *Optimal* refers to the situation where the riser angle is such that the operation can continue without any interference from the control system or operator.

- *Acceptable* refers to riser angle magnitudes which are not optimal, but not too far above the optimal angles. The control system or the operator may interfere to optimize the angle by positioning the vessel differently.

- *Significant* refers to the situation where the angle has increased beyond the acceptable limit. This is an intermediate phase between the situation where no disconnect should be prepared, and the situation where a disconnect must be prepared. If the control system or operator manages to improve the angle within an acceptable period of time, no disconnect should be prepared.

- *Critical* refers to riser angles above the limits of 2° and 4° (for the lower and upper angle, respectively). The operation must stop and a disconnect should be prepared.

Table 4.7: Riser angles status levels

	Category			
	Optimal	**Acceptable**	**Significant**	**Critical**
Lower angle	0-1°	1-1.5°	1.5-2°	>2°
Upper angle	0-1.5°	1.5-2.5°	2.5-4°	>4°

In Table 5.3, the limits for the top angle are larger than the limits for the lower angle. This is in accordance with what has previously been stated about the riser angles. A different vessel design (e.g. a wider moonpool) may allow for greater top angles, while the lower angle is more constrained by the BOP. It is worth noticing that the angle magnitudes in Table 5.3 are conservative compared to previously described angle limits, as mentioned in the introduction of this section.

4.7.4 Categorizing of influences

The analyzed influences (current, waves, drive-off and slow-drift motions) will be categorized according to the extent of severeness caused by the relevant influence, and combination of influences. The riser angle magnitude categories in Table 5.3 will be used, in addition to the information in Table 4.3 and 4.5.

Table 4.8: Level of severe angles caused by various conditions. *All harmonic vessel motions have period 120 [s].*

	Riser angle status (the most critical)	
	300 [m] water depth	**2000 [m] water depth**
Uniform current (0.6 [$\frac{m}{s}$])	Optimal	Acceptable
Worst regular wave	Significant	Significant
Regular wave case 4	Acceptable	Acceptable
Vessel drive-off, 100 [m]	Critical	Critical/Acceptable
Harmonic vessel motions, 30 [m]	Critical	Significant
Uniform current and vessel drive-off	Critical	Critical
Uniform current and regular wave 4	Acceptable	Significant
Vessel drive-off and regular wave 4	Critical	Critical
Harmonic vessel motions, 30 [m] and reg. wave 4	Critical	Critical
Harmonic motions, 30 [m] and unif. current	Critical	Critical

For deep water, the vessel drive-off to 100 [m] is classified as *critical/acceptable* in Table 4.8. The reason for this is, as previously discussed, that the top angle will be excessive *during* the vessel movement. Once the vessel has stopped however, the top angle will stabilize at an acceptable magnitude. It is also noticed that a regular wave with height 8 [m] and period 18 [s] is not critical in itself at any of the two water depths. Combined with a vessel drive-off or low-frequency harmonic motions of the vessel however, it will cause the top angle to become excessive. This observation leads us to the next section, which deals with superposition of low-frequency induced and wave-frequency induced riser angles.

4.7.5 Superposition of low-frequency and wave-frequency induced riser angles

In Sørensen [14], the total motion of a marine vessel is said to consist of a low-frequency and a wave-frequency component. By superposition, these are combined to form the total motion of the vessel, as seen in Figure 4.29.

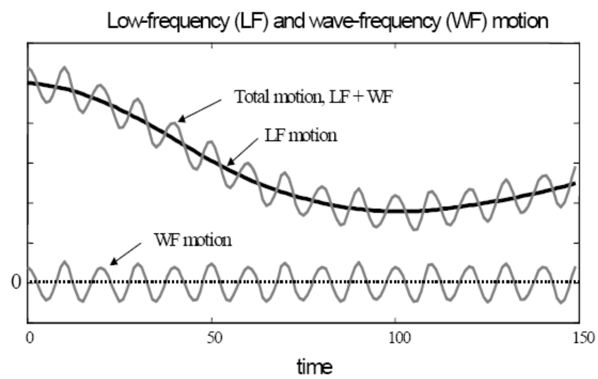


Figure 4.29: Superposition of motions. The total motion of the vessel consists of a low-frequency and a wave-frequency component (Sørensen [14]).

Similarly, the riser angles for a low-frequency motion (such as drive-off and low-frequency harmonic vessel motions) can be combined with the riser angles for a regular wave to form the total riser angles for a low-frequency harmonic vessel motion or drive-off with regular waves. The worst angle will then occur when the maximum low-frequency angle and wave-frequency angle occur at the same time. Figure 4.30 shows the upper riser angle for regular waves, a low-frequency motion of the vessel without waves present and finally the total angle for a combination of regular waves and low-frequency motion of the vessel. Since waves have little impact on the lower angle, only marginal differences will exist between motions with and without waves, and this angle is thus not included in the figure.

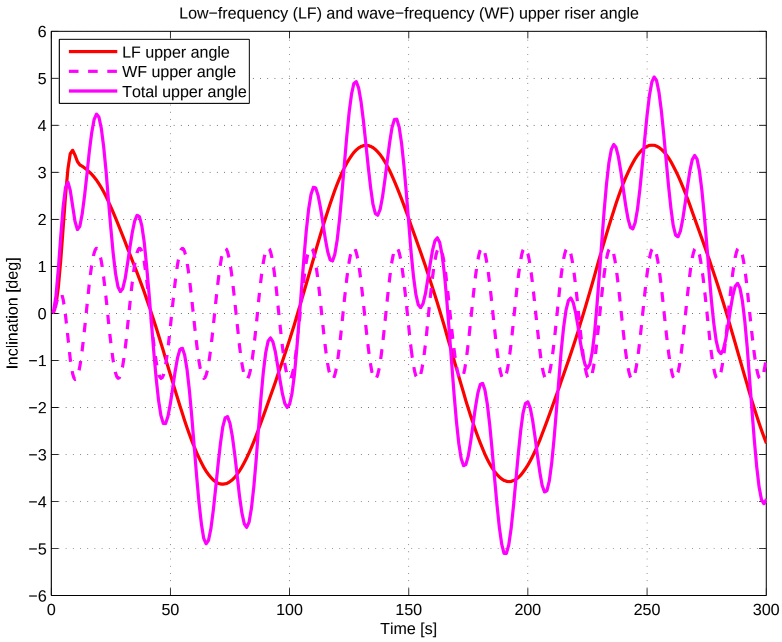


Figure 4.30: Superposition of riser top angles. The total riser angle consists of a low-frequency and a wave-frequency component.

Hence, knowing the riser angles resulting from a certain wave, one can apply superposition to find the maximum top angle for a condition where there are both low-frequency motions and waves. In this way, we know that with waves present, the resulting upper angle will at maximum always be the maximum top angle from the low-frequency motion plus the maximum top angle from the wave-frequency motion.

The relevant data from this section will be used as background information for developing an advisory system for the semi-submersible in Section 5: *Advisory system*.

5 Advisory system

Based on the analyses and observations made in the previous section, an advisory system for decision criteria for optimal positioning as well as disconnect shall be developed. Some general information about a dynamic positioning system in addition to main theory about mathematical modeling will be presented. These sections are based on Sørensen [14], Rustad [15] and Langen and Sigbjörnsson [16]. Principles for watch circles and DP status levels will then be described. Eventually, a set of rules applicable for dynamic positioned drilling vessels in shallow and deep water will be developed.

Before presenting the general theory about DP systems and mathematical modeling, the real-time control structure for dynamic positioning is introduced. In Figure 5.1 the control structure can be seen. On the lowest level are the actuators which carry out the demands from the controller. The controller is situated on the plant control level, and it receives input from the local optimization level. On this level, optimal positions and trajectories for a given condition is found, either manually or automatically. This thesis aims to develop rules to be implemented on the local optimization level. For a given weather, either the operator or a computer will hopefully be able to decide an optimal position based on riser response.

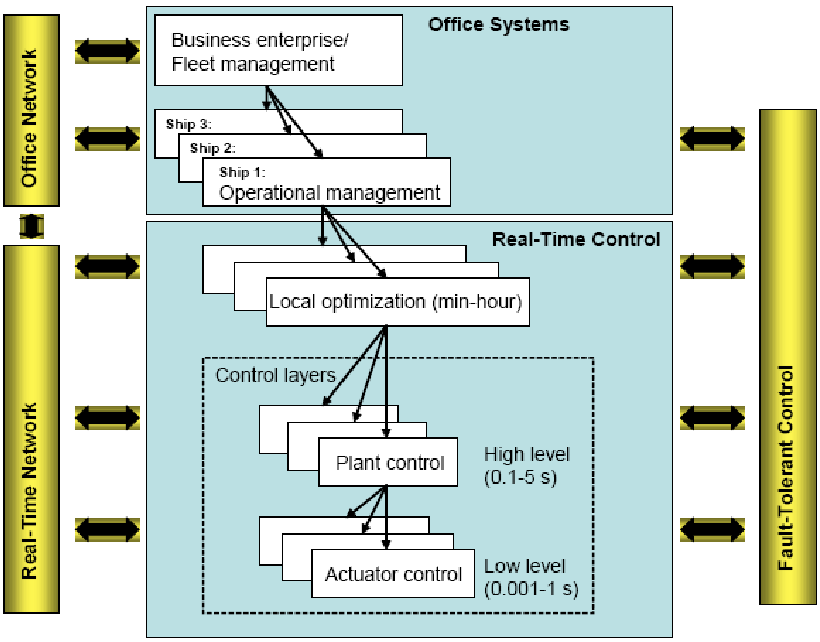


Figure 5.1: Control structure (Sørensen [14])

5.1 Dynamic positioning system

A dynamic positioning system carries out simultaneous control of the three horizontal motions (surge, sway and yaw). A dynamic positioned vessel maintains its position and heading by means of active thrusters. In thruster assisted position mooring, on the other hand, the thrusters are complementary to the mooring system. In this thesis, focus is on a dynamically positioned vessel. Hence, thruster assisted position mooring will not be addressed.

Figure 5.2 shows the general structure for a DP system. Measurements, such as wind and position measurements, enter the signal processing block where signal checking, voting and weighting are carried out. The vessel observer performs noise and wave filtering and calculates position and velocity estimates. In case of loss of sensor signals, the observer can also carry out *dead-reckoning*, which means that the *predicted* estimates from the observer are used in the control loop. In the controller, required thrust in each direction to keep the vessel on the desired location and heading is calculated. The reference model is needed when the vessel is to change position in order to ensure a smooth trajectory from the initial position to the desired position. Included in the control architecture in Figure 5.2 is also a block for *optimal set-point chasing*. Optimal set-point chasing implies that the optimal vessel position is found by minimizing one or more critical variables. For moored vessels a critical variable is the tension in the mooring lines, and for a dynamically positioned vessel carrying out drilling operation, critical variables are the riser angles. An advanced guidance system which calculates the vessel position based on the critical variable is hence implemented. The controller then computes the required thrust in order to obtain the given position. The thrust allocation calculates the required thrust force and direction commands to each device.

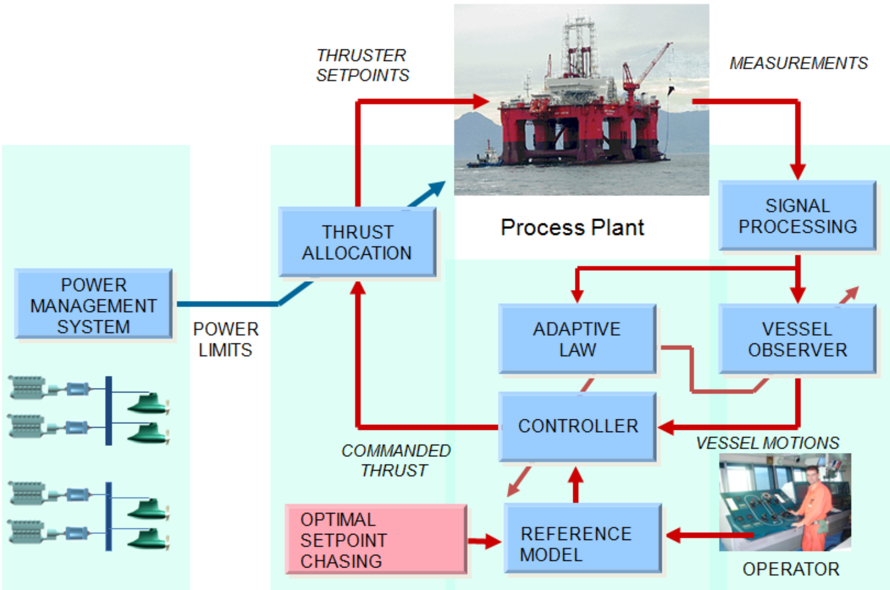


Figure 5.2: DP control architecture (Sørensen [14])

The controller in the DP system makes use of a *control plant model*. A physical system may be described by a process plant or a control plant. The process plant model is a comprehensive and accurate description of the system, while the control plant model is a simplified model accounting for the main physical properties. As a control system has to be computationally fast, detailed information about the system to be controlled must be omitted. In the following section, the mathematical modeling of the process plant and control plant will be presented.

5.2 Mathematical modeling of vessel

When deriving a mathematical model, in this case a control plant for the semi-submersible, one must keep in mind the application of the model. A dynamically positioned vessel may be regarded as a station keeping application. As previously mentioned, it is sufficient to derive a simplified mathematical model when the purpose is to design a controller. In this section, both a process plant and a control plant will be derived.

5.2.1 Kinematics

Figure 5.3 presents the reference frames for a semi-submersible. They can be described as follows:

- The earth-fixed frame is denoted as the $X_E Y_E Z_E$-frame. The position and heading of the vessel are in the earth-fixed frame.
- The reference-parallel frame $X_R Y_R Z_R$-frame (applicable for station keeping) is earth-fixed and rotated to the desired heading angle Ψ_d and translated to the desired x_d- and y_d-position coordinates with the x-axis positive forwards, the y-axis positive starboards and the z-axis positive downwards.
- The body-fixed XYZ-frame is fixed to the vessel body with the x-axis positive forwards, the y-axis positive starboards and the z-axis positive downwards. The center of gravity of the vessel can be assumed to lie on the center line of the vessel; COG=(x_G, 0, z_G) as the vessel is assumed to be port-starboard symmetric. The vessel velocity is calculated in the body-fixed frame, as are the loads acting on the vessel.

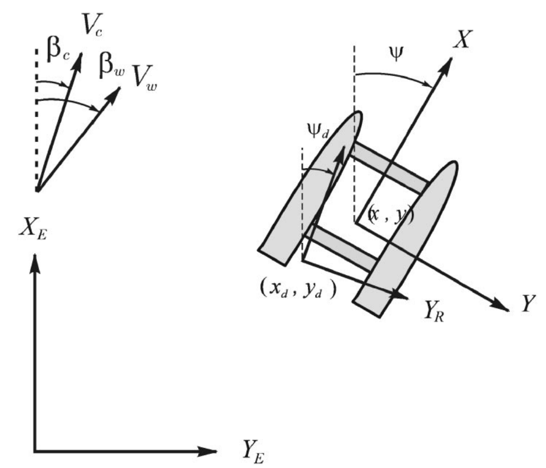


Figure 5.3: Vessel reference frames (Sørensen [14])

The earth-fixed position vectors η_1 and η_2 and the body-fixed velocity vectors ν_1 and ν_2 are given as

$$\boldsymbol{\eta}_1 = [\,x \quad y \quad z]^T, \boldsymbol{\eta}_2 = [\,\phi \quad \theta \quad \psi]^T, \boldsymbol{\nu}_1 = [\,u \quad v \quad w]^T, \boldsymbol{\nu}_2 = [\,p \quad q \quad r]^T \tag{5.1}$$

These vectors express the position and velocity in the six degrees of freedom; surge, sway, heave, roll, pitch and yaw. The linear and angular velocities of the vessel in the earth-fixed frame is given by the transformation

$$\dot{\boldsymbol{\eta}} = \begin{bmatrix} \dot{\boldsymbol{\eta}}_1 \\ \dot{\boldsymbol{\eta}}_2 \end{bmatrix} = \begin{bmatrix} \mathbf{J}_1(\boldsymbol{\eta}_2) & \mathbf{0}_{3x3} \\ \mathbf{0}_{3x3} & \mathbf{J}_2(\boldsymbol{\eta}_2) \end{bmatrix} \begin{bmatrix} \boldsymbol{\nu}_1 \\ \boldsymbol{\nu}_2 \end{bmatrix} = \mathbf{J}(\boldsymbol{\eta}_2)\boldsymbol{\nu}, \tag{5.2}$$

where $\mathbf{J}_1$ and $\mathbf{J}_2$ are the rotation matrices which transform the linear and angular body-fixed velocities into earth-fixed velocities.

5.2.2 Vessel model: process plant

The process plant is a comprehensive description of the real system. It is used in numerical performance and robustness analyses and testing of the control systems. It is common to separate the modeling of a vessel into a low-frequency (LF) model and a wave-frequency (WF) model. The LF model includes the second-order wave loads, current and wind loads as well as thruster forces and moments. The WF motion of the vessel is due to first-order wave-induced loads.

Nonlinear low-frequency vessel model

The nonlinear six-DOF body-fixed coupled equation of the low-frequency motions in surge, sway, heave, roll, sway and yaw is written as follows:

$$\mathbf{M}\dot{\boldsymbol{\nu}} + \mathbf{C_{RB}}(\boldsymbol{\nu})\boldsymbol{\nu} + \mathbf{C_A}(\boldsymbol{\nu}_\mathbf{r})\boldsymbol{\nu}_\mathbf{r} + \mathbf{D_{NL}}(\boldsymbol{\nu}_\mathbf{r}, \gamma_\mathbf{r})\boldsymbol{\nu}_\mathbf{r} + \mathbf{D}\boldsymbol{\nu} + \mathbf{G}(\boldsymbol{\eta})\boldsymbol{\eta} = \boldsymbol{\tau}_{wind} + \boldsymbol{\tau}_{wave2} + \boldsymbol{\tau}_{thr} \quad (5.3)$$

The effect of current is included in the relative velocity vector according to

$$\boldsymbol{\nu}_\mathbf{r} = [u - u_c \quad v - v_c \quad w \quad p \quad q \quad r]^T \quad (5.4)$$

The current components are defined as

$$u_c = V_c cos(\beta_c - \Psi), \quad v_c = V_c sin(\beta_c - \Psi) \quad (5.5)$$

V_c and β_c are the surface current velocity and direction, respectively. $\mathbf{C_{RB}}(\boldsymbol{\nu})$ and $\mathbf{C_A}(\boldsymbol{\nu}_\mathbf{r})$ are the skew-symmetric Coriolis and centripetal matrices of the rigid body and the potential induced added mass part of the current load. $\mathbf{D_{NL}}(\boldsymbol{\nu}_\mathbf{r}, \gamma_\mathbf{r})\boldsymbol{\nu}_\mathbf{r}$ is the six-dimensional nonlinear damping vector and $\mathbf{D}$ is the 6x6 dimensional strictly positive linear damping matrix caused by linear wave drift damping and laminar skin friction. $\mathbf{M}$ is the 6x6 dimensional system inertial matrix. $\mathbf{G}$ is the 6x6 dimensional generalized restoring coefficient matrix caused by buoyancy and gravitation. $\boldsymbol{\tau}_{wind}$ and $\boldsymbol{\tau}_{wave2}$ are the six-dimensional wind and second-order wave load vectors, and $\boldsymbol{\tau}_{thr}$ is the six-dimensional control vector consisting off forces and moments from the thruster system.

Linear wave-frequency model

The vessel is analyzed in regular sinusoidal waves, and the coupled equations in surge, sway, heave, roll, pitch and yaw are assumed to be linear. They are formulated as

$$\mathbf{M}(\omega)\dot{\boldsymbol{\nu}}_w + \mathbf{D_p}(\omega)\boldsymbol{\nu}_w + \mathbf{G}\boldsymbol{\eta}_w = \boldsymbol{\tau}_{wave1}, \quad (5.6)$$

where the wave-frequency motion vector $\boldsymbol{\nu}_w$ is defined as

$$\boldsymbol{\eta}_w = [\eta_{w1} \quad \eta_{w2} \quad \eta_{w3} \quad \eta_{w4} \quad \eta_{w5} \quad \eta_{w6}\,]^T \quad (5.7)$$

Furthermore, $\boldsymbol{\tau}_{wave1}$ is the first-order wave excitation vector, $\mathbf{M}(\omega)$ is the 6x6 mass matrix containing frequency-dependent added mass coefficients in addition to the vessel mass and moment of inertia. $\mathbf{D_p}(\omega)$ is the 6x6 wave radiation damping matrix. $\mathbf{G}$ is the 6x6 linearized restoring coefficient matrix.

5.2.3 Vessel model: control plant

The control plant is a simplified mathematical model of the system. It is not desirable to counteract the WF motions, as this would result in wear and tear of the thrusters, in addition to unnecessary fuel consumption. Hence, the control action of the propulsion system is produced by the low-frequency part of the vessel motion.

Linear low-frequency control plant model

In dynamic positioning systems it is normal to reduce the 6 DOF vessel model in Equation (5.3) to a 3 DOF problem containing the horizontal components surge, sway and yaw. However, for semi-submersibles, an unintentional coupling phenomena between the vertical and horizontal planes through the thruster action can be invoked. As the natural periods in roll and pitch are in the range of 30-70 [s], which is within the bandwidth of the controller, roll and pitch may be unintentionally excited by the thruster system. This phenomena is described in Sørensen and Strand [12]. Thus, the 3 DOF multivariable controller in surge, sway and yaw will be extended to account for couplings to roll and pitch. In order to derive the controller, the low-frequency process plant model in 5.3 is linearized. The LF control plant model is derived about zero vessel velocity. The linearized control plant in the reference parallel frame can be written

$$\mathbf{M}_i\dot{\boldsymbol{\nu}}_i + \mathbf{D}_i\boldsymbol{\nu}_i + \mathbf{G}_i\boldsymbol{\eta}_i = \boldsymbol{\tau}_{ic} + \mathbf{w}_i, \tag{5.8}$$

where i=5 represents the 5 DOF model in surge, sway, roll, pitch and yaw. The corresponding linear LF state-space model can be formulated as

$$\dot{\mathbf{x}}_5 = \mathbf{A}_5\mathbf{x}_5 + \mathbf{B}_5\boldsymbol{\tau}_{5c} + \mathbf{E}_5\mathbf{w}_5 \tag{5.9}$$

$$\mathbf{y}_5 = \mathbf{C}_5\mathbf{x}_5 + \mathbf{v}_5, \tag{5.10}$$

where

$$\mathbf{x}_5 = [\ u,\ v,\ q,\ p,\ r,\ x,\ y, \phi, \theta, \psi\ ]^T \tag{5.11}$$

is the 5 DOF state-space vector. $\boldsymbol{\tau}_{5c}$ is the commanded control vector, and $\mathbf{w}_5$, $\mathbf{y}_5$ and $\mathbf{v}_5$ are the disturbance, measurement and noise vectors, respectively.

Linear wave-frequency model

Synthetic white-noise-driven processes consisting of uncoupled harmonic oscillators with damping are used to model the WF motions. The synthetic WF model can be written in state-space form according to

$$\dot{\boldsymbol{\xi}}_{5w} = \mathbf{A}_{5w}\boldsymbol{\xi}_{5w} + \mathbf{E}_{5w}\mathbf{w}_{5w} \tag{5.12}$$

$$\boldsymbol{\eta}_{5w} = \mathbf{C}_{5w}\boldsymbol{\xi}_{5w} \tag{5.13}$$

$\boldsymbol{\eta}_{5w}$ is the measurement vector of the wave-frequency motion and $\mathbf{w}_{5w}$ is a zero-mean Gaussian white-noise vector.

5.3 Mathematical modeling of riser

The following section will describe the mathematical modeling of the riser, and it is based on Rustad [15], Langen and Sigbjörnsson [16] and Sørensen [14].

5.3.1 Coordinate systems

Four coordinate systems are applied; one for each of the riser elements (i-frame), one for the vessel (b-frame), one fixed to the seabed (f-frame) and eventually one fixed to the sea surface (global frame: g-frame). For each frame, the subscribt i = 1,2,3 denotes the direction (x, y or z) in which the unit vector points. The orientations of the coordinate systems can be seen in Figure 5.4. The origin of the body-fixed frame (b-frame) is in the center of gravity of the semi-submersible. The i-frames are located in the i-*th* node of the riser. The forces acting on each element, such as tension, effective weight and drag are computed in this frame and then transformed to the seabed-fixed f-frame. Also, the positions of the riser nodes in the global system are described relative to the i-frame.

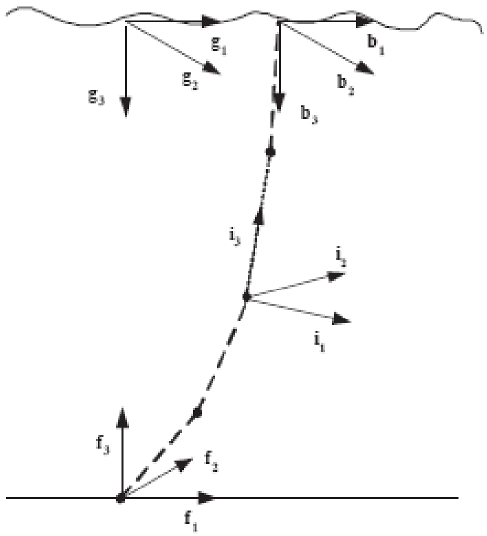


Figure 5.4: The coordinate systems (Rustad [15])

5.3.2 Top tension

In the modeling of the riser, a constant top tension is applied. The required top tension must be calculated for each waterdepth in order to provide the riser with sufficient tension for each depth, and it must be kept well below the yield stress for steel.

A marine riser is a long and slender structure with low elastic bending stiffness. The main contribution to resistance against static and dynamic forces is the geometric stiffness due to the *effective tension*. The top tension must be sufficiently high to prevent the riser from global buckling. This means that the effective tension must have a positive value at the lower end of the riser. Also, the top tension supports the weight of the riser. Consequently, the top tension must equal the *effective weight* of the riser *plus* a margin for the tension at the lower end to be positive. The effective weight (in Newton) of the riser per unit length is the sum of the weight of the riser, the internal fluid and the buoyancy:

$$w_e = A\rho_s g + A_i \rho_f g - A_e \rho_w g \tag{5.14}$$

where A, A_e and A_i are the cross-sectional total, internal and external area of the riser, respectively, and ρ_s, ρ_f and ρ_w are the density of steel, the internal fluid and sea water. g is the gravity constant. The effective weight plus the margin is thus the lower limit for the top tension. For each element, the effective weight is calculated as the effective weight per unit length times the length of the element:

$$w_{eff,i} = w_e \frac{l_r}{n} \tag{5.15}$$

where l_r is the total length of the riser and n is the number of elements. The effective tension in each element is now calculated as the effective tension in the previous element minus the effective weight of the actual element and is denoted P_i. The upper limit for the top tension is given by a percentage of the yield stress for steel. Since the top tension must support the weight of the riser, buoyancy modules are frequently used in order to reduce the required tension. These modules are connected to the riser joints and will influence the effective weight

of the riser.
The top tension vector $\mathbf{f}_{top}$, which will be applied in the riser FEM modeling later in this section, is given as a vector containing 2(n+1) zeros and the tension P_{top} in the vertical direction at the upper end:

$$\mathbf{f}_{top} = [\ \mathbf{0}_{1x(2n+1)} \quad P_{top}\ ]^T \tag{5.16}$$

The tensioner system for a drilling riser acts like a heave compensator because it adjusts the top tension according to the required tension in the riser because of heave motions caused by waves.

5.3.3 Riser FEM modeling

The finite element method (FEM) is applied to find the riser behavior. The method consists of the following steps (Langen and Sigbjörnsson [16]):

1. Discretization; the construction is divided into elements.
2. Element analysis; the element matrix, stiffness matrix and damping matrix are created. In addition, the element load vectors are established.
3. System analysis; the system matrices for mass, stiffness and damping are formed from the element matrices. The system load vectors are derived from the element load vectors.
4. Solving of the dynamic equation of motion.

The dynamic equilibrium of motion consists off two components; the low-frequency dynamic equation, where the loading terms are the low-frequency motion of the vessel and the current, and the wave-frequency dynamic equation, where the loading terms are the wave-frequency induced vessel motions and the hydrodynamic forces.

Discretization
The riser is divided into n elements. There are *n+1* nodes. These nodes are numbered from the bottom to the top, with node *1* at the seabed and node *n+1* at the connection between the vessel and the riser, see Figure 5.5.

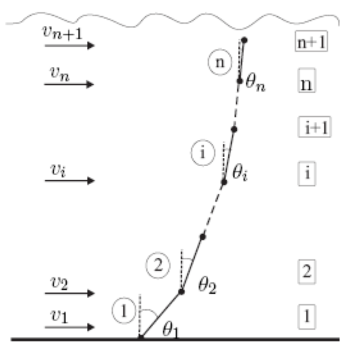


Figure 5.5: Numbering of the riser elements (encircled), nodes (boxed), current on each node and the inclination θ_i of each element relative to the global frame. (Rustad [15])

Element analysis

Each element is modeled by a bar element with two translational degrees of freedom in each end. This is sufficient at large water depths, because the riser behaves almost like a cable with the geometric stiffness as the main contribution to the stiffness. The geometric stiffness is due to the effective tension in the riser. The riser elements are hence modeled by bar elements with four degrees of freedom, because there are two translational degrees of freedom in each end, see Figure 5.6.

Figure 5.6: The riser element modeled as a bar element with four DOFs. x is transverse of the element, positive to the right, and z is along the element, positive upwards.

The node at the seabed is fixed, and the top node is fixed to the vessel in the x-direction. For each element, the inclination θ_i is taken as the angle between the element and the global coordinate system f-frame. l_i is the length of each element and is found as

$$l_i = \sqrt{\Delta x_i^2 + \Delta z_i^2} \tag{5.17}$$

where $\Delta x_i = x_{i+1} - x_i$ and $\Delta z_i = z_{i+1} - z_i$. x_i and z_i represent the horizontal and vertical nodal displacements, respectively, in end one of the bar element. x_{i+1} and z_{i+1} are the horizontal and vertical nodal displacements in end two of the bar element. The inclination θ_i for each element can now be found as

$$\theta_i = \arcsin \frac{\Delta x_i}{l_i} \tag{5.18}$$

This angle is both used in the transformations between the global and local coordinates systems and in the investigation of the riser behavior.

According to the previous, the full displacement vector is given as

$$\mathbf{r} = [\begin{array}{cccccccccccc} x_1 & z_1 & x_2 & z_2 & \dots & x_i & z_i & \dots & x_n & z_n & x_{vessel} & z_{n+1} \end{array}]^T \tag{5.19}$$

and the inclination vector is given as

$$\theta = [\begin{array}{ccccccc} \theta_1 & \theta_2 & \theta_3 & \dots & \theta_i & \dots & \theta_n \end{array}]^T \tag{5.20}$$

The element mass, stiffness and damping matrices can be derived.

The local mass matrix consists of three terms; the structural mass of the riser $\mathbf{m}_s$, the mass of the internal fluid $\mathbf{m}_f$ and the hydrodynamic added mass $\mathbf{m}_a$. These mass matrices are found by using the formula for *consistent* mass matrix in Langen and Sigbjörnsson [16]:

$$\mathbf{m}_i = \int_{V_i} \rho \mathbf{N}^T \mathbf{N} \, \mathrm{d}V = \rho A \int_0^l \mathbf{N}^T \mathbf{N} \, \mathrm{d}x \tag{5.21}$$

where ρ is the mass density, l is the element length, and the interpolation polynomial $\mathbf{N}$ gives the displacement $\mathbf{r}$ for the element as a function of the nodal displacements x_1, x_2, z_1 and z_2. $\mathbf{N}$ is given as

$$\mathbf{N} = [1 - \frac{x}{l}, \frac{x}{l}] \tag{5.22}$$

By applying Equation (5.21) and (5.22) on the node with two DOFs we now get

$$\mathbf{m}_{2x2} = \frac{\rho A l}{6} \begin{bmatrix} 2 & 1 \\ 1 & 2 \end{bmatrix} \tag{5.23}$$

The total structural mass for one element with nodal displacements x_1, z_1, x_2, z_2 is then

$$\mathbf{m}_{si} = \frac{\rho_s A_s l}{6} \begin{bmatrix} 2 & 0 & 1 & 0 \\ 0 & 2 & 0 & 1 \\ 1 & 0 & 2 & 0 \\ 0 & 1 & 0 & 2 \end{bmatrix} \tag{5.24}$$

where A_s is the cross sectional area of the riser and ρ_s is the density of steel. Similarly, for the internal fluid with density ρ_f and area equal to the internal area of the riser A_i, the mass is

$$\mathbf{m}_{fi} = \frac{\rho_f A_i l}{6} \begin{bmatrix} 2 & 0 & 1 & 0 \\ 0 & 2 & 0 & 1 \\ 1 & 0 & 2 & 0 \\ 0 & 1 & 0 & 2 \end{bmatrix} \tag{5.25}$$

The added mass for a circular cylinder in the x-direction equals the volume of the displaced fluid, $\rho_f A_e l$. The added mass in the z-direction is zero. The hydrodynamic mass for the element is then expressed as

$$\mathbf{m}_{ai} = \frac{\rho_w A_e l}{6} \begin{bmatrix} 2 & 0 & 1 & 0 \\ 0 & 0 & 0 & 0 \\ 1 & 0 & 2 & 0 \\ 0 & 0 & 0 & 0 \end{bmatrix} \tag{5.26}$$

where ρ_w is the density of water and A_e is the external riser area. By adding together the mass matrices above, the total local mass matrix for each element appears:

$$\mathbf{m}_i = \mathbf{m}_{si} + \mathbf{m}_{fi} + \mathbf{m}_{ai} \tag{5.27}$$

The local stiffness matrix consists of the geometric stiffness $\mathbf{k}_G$ and the elastic stiffness $\mathbf{k}_E$. The geometric stiffness is due to the effective axial tension P_i and this stiffness works in the lateral direction. The elastic stiffness acts in the axial direction. The geometric and elastic stiffness matrices are found by applying the formula for stiffness matrix in Langen and Sigbjörnsson [16]:

$$\mathbf{k}_i = \int_0^l EA\mathbf{B}^T\mathbf{B}\,\mathrm{d}x \tag{5.28}$$

where E is the Young's modulus of elasticity and $\mathbf{B}$ is expressed as

$$\mathbf{B} = \frac{d}{dx}\mathbf{N} = [\frac{1}{l}, \frac{1}{l}] \tag{5.29}$$

The stiffness matrix for each node then becomes

$$\mathbf{k}_{2x2} = \frac{EA}{l}\begin{bmatrix} 1 & -1 \\ -1 & 1 \end{bmatrix} \tag{5.30}$$

Since the elastic stiffness only has components in the axial direction, the local elastic stiffness matrix for each element will be

$$\mathbf{k}_{EAi} = \frac{EA}{l_i}\begin{bmatrix} 0 & 0 & 0 & 0 \\ 0 & 1 & 0 & -1 \\ 0 & 0 & 0 & 0 \\ 0 & -1 & 0 & 1 \end{bmatrix} \tag{5.31}$$

The geometric stiffness has components in the lateral direction, only, and the local geometric stiffness matrix for each element is:

$$\mathbf{k}_{Gi} = \frac{P_i}{l_i}\begin{bmatrix} 1 & 0 & -1 & 0 \\ 0 & 0 & 0 & 0 \\ -1 & 0 & 1 & 0 \\ 0 & 0 & 0 & 0 \end{bmatrix} \tag{5.32}$$

The total local stiffness matrix for each element is now found by adding together the two stiffness matrices:

$$\mathbf{k}_i = \mathbf{k}_{EAi} + \mathbf{k}_{Gi} \tag{5.33}$$

The damping loads are steady state hydrodynamic forces and moments due to forced harmonic rigid body motions (Faltinsen [11]). The damping expresses the ability of the structure to dissipate kinetic energy (Langen and Sigbjörnsson [16]). This means that the kinetic energy of the system will decrease if energy is not added. In the case of a riser, the contributions to damping are the *construction* damping and the *hydrodynamic* damping. Structural damping is due to the damping of the material in the structure, which again is caused by the inner friction in the material. A structural damping model gives a satisfactory description of the damping in many materials, and the structural damping can be represented by the *Rayleigh-damping*:

$$\mathbf{C}_r = \alpha_1 \mathbf{M}_r + \alpha_2 \mathbf{K}_r \tag{5.34}$$

The first term in this equation will damp out the low frequencies and originates from damping from rigid body motions, while the second term will damp out the high frequencies. However, we do not want the damping from rigid body motions, so the inertia term is omitted, and we then get

$$\mathbf{C}_r = \alpha_2 \mathbf{K}_r \tag{5.35}$$

α_2 can be determined by the damping ratio λ.

The hydrodynamic damping originates from the fluid pressure which is in phase with the velocity of the structure. This damping can be divided into two parts. The first part is caused by radiation (the structure generates waves that propagate away from the ship) and may be represented by potential theory. The other part, commonly referred to as *drag* force is due to the vortex shedding and viscous effects in the water. The drag force is assumed to be proportional to the square of the relative velocity between the water particles and the structure. The hydrodynamic damping is dependent on the geometry of the structure, and if the structure is "slender" compared to the wavelength, the drag damping will dominate and the radiation damping will be insignificant. As a rule of thumb, we say that the structure is "slender" if the wave length is more than 5 times the diameter:

$$\frac{\lambda}{D} > 5 \tag{5.36}$$

Here, the wave length λ must not be confused with the damping ratio, also denoted by λ. The hydrodynamic damping appears as the drag term in Morison's equation:

$$dF = \rho\pi\frac{D^2}{4}C_M a_1 + \frac{\rho}{2}C_D D|u-\dot{r}|(u-\dot{r}) \tag{5.37}$$

where u is the water velocity and $\dot{r}$ is the response velocity of the riser. C_D is the drag coefficient. The first term in Equation (5.37) is the added mass force and is included in the mass matrix. The drag term is calculated for each element and applied as concentrated forces in each node. The drag force vector $\mathbf{f}_{drag}$ will be placed at the right-hand side of the dynamic equation presented later in this section. Further, the structural damping is proportional to the system stiffness matrix $\mathbf{K}_r$, so we do not have to transform $\mathbf{C}_r$, because it is already given as the system damping matrix.

System analysis: transformation of riser elements

The system matrices for mass, stiffness and damping are to be derived from the element matrices. The transformation from i to f for the two-dimensional system with four DOFs is described by a rotation about the y-axis. In Figure 5.7 the relation between the i-frame and the f-frame is shown.

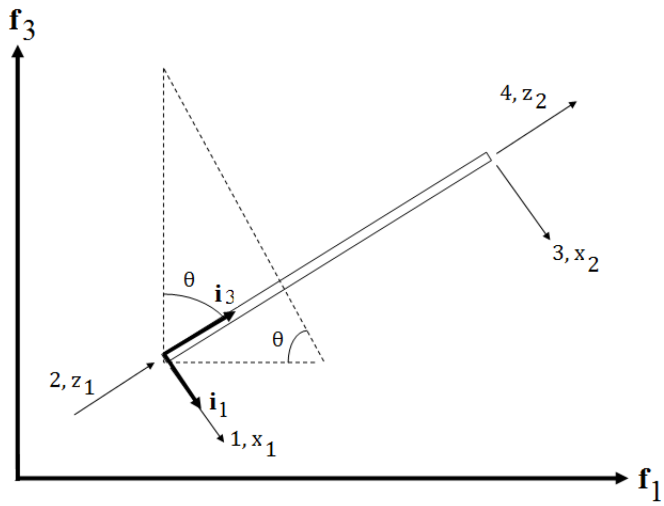


Figure 5.7: Transformation from the i-frame to the f-frame.

The transformation matrix from i to f for one node is written as:

$$\mathbf{T}^f_{0,i}(\mathbf{r}) = \begin{bmatrix} \cos\theta_i & \sin\theta_i \\ -\sin\theta_i & \cos\theta_i \end{bmatrix} \tag{5.38}$$

where θ_i is defined in the previous. This can be extended to include the whole bar element with four DOFs by superposing the transformation matrices for the two nodes:

$$\mathbf{T}^f_i(\mathbf{r}) = \begin{bmatrix} \mathbf{T}^f_{0,i}(\mathbf{r}) & 0_{2x2} \\ 0_{2x2} & \mathbf{T}^f_{0,i}(\mathbf{r}) \end{bmatrix} \tag{5.39}$$

The system mass matrix is found by concatenating the transformed mass matrices for each element i:

$$\overline{\mathbf{m}}_i = \mathbf{T}_i^f \mathbf{m}_i \mathbf{T}_i^{fT} = \begin{bmatrix} \overline{\mathbf{m}}_{11}^i & \overline{\mathbf{m}}_{12}^i \\ \overline{\mathbf{m}}_{21}^i & \overline{\mathbf{m}}_{22}^i \end{bmatrix} \tag{5.40}$$

$$\mathbf{M}_r = \begin{bmatrix} \overline{\mathbf{m}}_{11}^1 & \overline{\mathbf{m}}_{12}^1 & & & \\ \overline{\mathbf{m}}_{21}^1 & \overline{\mathbf{m}}_{22}^1 + \overline{\mathbf{m}}_{11}^2 & \overline{\mathbf{m}}_{12}^2 & & \\ & \overline{\mathbf{m}}_{21}^2 & \overline{\mathbf{m}}_{22}^2 + \overline{\mathbf{m}}_{11}^3 & & \\ & & & \cdots & \\ & & & \overline{\mathbf{m}}_{22}^{n-1} + \overline{\mathbf{m}}_{11}^n & \overline{\mathbf{m}}_{12}^n \\ & & & \overline{\mathbf{m}}_{21}^n & \overline{\mathbf{m}}_{22}^n \end{bmatrix} \tag{5.41}$$

where $\mathbf{m}_i$ is the local mass matrix for element i (given in Equation (5.27)) and $\overline{\mathbf{m}}_i$ is the global mass matrix for element i. The system mass matrix is a 2(n+1) x 2(n+1) matrix.
The system stiffness matrix is derived in the same way as the system mass matrix, and it becomes:

$$\mathbf{K}_r = \begin{bmatrix} \overline{\mathbf{k}}_{11}^1 & \overline{\mathbf{k}}_{12}^1 & & & \\ \overline{\mathbf{k}}_{21}^1 & \overline{\mathbf{k}}_{22}^1 + \overline{\mathbf{k}}_{11}^2 & \overline{\mathbf{k}}_{12}^2 & & \\ & \overline{\mathbf{k}}_{21}^2 & \overline{\mathbf{k}}_{22}^2 + \overline{\mathbf{k}}_{11}^3 & & \\ & & & \cdots & \\ & & & \overline{\mathbf{k}}_{22}^{n-1} + \overline{\mathbf{k}}_{11}^n & \overline{\mathbf{k}}_{12}^n \\ & & & \overline{\mathbf{k}}_{21}^n & \overline{\mathbf{k}}_{22}^n \end{bmatrix} \tag{5.42}$$

As stated in the previous subsection, the system damping matrix $\mathbf{C}$ has already been established as proportional to the system stiffness matrix.

Solving the dynamic equations of motion
As mentioned previously, the loads on the riser consist of low-frequency loads and wave-frequency loads. The low-frequency dynamic equation of motion is given as:

$$\mathbf{M}_r(r)\ddot{\mathbf{r}} + \mathbf{C}_r(\mathbf{r})\dot{\mathbf{r}} + \mathbf{K}_r(\mathbf{r})\mathbf{r} = \mathbf{f}_{top} + \boldsymbol{\tau}_{vessel_{LF}}(\mathbf{r}) + \boldsymbol{\tau}_{current}(\mathbf{u}_c, \mathbf{r}, \dot{\mathbf{r}}) \tag{5.43}$$

where $\mathbf{r}$ is the riser position vector given in Equation (5.19), $\boldsymbol{\tau}_{vessel_{LF}}$ is the loading term due to the low-frequency motions of the vessel, $\boldsymbol{\tau}_{current}$ is the current force and $\mathbf{u}_c$ is the current velocity vector. $\mathbf{f}_{top}$ is the top tension, given by Equation (5.16).
The DOFs at the bottom, x_1 and z_1 are fixed, and the horizontal DOF at the upper end of the riser, x_{vessel} is fixed to the vessel. We can omit the prescribed and fixed DOFs from the equation, so that is becomes:

$$\mathbf{r} = [\ x_2 \ \ z_2 \ \ \ldots \ \ x_i \ \ z_i \ \ \ldots \ \ x_n \ \ z_n \ \ z_{n+1}\ ]^T \tag{5.44}$$

The wave-frequency dynamic equation is expressed as

$$\mathbf{M}_r(r)\ddot{\mathbf{r}} + \mathbf{C}_r(\mathbf{r})\dot{\mathbf{r}} + \mathbf{K}_r(\mathbf{r})\mathbf{r} = \boldsymbol{\tau}_{vessel_{WF}}(\mathbf{r}) + \mathbf{f}_{drag} \tag{5.45}$$

The loading term $\boldsymbol{\tau}_{vessel_{WF}}$ is due to the wave-frequency vessel motions, while $\mathbf{f}_{drag}$ is the drag forces, given by the last term in Equation (5.37).

5.3.4 Computational procedure

When the necessary relations, matrices and vectors are found, the computation of the resulting position of the riser due to current, semi-submersible motion and top tension can be found. The mass matrix $\mathbf{M}_r$ is assumed to be constant, but the stiffness matrix $\mathbf{K}_r$, and hence also the damping matrix $\mathbf{C}_r$ (by Equation (5.35)) are nonlinear functions of displacement and velocity, respectively. Also, the drag forces will depend on the relative velocity between the water and the riser. The nonlinearities are solved numerically by incremental formulation with the Newmark-beta time integration method and Newton-Raphson equilibrium iteration.
A quasi-static algorithm is performed to find the equilibrium between the internal and the external forces. The external forces are the drag forces, the top tension and the forces from the moving semi-submersible. The quasi-static algorithm consists of three major steps:

1. Initialization; Axial effective tension in each element, caused by the top tension P_{top} and the effective weight of the element (see Section 5.3.2 about top tension) is found. This will result in increased element lengths, and the element stiffness matrix will have to be updated. The updated system stiffness matrix is found by concatenating the local stiffness matrices.

2. Moving of vessel to an offset position and adding of current forces;

3. Equilibrium equations; The resulting internal force in each node should be balanced with the external force in each node.

5.4 Horizontal-plane controller with roll and pitch damping

The conventional horizontal-plane controller consists of a linear horizontal-plane PD control law, integral action, wind feedforward control action and model reference feedforward control action. For semi-submersibles, wind loads are dominating, and in order to counteract the forces from wind rapidly, a wind feedforward controller is introduced. Also, the model reference feedforward control action is needed to improve the performance of the controller during tracking operations.

The resulting horizontal-plane station keeping control law is written

$$\boldsymbol{\tau}_{3c} = \boldsymbol{\tau}_w + \boldsymbol{\tau}_t + \boldsymbol{\tau}_i + \boldsymbol{\tau}_{pd}, \tag{5.46}$$

where

$$\boldsymbol{\tau} = -\mathbf{G}_w \hat{\boldsymbol{\tau}}_{wind} \tag{5.47}$$
$$\boldsymbol{\tau}_t = \mathbf{M}_3\mathbf{a}_d + \mathbf{D}_3\mathbf{v}_d + \mathbf{d}_3(\mathbf{v}_d) + \mathbf{C}(\mathbf{v}_d)\mathbf{v}_d \tag{5.48}$$
$$\dot{\boldsymbol{\tau}}_i = \mathbf{A}_{wi}\boldsymbol{\tau}_i + \mathbf{G}_i\mathbf{z} \tag{5.49}$$
$$\boldsymbol{\tau}_{pd} = -\mathbf{G}_p\mathbf{e}_2 - \mathbf{G}_d\mathbf{e}_1 \tag{5.50}$$

are the wind and reference feedforward action, integral action and PD control laws, respectively. $\mathbf{G}_w$, $\mathbf{G}_i$, $\mathbf{G}_p$ and $\mathbf{G}_d$ are controller gain matrices, while the error vectors in the PD control law are defined as

$$\mathbf{e}_2 = \mathbf{R}^T(\psi_d)[\hat{\boldsymbol{\eta}} - \boldsymbol{\eta}_d]^T \tag{5.51}$$
$$\mathbf{e}_1 = \dot{\mathbf{e}}_2, \tag{5.52}$$

where $\mathbf{R}^T(\psi_d)$ is the rotation matrix from the earth-fixed to the body-fixed frame when only the horizontal motions are considered. Furthermore, $\hat{\boldsymbol{\eta}} = [\hat{x}, \hat{y}, \hat{\psi}]^T$ is the estimated position vector, while $\hat{\boldsymbol{\tau}}$ is the estimated wind force vector. In the integral action control law, $\mathbf{A}_{wi}$ is the anti-windup precaution matrix, and $\mathbf{z}$ is a property space which expresses the variables to be controlled and is defined as $\mathbf{z} = \mathbf{e}_2$. In the reference feedforward control action, $\mathbf{a}_d$ and $\mathbf{v}_d$ are the desired generalized reference acceleration and velocity vectors.

As previously mentioned, unintentional coupling between the horizontal and vertical degreed of freedom may occur for semi-submersibles. Hence, the horizontal-plane controller should be extended to include roll and pitch damping. The surge and sway feedback loops will be extended to incorporate feedback from the low-frequency estimated pitch and roll angular velocities, $\hat{p}$ and $\hat{q}$. The roll and pitch control law can be formulated according to

$$\boldsymbol{\tau}_{rpd} = -\mathbf{G}_{rpd} \begin{bmatrix} \hat{p} \\ \hat{q} \end{bmatrix} \tag{5.53}$$

$\mathbf{G}_{rpd}$ is the roll-pitch controller gain matrix and defined as

$$\mathbf{G}_{rpd} = \begin{bmatrix} 0 & g_{xq} \\ g_{yp} & 0 \\ g_{\psi p} & 0, \end{bmatrix} \tag{5.54}$$

where g_{xq}, g_{yp} and $g_{\psi p}$ are controller gains. Hence, the resulting control law will be as follows

$$\boldsymbol{\tau}_{5c} = \boldsymbol{\tau}_{3c} + \boldsymbol{\tau}_{rpd} \tag{5.55}$$

5.5 Local optimization: optimal set-point chasing

In Section 5.1, optimal set-point chasing was defined as vessel positioning based on minimization of one or more variables. Optimal set-point chasing takes place on the local optimization level in Figure 5.1 and gives input to the high-level controller.

5.5.1 Reference model

The reference model generates a smooth trajectory for the vessel to follow when moving from one position and/or heading to another in order to optimize the riser angles. Full-scale experiments have proved that the following reference model in the earth-fixed frame is appropriate

$$\mathbf{a}_d^e + \boldsymbol{\Omega}\mathbf{v}_d^e + \boldsymbol{\Gamma}\mathbf{x}_d^e = \boldsymbol{\Gamma}\mathbf{x}_{ref} \tag{5.56}$$

$$\dot{\mathbf{x}}_{ref} = -\mathbf{A}_f\mathbf{x}_{ref} + \mathbf{A}_f\boldsymbol{\eta}_r \tag{5.57}$$

$\mathbf{a}_d^e$, $\mathbf{v}_d^e$ and $\mathbf{x}_d^e$ define the desired vessel acceleration, velocity and position trajectories in the earth-fixed frame. $\boldsymbol{\eta}_r = [x_r \;\; y_r \;\; \psi_r]^T$ represents the new reference coordinates. The vector $\mathbf{x}_{ref}$ defines the filtered reference coordinates. $\boldsymbol{\Omega}$ and $\boldsymbol{\Gamma}$ are diagonal damping and stiffness matrices, respectively. $\mathbf{A}_f$ is a set-point filter gain matrix.

An important part of the local optimization is the optimal criteria. In Sørensen et al. [5] a quadratic loss function is introduced in order to minimize the riser top and bottom angle. Relative weighting of the top and bottom angles is performed by giving more or less priority to one of the angles.

In this study, the optimal vessel positioning accounting for riser angles will be sought based on the simulations in Section 4. The optimal positioning will also include a maximum permissible radius of vessel motion for given weather conditions. In the following sections, decision criteria for optimal positioning and disconnect will be developed and explored. Certain "rules" for positioning and disconnect will then be input to a possible local optimization algorithm, either manually or automatically controlled.

5.6 Decision criteria

In Section 4.7:*Synthesis*, the riser response in shallow and deep water for various influences was collected and categorized according to the impact on the riser angles, see Table 4.8. In this section, decision criteria for optimal positioning of the vessel, as well as decision criteria for disconnect will be developed.

The principles of *watch circles* were first presented in Section 1. Dynamically positioned vessels use color codes to indicate when the vessel offset is acceptable for operation (green zone) and when a disconnect should be prepared (yellow/red zone). A more detailed description of each zone, as well as possible reasons for the relevant condition, will be presented in the following section. However, the limits for the different zones do not necessarily take into account the more complex riser behavior in deep water. Thus, the limits may be erroneous. Based on the observations from the simulations in Section 4, watch circles for shallow and deep water, with and without current, will be presented.

The author has received a working document from Statoil which is used as input to this section. Please note that the numbers are indicative.

5.6.1 DP status level

In drilling and well intervention, watch circles (see Figure 1.1) are used to indicate whether the position of the vessel should initiate halt in operation or preparation for disconnect. Green, yellow and red zones indicate the status of the unit. In addition, an advisory status is included. Table 5.1 describes the different DP status levels.

Table 5.1: DP status level definitions

DP status level	Notes/Actions
Green status	No action. Operation progress.
Advisory status	Informative status prior to alarms. Used by operational personnel to inform supervisors of certain changes taking place in the DP system and/or operation. No lights or bells.
Yellow status	Yellow status lighting or audible alarm. Degraded operational status: the drill floor shall start preparing for disconnection if connected to the well and/or termination of other operations. The senior DP operator and duty driller shall confer and decide if any further action is necessary or if operations can continue.
Red status	Red status lighting and audible alarm. Emergency status: emergency disconnect sequence to be initiated. All necessary actions required preventing loss of life or damage to equipment or the environment shall be taken.

The DP status levels in Table 5.1 are caused by different influences, either internal in the vessel itself or any external object or condition. In Figure 5.8 possible causes for the relevant DP status are given.

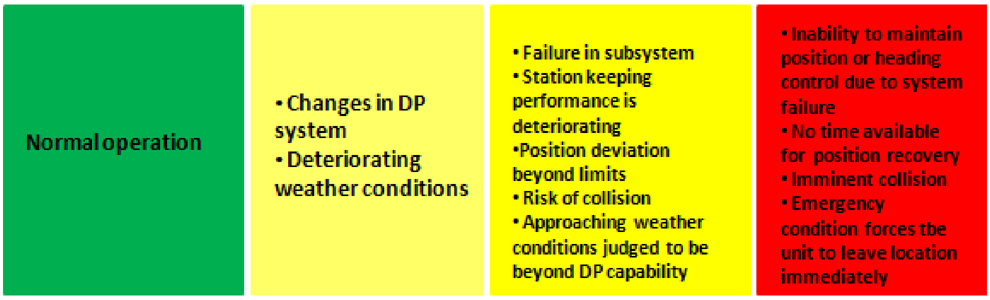


Figure 5.8: Condition characteristics for DP status levels: Green, Advisory, Yellow and Red status levels.

The limits for the various DP status levels are set by the owner of the vessel. These are dependent on the water depth. In Table 5.2 guidance limits for the different DP status levels can be seen. In the table, the following abbreviations are used:

- A: Advisory status
- Y: Yellow status
- R: Red alert status

Table 5.2: DP status level versus position offset (Typical data)

	Water depth [m]					
	200-350			>1000		
DP status level	A	Y	R	A	Y	R
Vessel offset [m]	5	8	12	5	14	25

First, notice that the vessel offset for advisory status is the same for the two different water depth ranges. This reflects the general rule that an offset from the initial position shall always be notified, even if it has an insignificant impact, because it may indicate a failure in the DP system and/or alert the operator about an incoming problem. According to the limits in Table 5.2, the watch circles for advisory status, yellow status and red alert status will be as in Figure 5.9.

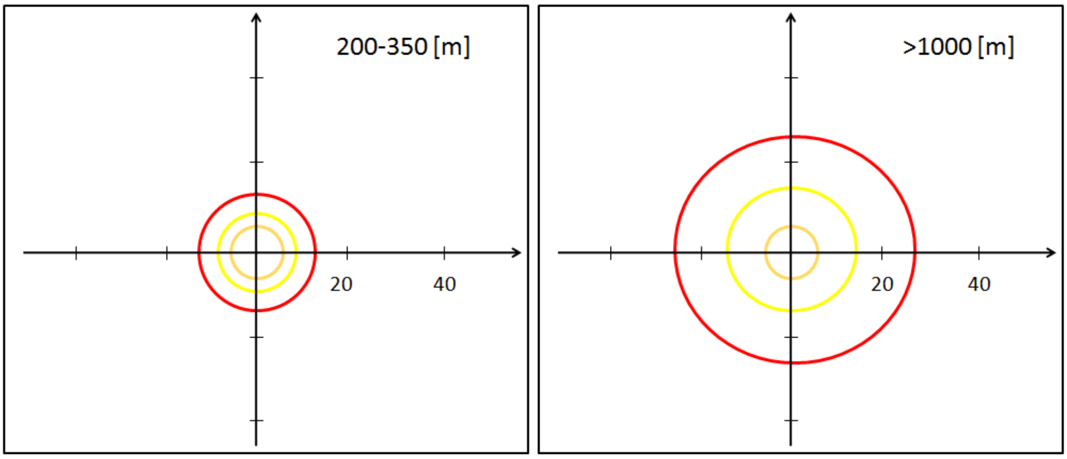


Figure 5.9: Conventional watch circles for water depth ranges 250-350 [m] and >1000 [m]. Orange circle: limit for transition to advisory status. Yellow circle: limit for transition to yellow status. Red circle: limit for transition to red alert status.

In the next section, watch circles for the riser at 300 and 2000 [m] depth will be developed based on the results from Section 4.

5.6.2 Decision criteria for optimal positioning and disconnect

According to Sørensen [14], the objective of the dynamic positioning system is to keep the riser angles within the required limits for drilling operations for the longest possible period of time by proper selection of the desired vessel position coordinates. As the top tension can not exceed a predefined maximum level, the solution is not to increase the top tension such that the riser angles are acceptable. Hence, the vessel must be positioned such that both angles are within their acceptable limits for the longest possible period of time.

The last question from Section 3.1:*Main questions to answer* will be reviewed. The three others have been answered in Section 4, either directly or indirectly.

- How can the semi-submersible be positioned such that the bottom (and top) angle will be acceptable for a given condition?

However, this section will also aim to answer the following question:

- For which vessel offset and/or weather condition must a disconnect be prepared/carried out?

The watch circles which were introduced in the previous section are good tools to use when considering these two questions, and also to present the possible optimal and critical positions of the vessel. However, in addition to watch circles, certain instructions must be given concerning the way of how to use these watch circles, and how to move the vessel in order to ensure acceptable angles during the movement. The riser angle status levels presented in Section 4.7.3:*Categorizing of riser angles* will be used to define the different zones in the watch circle system, and they are given below in Table 5.3. Instead of the *advisory status level* used in Figure 5.9, an optimal status level, as defined in Table 5.3, is used in the watch circles established in this section.

Table 5.3: Riser angles status levels

	Category			
	Optimal	**Acceptable**	**Significant**	**Critical**
Lower angle	0-1°	1-1.5°	1.5-2°	>2°
Upper angle	0-1.5°	1.5-2.5°	2.5-4°	>4°

When establishing the watch circles for the two water depths, the following color codes are applied:

- Green: refers to *optimal* angles.
- Yellow: refers to *significant* angles.
- Red: refers to *critical* angles.

The status level *acceptable* in Table 5.3 will hence be the area outside the green zone but within the yellow zone.

Whereas current must be considered when establishing watch circles, the effect from regular waves can be superpositioned with the response without waves. Hence, knowing the riser angle magnitudes for a given wave, the maximum angles for a first order wave combined with low-frequency motion can be found by adding together the maximum angles for the wave-frequency and low-frequency motion (see Figure 4.30 in Section 4.7.5). The angles caused by first order waves will thus decrease the magnitude of the allowable offset for a given current, but this will not be implemented in the watch circles. First-order waves will mainly affect the top angle, and depending on the wave, 1-3.5° (see Figure 4.10 in Section 4.3.2) should be added to the maximum top angle resulting from the low-frequency motion.

Shallow water

In shallow water, the objective is to avoid any vessel offset, as even small excursions from the zero offset position will result in significant angles. As current affects the riser only marginally and the angles are sensitive to offsets, no measures should be taken to position the vessel differently when there is current acting. Hence, the aim is to establish watch circles for the condition without current and the condition with a uniform current present. In Table 5.4 are given the static riser angles presented in Section 4.7.1.

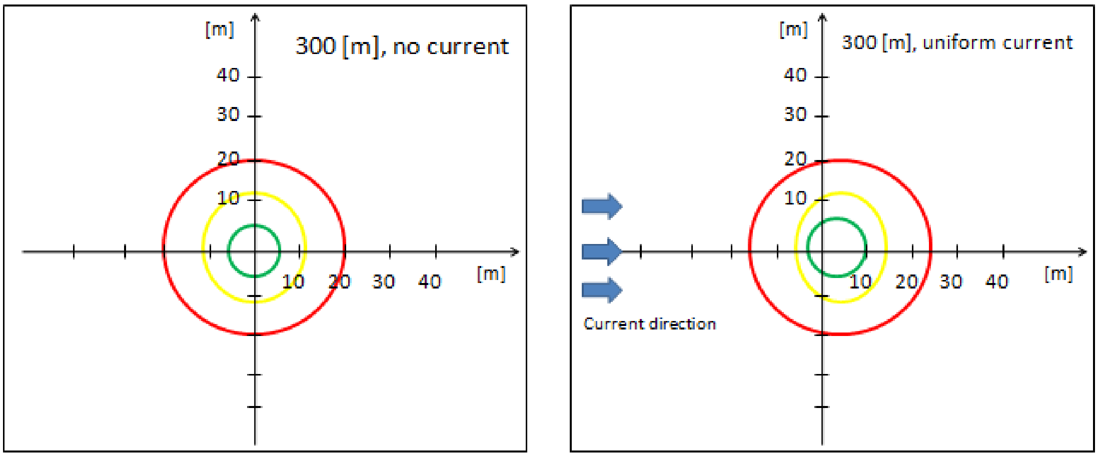
Table 5.4: Static riser angles at 300 [m] water depth for different vessel offsets. The uniform current has a velocity of 0.6 [$\frac{m}{s}$]. Red numbers indicate excessive angles.

		Vessel offsets [m]				
		0	10	20	25	30
Static	No current		0.8	1.3	1.8	2.0
lower	Uniform current, positive offset	0.2	0.9	1.6	1.9	2.2
angle [°]	Uniform current, negative offset		-0.5	-1.1	-1.7	
Static	No current		2.1	3.6	4.1	5.4
upper	Uniform current, positive offset	-0.6	1.6	3.2	4.1	4.9
angle [°]	Uniform current, negative offset		-3.0	-5.1	-7.0	

Based on the riser angle magnitudes in Table 5.4, suggested watch circles for the riser in shallow water are presented in Table 5.5 and Figure 5.10. These are qualitative and give no accurate coordinates for transition from one zone to another. They indicate, however, that the maximum vessel offset before a disconnect should be prepared is larger than the conventional limit, as in Table 5.2 and Figure 5.9.

Table 5.5: DP status level versus position offset, 300 m (G=green, Y=yellow, R=red)

	No current			Uniform current		
DP status level	G	Y	R	G	Y	R
Vessel offset, pos. direction [m]	5	12	20	10	15	25
Vessel offset, neg. direction [m]	5	12	20	2	5	15



(a) No current (b) Uniform current

Figure 5.10: Watch circles for 300 [m] water depth

Compared to Figure 5.9, the watch circles for the case without current allow for larger offsets. The green circle in Figure 5.10(a) coincide with the advisory zone in Figure 5.9, but the yellow and red circles are clearly larger. In case of a uniform current, all three circles are shifted to the left. The uniform current will benefit the top angle when the vessel moves in the same direction as the current, and it will benefit the lower angle in the opposite case. The upper angle will become non-optimal faster than the lower angle, however, and hence we can allow the vessel to move further in the positive direction than in the negative direction.

The current enters from one direction, only. Hence, if the vessel is to drive off or have low-frequency harmonic vessel motions in another direction than the current direction, the limits for vessel offset will be the same as for no current, given that the riser has a static deflection in the x-direction because of the current. Thus, the allowed offset perpendiculary on the current will be the same as for no current.

When there are waves present, the watch circles in Figure 5.10 will be smaller. For first order waves with a period of 10 [s] and height 4 [m], the magnitude top angle will at maximum be 2° more than for the static offset angle. The lower angle is only marginally affected by the wave. In the case of a uniform current and a positive offset, this means that the maximum top angle will be 3.6° at 10 [m] offset and 6.1° at 25 [m] offset. Hence, the allowable offsets become significantly smaller.

Deep water

In Section 4.7.2, three main conclusions concerning the riser behavior in deep water were found:

- Rather large vessel offsets cause non-critical static riser angles, but the top angle during the vessel motion will in most cases be excessive.
- The excessive top angle during a vessel movement can be decreased significantly if the vessel velocity decreases.
- An optimization of the riser angles in a uniform current will imply a compromise, as the angles can not be reduced simultaneously.

It has also been shown that for any motion at the top end of the riser, it takes about 35 [s] for the lower angle to respond, and it increases more slowly than the top angle. Hence, in case of a drive-off, it will take some time for the lower angle to become excessive.

The reader should keep in mind that all limits presented in this section are for the static offset condition. The maximum top angle during a rapid transition from one position to another will be significantly higher than the static top angle once the vessel movement has stopped. If one allows for temporary excessive top angles, the watch circles presented in this section may be cost saving, as they allow for significantly larger offsets than the traditional guidance limits. Hence, the operation may be upheld for a longer period of time and an unnecessary disconnect can be avoided.

In contrast with shallow water, where the vessel should not be moved away from the zero offset position, the vessel in deep water may be positioned elsewhere than at its initial position in order to improve one of the angles. In Table 5.6 are given the static riser angles presented in Section 4.7.2.

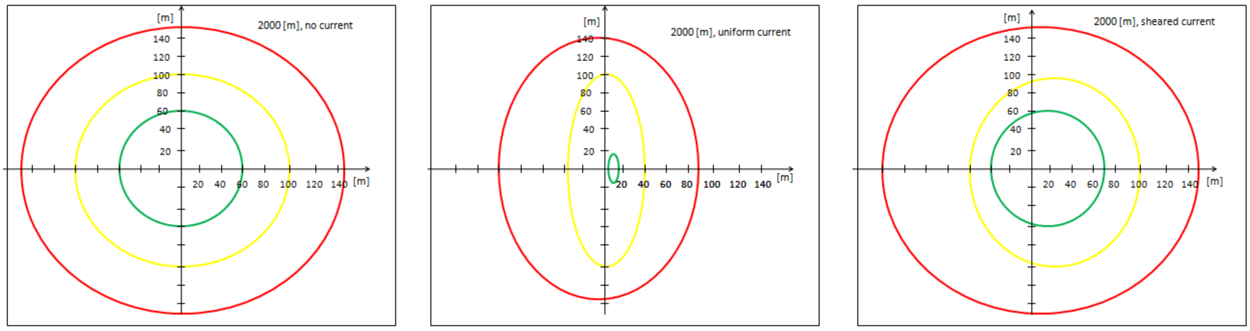
Table 5.6: Static riser angles at 2000 [m] water depth for different vessel offsets. The uniform current has a velocity of 0.6 [$\frac{m}{s}$], while the sheared current has a velocity of 0.1 [$\frac{m}{s}$] at the sea bottom and 0.6 [$\frac{m}{s}$] at the surface. Red numbers indicate excessive angles.

		Vessel offsets [m]							
		0	20	40	50	60	70	100	150
Static lower angle [°]	No current					0.8		1.3	2.0
	Uniform current, positive offset	0.9	1.2	1.5	1.6	1.7	1.9	2.3	3.0
	Uniform current, negative offset			0.4	0.3	0.1	0.0	-0.4	-1.0
	Sheared current, positive offset	0.1					1.0	1.4	2.1
	Sheared current, negative offset			-0.4	-0.6			-1.2	-1.9
Static upper angle [°]	No current					1.5		2.5	3.5
	Uniform current, positive offset	-1.7	-1.3	-0.8	-0.6	-0.3	-0.1	0.7	1.8
	Uniform current, negative offset			-2.6	-2.9	-3.2	-3.4	-4.0	-5.3
	Sheared current, positive offset	-0.7					1.0	1.7	2.9
	Sheared current, negative offset			-1.6	-1.9			-3.1	-4.2

Watch circles for the case without current and the case with a uniform and sheared current will be developed. No angle will be given priority to, hence there will be no optimizing of one of the angles. This will be addressed later in this section. Based on the riser angle magnitudes in Table 5.6, suggested watch circles for the riser in deep water are presented in Table 5.7 and Figure 5.11.

Table 5.7: DP status level versus position offset, 2000 m (G=green, Y=yellow, R=red, curr=current, unif.=uniform, sh=sheared).

	No curr.			Unif. curr.			Sh. curr.		
DP status level	G	Y	R	G	Y	R	G	Y	R
Vessel offset, pos. direction [m]	60	100	150	<20	40	>70, <100	70	100	150
Vessel offset, neg. direction [m]	60	100	150	0	<40	100	40	60	140



(a) No current (b) Uniform current (c) Sheared current

Figure 5.11: Watch circles for 2000 [m] water depth

An instant remark is that the allowed offsets are significantly larger than what is proposed in Table 5.2 and Figure 5.9.

In the case without current, the vessel may be moved 150 [m] in each direction before the angles become excessive and a disconnect should be prepared and carried out. Also, the angles will be optimal within a radius of 60 [m] from the initial position. However, with current present, as in Figure 5.11(b) and 5.11(c), the transition limits change.

For a uniform current, the green circle is considerably shrunk. The reason for shifting it to the left for the zero offset position is that the top angle will be non-optimal for zero offset, while the lower angle can tolerate a slight offset in the positive direction before it exceeds 1° which means that it is no longer optimal. However, it exceeds 1° for an offset of 20 [m]. At an offset of 40 [m] in the positive direction, the lower angle reaches 1.5°, while the upper angle reaches 2.5° at an offset of 40 [m] in the negative direction. According to the riser angle status levels in Table 5.3, these offsets constitute the yellow watch circle. Eventually, the critical lower angle is reached somewhere in between a static offset of 70 and 100 [m] in the positive direction, while the critical top angle is reached at a static offset of 100 [m] in the negative direction.

For a sheared current, the watch circles are also shifted to the left, but the green circle is significantly larger than in the case of a uniform current. Because the current contributes to straightening out a big part of the riser without causing the lower angle to become unacceptable, a greater offset is allowed in the positive direction than what was the case without current. However, in the negative direction the green and yellow limits are equivalently smaller. This is because the current force at the bottom is too small to benefit the lower angle, while it is large enough close to the surface to deflect the top of the riser such that the top angle quickly becomes unacceptable.

For the sheared current, the angles are optimal when the offset is zero, and there are good margins in every direction. Hence, no optimizing of angles by moving the vessel to a static offset position is necessary. In case of a uniform current, the top angle is not optimal for the zero offset position, and this is reflected in Figure 5.11(b) by the fact that the green circle does not has its origin in the zero offset position. In this case, one must accept that even small offsets will result in non-optimal angles. By moving the rig one may optimize one angle and improve the margins drastically. However, this will worsen the other angle significantly.

In Table 5.6, it can be seen that the lower angle is zero for a negative offset of 70 [m] in case of a uniform current. This offset will however imply a top angle of -3.4°. Likewise, the top angle is very small (-0.1°) for a positive offset of 70 [m] in the case of a uniform current. The lower angle is 1.9° for this offset. The limits for the watch circles for the vessel by optimizing either the lower or upper angle can be seen in Table 5.8. The watch circles can be seen in Figure 5.12.

Table 5.8: DP status level versus position offset, 2000 m (G=green, Y=yellow, R=red). Uniform current. Optimizing one angle.

	Opt. lower angle			Opt. upper angle		
DP status level	G	Y	R	G	Y	R
Vessel offset, pos. direction [m]	<20	40	90	>100,<150	>150	>150
Vessel offset, neg. direction [m]	150	>150	>150	<0	<40	100

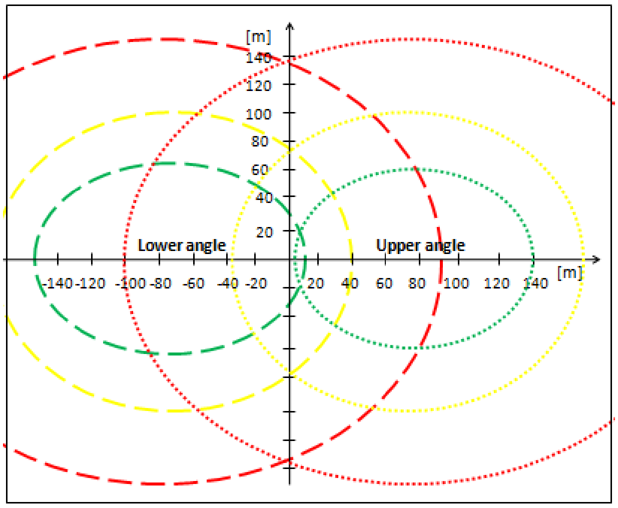


Figure 5.12: Watch circles for optimizing of one riser angle in uniform current. Yellow circle: limit for transition to yellow status. Red circle: limit for transition to red alert status.

It is evident that - by optimizing óne angle - the other angle will become unacceptable and possibly excessive. However, as mentioned previously, the magnitude of the top angle is mostly constrained by the moonpool design. If one can allow for larger top angles, one can position the vessel with a negative offset compared to the current and hence obtain good margins for the lower angle.

As was the case with the riser in shallow water, the presence of first-order waves will worsen the top angle by 1-3° depending on the period and height of the waves. With a uniform current with velocity 0.6 $[\frac{m}{s}]$ and first-order waves with height 8 [m] and period 18 [s], the top angle will be close to critical, and small offsets in the negative current direction will result in an excessive top angle.

5.6.3 Guidelines for disconnect and positioning

In Table 4.8 in Section 4.7.4, the various influences, as well as combinations of these are classified according to the level of severeness of the resulting riser angles. In the previous sections, guidance limits and watch circles based on the riser angles for different vessel offsets and current conditions have been developed. In this section, some aspects of the operation will be considered. First, alarm for vessel offset will be considered. The time to disconnect will also be addressed, as the speed at which the vessel is moving and the time it takes for execution of the disconnect sequence bears directly on the point in time when the disconnect should be initiated (Stockton [17]). Furthermore, in the previous, positioning of the vessel in order to improve the riser angles has been discussed. The acceptable vessel velocity when re-locating the vessel will be addressed. Eventually, the question whether the advisory system for riser angles should be manual or automatic will be briefly discussed.

Alarm for vessel offset

Both in shallow and deep water, there should be notification in case of a vessel offset *even* though a disconnect may be avoided in deep water. Conventional DP status levels, as in Table 5.2 in Section 5.6.1, states that a vessel offset of 5 [m] should initiate the *advisory status*, which means that any vessel offset of more than 5 [m] from the zero offset position may indicate malfunctions or failure in the DP system, or resonance between the vessel and second-order wave loads. A vessel offset of 5 [m] is normally not caused by first-order waves and swells, and it gives an early notification of a possible drive-off or low-frequency harmonic motions resulting from malfunctions, failure or resonance between vessel and waves. Hence, even though it has been established that critical offsets at 2000 [m] water depth will, depending on the current, generally be much more than 5-10 [m] away from the zero offset position, a notification, should be given to the operator at an offset of 5 [m]. There should not be initiated lighting and audible alarms until the yellow zone is reached.

Disconnect

The time to disconnect must be *less* than the time for the lower angle to reach a magnitude where serious damage to the well or the BOP may occur. Since the magnitude of the lower angle affects the well and the BOP directly, this angle is assumed to be more critical than the top angle in this thesis. A lower angle of 2° has been used as the magnitude where a disconnect should be prepared, but not executed. In Sørensen et al. [5], riser angles larger than 6-8° are classified as fatal. Hence, if a lower angle of 6° is a fatal magnitude, the time to disconnect should be less than the time for the lower angle to reach 6°. The drive-off situation mainly studied in this thesis is a drive-off to a vessel offset of 100 [m] during 100 [s]. At 300 [m], when there is no/insignificant current and waves, the lower angle reaches 2° after 50 [s], and it reaches 6° after approximately 80 [s] (see Figure 4.13). In 30 [s], the disconnect must thus be prepared and executed. Seen the little time available for disconnect, the preparation for disconnect should hence begin at the yellow limit, which is reached after 25 [s] in Figure 4.13, which corresponds to a vessel offset of just above 10 [m]. At 2000 [m] water depth, the lower angle has not reached a magnitude of 6° in any of the simulations, even in the case of a uniform current in combination with a drive-off to 150 [m] from the zero offset position. Hence, in deep water the time to disconnect is not as limited by the time for the vessel offset to cause a severe lower angle as in shallow water. The reader should keep in mind that the lower angle will *not* follow the same lapse as the top angle, which becomes excessive during the vessel movement, but merely increase slowly as the vessel offset increases. In the situation where the vessel drives off at full throttle, the lower angle will still use 35 [s] to just respond to the movement, and a large offset (>150 [m]) is required for the lower angle to reach a fatal magnitude.

Positioning

The vessel may be moved to an offset location in the case of a strong current which causes non-optimal static riser angles. In shallow water, the vessel should not be deliberately moved from its zero offset position in order to optimize the riser angles. The riser in shallow water is sensitive to offsets, and current will not cause non-optimal angles. In deep water, the uniform current profile with a velocity of 0.6 $[\frac{m}{s}]$ results in static upper and lower angles of -1.7 and 0.9° , respectively. In order to improve the lower angle, the vessel may be moved in the negative current direction, see Figure 5.12. In order to improve the upper angle, the vessel must be moved to a positive offset. In any case, the transfer of the vessel must be slow. A constant vessel velocity below 0.5 $[\frac{m}{s}]$ will not result in upper angles in excess of 5.3° when the vessel is moved 100 [m] in the opposite direction of a uniform current with velocity 0.6 $[\frac{m}{s}]$.

Manual or automatic control

The aim of Section 5.6.2 was to develop rules to be implemented on the local optimization level, which gives input to the DP controller, see Figure 5.1. Figure 5.2 shows that the reference model, which is input to the controller may receive input from both the operator *and* a block for optimal set-point chasing. The guidelines developed in the present study requires manual input, as the guidelines are more qualitative than quantitative. A sophisticated advisory system, where the output are optimal positioning as well as transition limits for the yellow and red DP status level for a range of current velocities and current directions, requires more extensive and complex analyses than what have been carried out in this thesis. Hence, based on the watch circles developed in the previous, the operator may decide where to position the vessel and when to prepare for a disconnect. In the case where the DP system automatically initiates a disconnect for a given vessel offset, the operator may override the control system by interrupting the disconnect manually. This may be the case in deep water, where it has been found that the traditional limits will cause the riser to be disconnected when not necessary. According to the resulting angles from the simulations in this thesis, the lower angle will not become fatal within an offset of 150 [m] and even more. In shallow water, however, where the time is limited and a rapid decision is critical, the operator should *not* interrupt the preparation for disconnect in case of a drive-off.

The reader should keep in mind that all guidance limits and watch circles developed in this section are purely based on analyses in RIFLEX with unidirectional current,regular waves and prescribed low-frequency motions of the vessel. More extensive analyses should be performed in order to confirm the riser angles for various conditions, and also to develop a more sophisticated advisory system.

6 Concluding remarks

6.1 Conclusion

This thesis has focused on the behavior of a drilling riser connected to a semi-submersible for various vessel motions as well as weather conditions. Specifically, the lower and upper riser angles have been investigated. In order to ensure a safe operation, these angles must be within acceptable limits. While the allowable magnitude of the upper riser angle may be modified by changing the moonpool design, the lower angle is more constrained. An excessive lower angle may imply damage to the BOP, and a blow-out may be the final result. Two water depths have been investigated: 300 [m], which has been classified as *shallow* water depth in this thesis, and 2000 [m], which is a typical *deep* water depth. The object was to identify decision criteria for optimal position and disconnect based on the riser angles. The main conclusion is that the traditional offset limits for where to disconnect from the well might be too conservative.

The riser behavior has been analyzed using the commercial software RIFLEX. The riser in shallow and deep water are modeled equally, except from the top tension and the riser component types. The riser at 2000 [m] requires a higher top tension in addition to buoyancy modules in order to reduce the required top tension. Unidirectional current profiles, regular waves and vessel motions were implemented in the analyses in order to investigate the riser angles for various environmental conditions. The vessel motions comprise of various vessel drive-offs, which is an uncontrolled excursion of the vessel resulting from a failure in the DP system, in addition to low-frequency harmonic motions of the vessel. For the purpose of future monitoring of the riser angles, the mathematical modeling of the riser and the vessel is included. Also, the main principles and structure of a horizontal-plane controller with roll and pitch damping have been formulated. For small water-plane-area vessels, such as semi-submersibles, an unintentional coupling phenomena between the horizontal-plane and the vertical-plane through the thruster action may be invoked. This may result in excitation of roll and pitch, and this must be taken into account by the controller.

The simulations revealed significant differences in the riser behavior in shallow waters and deep waters. At 300 [m] water depth, a vessel excursion from the zero offset position will rapidly give excessive riser angles. Current only marginally affects the riser at 300 [m]. At 2000 [m] water depth, however, the current has a significant impact on the riser. This is because the riser becomes more flexible when it becomes longer, and also because of the increased area due to the buoyancy modules. Vessel excursions will cause the upper angle to grow excessive because of the vessel velocity dependence of this angle. The lower angle will not respond immediately to a motion at the top end, and it increases slowly as the offset increases. For a static vessel offset within a radius of 100 [m] from the zero offset position, and with no current present, both angles stabilize at acceptable magnitudes. Regular waves have been found to affect the upper angle significantly more than the lower angle, both in shallow and deep water. By superposition, the maximum upper riser angle for a low-frequency motion in combination with waves can be found by adding together the maximum top angle for the low-frequency and the wave-frequency induced upper angle.

Guidance limits for the DP status levels based on the riser angles have been proposed. These indicate the vessel offsets for which the operation should continue without intervention, when the operator should position the vessel differently in order to improve the angles, and when a preparation for disconnect should be carried out. Compared to conventional guidance limits, the proposed limits are less conservative, especially in deep waters. However, a crucial aspect which must be taken into account in future studies is the fact that the upper riser angle magnitude will be in excess of the critical value for a limited period of time while the vessel is moving. If one can allow for temporary excessive top angles, an emergency disconnect resulting from the excessive angle can be avoided. Hence, the operation may be upheld for a longer period of time, and an unnecessary - and costly - disconnect may be avoided. These findings could be of industrial interest, and further studies should be carried out in order to confirm the results and propose monitoring methods based on these.

6.2 Proposals for further work

In order to implement an advisory system on drilling vessels, a monitoring system should be developed based on the findings in this study, in addition to future and more fulfilling analyses.

Some simplifications have been made during this study. Unidirectional current and regular waves have been applied. The current speed is based on mete-ocean data, while the current profile is unidirectional. Even though RIFLEX allows for three-dimensional analyses, only the motions and response in the xz-plane has been considered. Furthermore, the effect from wind has not been investigated. The top tension is kept constant for each water depth. However, for a given current or a vessel offset, the top tension could change.

The developed watch circles are time invariant and are valid for *static* offsets, only. However, we have seen that for vessel motions, the upper riser angle takes very different values dependent on the speed of the motion. Also, the current may not be steady. Hence, the watch circles for a given condition may vary depending on the vessel speed and the current. One should also conduct fatigue analyses to investigate the long-term effect from temporary contact between the top of the riser and the moonpool. By allowing for temporary excessive top angles, the operator will have more time to decide whether to disconnect or not, instead of carrying out a disconnect whenever the upper angle exceeds the critical value.

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A Riser data

In this appendix, information concerning the riser and the modeling of the riser is included.

The riser is divided into 9 segments of different length. Both the riser at 300 and 2000 [m] water depth have a 50 [m] long segment below the sea bottom.

A.1 Riser segment numbering

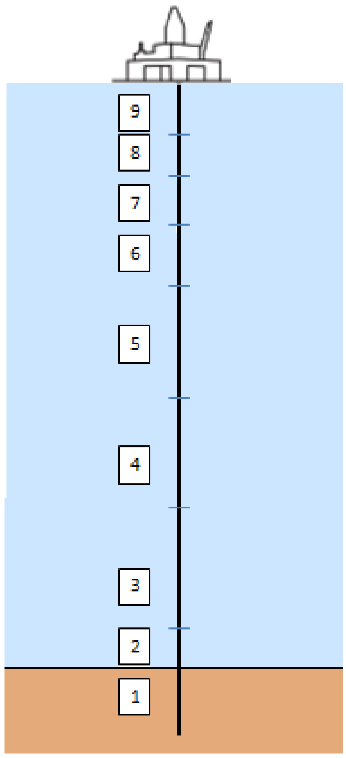

Figure A.1: Riser segment numbering

A.2 Riser segment data

Table A.1: Riser components

Component type	1	2
External diameter [m]	0.5334	0.5334
Internal diameter [m]	0.5014	0.5014
Density of material [$\frac{kg}{m^3}$]	8250	8250
Density of mud [$\frac{kg}{m^3}$]	1300	1300
Thickness of buoyancy material [m]	-	0.15
Density of buoyancy material [$\frac{kg}{m^3}$]	-	400

Table A.2: Riser segment data at 2000 [m] water depth

Riser segment	Component type	Length [m]
1	1	50
2	1	3
3	2	582
4	2	200
5	2	1100
6	1	50
7	1	30
8	1	3
9	1	32

Table A.3: Riser segment data at 300 [m] water depth

Riser segment	Component type	Length [m]
1	1	50
2	1	3
3	1	80
4	1	30
5	1	148
6	1	2.5
7	1	1.5
8	1	3
9	1	32

B Simulation data

B.1 Transfer functions

The vessel transfer functions are located on the file dsa500.dat, and it is referred to at the end of the inpmod-file. dsa500.dat is found in *Simulation files* on the attached CD.

B.2 Simulation of environmental conditions

Current and regular waves are easily introduced in the analyses by adding the relevant input line in the INPMOD file.

Regular waves in combination with irregular vessel motions are modeled by defining a wave spectrum that will give a peak for the desired period T_{max}, only.

B.3 Simulation of vessel motions

B.3.1 Vessel drive-off

In the DYNMOD module in RIFLEX, irregular analysis is applied, and a DAT-file containing the time series for the low-frequency motion is given as input. The DAT-file may contain wave-frequency motions as well. The low-frequency motion is generated by the superposition of a quadratic function and a constant value in the MATLAB-file *stepfunc*. In order to have a smooth transition from the quadratic function to the constant value (to avoid an error in RIFLEX), the generated time series are modified in excel before it is copied into a DAT-file.

The DAT-files are named in the following way:

- stepxm_xs_1: a drive-off to x [m] during x[s], with a time increment of 1 [s]
- stepxm_xs: a drive-off to x [m] during x[s], with a time increment of 0.5 [s]
- stepnegxm_xs_1: a drive-off to -x [m] during x[s], with a time increment of 1 [s]
- stepnegxm_xs: a drive-off to -x [m] during x[s], with a time increment of 0.5 [s]
- stepxm: a drive-off to x [m] during a certain amount of time, can easily be found by studying the DAT-file of interest.

All DAT-files used in the analyses can be found in *Simulation files* on the attached CD.

A vessel drive-off in combination with regular waves is simulated by applying the method described in B.2.

RIFLEX files applied:

- 300c_inpmod.inp/2000c_inpmod.inp
- 300c_stamod.inp/2000c_stamod.inp
- 300irreg_dynmod.inp/2000irreg_dynmod.inp

B.3.2 Low-frequency harmonic motions

Regular analysis is applied, and the amplitude and period of the harmonic motion are defined in under the input line REGULAR VESSEL MOTION.

RIFLEX files applied:

- 300c_inpmod.inp/2000c_inpmod.inp
- 300c_stamod.inp/2000c_stamod.inp
- 300c_dynmod.inp/2000c_dynmod.inp

B.4 Finding eigenvalues

The eigenvalues of the riser in shallow and deep water are easily found by choosing the option *Eigenvalue analysis* in the DYNMOD module.

RIFLEX files applied:

- 300c_inpmod.inp/2000c_inpmod.inp
- 300c_stamod.inp/2000c_stamod.inp
- eigenvalue_dynmod.inp

C RIFLEX input files

All RIFLEX files listed here are found in *Simulation files* on the attached CD.

C.1 Input files - 300 m

C.1.1 300c_inpmod

```
'
'       File name ..... :   300c_inpmod.inp
'       Content ....... :   Input file for tensioned riser, 300 m water depth
'       Anna Ervik, June 2011
' -----------------------------------
'
   INPMOD IDENTIFICATION TEXT  3.6
+
+  Master thesis spring 2011
+
'
' -----------------------------------
'
   UNIT NAME SPECIFICATION
  sec  meter  mg    kN  9.81  1.0
'
' -----------------------------------
'
   NEW SINGLE RISER
  AR   RISER
'
'------------------------------------
'
   ARBITRARY SYSTEM AR
' nsnod  nlin  nsnfix  nves nricon  nspr  nakc
    3     2      3      1     0      22
' ibtang   zbot   ibot3d
   1       -300.    0
' stfbot   stfaxi   stfflat   friaxi   frilat
    5000.       2500.      2500.       0.35       0.9
' ilinty   isnod1   isnod2
    1         1        2
    2         2        3
'
' Boundary conditions : Fixed or prescriebed supernodes
'
'  isnod ipos    ix    iy    iz     irx    iry   irz    chcoo chupro
     1     0     1     1     1      1      1     1      GLOBAL
'   x0      y0      z0       x1       y1      z1     rot    dir
    0.0     0.0    -350.0   0.0      0.0    -350.0  0.0   0.0
'  isnod ipos    ix    iy    iz     irx    iry   irz    chcoo chupro
     2     1     1     1     0      0      0     1      GLOBAL
'   x0      y0      z0       x1       y1      z1     rot    dir
    0.0     0.0     0.0      0.0     0.0     0.0     0.    0.0
'  isnod ipos    ix    iy    iz     irx    iry   irz    chcoo chupro
     3     1     1     1     0      0      0     1      GLOBAL
'  x0      y0      z0       x1       y1      z1     rot    dir
   0.0     0.0     10.0      0.0     0.0     10.0     0.    0.0
'
' ives chhftr xg      yg      zg    headng
   1  dsa500  0.     0.0    -3.0     0.0
'
```

```
'LINEAR SPRINGS
'ILIN ISEG INOD ILDOF STIFF DAMP A2
  1    1    1    1     3900
  1    1    1    2     3900
  1    1    2    1     3900
  1    1    2    2     3900
  1    1    3    1     3900
  1    1    3    2     3900
  1    1    4    1     3900
  1    1    4    2     3900
  1    1    5    1     3900
  1    1    5    2     3900
  1    1    6    1     3900
  1    1    6    2     3900
  1    1    7    1     3900
  1    1    7    2     3900
  1    1    8    1     3900
  1    1    8    2     3900
  1    1    9    1     3900
  1    1    9    2     3900
  1    1    10   1     3900
  1    1    10   2     3900
  1    1    11   1     3900
  1    1    11   2     3900
'-------------------------------
'------ LINE DATA --------------
'-------------------------------
'
    NEW LINE DATA
' ilinty nseg icnlty ifluty
    1      9    0     100
' icmpty icn1ty iexwty nelseg  slgth
    1       0        0   10    50
    1       0        0    3     3
    1       0       0   100   80
    1       0       0   50   30
    1       0       0   200   148
    1       0        0    20    2.5
    1       0        0    10    1.5
    1       0        0    3     3
    1       0        0   10    32
'
 NEW LINE DATA
' ilinty nseg icnlty ifluty
    2      1    0     0
' icmpty icn1ty iexwty nelseg  slgth
    1       3        0   1     10.
'-------------------------------
'------ COMPONENT DATA ---------
'-------------------------------
'
        NEW COMPONENT CRS0
'  Bare riser, density increased to account for couplings
'        icmpty  temp
        1       20.
'
'       diast   thst   densst  thex     densex
        0.5334  0.016  8.25    0.0      0.0
'
'       matkind emod       gmod
```

```
        1       206000000. 80000000.
'
'       dh is the hydrodynamic diameter (also used by VIVANA)
'
'        cqx      cqy      cax     cay     clx   cly    icode   dh
      0.0      0.8      0.      1.0     0.    0.     2       0.5334
'
'        tb            ycurmx
      14380.   0.4329
'  --------------------------------------------------------
'
        NEW COMPONENT CRS0
'  Riser with buoyancy material to reduce needed top tension
'          icmpty  temp
        2       20.
'
'       diast   thst   densst  thex     densex
        0.5334  0.016  8.25    0.15     0.4
'
'       matkind emod       gmod
        1       206000000. 80000000.
'
'       dh is the hydrodynamic diameter (also used by VIVANA)
'
'        cqx      cqy      cax     cay     clx   cly    icode   dh
      0.0      0.8      0.      1.0     0.    0.     2       0.83
'
'        tb            ycurmx
      14380.   0.4329
'
NEW COMPonent CONB
' icmpty
       3
'     am      ae
       0.     0.
' icoo   cdx    cdy    cdz    amx     amy    amz
  LOCAL   0.     0.     0.     0.      0.     0.
'  irx     iry    irz
     1       0     0
'
'------------------------------
'   COMPONENT F L U I D
'------------------------------
'
    NEW COMPONENT FLUID
' icompty
    100
' RHOI VVELI PRESSI DPRESS IDIR
  1.3   1      1     1      2
'
'------------------------------
'   COMPONENT B O D Y
'------------------------------
'
'    NEW COMPONENT BODY
' icompty
'   13
'
'       Mass and volume
'       am                ae
```

```
'        56.0E+6          54634.0
'
'   Hydrodynamic force coeff
'  icoo       cdx   cdy  cdz   amx      amy      amz
'   GLOBAL      20.  20.  10.   190.     190.     130.
'
'------------------------------
'   ENVIRONMENTAL DESCRIPTION
'------------------------------
'
    ENVIRONMENT IDENTIFICATION
  Environment descriptions
' idenv
  ENVIR
'------------------------------
    WATERDEPTH AND WAVETYPE
' wdepth  noirw  norw  ncusta
  300.    1       1      4
'------------------------------
    ENVIRONMENT CONSTANTS
' airden  watden  wakivi
  .0013   1.025   1.89E-6
'------------------------------
NEW IRREGULAR SEASTATE
' nirwc   iwasp1   iwadr1   iwasp2   iwadr2
  1       5        0        0        0
WAVE SPECTRUM WIND
'ndfrq1
  7
'frq            dspden
  0              0
  0.3400         0
  0.3470         0
  0.3480       2067.6
  0.3500       2067.6
  0.3510         0
  0.5000         0
DIRECTION PARAMETERS
' wadr1   expo1
  0.      1.
'
'NEW IRREGULAR SEASTATE
'                     2: JW, Hs = 16.5, TP=16.5, G = 3.0
' nirwc   iwasp1   iwadr1   iwasp2   iwadr2
'  2       9        0        0        0
'WAVE SPECTRUM WIND
' sigwh   peakpe   gamma
'  16.5    16.5     3.0
'DIRECTION PARAMETERS
' wadr1   expo1
'  90.       1.
'------------------------------------------------------------------
REGULAR WAVE DATA
' inrwc   amplit  period  wavdir
  1       2.0     17.0    0.0
'-------------------------------------------------------------------
    NEW CURRENT STATE
' icusta nculev
  1      3
' curlev  curdir  curvel
```

```
  0.       0.     0.0001
  -150.   0.     0.0001
  -300.   0.     0.0001
'------------------------------
    NEW CURRENT STATE
' icusta nculev
  2      3
' curlev  curdir  curvel
   0.       0.    0.3
 -150      0.    0.3
 -300.     0.    0.3
'------------------------------
    NEW CURRENT STATE
' icusta nculev
  3      3
' curlev  curdir  curvel
  0.       0.      0.6
  -150.   0.      0.6
  -300    0.      0.6
'------------------------------
    NEW CURRENT STATE
' icusta nculev
  4      3
' curlev  curdir  curvel
  0.       0.      1.0
  -150.   0.      1.0
  -300    0.      1.0
'------------------------------
    TRANSFER FUNCTION FILE
' chftra
   dsa500.tra
'
'------------------------------
'
     END
```

C.1.2 300c_stamod

```
'
'  File name ..... :   300c_stamod.inp
'  Content ....... :   input file for tensioned riser, 300 m water depth
'  Anna Ervik, June 2011
'
'---------------------------------------------------------
'
    STAMOD CONTROL INFORMATION  3.6
'---------------------------------------------------------
+
+  Master thesis spring 2011.
+
'
'---------------------------------------------------------
' irunco  idris  ianal  iprdat  iprcat  iprfem  ipform  iprnor  ifilfm  ifilco
'---------------------------------------------------------
   1      RISER     1     2      5       1       2       1     2
'---------------------------------------------------------
    RUN IDENTIFICATION
'---------------------------------------------------------
' idres
 STRISER
'
'---------------------------------------------------------
    ENVIRONMENT REFERENCE IDENTIFIER
'---------------------------------------------------------
' idenv
  ENVIR
'
'---------------------------------------------------------
    STATIC CONDITION INPUT
'---------------------------------------------------------
' nlcomp  icurin  curfac
    2       1      1.
'   0       0      0.0
'
'  ilin   ilseg   ilnode   ildof   rlmag
     1       9       11       3    1650.
     2       1        2       3      10.
'---------------------------------------------------------
    COMPUTATIONAL PROCEDURE
'---------------------------------------------------------
'
    FEM
'
'---------------------------------------------------------
    FEM ANALYSIS PARAMETERS
'---------------------------------------------------------
'
    LOAD GROUP DATA
'   NSTEP     MAXIT     RACU
    1         100       1.00E-6
    SPRING
'
    LOAD GROUP DATA
'   NSTEP     MAXIT   RACU
    1         100     1.00E-6
    SFOR
'
```

```
    LOAD GROUP DATA
'   nstep  maxit      racu
    10      10      1.E-6
'   lotype
    VOLU
'
    LOAD GROUP DATA
'   nstep  maxit      racu
    20     100      1.E-6
'   lotype
    DISP
'
    LOAD GROUP DATA
'   nstep  maxit      racu
    100     100      1.E-6
'   lotype
    CURR
'
'-------------------------------------------------------
'   PARAMETER VARIATION DEFINITION
'-------------------------------------------------------
' NSTVAR IOFPOS ICUVAR IFOVAR MAXIPV RACUPV
'    1      1      0      0      5      1.E-6
'-----------------------------------------------------
'   STATIC OFFSET INCREMENTS
'------------------------------------------------------
' IREF DXOFF DYOFF DZOFF IROT DROT
'    -1   1    0     0     0    0
'------------------------------------------------------
' STAMOD PRINT CONTROL
'------------------------------------------------------
' ISTEP ISFOR ISPOS
'   1      0     1
'
'------------------------------------------------------
'
 END
```

C.1.3 300c_dynmod

```
'
'      File name ..... :   300c_dynmod.inp
'      Content ....... :   dynamic analysis of tensioned riser
'      Anna Ervik, June 2011
' ----------------------------------
'
      DYNMOD CONTROL INFORMATION  3.6
' -------------------------------------------------------------------
+
+  Master thesis spring 2011.
+
' -------------------------------------------------------------------
'     irunco ianal  idris   idenv   idsta   idirr idres
     ANAL    REGU   RISER  ENVIR   STRISER  IDIRR DYNRISER
' -------------------------------------------------------------------
'        IRREG TIMESERIES PARAM
' -------------------------------------------------------------------
'   irand  time  dtwf
'    1      2048. 1.
' -------------------------------------------------------------------
'        IRREG RESP ANALYSIS
' -------------------------------------------------------------------
' ircno   time    dt      irwav   irmot   irlfm   tbeg    iscale
'  1       2047.0    1.0     FILE     FILE    FILE    0.0
'
'WAVE TIME SERIES
' chftsf    iform   icotim  icowav
'  100sneg.dat   ASCI    1       2
' wavdir    xgwav   ygwav   tmin    tmax
'  0.0
'
'WFMO TIME SERIES
'ives      chftsf     iform   ikind  irot   icotim  -xg   -yg   -zg   '-xgr -ygr -zgr
'  1         100sneg.dat ASCI    DYND   RADI    1       3 0 0 0 0 0
'
'LFMO TIME SERIES
'ives      chftsf     iform   ikind   irot  icotim  -xg   -yg   -zgr
'  1        100sneg.dat  ASCI     DYND   RADI    1       4     0    0
'
' -------------------------------------------------------------------
'        IRREG WAVE PROCEDURE
' -------------------------------------------------------------------
' iuppos  icosim kinoff chstep nodstp zlower zupper
'    1       1      0      NODE   1     -300. 0.
' -------------------------------------------------------------------
'         IRREG FOURIER PRINT
' -------------------------------------------------------------------
'    ipmoti  ipwafo  iphfts  iplfts  iptomo  ipveac
'      0       0       0       0       0        0
'' ------------------------------------------------------------------
      REGUL WAVE ANAL
' -------------------------------------------------------------------
'    nper nstppr irwcn imotd
       15   120     1     1
' -------------------------------------------------------------------
        REGULAR WAVE LOAD
' -------------------------------------------------------------------
'    iwtyp isurf iuppos
'                   -  airy
```

```
     1      2     2
' -----------------------------------------------------------------
'       REGULAR VESSEL MOTION
' xamp  yamp zamp xramp yramp zramp per
'   30     0   0    0     0     0     60
' xpha  ypha  zpha xrpha yrpha zrpha
'   0      0    0    0     0      0
'------------------------------------------------------------------
      REGWAVE PRINT OPTION
' -----------------------------------------------------------------
'     nprend nprenf  nprenc
         1       1       1
' -----------------------------------------------------------------
         TIME DOMAI PROCEDURE
' -----------------------------------------------------------------
'                                  -  nonlinear analysis  : Newmark
'    itdmet inewil idisst iforst icurst istrst
     2      1      1      1      1        1
'    betin gamma  tetha    a1     a2   a1t  a1to  a1b   a2t  a2to  a2b
    4.0    .5     1.0      0.0   0.3    0.   0.    0.    0.   0.    0.
'    indint indhyd maxlit epshyd ntramp indrel iconre istepr ldamp
      1      1      5     0.05     12.    0   0       0      1
' -----------------------------------------------------------------
        NONLINEAR INTEGRATION PROCEDURE
' -----------------------------------------------------------------
'     itfreq isolit  maxit   daccu   icocod
        1      1      10     1.0E-6     1   1   1
'-----------------------------------------------------------------
'DYNAMIC NODAL FORCES
' ndcomp   cinput    chfloa
'   1        FILE     topten.dat
'  ilin   ilseg   ilnod   ildof   chicoo
'   1      9       11       3       GLOBAL
' -----------------------------------------------------------------
       DISPLACEMENT RESPONSE STORAGE
' -----------------------------------------------------------------
'        idisp nodisp  idisfm  cfndis
           1    10        2      300eigen_4_17_noddis
'        ilin   iseg   inod
           1      1     ALL
           1      2     ALL
           1      3     ALL
           1      4     ALL
           1      5     ALL
           1      6     ALL
           1      7     ALL
           1      8     ALL
           1      9     ALL
           2      1     ALL
'-----------------------------------------------------------------
       FORCE RESPONSE STORAGE
' -----------------------------------------------------------------
'        iforc noforc  iforfm  cfnfor
           1     9
'        ilin  iseg  inod
          1      1     ALL
           1      2     ALL
           1      3     ALL
           1      4     ALL
           1      5     ALL
```

```
          1      6     ALL
          1      7     ALL
          1      8     ALL
          1      9     ALL
' -------------------------------------------------------------------
       CURVATURE RESPONSE STORAGE
' -------------------------------------------------------------------
'        icurv nocurv  icurfm  cfncur
         1   9
'        ilin  iseg  inod
          1      1     ALL
          1      2     ALL
          1      3     ALL
          1      4     ALL
          1      5     ALL
          1      6     ALL
          1      7     ALL
          1      8     ALL
          1      9     ALL
' -------------------------------------------------------------------
       ENVELOPE CURVE SPECIFICATION
' -------------------------------------------------------------------
'       ienvd  ienvf  ienvc  tenvs  tenve  nprend   nprenf  nprenc
         1      1      1     0.     1.E+6    1        1       1
' -------------------------------------------------------------------
       STROKE RESPONSE STORAGE
'--------------------------------------------------------------------
'       istro  inodst  iopstr   setlen  xrstro  yrstro  nlinst
         2      2       1      0.0     0.0     0.0     1
'--------------------------------------------------------------------
       END
' -------------------------------------------------------------------
```

C.1.4 300irreg_dynmod

```
'
'       File name ..... :   300irreg_dynmod.inp
'       Content ....... :   dynamic analysis of tensioned riser, 300
'       Anna Ervik, June 2011
' ---------------------------------
'
      DYNMOD CONTROL INFORMATION  3.6
' ----------------------------------------------------------------
+
+  Master thesis spring 2011.
+
' ----------------------------------------------------------------
'     irunco ianal  idris   idenv   idsta   idirr idres
     ANAL    IRREGU   RISER  ENVIR   STRISER  IDIRR DYNRISER
' ----------------------------------------------------------------
         IRREG TIMESERIES PARAM
' ----------------------------------------------------------------
'   irand  time  dtwf
'    1      2048. 0.5
     1      801   1
' ----------------------------------------------------------------
        IRREG RESP ANALYSIS
' ----------------------------------------------------------------
' ircno   time    dt      irwav   irmot   irlfm   tbeg    iscale
'  1       2047.0    0.5     FILE    FILE    FILE    0.0
   1       800.0    1.0     FILE     FILE    FILE    0.0
'
WAVE TIME SERIES
' chftsf    iform   icotim  icowav
  100s_incrvel_20.dat   ASCI    1       2
' wavdir    xgwav   ygwav   tmin    tmax
  0.0
'
WFMO TIME SERIES
'ives      chftsf   iform ikind irot icotim -xg -yg -zg -xgr -ygr -zgr
  1         100s_incrvel_20.dat ASCI    DYND   RADI    1  3 0 0 0 0 0
'
LFMO TIME SERIES
'ives      chftsf     iform   ikind   irot  icotim  -xg   -yg   -zgr
  1  100s_incrvel_25.dat  ASCI     DYND   RADI    1       4     0     0
'
' ----------------------------------------------------------------
        IRREG WAVE PROCEDURE
' ----------------------------------------------------------------
' iuppos  icosim kinoff chstep nodstp zlower zupper
    1       1      0      NODE   1     -300. 10.
' ----------------------------------------------------------------
         IRREG FOURIER PRINT
' ----------------------------------------------------------------
'    ipmoti  ipwafo  iphfts  iplfts  iptomo  ipveac
      0       0       0       0       0        0
'' ---------------------------------------------------------------
'       REGUL WAVE ANAL
' ----------------------------------------------------------------
'    nper nstppr irwcn imotd
'      15   120     1     1
' ----------------------------------------------------------------
'         REGULAR WAVE LOAD
' ----------------------------------------------------------------
```

```
'    iwtyp isurf iuppos
'                   -  airy
'     1      2     2
' -------------------------------------------------------------------
'       REGULAR VESSEL MOTION
' xamp  yamp zamp xramp yramp zramp per
'   50     0   0    0     0     0     600
' xpha  ypha  zpha xrpha yrpha zrpha
'   0      0    0    0     0      0
'--------------------------------------------------------------------
'       REGWAVE PRINT OPTION
' -------------------------------------------------------------------
'     nprend nprenf  nprenc
'         1       1       1
' -------------------------------------------------------------------
          TIME DOMAI PROCEDURE
' -------------------------------------------------------------------
'                                    -  nonlinear analysis  : Newmark
'    itdmet inewil idisst iforst icurst istrst
     2      1      1      1      1        1
'    betin gamma  tetha    a1     a2   a1t  a1to  a1b   a2t  a2to  a2b
    4.0    .5    1.0      0.0   0.3    0.   0.    0.    0.   0.    0.
'    indint indhyd maxlit epshyd ntramp indrel iconre istepr ldamp
      1      1      5     0.05     12.    0   0       0      1
' -------------------------------------------------------------------
         NONLINEAR INTEGRATION PROCEDURE
' -------------------------------------------------------------------
'     itfreq isolit  maxit   daccu   icocod
        1      1      10     1.0E-6     1   1   1
'-------------------------------------------------------------------
'DYNAMIC NODAL FORCES
' ndcomp   cinput    chfloa
'   1        FILE     topten.dat
'  ilin   ilseg   ilnod   ildof   chicoo
'   1      9       11       3       GLOBAL
' -------------------------------------------------------------------
        DISPLACEMENT RESPONSE STORAGE
' -------------------------------------------------------------------
'        idisp nodisp  idisfm  cfndis
           1    10        2      300step25_c_incrvel_noddis
'        ilin   iseg   inod
           1      1     ALL
           1      2     ALL
           1      3     ALL
           1      4     ALL
           1      5     ALL
           1      6     ALL
           1      7     ALL
           1      8     ALL
           1      9     ALL
           2      1     ALL
'-------------------------------------------------------------------
        FORCE RESPONSE STORAGE
' -------------------------------------------------------------------
'        iforc noforc  iforfm  cfnfor
           1     9
'        ilin  iseg  inod
          1      1     ALL
           1      2     ALL
           1      3     ALL
```

```
           1      4     ALL
           1      5     ALL
           1      6     ALL
           1      7     ALL
           1      8     ALL
           1      9     ALL
' --------------------------------------------------------------------
        CURVATURE RESPONSE STORAGE
' --------------------------------------------------------------------
'        icurv nocurv  icurfm  cfncur
          1   9
'        ilin  iseg  inod
           1      1     ALL
           1      2     ALL
           1      3     ALL
           1      4     ALL
           1      5     ALL
           1      6     ALL
           1      7     ALL
           1      8     ALL
           1      9     ALL
' --------------------------------------------------------------------
        ENVELOPE CURVE SPECIFICATION
' --------------------------------------------------------------------
'       ienvd  ienvf  ienvc  tenvs  tenve  nprend   nprenf  nprenc
          1      1      1     0.     1.E+6    1        1       1
' --------------------------------------------------------------------
        STROKE RESPONSE STORAGE
'---------------------------------------------------------------------
'       istro  inodst  iopstr   setlen  xrstro  yrstro  nlinst
          2      2        1      0.0     0.0     0.0     1
'---------------------------------------------------------------------
        END
' --------------------------------------------------------------------
```

C.2 Input files - 2000 m

C.2.1 2000c_inpmod

```
'
'       File name ..... :   2000c_inpmod.inp
'       Content ....... :   Input file for tensioned riser, 2000 m water depth
'       Anna Ervik, June 2011
' -----------------------------------
'
   INPMOD IDENTIFICATION TEXT  3.6
+
+  Master thesis spring 2011
+
'
' -----------------------------------
'
   UNIT NAME SPECIFICATION
  sec  meter  mg    kN  9.81  1.0
'
' -----------------------------------
'
   NEW SINGLE RISER
  AR   RISER
'
'------------------------------------
'
   ARBITRARY SYSTEM AR
' nsnod  nlin  nsnfix  nves nricon  nspr  nakc
    3     2      3      1     0      22
' ibtang   zbot   ibot3d
   1       -2000.    0
' stfbot   stfaxi   stfbat   friaxi   frilat
    5000.       2500.      2500.       0.35       0.9
' ilinty   isnod1   isnod2
    1         1        2
    2         2        3
'
' Boundary conditions : Fixed or prescriebed supernodes
'
'  isnod ipos    ix    iy    iz     irx    iry   irz    chcoo chupro
     1     0     1     1     1      1      1     1      GLOBAL
'            x0      y0      z0       x1       y1      z1     rot    dir
             0.0     0.0    -2050.0   0.0      0.0    -2050.0  0.0   0.0
'  isnod ipos    ix    iy    iz     irx    iry   irz    chcoo chupro
     2     1     1     1     0      0      0     1      GLOBAL
'            x0      y0      z0       x1       y1      z1     rot    dir
             0.0     0.0     0.0      0.0     0.0     0.0     0.    0.0
'  isnod ipos    ix    iy    iz     irx    iry   irz    chcoo chupro
     3     1     1     1     0      0      0     1      GLOBAL
'            x0      y0      z0       x1       y1      z1     rot    dir
             0.0     0.0     10.0      0.0     0.0     10.0     0.    0.0
'
' ives chhftr xg      yg      zg    headng
   1  dsa500  0.0     0.0    -3.0     0.0
'
'LINEAR SPRINGS
'ILIN ISEG INOD ILDOF STIFF DAMP A2
  1    1    1    1     3900
  1    1    1    2     3900
  1    1    2    1     3900
```

```
  1    1    2    2     3900
  1    1    3    1     3900
  1    1    3    2     3900
  1    1    4    1     3900
  1    1    4    2     3900
  1    1    5    1     3900
  1    1    5    2     3900
  1    1    6    1     3900
  1    1    6    2     3900
  1    1    7    1     3900
  1    1    7    2     3900
  1    1    8    1     3900
  1    1    8    2     3900
  1    1    9    1     3900
  1    1    9    2     3900
  1    1    10   1     3900
  1    1    10   2     3900
  1    1    11   1     3900
  1    1    11   2     3900
'------------------------------
'------ LINE DATA --------------
'------------------------------
'
    NEW LINE DATA
' ilinty nseg icnlty ifluty
    1      9    0     100
' icmpty icn1ty iexwty nelseg  slgth
    1       0        0   10    50
    1       0        0    3     3
    2       0        0    100   582
    2       0        0    50    200
    2       0        0    200   1100
    1       0        0    20    50
    1       0        0    10    30
    1       0        0    3     3
    1       0        0    10    32
'
    NEW LINE DATA
' ilinty nseg icnlty ifluty
    2      1    0     0
' icmpty icn1ty iexwty nelseg  slgth
    1       3        0   1     10.
'------------------------------
'------ COMPONENT DATA ---------
'------------------------------
'
        NEW COMPONENT CRS0
'  Bare riser, density increased to account for couplings
'        icmpty  temp
        1       20.
'
'       diast   thst   densst  thex     densex
        0.5334  0.016  8.25    0.0      0.0
'
'       matkind emod       gmod
        1       206000000. 80000000.
'
'       dh is the hydrodynamic diameter (also used by VIVANA)
'
'        cqx      cqy      cax     cay     clx   cly    icode   dh
```

```
        0.0      0.8      0.      1.0     0.    0.     2       0.5334
'
'        tb            ycurmx
      14380.   0.4329
'  -------------------------------------------------------
'
        NEW COMPONENT CRS0
'  Riser with buoyancy material to reduce needed top tension
'          icmpty  temp
        2       20.
'
'       diast   thst   densst  thex     densex
        0.5334  0.016  8.25    0.15     0.4
'
'       matkind emod       gmod
        1       206000000. 80000000.
'
'       dh is the hydrodynamic diameter (also used by VIVANA)
'
'        cqx      cqy      cax      cay      clx   cly    icode   dh
      0.0      0.8      0.      1.0     0.    0.     2       0.83
'
'        tb            ycurmx
      14380.   0.4329
'
NEW COMPonent CONB
' icmpty
       3
'     am      ae
       0.     0.
' icoo   cdx    cdy    cdz    amx     amy    amz
  LOCAL   0.     0.     0.     0.      0.     0.
'  irx     iry    irz
     1       0     0
'
'-------------------------------
'   COMPONENT F L U I D
'-------------------------------
'
    NEW COMPONENT FLUID
' icompty
   100
' RHOI VVELI PRESSI DPRESS IDIR
  1.3   1      1     1      2
'
'-------------------------------
'   ENVIRONMENTAL DESCRIPTION
'-------------------------------
'
    ENVIRONMENT IDENTIFICATION
  Environment descriptions
' idenv
  ENVIR
'-------------------------------
    WATERDEPTH AND WAVETYPE
' wdepth  noirw  norw  ncusta
  2000.    1      1     4
'-------------------------------
    ENVIRONMENT CONSTANTS
' airden  watden  wakivi
```

```
  .0013   1.025   1.89E-6
'-------------------------------
NEW IRREGULAR SEASTATE
' nirwc   iwasp1   iwadr1   iwasp2   iwadr2
  1       5        0        0        0
WAVE SPECTRUM WIND
'ndfrq1
  7
'frq            dspden
  0              0
  0.3400         0
  0.3470         0
  0.3480       2067.6
  0.3500       2067.6
  0.3510         0
  0.5000         0
DIRECTION PARAMETERS
' wadr1   expo1
  0.      1.
'-----------------------------------------------------------------
REGULAR WAVE DATA
' inrwc   amplit  period  wavdir
  1       4.0     15.78    0.0
'------------------------------------------------------------------
    NEW CURRENT STATE
' icusta nculev
  1      3
' curlev  curdir  curvel
  0.       0.     0.0001
  -1000.   0.     0.0001
  -2000.   0.     0.0001
'-------------------------------
    NEW CURRENT STATE
' icusta nculev
  2      3
' curlev  curdir  curvel
   0.       0.    0.3
 -1000      0.    0.3
 -2000.     0.    0.3
'-------------------------------
    NEW CURRENT STATE
' icusta nculev
  3      3
' curlev  curdir  curvel
  0.       0.      0.6
  -1000.   0.      0.6
  -2000    0.      0.6
'-------------------------------
    NEW CURRENT STATE
' icusta nculev
  4      5
' curlev  curdir  curvel
  0.       0.0      0.6
  -500    0.0      0.4
  -1000    0.0      0.2
  -1500    0.0      0.1
  -2000    0.0      0.1
'-------------------------------
    TRANSFER FUNCTION FILE
' chftra
```

```
   dsa500.tra
'
'-------------------------------
'
     END
```

C.2.2 2000c_stamod

```
'
'  File name ..... :   2000c_stamod.inp
'  Content ....... :   input file for tensioned riser, 2000 m water depth
'  Anna Ervik, June 2011
'-------------------------------------------------------
'
    STAMOD CONTROL INFORMATION  3.6
'-------------------------------------------------------
+
+  Master thesis spring 2011.
+
'
'-------------------------------------------------------
' irunco  idris  ianal  iprdat  iprcat  iprfem  ipform  iprnor  ifilfm  ifilco
'-------------------------------------------------------
   1      RISER     1     2      5       1       2       1     2
'-------------------------------------------------------
    RUN IDENTIFICATION
'-------------------------------------------------------
' idres
 STRISER
'
'-------------------------------------------------------
    ENVIRONMENT REFERENCE IDENTIFIER
'-------------------------------------------------------
' idenv
   ENVIR
'
'-------------------------------------------------------
    STATIC CONDITION INPUT
'-------------------------------------------------------
' nlcomp  icurin  curfac
    2       4      1.
'   0       0      0.0
'
'  ilin   ilseg   ilnode   ildof   rlmag
      1       9       11       3    4000.
      2       1        2       3      10.
'-------------------------------------------------------
    COMPUTATIONAL PROCEDURE
'-------------------------------------------------------
'
    FEM
'
'-------------------------------------------------------
    FEM ANALYSIS PARAMETERS
'-------------------------------------------------------
'
    LOAD GROUP DATA
'   NSTEP     MAXIT     RACU
    1         100       1.00E-6
    SPRING
'
    LOAD GROUP DATA
'   NSTEP     MAXIT   RACU
    1         100     1.00E-6
    SFOR
'
    LOAD GROUP DATA
```

```
'   nstep  maxit      racu
    10      10      1.E-6
'   lotype
    VOLU
'
    LOAD GROUP DATA
'   nstep  maxit      racu
    50     100      1.E-6
'   lotype
    DISP
'
    LOAD GROUP DATA
'   nstep  maxit      racu
    100     100      1.E-6
'   lotype
    CURR
'
'------------------------------------------------------------
'
 END
```

C.2.3 2000c_dynmod

```
'
'       File name ..... :   2000c_dynmod.inp
'       Content ....... :   dynamic analysis of tensioned riser
'       Anna Ervik, June 2011
' -----------------------------------
'
      DYNMOD CONTROL INFORMATION  3.6
' ------------------------------------------------------------------
+
+  Master thesis spring 2011.
+
' ------------------------------------------------------------------
'     irunco ianal  idris   idenv   idsta   idirr idres
     ANAL    REGU   RISER  ENVIR   STRISER  IDIRR DYNRISER
' ------------------------------------------------------------------
'         IRREG TIMESERIES PARAM
' ------------------------------------------------------------------
'   irand  time  dtwf
'    1      2048. 1.
' ------------------------------------------------------------------
'        IRREG RESP ANALYSIS
' ------------------------------------------------------------------
' ircno   time    dt      irwav   irmot   irlfm   tbeg    iscale
'  1       2047.0    1.0     FILE     FILE     FILE    0.0
'
'WAVE TIME SERIES
' chftsf    iform   icotim  icowav
'  100sneg.dat ASCI    1       2
' wavdir    xgwav   ygwav   tmin    tmax
'  0.0
'
'WFMO TIME SERIES
'ives      chftsf     iform   ikind  irot   icotim  -xg   -yg   -zg  '-'xgr -ygr -zgr
'  1         100sneg.dat ASCI    DYND   RADI    1       3 0 0 0 0 0
'
'LFMO TIME SERIES
'ives      chftsf     iform   ikind   irot  icotim  -xg   -yg   -zgr
'  1        100sneg.dat  ASCI     DYND   RADI    1       4     0    0
'
' ------------------------------------------------------------------
'         IRREG WAVE PROCEDURE
' ------------------------------------------------------------------
' iuppos  icosim kinoff chstep nodstp zlower zupper
'    1       1      0      NODE   1     -2000. 0.
' ------------------------------------------------------------------
'         IRREG FOURIER PRINT
' ------------------------------------------------------------------
'    ipmoti  ipwafo  iphfts  iplfts  iptomo  ipveac
'      0       0       0       0       0        0
'' -----------------------------------------------------------------
      REGUL WAVE ANAL
' ------------------------------------------------------------------
'    nper nstppr irwcn imotd
      15   120     1     1
'       15   120      0     2
' ------------------------------------------------------------------
        REGULAR WAVE LOAD
' ------------------------------------------------------------------
'    iwtyp isurf iuppos
```

```
     1      2     2
' ------------------------------------------------------------------
'       REGULAR VESSEL MOTION
' xamp  yamp zamp xramp yramp zramp per
'   30     0   0    0     0     0  1200
' xpha  ypha  zpha xrpha yrpha zrpha
'   0      0    0    0     0      0
'-------------------------------------------------------------------
      REGWAVE PRINT OPTION
' ------------------------------------------------------------------
'     nprend nprenf  nprenc
         1       1       1
' ------------------------------------------------------------------
          TIME DOMAI PROCEDURE
' ------------------------------------------------------------------
'                                  -  nonlinear analysis  : Newmark
'    itdmet inewil idisst iforst icurst istrst
     2      1      1      1      1        1
'    betin gamma  tetha    a1     a2   a1t  a1to  a1b   a2t  a2to  a2b
    4.0    .5     1.0      0.0   0.3    0.   0.    0.    0.   0.    0.
'    indint indhyd maxlit epshyd ntramp indrel iconre istepr ldamp
      1      1      5     0.05     12.    0   0       0      1
' ------------------------------------------------------------------
         NONLINEAR INTEGRATION PROCEDURE
' ------------------------------------------------------------------
'     itfreq isolit  maxit   daccu   icocod
        1      1      10     1.0E-6     1   1   1
'-------------------------------------------------------------------
'DYNAMIC NODAL FORCES
' ndcomp   cinput    chfloa
'   1        FILE     topten.dat
'  ilin   ilseg   ilnod   ildof   chicoo
'   1      9       11       3       GLOBAL
' ------------------------------------------------------------------
        DISPLACEMENT RESPONSE STORAGE
' ------------------------------------------------------------------
'        idisp nodisp  idisfm  cfndis
           1    10        2      2000eigen_15_noddis
'        ilin   iseg   inod
           1      1     ALL
           1      2     ALL
           1      3     ALL
           1      4     ALL
           1      5     ALL
           1      6     ALL
           1      7     ALL
           1      8     ALL
           1      9     ALL
          2      1    ALL
'-------------------------------------------------------------------
        FORCE RESPONSE STORAGE
' ------------------------------------------------------------------
'        iforc noforc  iforfm  cfnfor
           1     9
'        ilin  iseg  inod
          1      1     ALL
           1      2     ALL
           1      3     ALL
           1      4     ALL
           1      5     ALL
```

```
            1      6     ALL
            1      7     ALL
            1      8     ALL
            1      9     ALL
' ------------------------------------------------------------------
        CURVATURE RESPONSE STORAGE
' ------------------------------------------------------------------
'        icurv nocurv  icurfm  cfncur
           1   9
'        ilin  iseg  inod
            1      1     ALL
            1      2     ALL
            1      3     ALL
            1      4     ALL
            1      5     ALL
            1      6     ALL
            1      7     ALL
            1      8     ALL
            1      9     ALL
' ------------------------------------------------------------------
        ENVELOPE CURVE SPECIFICATION
' ------------------------------------------------------------------
'       ienvd  ienvf  ienvc  tenvs  tenve  nprend   nprenf  nprenc
          1      1      1     0.     1.E+6    1        1       1
' ------------------------------------------------------------------
        STROKE RESPONSE STORAGE
'-------------------------------------------------------------------
'       istro  inodst  iopstr   setlen  xrstro  yrstro  nlinst
          2      2        1      0.0     0.0     0.0     1
'-------------------------------------------------------------------
        END
' ------------------------------------------------------------------
```

C.2.4 2000irreg_dynmod

```
'
'      File name ..... :   anna_dynmod.inp
'      Content ....... :   dynamic analysis of tensioned riser, 2000 m water depth
'      Anna Ervik, June 2011
' ----------------------------------
'
      DYNMOD CONTROL INFORMATION  3.6
' ------------------------------------------------------------------
+
+  Master thesis spring 2011.
+
' ------------------------------------------------------------------
'     irunco ianal  idris   idenv   idsta   idirr idres
     ANAL    IRRE   RISER  ENVIR   STRISER  IDIRR DYNRISER
' ------------------------------------------------------------------
        IRREG TIMESERIES PARAM
' ------------------------------------------------------------------
'   irand  time  dtwf
    1      801. 1.
' ------------------------------------------------------------------
       IRREG RESP ANALYSIS
' ------------------------------------------------------------------
' ircno   time    dt      irwav   irmot   irlfm   tbeg    iscale
  1       800.    1.0     FILE     FILE     FILE    0.0
'
WAVE TIME SERIES
' chftsf    iform   icotim  icowav
  100sneg_1_incrvel_30.dat ASCI    1       2
' wavdir    xgwav   ygwav   tmin    tmax
  0.0
'
WFMO TIME SERIES
'ives      chftsf     iform   ikind  irot   icotim  -xg   -yg   -zg  '-xgr -ygr -zgr
  1    100sneg_1_incrvel_30.dat ASCI    DYND   RADI   1  3 0 0 0 0 0
'
LFMO TIME SERIES
'ives      chftsf     iform   ikind   irot  icotim  -xg   -yg   -zgr
  1  150sneg_incrvel_2.dat  ASCI  DYND   RADI   1    4     0    0
'
' ------------------------------------------------------------------
        IRREG WAVE PROCEDURE
' ------------------------------------------------------------------
' iuppos  icosim kinoff chstep nodstp zlower zupper
    1       1      0      NODE   1     -2000. 0.
' ------------------------------------------------------------------
        IRREG FOURIER PRINT
' ------------------------------------------------------------------
'    ipmoti  ipwafo  iphfts  iplfts  iptomo  ipveac
      0       0       0       0       0       0
'' -----------------------------------------------------------------
'      REGUL WAVE ANAL
' ------------------------------------------------------------------
'    nper nstppr irwcn imotd
'      15   120     1     1
'       15   20      1     1
' ------------------------------------------------------------------
'         REGULAR WAVE LOAD
' ------------------------------------------------------------------
'    iwtyp isurf iuppos
```

```
'                  -  airy
'     1      2     2
' -----------------------------------------------------------------
'       REGULAR VESSEL MOTION
' xamp  yamp zamp xramp yramp zramp per
'   10     0   0    0     0     0     60
' xpha  ypha  zpha xrpha yrpha zrpha
'   0      0    0    0     0      0
'------------------------------------------------------------------
'      REGWAVE PRINT OPTION
' -----------------------------------------------------------------
'     nprend nprenf  nprenc
'         1       1       1
' -----------------------------------------------------------------
         TIME DOMAI PROCEDURE
' -----------------------------------------------------------------
'                                  -  nonlinear analysis  : Newmark
'    itdmet inewil idisst iforst icurst istrst
      2      1      1      1      1        1
'    betin gamma  tetha    a1     a2   a1t  a1to  a1b   a2t  a2to  a2b
     4.0    .5     1.0      0.0   0.3    0.   0.    0.    0.   0.    0.
'    indint indhyd maxlit epshyd ntramp indrel iconre istepr ldamp
       1      1      5     0.05     12.    0   0       0      1
' -----------------------------------------------------------------
        NONLINEAR INTEGRATION PROCEDURE
' -----------------------------------------------------------------
'     itfreq isolit  maxit   daccu   icocod
        1      1      10     1.0E-6     1   1   1
'------------------------------------------------------------------
'DYNAMIC NODAL FORCES
' ndcomp   cinput    chfloa
'   1        FILE     topten.dat
'  ilin   ilseg   ilnod   ildof   chicoo
'  1      9       11       3       GLOBAL
' -----------------------------------------------------------------
       DISPLACEMENT RESPONSE STORAGE
' -----------------------------------------------------------------
'        idisp nodisp  idisfm  cfndis
           1    10        2      2000stepneg150_c4_noddis
'        ilin   iseg   inod
           1      1     ALL
           1      2     ALL
           1      3     ALL
           1      4     ALL
           1      5     ALL
           1      6     ALL
           1      7     ALL
           1      8     ALL
           1      9     ALL
          2      1     ALL
'------------------------------------------------------------------
       FORCE RESPONSE STORAGE
' -----------------------------------------------------------------
'        iforc noforc  iforfm  cfnfor
           1     9
'        ilin  iseg  inod
          1      1     ALL
           1      2     ALL
           1      3     ALL
           1      4     ALL
```

```
          1      5     ALL
          1      6     ALL
          1      7     ALL
          1      8     ALL
          1      9     ALL
' -------------------------------------------------------------------
      CURVATURE RESPONSE STORAGE
' -------------------------------------------------------------------
'        icurv nocurv  icurfm  cfncur
         1   9
'        ilin  iseg  inod
          1      1     ALL
          1      2     ALL
          1      3     ALL
          1      4     ALL
          1      5     ALL
          1      6     ALL
          1      7     ALL
          1      8     ALL
          1      9     ALL
' -------------------------------------------------------------------
      ENVELOPE CURVE SPECIFICATION
' -------------------------------------------------------------------
'       ienvd  ienvf  ienvc  tenvs  tenve  nprend   nprenf  nprenc
         1      1      1     0.     1.E+6    1        1       1
' -------------------------------------------------------------------
      STROKE RESPONSE STORAGE
'--------------------------------------------------------------------
'       istro  inodst  iopstr   setlen  xrstro  yrstro  nlinst
         2      2       1      0.0     0.0     0.0     1
'--------------------------------------------------------------------
      END
' -------------------------------------------------------------------
```

C.3 Input file - eigenvalue_dynmod

```
'
'       File name ..... :   eigenvalue_dynmod.inp
'       Content ....... :   Eigenvalue analysis of tensioned riser
'       Anna Ervik, June 2011
' -----------------------------------
'
      DYNMOD CONTROL INFORMATION  3.6
' ------------------------------------------------------------------
+
+  Master thesis spring 2011.
+
' ------------------------------------------------------------------
'     irunco ianal  idris   idenv   idsta   idirr idres
     ANAL    EIGE   RISER  ENVIR   STRISER  IDIRR DYNRISER
' ------------------------------------------------------------------
        FREE VIBRATION OPTIONS
' ------------------------------------------------------------------
' neig   nvec
  13      0
'eps1 eps2 eps3 ksr maxit kex shift maxniv
 0    0    0    1   -2     1   0     100
'-------------------------------------------------------------------
         EIGE PRIN OPTI
'-------------------------------------------------------------------
' npeig  npvec  ipresw
  13       0      0
'-------------------------------------------------------------------
END
```